Émile Jean Louis Chappin

Simulating Energy Transitions

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GENERATION
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Simulating Energy Transitions

Simulating Energy Transitions

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op donderdag 16 juni 2011 om 10:00 uur
door

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Bestuurskundig ingenieur
geboren te Zoetermeer.

Dit proefschrift is goedgekeurd door de promotor:

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Samenstelling promotiecommissie:

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ISBN 978-90-79787-30-2

Published and distributed by: Next Generation Infrastructures Foundation
P.O. Box 5015, 2600 GA Delft, The Netherlands

Phone: +31 15 278 2564
Fax: +31 15 278 2563
E-mail: info@nextgenerationinfrastructures.eu
Website: http://www.nextgenerationinfrastructures.eu

This research was funded by the Next Generation Infrastructures Foundation and Delft University of Technology.

Keywords: transition, energy, agent-based modelling, socio-technical system, infrastructure, policy, intervention

Cover: oil painting *Leap* by Rosilyn Young (Roz), used with permission
Typeset by the author in LaTeX 2_ε in 10pt URW Garamond 8
Printed in the Netherlands by Gildeprint on G-print FSC Mixed Sources
Available at http://www.chappin.com/ChappinEJL-PhDthesis.pdf

FSC
Cert no. CU-COC-811465

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Acknowledgements

This dissertation is the result of four years of research at the Energy and Industry section in the faculty of Technology, Policy, and Management of Delft University of Technology. I greatly appreciate all who have contributed directly or indirectly to the content of the thesis, to the underlying work, and to my personal life during this period.

First and foremost, I express my gratitude to my copromotor dr. ir. Gerard Dijkema, who has proved remarkably effective in *shaping* my thesis as well as me as a person. The optimism and trust, the creative input, and all created opportunities have allowed me to excel during the last years. Furthermore, I would like to acknowledge the valuable contribution and the astounding sharpness of my promotor prof. dr. ir. Margot Weijnen.

I am honoured to have a highly knowledgeable committee. I appreciate all committee members for their participation and for their input in the process of finalizing this work. I acknowledge the feedback of prof. dr. ir. Alexander Verbraeck, who had to withdraw from the committee.

I am thankful to dr. Fereidoon Sioshansi, who asked the right questions at the right time: the outcome has become cornerstone to the thesis. I am grateful to ir. Frits Otte, who has enabled me to get an indication of the merits of the work by confronting the actual decision makers at the Dutch Ministry of Economic Affairs.

I have always felt welcome at the Energy & Industry section and I am grateful to my colleagues for their openness and their friendship. I have great memories of many travels together with Laurens, most notably those of the NGInfra Academy, of ‘dancing’ in Copacabana, and of feeling like ‘Roman senators’ while having a bath in the ancient Roman-style bathhouse in Istanbul. I am grateful for enjoying music with Ivo, when singing in our building’s basement, when playing together, and for all our music-oriented discussions. I appreciate Petra for the early opportunities to start teaching. I (also) enjoyed the talks about typesetting with Koen, and I remember various enjoyable and efficient programming sessions and discussions. Of course, we share great memories of our trip all around Lake Erie with Michiel. I admire Andreas’ and Alfredas’ optimism. Igor’s way of explaining the grand scheme of things is inspirational to many people. Chris is a true industrial ecologist. I thank Sharad and Reinier for their companionship. I am thankful for all the opportunities that Judith, Leslie, and Paulien have provided through Next Generation Infrastructures, which have substantiated the societal value and have raised the public awareness of the research underlying this dissertation and have done much more then funding my research. The MSc thesis projects and interns of Maarten, Robert, Donovan, and Amit have been vital for my dissertation. Our discussions and all their thorough research have allowed me to go the extra mile and both have allowed and forced me to think of what was truly important in the context of this dissertation.

I would like to thank my paranimfs Timo and Steven for their support throughout the years. My friendship with Timo lights up many of my days. I would be a different person if we had not decided to start making music together and combine many of our music-related efforts in our foundation. Steven's immense creativity continues to surprise me. Our lengthy discussions have been great fun and have always inspired me.

My family has always provided a solid and home base and has been the foundation for everything. I am grateful for all the editing work, for selecting and collecting so many relevant newspaper articles, for all those great (Christmas) dinners, for all the games, and for the research we will be doing together. Geertje, I treasure you for sharing the most precious times, for helping me to find a balanced life, and just for who you are.

The words of Aragorn, spoken at the dawn of battle in *the Return of the King* grasp both my optimism and my appreciation for all who joined me on my journey:

> *"A day may come when the courage of men fails, when we forsake our friends and break all bonds of fellowship, but it is not this day. An hour of woes and shattered shields, when the age of men comes crashing down! But it is not this day!"*

I sincerely hope this thesis may become a step towards a better way in which we live our lives. Well…now – as Elphaba sings in *Wicked* – I think *"it's time to trust my instincts, close my eyes, and leap!"* I sincerely hope this thesis helps our instincts and aids us in making the right choices. Let us take a leap of faith!

Émile Jean Louis Chappin – April 2011

1 Introduction and Problem

> You must be the change you wish to see in the world.
> *Mahatma Gandhi*

1.1 Transition of energy infrastructure systems

Energy infrastructures are the backbone of society, fundamental for many of our daily activities. For energy infrastructures (systems that satisfy needs for energy, Ajah, 2009) environmental, economic, and social sustainability are vital. Therefore, we have to address issues such as scarcity and the depletion of resources, accessibility, affordability, reliability and quality of energy services, and security of energy supply. It is widely acknowledged that we have to change our energy infrastructure systems during the 21st century in order to deal with these issues, for instance through the massive introduction of renewable energy technologies and by reduction of energy use. Core to this thesis is to explore simulation models as a tool for ex-ante assessment of actions proposed to bring about structural change in our energy infrastructures and achieve a transition.

The need for change has been addressed, for instance by setting EU and national targets for renewable energy. Despite considerable efforts and budgets of the Dutch government (Ministry of VROM, 2001), some say that more is required to actually achieve a transition (cf. RMNO, 2010). Safeguarding our infrastructures is not only about technical aspects. Also governance aspects are relevant in order to prevent the improper functioning of markets and ineffective/inefficient realization of long term public values (WRR, 2008). When decisions are made regarding all the issues concerning our energy infrastructures, how can we be assured *now* that we do the right thing, in the right way, at the right time?

Change in large systems, such as our infrastructure systems, is the central topic of the scientific literature on *transitions* (Geels, 2002b) and *transition management* (Rotmans, 2003; Loorbach, 2007). These fields of research have grown considerably in the 21st century. Despite all the research efforts, applying transition management in the real world is not trivial – if possible at all. One approach is to use *simulation models*, but simulations have yet to be explored (see Figure 1.1 and appendix A). If we are able to capture transitions in simulation models, we may contribute new insights to the body-of-knowledge on transitions and transition management.

This thesis discusses energy infrastructures systems with respect to *how* and *to what extent* we can 1) model them and 2) influence their course of development. If we are able

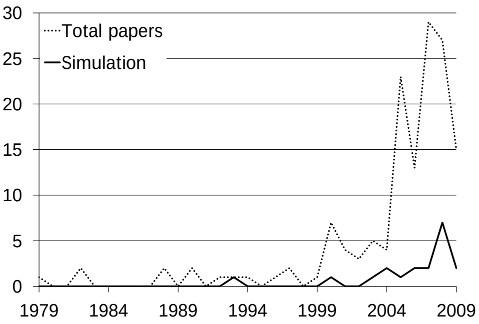

Figure 1.1 – Transition literature statistics: simulation

to simulate change in our energy infrastructures, will that improve the decision making regarding energy infrastructures? This thesis is about *how* such simulation models can be developed, run, interpreted, and used. If we can make transitions appear 'before our eyes' in a simulated environment, we may better understand the mechanisms underlying change. Whether or not such simulations enable us to improve actual decisions made regarding our energy infrastructures – for reasons of environmental sustainability, accessibility, affordability or security of supply – is the next step.

1.2 Society and technology

Mankind has always been creative in finding new ways to do things better by introducing new technology, which can be defined as *practical applications of knowledge*[1] (Merriam-Webster, 2007). Technology both enables new activities and increases the efficiency of existing activities. Man started using stone as a technology at least 2.5 million years ago (de Heinzelin et al., 1999). The first energy technology may have been the use of fire for cooking. Mastering fire not only broadened the range of foods that could be eaten, but also improved the nutrient value of the food that was already eaten: technology brought new possibilities *and* increased the efficiency of current practice.

In this thesis, we adopt a socio-technical system's perspective (Hughes, 1987; Ottens et al., 2006). *Infrastructures* are huge socio-technical systems that enable suppliers and consumers of goods and services to connect. The first infrastructures facilitated transport: Romans and Greeks already developed paved streets and ever since 4,000 BC there have been canals. Since, many infrastructures have been developed for critical societal functions: for the supply of various energy carriers and services, for various modes of transport and telecommunication, for the supply of drinking water, and for the removal of waste water. Individual technological elements in these infrastructures, therefore, are part of technical *systems*[2], which is typically defined as *a set of entities forming an integrated*

---

[1] The creative aspect of technology creation can already be found in it origins. The Greek *τεχνολογια* (tech-nología) literally translates as *discipline of art or skill* and clearly refers to the creative process of knowledge development.

[2] System stems from the Greek *συστημα* (systēma), which translates to *composition*. As a composition may imply a composer, the Greek origin of the word system may well point at the fact that a system is a 'thing' with components that is useful to observe and design.

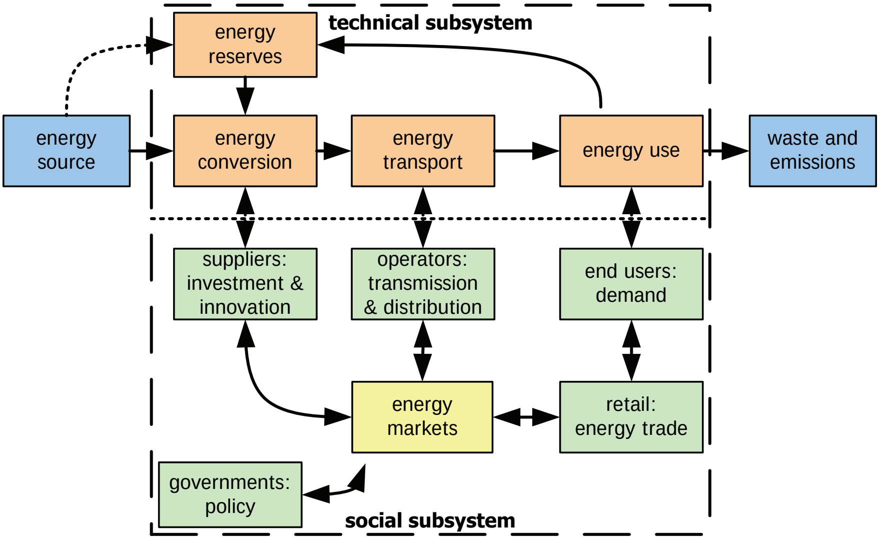

Figure 1.2 – Energy infrastructures as socio-technical systems

whole. However, an infrastructure is more than the collection of interconnected physical elements. It also contains social elements, such as individuals, governments, and firms. In addition, institutions such as legislation, regulation, standards, and market places emerged on top of many technological elements in infrastructures that facilitate the generation and transfer of goods and services.

Our socio-technical systems perspective points out to us that change in social elements and technological elements cannot be fully separated: in order to understand how infrastructure systems change, the relations between technical elements, between social elements and between social and technical elements need to be discussed. Technological change is not purely a task of 'hard engineers': innovation of systems entails developing, designing, and implementing new technological elements and their interdependencies with other system elements (Lundvall, 1985). Innovation of systems relates to relationships between man and technology, which are both part of the socio-technical system we call society.

In addition to the fact that infrastructures are socio-technical, they are *complex*. Infrastructure systems contain huge numbers of elements that interact in a non-simple way (Simon, 1962). These systems are affected by all sorts of actions taken and decisions made by various actors that are part of these systems. The complexity is especially large in infrastructures, because they contain a whole hierarchy of systems (Simon, 1973). For example, an electric boiler is a system within a house, which is a system within a city, which is a system within a country, etcetera. This complexity of infrastructures results in many feedback loops. Infrastructures are multi-actor, multi-objective, multi-level, and multi-time scale.

A huge number of actors are part of our energy infrastructures – each with its own (private and/or public) interests, its own means, and its own preferences (see Figure 1.2 for main components and relationships in energy systems). Many governments – supranational, national, regional, and local – are responsible for the well functioning of (parts of) infrastructures and for this purpose they set up policies, legislation and regulations to do so. Decisions regarding energy infrastructures include the selection of energy sources and the choice of and investment in energy conversion technologies, energy transport, organization of energy sectors, and the mitigation of externalities. Depending on the energy policy in individual countries, governments and/or companies invest in parts of physical energy infrastructures and operate them; large and small consumers acquire and use their appliances. Physical and virtual marketplaces emerged in which numerous actions of individuals and businesses are taking place. Besides, actors are reflexive and adaptive. Their decisions are driven by all kinds of developments, such as innovations, competition, geopolitics and globalization.

1.3 Policy interventions in energy infrastructures

The complexity of infrastructures has complications for 1) how infrastructures can be *designed* and 2) *interventions* by strategic decision makers. Energy infrastructures were not *designed* as today's large integrated systems. A variety of governments have made policies to change physical infrastructures and the way they are organized. In their policy decisions, governments face *deep uncertainty* (Agusdinata, 2008, p. 1), which refers to a condition in which analysts do not know or cannot agree upon the appropriate conceptual models to describe interactions among a system's variables, the probability distributions to represent uncertainty about key parameters in the models, and/or how to value the desirability of alternative outcomes (Lempert et al., 2003, p. xii).

Decisions regarding energy infrastructures have a typically long relevant time span, during which the structure of infrastructure changes. However, all decisions are bound by deep uncertainty, because infrastructures are capital intensive and have a long life span. It is impossible to start all over again and redesign our infrastructures. For how can we be certain that we have an adequate design for at least a couple of generations? Too many possible developments affect the long-term rationale of such a design: deep uncertainty prevents us to determine what the 'optimal' design is. Similarly, many crucial choices that still affect our infrastructure were made in times that were very different from ours. Therefore, in a complex system, the notion of optimal design is useless. The 'optimal' state would refer to a specific moment in time and is perspective-dependent. Both are reasons why no system-level optimum exists when that system is complex. An 'optimal' design can only refer to a robust solution that – within a certain time-frame – leads to a system flexible enough to be resilient against certain more or less probable events.

The fact that infrastructures can only be developed and improved over decades means that we *shape* them while these infrastructures are *evolving*. Shaping our infrastructures is fundamentally different from designing in the tradition of engineering design. Infrastructures are evolving; each actor can only try to affect its future path by pushing and pulling the knobs and valves available to him. Shaping our infrastructures in a *desired evolutionary direction* is also incredibly difficult, as some flaws cannot be predicted. In the context of globalization, electrification, sustainability, and depletion of resources, we need to gain insight into the long term outcomes of the decisions we are making today.

Since transition management has gained much attention in political and scientific arenas, we aim at connecting the notions of policy intervention in evolving infrastructures and transition management (see Box 1). Deep uncertainty makes the potential for transition management at least troublesome: when change-over processes considered as transitions are expected to take decades, how can we know what actions we have to take now in order to shape the development of our energy infrastructures so that the preferred transition will occur over decades? Rotmans and Kemp (2008), key authors on transitions and transition management, have realized this: “We still cannot answer unequivocally the question whether transition management really works. And it might take another decade before we can answer it.” But it is really a paradox. At the end of the day, how can we attribute it to transition management activities, whether the transition was successful or not? And in more general terms, how could change in the long run be attributed to specific interventions of actors in an infrastructure? This is, however, no argument to wait: policy issues regarding energy infrastructures have to be solved. In essence, transition management is about what to do *now*, so we can be assured that in time, our infrastructures develop according to what is desired.

1.4 The toolbox for informed interventions

The consequences of the complexity of our energy infrastructures (regarding deep uncertainty, ‘optimal design’, and, therefore, the notion of shaping) also apply to efforts of *modelling* and *simulation* of energy infrastructures. Where assessments of the merits of intervention – regarding government policy or business strategy decisions – are quantitative, a variety of tools appear at the scene. As we intend to focus on the dynamics of infrastructure systems, we focus on *simulation models*: models that simulate how a system may change over time. A variety of perspectives are necessary to grasp the complexity of such systems (Nikolic, 2009), using a variety of modelling paradigms (Yücel, 2010). We set out for simulations of energy transitions from a complex socio-technical systems perspective – for which the traditional approaches may be problematic.

Supporting interventions by actors in infrastructures, econometric models, scenario analyses, Computational General Equilibrium (CGE) models, and System Dynamics (SD) are dominant. Econometric models use statistical fitting to show correlations. This points out which relations are significant and can be used to find key parameters that may be affected by interventions. In scenario analysis (cf. Fahey and Randall, 1998) a selection of internally consistent possible futures is defined. What-if cases are tested in these alternative futures, by showing the possible effects of interventions. The aim is to find interventions that are robust. Qualitative and quantitative methods exist for scenario analysis. Examples regarding energy infrastructures are the *Energy Transition Model*[3] and the Roadmap 2050[4] (European Climate Foundation, 2010). Quantitative scenario analyses typically are spreadsheets with static relationships between parameters.

Simulation models aim to capture part of the behaviour of real-world systems. An important class of simulation models used for public policy is Computational General Equilibrium (CGE) models (de Melo, 1988; Devarajan, 2002). CGEs are focused on macro-economics, are data-rich, have a broad scope, are well understood, and are fast.

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[3] http://www.energytransitionmodel.com

[4] http://www.roadmap2050.eu

Transition policy in the Netherlands focuses on the energy sector. Dutch energy transition policy came into being in 2001, when the Dutch Ministry of the Environment published their fourth national environmental act (Dutch: Nationaal Milieubeleidsplan 4, Ministry of VROM, 2001). A transition is the period in which system innovations solve wicked environmental problems. The environmental problems mentioned relate to biodiversity, climate change, resource scarcity, health, environmental hazards, the living environment, and new externalities. Despite efforts of the Ministry of Economic Affairs, the resources available declined with the sense of urgency in the next couple of years. This was the reason for a combined advice by the Dutch Council for Housing, Spatial Planning and the Environment and the Dutch Energy Council (VROM-Raad and Algemene Energieraad, 2004). The councils claimed the need for leadership, powerful national policy and international collaboration, a consistent vision, and an institute representing all actors involved.

In January 2005 the Dutch government created the *Task Force Energy Transition* (in Dutch: Task Force Energietransitie) with members from industry, governments and research institutes. In their transition action plan the task force identified six platforms – green gas, sustainable mobility, green resources, chain efficiency, sustainable electricity, and built environment – responsible for 'executing' the energy transition (Task Force Energietransitie, 2006a). The task force focused on agenda setting and stating ambitions. Their intermediate report mainly showed specifications of the platforms and, for instance, the need for and additional investment by the Dutch government of €3, 890 million for 2007–2010, required to be able to execute the platforms (Task Force Energietransitie, 2006b).

After this intermediate report, a coordinating counsel for the energy transition (in Dutch: Regieorgaan Energietransitie, http://www.energietransitie.nl) materialized and took over the role of the task force. Since, this counsel governs the progress of the platforms. An additional platform regarding greenhouses was formed and many pilot projects regarding the seven platforms have been initiated (EnergieTransitie, 2010; Interdepartementale Programmadirectie Energietransitie, 2010).

Box 1 – Transition policy in the Netherlands

CGEs are solved by finding a state of equilibrium at each modelled time step under given trends for exogenous parameters.

The other important simulation paradigm is System Dynamics (SD). SD models are sets of differential equations, modelling the feedback relations within and between system levels, by representing aggregate variables as stocks and flows (Forrester, 1958; Sterman, 2000).

These tools and simulation paradigms are useful for policy interventions, but we need to expand the repertory of simulations for two reasons. First, the tools are limited in their ability to capture the *long-term* dynamics in infrastructures. Second, interventions in complex systems may change the *structure* of the system, causing the dynamics to change as well. That is why it is very difficult to analyse the long-term effects of interventions in complex systems.

1.5 Exploring new ground

The focal point of this thesis is to explore the use of simulations to capture the long-term consequences of policy interventions (or the lack thereof) in the evolution of energy infrastructures. The challenge for the modelling and simulation platform to be developed is to capture change in the structure and dynamics of these complex systems, because the structure and dynamics of the infrastructure systems change. These systems are complex, path dependent, and they are intractable. This has a number of complications for modelling and simulation.

First, energy infrastructures are large-scale socio-technical systems, in which both social and technical aspects are relevant. Simulations are traditionally focused on either the social (simulating humans, their decisions and interactions, and institutions) or on the technical (simulating technical units and systems) – the interactions are less understood and modelled. Second, the 'future space' of energy infrastructures is enormous, because any combination of decisions results in another future. Dealing with all these futures is impossible (Nikolic, 2009). These complications imply that a variety of models grasping a variety of types of data is necessary, from different paradigms and disciplines, that do not even connect on a conceptual level.

The literature on transitions and transition management only contains a few quantitative simulation models regarding interventions in energy infrastructures (notably Chakravorty et al., 2006; Alkemade et al., 2009; Keppo and Rao, 2007; Perrels, 2008). *None* of them allows for an evolving system structure. The dilemma is to be generic enough to be able to grasp change in the system structure *as well as* specific enough to isolate the long-term effect of specific interventions. Or in terms of Occam's Razor (cf. Sober, 1994), how can we define, model and simulate evolving energy infrastructures in such a way that we can deal with this dilemma? *How can simulations of transitions show whether or not the changes observed can be attributed to specific interventions modelled?*

1.6 Audience, objectives and questions

In this section, we successively outline the audience for which this thesis is intended, the objective of the research, and the research questions that we set out to answer.

1.6.1 Audience

We see the strategic decision makers in energy infrastructures as our problem owners. Regional, national, and international governments make decisions on energy policy. Energy companies, energy infrastructure providers, technology providers, and energy users make their own decisions and are (to some extent) affected by the decisions of governments. They are, therefore, part of the audience of this thesis. The thesis is relevant for complex systems researchers, and more specifically, for modellers.

1.6.2 Research objective

The main objective of this research is to *simulate evolving energy infrastructure systems, and to create the enabling modelling and simulation platform. The simulation results are meant to support public and private actors in their strategic decision-making.* We aim to develop the theoretical framework for exploring the consequences of interventions in energy infrastructures. Our objective is to evaluate the impact of policy decisions and to demonstrate the applicability of modelling and simulation to grasp energy transitions and transition management. Through simulations, we intend to come up with quantitative insights in managing or shaping energy transitions. Eventually, this should allow public and private actors to better anticipate the effects of their decisions.

1.6.3 Research questions

The central research question is as follows:

> *How can we assess the long term consequences of policy interventions in evolving energy infrastructure systems?*

The following research questions are discussed in this thesis:

1. Can we trace the effects of specific interventions in evolving energy infrastructure systems?
2. Can we develop, run, and interpret *simulation models* that capture change in the structure and dynamics of evolving energy infrastructure systems?
3. How can simulations be *interpreted* when the system structure changes?
4. How can the understanding of evolving energy infrastructure systems be increased?

1.7 Structure of this manuscript

The structure of this thesis is depicted in Figure 1.3. In the thesis, two parts can be distinguished, a theoretical part (chapters 2–3) and a practical part with cases (chapters 4–8). Finally, we end with the synthesis of the research.

1.7.1 Developing a body of knowledge on energy transitions

Chapter 2 The literature on transitions and transition management is analysed using a socio-technical system's perspective. We find out what transitions are, what the main notions on transitions in the literature are, how the literature developed and where its strengths and weaknesses lie. We explore and develop the *design* space for energy transitions, subject to available technology, economics and regulation.

Chapter 3 Using the developed perspective on transitions, we develop a *modelling framework* that allows for building simulation models of energy infrastructure systems. We also present a *typology* that allows for a classification of transition models.

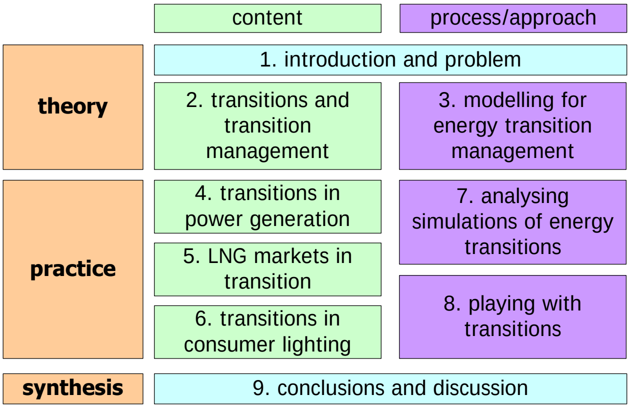

Figure 1.3 – Structure of this thesis

1.7.2 Applications of simulations of energy transitions

To develop feasible transition scenarios incorporating actions of owners/investors and policy of governments, notions from the theory are used in case studies. Using the framework of chapter 3 simulation models are developed to come up with feasible and promising designs of transitions, while focusing on public policy that aims to manage energy transitions. Cases were selected on different parts of the value chain (production, transport, and consumption), and types of policies (governance, policy instrument, and regulation). In the cases, we build upon existing work on Agent-Based Models (Nikolic, 2009; van Dam, 2009, ABM). It has been shown to be a promising approach, but it is relatively new for modelling energy infrastructures. In ABMs, the energy industry is represented as interconnected *agents*. Simulations show the evolution of actor behaviour and the emergence of system structures under different policies and scenarios.

Chapter 4 Power generation is one of the main sources of CO_2 emissions. In the EU, an emissions trading scheme has been implemented to reduce emissions from this and other sectors, but so far it has not performed as expected. We tackle the issue of CO_2 emission reduction by power generation. We describe an agent-based model in which power producers are represented as agents, investing in power plants, operating them and selling electricity in the market. In a number of experiments we research the merits of alternative policy interventions.

Chapter 5 Liquefied natural gas (LNG) allows the connection to remote sources of natural gas by shipping it as a liquid. We explore the nature of the contracts in the market for liquefaction, shipping and regasification of natural gas with an agent-based model. The agents invest in, own, and operate these facilities and negotiate contracts. Each agent optimizes his behaviour by maximizing his expected return on investment. We explore the system structure emerging from the contracting behaviour of agents.

Chapter 6 Lighting represents a large fraction of the electricity consumption of households. Although alternatives are available at lower life-cycle costs, incandescent light bulbs have remained dominant. We developed an agent-based model in which households are modelled as heterogeneous agents with their own perceptions and portfolios of bulbs. The effect of the phased ban on incandescent light bulbs in the EU is evaluated and compared to alternative policies.

Chapter 7 A new approach for the analysis of simulation data is presented. The *dynamic path approach* intends to analyse simulation results by estimating how relevant causal relationships between a set of modelled parameters develop over time. Simulation data from the case on transitions in power generation (chapter 4) is used to demonstrate the approach.

Chapter 8 The case on transitions in power generation is translated into in a *serious game*. This game has features similar to the agent-based model presented in chapter 4. In this serious game, human players replace the agents. Playing the game increases the understanding of long-term effects of policy interventions on evolving power generation infrastructure.

1.7.3 Synthesis

Chapter 9 By means of the theoretical developments in the first part and the experience of the cases in the second part of the thesis, conclusions are drawn on the merits of simulation models for management of energy transition, and on the viability of transition management in complex systems.

2 Transitions and Transition Management

> Well... a regime change. Caused by a bizarre and unexpected twister of fate.
> *Stephen Schwartz – Wicked, 2003*

2.1 Introduction

In chapter 1, we highlighted the field of *transitions*, strongly related to the focal point of this thesis[1]. Focusing on policy interventions, in-depth understanding of transitions – and in the long term effects of specific interventions – may enable transition *management*. In this chapter we will lay the foundations for simulations of such interventions that allows assessing the validity of energy transition management. We have analysed literature on transitions and transition management. As the literature on transitions and transition management is rapidly growing, we provide both an overview of the notions in the literature and extract input for our modelling framework that is discussed in the next chapter.

The literature on transitions contains publications from 25 countries, the combined publications of the Netherlands, the UK, and the US count for a share over 70% (see Figure 2.1). The US was most important before 2000, but authors from the Netherlands have been dominant since. The publications in the last decade broadened the scope of the transition literature dramatically: the number of authors enormously increased and an international, multidisciplinary field with many perspectives and conceptual models of transitions developed, exploring those concepts by applying them to cases.

In section 2.2, we ask ourselves what transition are, by elaborating on a socio-technical system's perspective. We analyse the literature on transitions using that perspective and redefine the notion of transition based on our findings. Afterwards, in section 2.3, we shift our focus away from autonomous transitions and elaborate on the *management* of energy transitions. We argue that, ideally, transitions are *designed*. We apply a design approach on transitions and find knowledge gaps that currently prevents proper transition design processes (section 2.4). This analysis points at the need for simulations that allow for *testing* possible transition management strategies. We end with conclusions on

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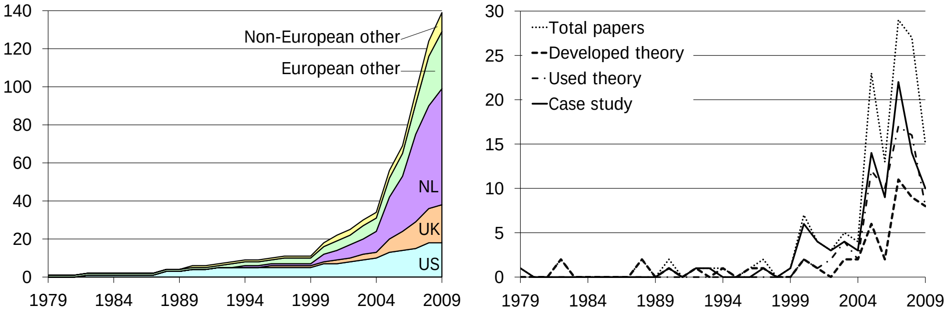
[1] This chapter is partly based on Chappin and Dijkema (2010b).



(a) Country of the first author

(b) Theory and case studies

Figure 2.1 – Transition literature statistics: country of first author, theory, and case studies

the analysis and requirements simulations of energy transitions, which is the input for the work on *modelling* transitions in chapter 3. This chapter is based on an extensive transition literature review. The methodology and results are described in appendix A.

2.2 What are transitions?

What are transitions in the context of energy infrastructures, sustainability, and policy design? To answer this question, we set the scene by defining a new perspective on transitions, using socio-technical systems thinking. This perspective allows us to look at human aspects as well as technological aspects of energy systems, which prove to be a key to increase the understanding of energy transitions. Afterwards, we discuss the literature on transitions, which can be considered of a qualitative nature: most of the papers used case studies in which they either developed theory on transitions or adopted it (see Figure 2.1). We use the literature on transitions with respect to the definitions of transition, focusing on the notion of change in transitions. Theory on unplanned transitions is analysed from the new perspective. We give an overview of transition classifications. This section concludes with a new definition for transitions and key elements from the literature on unplanned transitions, that serve as an input for the next section.

2.2.1 A system's perspective on transitions

Socio-technical systems What is a system's perspective? And which system's perspective do we have to take? Thinking in systems originates from the 1950s (Dijkema, 2004; Bekebrede, 2010), describing *patterns* in systems (von Bertalanffy, 1950, 1968; Boulding, 1956). We adopt the definition for system of Asbjørnsen (1992). "a structured assemblage of elements and subsystems, which interact through interfaces".

Since the early days, systems thinking developed into a myriad of *perspectives*. For instance, system *dynamics* focuses on models in which the *structure* of systems are characterized by stocks and flows (Forrester, 1958). Systems *engineering* focuses on the design and implementation of the components and interfaces in systems (Asbjørnsen, 1992). In *complex* systems thinking, systems contain *many* components that interact in many ways (Waldrop, 1992). Complexity results in emergent system properties, which are features qualitatively different from the features of the system's parts (Kroes, 2009). Complex *adaptive* systems (CAS) focus on systems that adapt as a whole. These systems are self-organizing. Complex adaptive systems studies were applied to physical systems (Holland, 1996; Kauffman, 1993) as well as social systems (Axelrod and Cohen, 2001; Teisman, 2005). Specifically on the *interface* of social and technical systems, we find the perspective of large-technical systems (Hughes, 1987), or *socio-technical systems* (Ottens et al., 2006; van Dam, 2009; Nikolic, 2009). Socio-technical systems contain both social networks obeying social laws, such as legislation and economic contracts, and physical networks obeying physical laws, such as the conservation of mass (Ottens et al., 2006).

We have argued in chapter 1 that energy infrastructures are true socio-technical systems and we adopt this as our perspective. Regarding transitions, change involves both the structure and the content of *physical* systems, their interconnections, and the body-of-rules and institutions that govern *actor* behaviour and decision-making. A transition in very general terms is a "passage from one state to another" (Merriam-Webster, 2007), in a system this implies passage from one *systems state* to another. From our socio-technical system's perspective, transitions emerge over time as fundamental change (Dijkema and Basson, 2009) out of the interactions of the many actors in the system that act upon or make use of elements in the physical world which also change during transition.

In much of the literature, the goal of transition is assumed to be 'sustainability'. Systems are said to change from 'unsustainable' into 'sustainable' (cf. van den Bergh and Bruinsma, 2008). From our perspective, a transition towards a sustainable energy supply, for example, would include substantial change in the behaviour of producers of energy and consumers in a variety of sectors, governments in their priorities and policies, and in the physical infrastructure, power plants, domestic and industrial appliances, electricity grids, etc. We conjecture that transition has no intrinsic link to sustainability. Dictionary definitions point to that. A transition occurs when the structure and content of systems change, for example through process system innovation (Dijkema, 2004) or system innovation (Lehmann-Waffenschmidt, 2007). In the course of the process, the system *characteristics* such as 'sustainability' may or may not change or emerge.

Large-scale socio-technical systems are characterized by 'distributed control': there exists no single actor that can 'engineer' such a system. Instead, these systems evolve as a result of the (inter)action of all actors involved, and each actor can only partially influence the path of an energy infrastructure as it evolves over time. In our energy infrastructures, many actors, who have specific goals and means to reach them, are active. They act upon their physical assets in the physical networks. Infrastructures are, therefore, large-scale socio-technical systems: systems in which social and technical components, which are interdependent, are distinguished. Moreover, infrastructures are huge, which makes them complex. Subsystems themselves are systems (Simon, 1973) – complex systems are hierarchical. Components or subsystems interact on different levels. On a given level, components are relatively free to operate, but they are dependent on higher (slower changing) and lower (faster changing) levels (Holling, 2001).

Since control is distributed, each actor's span of control is limited and steering actions will often not yield to the desired outcome. All actors, however, operate in and interact through the economy. While their actions and operations may be seen to be driven

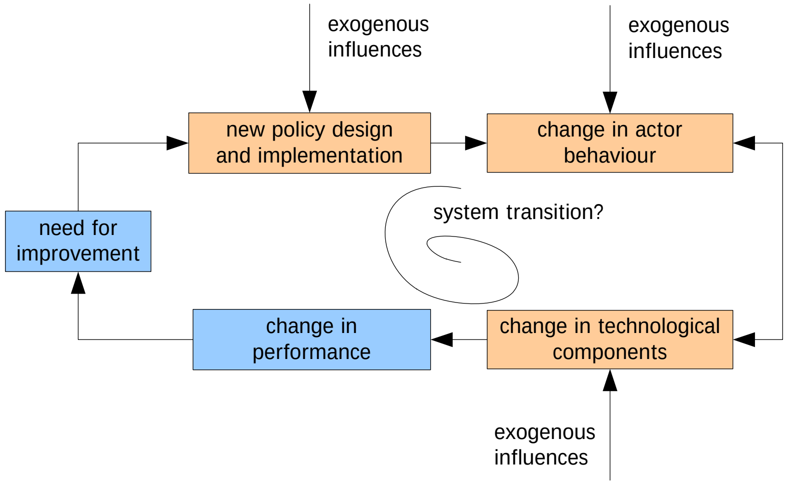


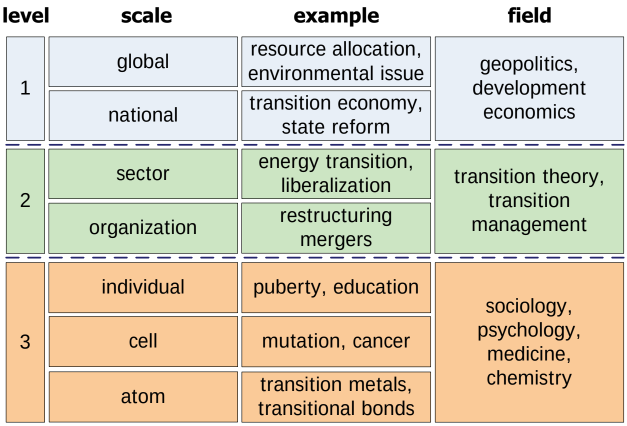
Figure 2.2 – From policy design to a change in performance in large-scale socio-technical systems

by demand, innovation, resource availability, technological capability etc., they are also governed by the rules and regulations set and enforced by the government. Our infrastructure systems are evolutionary, they exhibit path-dependency and lock-in. Options in the future are shaped by current choices like current options have been shaped by the past. The systems we observe today were not designed as such, they evolved to their present state (Nikolic et al., 2009; Herder et al., 2008).

In due course, whole infrastructures become outdated – they may not be equipped to meet present or future needs such as sustainability, reliability, flexibility, and affordability. And that pushes the need for new public policy (see Figure 2.2). It drives the public policy process and results in true complexity, because (1) changes in technical components of large-scale socio-technical systems often only materialize when changing preferences or perceptions of stakeholders lead to new policy, strategy, and decisions, (2) in any cycle of policy design or strategy formulation with time an improved system is intended, and (3) the changes involved may materialize at a time that perceptions and preferences have changed. With time, this process may imply a substantial change of the system state – the system structure and possibly also the performance – and hence must be labelled a *system transition*. Such a transition typically spans decades wherein the combination of external influence, actor behaviour and actor interaction is dynamic and complex. Consequently, a system transition is by definition an emerging property of a large-scale socio-technical system. In the context of public policy, therefore, we may require such a system transition. Ideally, we acquire the understanding of how we can invoke a transition, while acknowledging the complexity of these vast systems and the roles all the players have.

Systems scale The word transition is used for quite a variety of different concepts in different domains. One can distinguish transitions on a variety of *scales* (see Figure 2.3), which can be classified in three groups. We will discuss the relevance of each of those groups, given our system's perspective.

First, one could look at the level of societies or at the global level (1 in Figure 2.3).



level	scale	example	field
1	global	resource allocation, environmental issue	geopolitics, development economics
	national	transition economy, state reform	
2	sector	energy transition, liberalization	transition theory, transition management
	organization	restructuring mergers	
3	individual	puberty, education	sociology, psychology, medicine, chemistry
	cell	mutation, cancer	
	atom	transition metals, transitional bonds	

Figure 2.3 – Hierarchy of relevant system scales in which transition research can be relevant, including their domains and examples

At the national level, questions related to state reform are relevant. Even higher is the global level, where international issues, such as issues regarding fossil resources, the debate around climate change, and the global financial crisis play a role. These two highest levels relate to scientific fields such as developing economics (e.g. Stiglitz, 2002; North, 2005) and geopolitics (e.g. Kjellén, 1917; Kliot and Waterman, 1991). The demographic transition is an important example, which refers to the shift from a pre-industrialized society to a industrial society, in which high birth and death rates both decline, and population stabilizes (Lee, 2003a; Caldwell, 2006). Although for public policy transitions on these scales can be relevant, they have not been addressed explicitly in that context.

At the intermediate scales (2 in Figure 2.3), transitions deal with changes on the sectoral and organizational level. Here, transitions relate to restructuring sectors, sector-specific public policy and organizational reform. These levels are, therefore, strongly connected to public policy. As will be discussed below, this is at the core of the transition and transition management literature.

Finally, one could go to the individual level, or even to the cell or atom level. Transitions relate here to psychological issues (e.g. Nicolson, 1998) and on the atom level to transitions in chemical state of atoms and molecules, i.e. the co-existence of multiple spatial arrangements of atoms in a molecule (e.g. Greenwood and Earnshaw, 1997; Silverstein et al., 1981).

2.2.2 Definitions of transitions

Transitions have been defined in a variety of ways, on a number of aspects (see Table 2.1): the type of system they apply to, the type, speed and size of the change are considered a transition, requirements before, during and after the transition and the type of problem they are related to. Furthermore, several definitions make use of other concepts, such as regimes, societal systems, socio-technical systems, etc. We explore these definitions as input on our perspective on transitions in energy infrastructure systems.

Transitions were first defined at the level of *organizations*. Ackerman (1982) concep-

Table 2.1 – Components of transition definitions

Component	Variations
Type of system	Organization, socio-technical system, societal system, technological system, large complex technological system
Type of change	Irreversible, gradual, mode of operation, system state, structural, fundaments, major, socio-technical regime, system innovation, structural innovations, technological transformation, functioning
Size of change	Substantial, major, fundamental, incremental, radical, profound
Speed of change	Radical, rapid, gradual
Before and after	Relatively stable
During	Relatively unstable
Reason	Wicked problem threatening development, demand for sustainability

tualizes a transition as change *to a new state* of an organization. Literature starting in the nineties of the last century deal with transitions of sectors. Rotmans (1994) defines transitions as: "the shift from a relative stable system through a period of relatively rapid change during which the system reorganizes irreversibly into a new (stable) system again". The three main components of this definition are that the change should be rapid, that the system should be relatively stable before and after the transition and that a transition is irreversible. Rotmans also co-authored a major UN report in which a very different definition for transitions was adopted: "a gradual, continuous shift in society from one *mode of operation* to another" (Matthews et al., 1997). Speed nor size of change are made explicit in this definition. De Vries and Riele (2006) and De Haan (2010) adopt the idea that transitions are a change in mode of operation. According to De Vries and Riele (2006) "represent development paths that often have already been experienced by sub-populations and that provide insight into likely futures, dependent on economic, social, and environmental circumstances". De Haan (2010) also highlights in its initial definition on change of the *functions* of societal systems.

Shove and Walker (2007) rephrase this mode of operation to the *system state*: transitions are "substantial change and movement from one state to another". Van der Brugge et al. (2005) propose quite a similar definition, namely that a transition is a "structural change in the way a societal system operates". In addition, they claim that "transitions are the result of slow social change and short-term fluctuations or events that suddenly initiate a highly non-linear response" (Van der Brugge et al., 2005). With that, they specify the *process* of change: the transition is characterized by a period of fast changes.

Rotmans et al. (2001) also proposed another definition, in which the kind of change is not a mode of operation, but rather the structure of society. Transition is defined as "gradual, continuous processes of change where the structural character of a society (or a complex sub-system of society) transforms" (Rotmans et al., 2001), recently adopted by Loorbach et al. (2008). This definition points at change in the *structure* of a system, which is close to how Wiek et al. (2006) perceive transitions: "structured developments from one relatively stable state to another. A transition is the large-scale, long-term development of a system in which some of its *fundaments* (i.e. knowledge, rules, norms, practices, and structures) significantly change." This is an interesting description, because it operationalizes what is meant with the system's state.

Recent transition definitions are phrased as *societal* transitions, for instance defined as "structural *innovations* of *societal systems* in reaction to *wicked problems* threatening development" (Rotmans, 2003). New in these definition are both the concept of innovation, and the inclusion of the *reason* for transition. Wicked problems usually refer to issues, entrenched throughout large parts of society, for which no definitive or objective problem formulation or solution exists (Rittel and Webber, 1973; Douglas and Wildavski, 1983; Hoppe, 1989; Hisschemöller, 1993; WRR, 2006). Examples of such problems are climate change, health care, AIDS and urban decay.

Geels (2002a) introduces the concept of *technological transitions*: "major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled". In later publications Geels (2004, 2005d,c,b) rephrases technological transitions in his definitions to transitions. In addition, Geels and Schot (2007) define technological transitions as "changes from one *socio-technical regime* to another". They refer to the concept of regime that is the middle level in the Multi-Level Perspective (MLP, discussed below). A socio-technical regime typically is a set of "patterns of artefacts, institutions, rules and norms assembled and maintained to perform economic and social activities" (Berkhout et al., 2003).

Tukker and Butter (2007) use the notion of *system innovations* in his definition of transitions: "Transitions are radical system innovations that *usually* take 1–2 generations" (Tukker and Butter, 2007). Faber and Frenken (2009) reformulate that into the substitution of systems: "A technological transition is generally understood as the *substitution* of a large complex technological system by a new system" (Faber and Frenken, 2009).

2.2.3 What is 'change' in the context of transitions?

In the definitions of transitions, the concept of change is ubiquitous. However, change is ambiguous and multidimensional: we can distinguish the *size*, the *speed*, and the *type* of change (see Table 2.1). In definitions, these dimensions are often intertwined. Let us look more careful to those properties of change in the definitions of transitions.

Size of change The size of the change is one of the key components of transition definitions. Intuitively, one thinks of a transition as meaning a relatively *large* change. The literature is vague on this point. It depends on the perspective: a large change from a top-down perspective is a big change. From a bottom-up perspective, a large change implies a great many changes. It is even more vague, because this also is interrelated with the type of change. Therefore, what some call a transition, is for others not more than a process of change. The result is a variety of definitions. First, as substantial change, meaning the change is significant and relevant. Second, as major change, which is an important change (compared to other, regular changes). Third, as fundamental change, which can be defined as change in the essential structure or function. Also incremental and radical change are mentioned, which are more ambiguous. Those are discussed below, because in the literature, they are more related to speed and type of change.

Mulder (2007) distinguishes radical from incremental change, by looking at the potential factor of improvement. In that sense radical change is a big change and incremental a small change. Basing his work on the well-known innovation typology of (Abernathy and

Clark, 1985), Mulder elaborates that transition is the result of multiple architectural innovations. Such innovations depart from established systems of productions and open up new linkages to markets and users (Abernathy and Clark, 1985). An example of an architectural innovation mentioned by Mulder (2007) is the introduction of the mobile phone. As Mulder concludes, transitions apply only to radical and not incremental technological changes. Mulder distinguishes three technological dimensions: knowledge (van de Poel, 2003), integration of physical objects (Hughes, 1987) and functions (Bijker et al., 1987).

Another discussion on radical change, by Perrels (2008), splits the term radical in a product and a process aspect. Radical change implies a shift to something completely different as well as in a relative short amount of time. That means, radical change is both fundamental change *and* rapid change (see below). Perrels (2008) argues that striving for rapid change is counterproductive, since it may prevent long-term solutions, it often is impossible in a wide variety of sectors and it encounters strong opposition.

Speed of change As said above, radical change has a speed aspect, which is similar to rapid change. Rapid change is change at a high speed. In contrast, also gradual change is mentioned in the literature, which implies change in small steps. Other definitions firmly point out that transitions take decades (e.g. Rotmans et al., 2001).

Type of change The most important but ambiguous dimension of change is *what* changes. When can we call a process of change a transition? Definitions of transitions in the literature use a variety of 'things' that change. First mentioned is change in the *mode of operation* (Matthews et al., 1997; de Vries and Riele, 2006). The only example given, by Matthews et al. (1997) is the shift from an agricultural to an industrial economic base. Ambiguous is whether this only implies change in the components of the system. Also *irreversible* change is mentioned (Rotmans, 1994). This seems an unnecessary addition as any large real-world process is irreversible. Bigger change is implied by definitions speaking about *structural innovations* and *system innovations*. Definitions that focus on technological transformations strongly focus on the technology itself, and less on interconnection between technology and economy. Change in socio-technical regime relates to the notion of relatively stable parts of society, which will be discussed below.

2.2.4 Theory on transitions: phases, regimes and niches

At the core of the notion of transitions appears to be *what* is changing. We expect to clarify this by looking at related theory and find out what constitutes a transition. We look more closely to widely adopted conceptualizations of how transitions emerge: phases, regimes and niches. Although strongly interrelated, we distinguish the topic of *unplanned* transitions from the *management* of transitions. The first focuses on autonomous transitions and mainly uses historic analyses of past transitions to find the mechanisms behind. It is the end of the 20th century when the literature on transitions takes off. The publication that is referred back to as the first publication, a RIVM report from the Netherlands by Jan Rotmans (Rotmans, 1994), could not be accessed. A second main report (of which Jan Rotmans is one of the authors) is a UN publication in which transitions are acknowledged to be a relevant topic for research which also may be steered by governmental

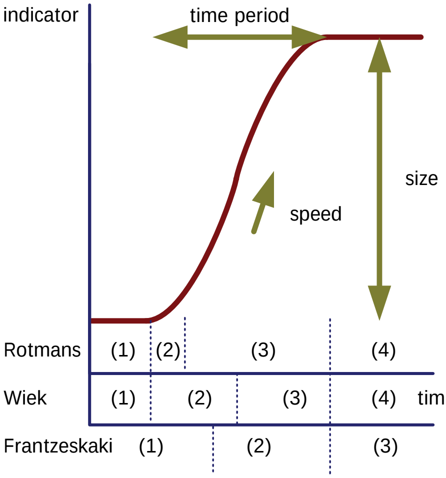


Figure 2.4 – Phases and indicators in transitions

policy (Matthews et al., 1997). Two central notions characterize this part of the literature: a construct of transition *phases* and one of *niches and regimes*.

Phases in transitions Similar to the classic life-cycle of an innovation, research on past transitions (Rip and Kemp, 1998; Geels and Kemp, 2000; Verbong, 2000; Rotmans et al., 2001) resulted in the definition of the Multi-Phase Perspective (MPP). The idea stems from the population as indicator of demographic transition (Rotmans et al., 2000). Four transition phases are identified in the pathway of transitions (Rotmans et al., 2001, see Figure 2.4), and redefined afterwards by Wiek et al. (2006). Both Rotmans et al. (2001) and Wiek et al. (2006) define four phases, but with slightly different names and a different boundary between the second and third phase (see Figure 2.4). Frantzeskaki and de Haan (2009) include only three phases.

Phase 1 is the phase of pre-development (Rotmans) or the pre-transitional phase (Wiek). In this phase, the system is relatively stable, as Rotmans calls it: it is in a dynamic equilibrium. After what can be called the take-off point, we enter phase 2. This is called the take-off phase (Rotmans) or the acceleration phase (Wiek). In this phase, the state of the system starts changing. The end of phase 2 is either after some change (according to Rotmans), or on the turning point (where the slope is highest, according to Wiek). Therefore, phase 3 is called either breakthrough, where the major change occurs, or stabilization where change slows down. Phase 3 ends at the terminal point. Rotmans calls the final phase the stabilization phase; change comes to a halt at the beginning of this phase. Wiek calls it the post-transitional phase, in which the system has been stabilized and a new dynamic equilibrium is reached. Frantzeskaki proposes a different model of the state before and after the transition. Where Rotmans and Wiek have stable beginning and end states, depicted as horizontal lines, Frantzeskaki conceptualizes the performance indicator with a continuously positive slope. In addition, no distinction is made between the first two phases defined by Rotmans. Where Rotmans and Wiek see a transition as a period in which the performance improves gradually, Frantzeskaki conceptualizes a transition as a period of *fast* improvement in-between periods of *slow* improvement.

In this perspective, three system dimensions are identified, for a (set of) given indicator(s): the time period of a transition, the speed and the size of the change. The main differences between the versions are 1) the distinction between phase 1 and 2, and 2) the timing of the border between phase 2 and 3: either it is the point between take-off and breakthrough or the turning point. The version of Wiek et al. (2006) is most symmetrical.

The multi-phase perspective is not only used by Rotmans himself (Rotmans et al., 2000, 2005), but also by his direct colleagues (Bergman et al., 2008; Van der Brugge et al., 2005; Van der Brugge and Rotmans, 2007; Loorbach, 2007; Loorbach et al., 2008; Schilperoord et al., 2008; Timmermans, 2006, 2008; Timmermans et al., 2008), in Rotterdam, the Netherlands and by others (Elzen et al., 2004; Martens and Rotmans, 2005; Caron-Flinterman et al., 2007; Squazzoni, 2008; Frantzeskaki and de Haan, 2009; Ros et al., 2009), from the Netherlands, the UK and Italy.

Regimes and niches The theory by Kemp (1994); Kemp et al. (1998); Rip and Kemp (1998), from Maastricht, the Netherlands on niche management and regime shifts is the underlying theory of many publications in the transition literature. These authors connect the concept of *regimes* to transitions, arguing that a transition is a shift from one regime to another. However, the concept of regimes is debated in the literature. The notion of technological regimes was introduced by Nelson and Winter (1982), referring to the *shared routines* in a community of engineers, guiding their R&D activities. More recently, Rip and Kemp (1998) included in this concept the complete *rule-set* or *grammar* embedded in a complex of engineering practices. In this context, a regime refers to 'how things are done'.

The regime concept developed further. Many elements are connected in one of the main publications on transitions and transition management, published somewhat later by Rotmans et al. (2000), a Dutch Merit report, from Maastricht, the Netherlands[2]. Two Dutch documents form the background. First, Geels and Kemp (2000), describes the case. Second, Verbong (2000) describes the history of the Dutch energy sector. Rotmans became an important author of transition literature. Although located at different universities throughout the Netherlands, the authors of the Merit report have collaborated in many articles since it was published.

The authors introduce that regimes also include *shared perceptions and assumptions* regarding *problems and solutions*. Furthermore, Rotmans et al. (2000) adopt the conceptualization of Rip and Kemp (1998) that new or variations of technologies or practices form at the niche level. Furthermore, Rotmans et al. (2000) link the *success* of novel technologies in some way to 'structural problems' in the regime. Niches are what is different from the regime.

On the topic of regimes, Geels (2004), from Twente and afterwards Eindhoven, the Netherlands, introduced *socio-technical regimes*, consisting of the coordination within and alignment of the activities of a group of engineers, firms, scientists, users, policy makers, and societal groups. Geels and Kemp (2007): "The socio-technical regime forms the meso level in the multi-level perspective" (MLP). In addition, many definitions of transitions

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[2] In this report transition management is discussed as well, including a case on the transition to a low-emission energy supply in the Netherlands. In the report, it functions as an example of how transition management and transition thinking should be used in the Netherlands. In section 2.3, we will elaborate on this subject.

include a regime shift. Holtz et al. (2008) analysed the variety of notions that exist of regime in the literature. Based on his analysis, Holtz et al. (2008) conclude in the following definition of regime:

> "A regime comprises a coherent configuration of technological, institutional, economic, social, cognitive and physical elements and actors with individual goals, values and beliefs. A regime relates to one or several particular societal functions bearing on basic human needs. The expression, shaping and meeting of needs is an emergent feature of the interaction of many actors in the regime. The specific form of the regime is dynamically stable and not prescribed by external constraints but mainly shaped and maintained through the mutual adaptation and co-evolution of its actors and elements."

Core to the Multi-Level Perspective (MLP) is a regime *shift*, the foundations of which were developed by Rip and Kemp (1998). Many developments and applications of the MLP are published by Geels and Kemp (2000); Geels (2002b). In the MLP, three analytical and heuristic levels for system innovations can be used to find out how transitions come about. Figure 2.5 visualizes the MLP.

On the micro level, technological niches form in which inventions take place and new technologies emerge under protected conditions. Under these circumstances, the potential of new technologies can be exploited. If technologies mature and they have the potential to commercialize, i.e. be strong enough to survive market conditions, it is possible that a technology can break open the regime at the meso level – an innovation may take place. The regime level is, as Holtz et al. (2008) describe, a stable configuration. Geels and Kemp (2000): "a patchwork of regimes are in dynamic equilibrium." Newly introduced is the *macro level* consisting of *landscape developments*, which are typically slowly moving parameters that may enforce pressure on the regime. These pressures may allow for innovations. In this conceptualization, transitions occur when novelties on the micro level evolve and are taken up to modify the patchwork of regimes and eventually transform the landscape on the macro level (Geels, 2005d).

The MLP is again presented by Rotmans et al. (2001) in which it is also applied to the transition from coal to gas in the Netherlands. So far, the developments come together in the Ph.D. thesis of Geels (2002b), which is considered the main reference from this point on. Later, Geels refines the MLP in three steps. First, Geels (2004) connects the MLP to the notion of *system innovations*. Second, the MLP is used to characterize transition pathways (Geels, 2005c, discussed below). Finally, Geels and Schot (2007), clarify their conceptualization in respond to critiques, mainly from Smith et al. (2005). In the meantime, the MLP has been used to describe and analyse past transitions. Frank Geels, often together with René Kemp, adopted the MLP in many case studies, such as the transition from steam engines to electric engines (Geels and Kemp, 2000), the transition from sailing ships to steamships (Geels and Kemp, 2000; Geels, 2002a), the transition from surface water to piped water and personal hygiene (Geels, 2005a) (see appendix A for an overview). Also colleagues of Frank Geels have adopted the MLP in case studies: the transition to low emission energy supply (Rotmans et al., 2000; Hofman et al., 2004; Verbong and Geels, 2007; Loorbach, 2007; Loorbach et al., 2008), the transition in Dutch water management (Van der Brugge et al., 2005; Loorbach, 2007), the transition of European water resources (Van der Brugge and Rotmans, 2007; Van der Brugge and

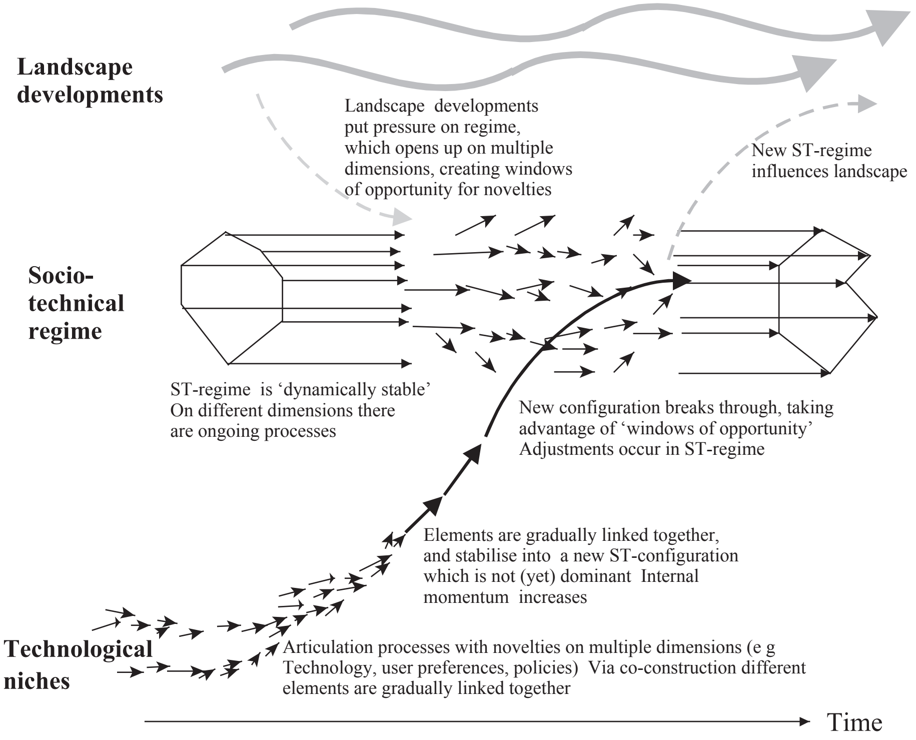

Figure 2.5 – How transitions come about in the Multi-Level Perspective (Geels, 2002b, p. 1263)

van Raak, 2007), the transition from horse-drawn carriages to cars (Bergman et al., 2008), the transition from sailing ships to steam ships (Bergman et al., 2008), road transport in Germany (Schilperoord et al., 2008), and Transition Arena Parkstad Limburg (Loorbach, 2007). Many developments end up in a book edited by Frank Geels and colleagues (Elzen et al., 2004). The MLP has been used in case studies of others: the transition to a low emission energy supply (Kern and Smith, 2008; Rohracher, 2008; Wang and Chen, 2008), transition to a hydrogen economy (Agnolucci and Ekins, 2007), patient participation in decision-making on biomedical research (Caron-Flinterman et al., 2007), transition management in the Finnish context (Heiskanen et al., 2009), and the transition to sustainable mobility in the UK and Sweden (Nykvist and Whitmarsh, 2008), in Sweden.

Although popular, the MLP has also been criticized. Genus and Coles (2008) focus on two aspects: first, there has been a focus on 'winning' technologies. Second, they claim that the conduct of historical case studies have been poor. Recommendations are given for systematic research in order to value the MLP. Specifically, Genus and Coles (2008) recommend to analyse the contribution and interaction of diverse groups, i.e. focus on decisions by people, organizations and governments in the process of transition. Also Agnolucci and Ekins (2007) criticizes the MLP on several issues. For instance, the demarcation of the regimes is ambiguous. The regime–landscape distinction on basis of the speed of change is far from obvious, as landscape developments as well as regime develop-

Table 2.2 – Classifications of transitions

Source	Dimensions	Trajectories
Freeman and Perez (1988)	Scale of innovation	Incremental Radical Technology system Techno-economic paradigm
Geels and Kemp (2000)	Dependence of new and old	Contestation and substitution Cumulation and transformation
Berkhout et al. (2003) & Smith et al. (2005)	Coordination, resources	Endogenous renewal Re-orientation of trajectories Emergent transformation Purposive transition
Geels and Kemp (2007), Suarez and Oliva (2005) & Geels and Schot (2007)	Scale, timing of interactions & nature of interactions	Reproduction Transformation De-alignment and re-alignment Technological substitution Reconfiguration pathways

ments may be fast. Furthermore, Berkhout et al. (2004) and Smith et al. (2005) show that also regimes are nested, which causes the niche–regime distinction to depend on the level of aggregation the analyst chooses.

Regarding regime *shifts*, Van der Brugge and van Raak (2007) quote Pahl-Wostl (2007) when they describe six dimensions along which regime shifts should occur. These dimensions refer in a way to the Dutch *Polder-model*, in which consensus is sought within relevant stakeholders. Amongst other things, Pahl-Wostl (2006, 2007) refers to increase the scale of participation, multiple sectors, a variety of scales, and information sharing. The work on niches and regimes is input for the notion of Strategic Niche Management, which is discussed in section 2.3.

2.2.5 Classifications of transitions

Theory on (unplanned) transitions includes various sets of classifications (or typologies, taxonomies). Acknowledging that every transition is unique, it may be useful to distinguish types of transitions. Classifications usually define one or more *dimensions*, that can be varied. Combinations of values on those dimensions correspond to transition *pathways*. Each observed transition can be classified according to these pathways. The main choice for a typology, therefore, is its dimensions. The transition typologies in the literature contain dimensions on location of resources and coordination (Berkhout et al., 2003, 2004; Smith et al., 2005), frequency, amplitude, speed and scope (Suarez and Oliva, 2005), and timing and nature of interactions (Geels and Schot, 2007). Classifications with only one dimension are de facto a list of trajectories. An overview of the transition classifications is given in Table 2.2.

System innovation typology Freeman and Perez (1988) distinguish a variety of types of innovations. Their typology forms the basis for the multi-level perspective by Geels and Schot (2007), which was described above. Freeman and Perez (1988) define *incremental* innovations on the lowest level, that occur more or less continuously and change no fundamentals. In contrast, *radical* innovations are discontinuous, often combining innovation in product, process, and organization. On an even large scale, one can find changes of *technology system*. Such innovations have an even broader effect and can lead to the development of a new sector. On the highest level, changes in the *techno-economic paradigm* are found to affect the entire economy.

Transition routes Geels and Kemp (2000) encompass two distinct trajectories by which transitions can emerge. The first route is transition by *contestation and substitution*, which Geels and Kemp (2000) claim to be most common: a new technology competes with the incumbent technology and takes over in an *S*-shaped curve (comparable to Figure 2.4). This is the classic innovation-diffusion pattern (Rogers, 1962). The second transition route is called 'cumulation and transformation' and does not entail a takeover, but rather an uptake of a new element by which the existing situation transforms. In contrast to the first route, old and new technologies do not have to be independent or separate.

Ideal types of transitions Berkhout et al. (2003, 2004) define two dimensions to create four ideal types of transitions. The first dimension refers to whether change is *coordinated* at the regime level or whether it "emerges out of normal behaviour of agents within the regime". Coordination of change can, therefore, be seen as activities for *management* of transitions. The second dimension refers to whether essential *resources* are located within or outside the regime. The combinations of these two dimensions lead to four 'ideal types' of transitions (see Figure 2.6). Berkhout et al. (2003) also characterize the transition of these four ideal types. *Endogenous renewal* refers to change that is coordinated by the regime and selection that took place with resources available to the regime. Berkhout et al. (2003) claim that such a transformation process is incremental and path-dependant, and that the alignment of smaller changes will be the basis for transition. *Re-orientation of trajectories* refers to change that is not coordinated by the regime, but that is fed by resources from the regime. Such transitions are widely anticipated or intended, but arose by, for instance, technological opportunities (Smith et al., 2005). *Emergent transformations* refer to apparently autonomous changes, arising from uncoordinated pressures and resources outside the regime. Most of the transitions in the literature are of this form. *Purposive transitions* are intended changes that arise from resources outside the regime. Transition management focuses mainly on these.

In addition to the fact that this typology can be used for classifying and analysing past transitions, it may lead to their management. Smith et al. (2005) claim it can "aid policy-makers who wish to intervene in a more informed way [. . .] altering the given context of selection pressure and adaptive capacity, thereby modifying transformation processes, in terms of their pace and orientation."

Typology of change In addition to their two transition routes, Geels and Kemp (2007) distinguish transition from reproduction and transformation. By *reproduction*, the system is improved, while the current regime is maintained. In contrast, by *transformation*, significant changes in its rules are forced by pressures on the current regime. This is different from *transition*, where a shift occurs from one socio-technical system to another.

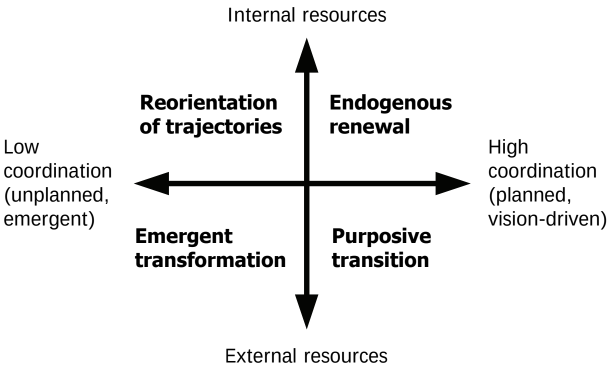

Figure 2.6 – Ideal types of transitions, adapted from Berkhout et al. (2003, p. 24) and Smith et al. (2005, p. 1499)

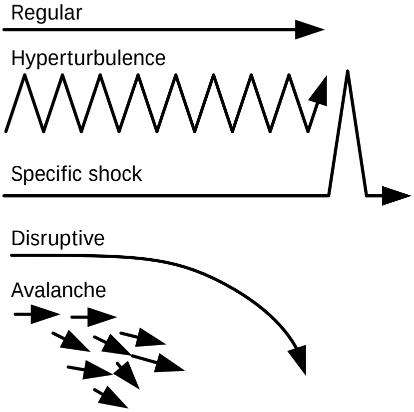

Figure 2.7 – Typology of environmental change, developed by Suarez and Oliva (2005) and adapted from Geels and Schot (2007, p. 404)

Geels and Schot (2007) adapt this typology of change by using a typology environmental change (Suarez and Oliva, 2005, see Figure 2.7). This typology is based on the frequency, amplitude, speech, and scope of processes of change. On their domain, frequency refers to the number of environmental disturbances per unit of time, amplitude to the magnitude of deviation from initial conditions, speed to the rate of change, and scope to the number of environmental dimensions that are affected. Suarez and Oliva (2005) acknowledge five types of environmental change (see Figure 2.7). *Regular* change has a low frequency, amplitude, speed, and scope. *Hyper-turbulence* is characterized by a high frequency and speed. Because amplitude and scope are rather low, this is not considered a significant change. A *specific shock*, however, refers to change with high altitude and high speed. A shock can change the system to a different level or can come back to the original level very fast. *Disruptive* change has large altitude and change relates to only one dimension. Finally, *avalanche* implies change at high altitude, speed and scope. This refers to change on multiple dimensions.

As said, this is input for Geels and Schot (2007) to extend their typology of change. Focusing on the timing and the nature of interactions, they operationalize transition in reproduction, transformation (both denoted above), and technological substitution, reconfiguration, and de-alignment and re-alignment. On the topic of *de-alignment and re-alignment* Geels and Schot (2007) claim: “If landscape change is divergent, large and sudden (‘avalanche change’), then increasing regime problems may cause regime actors to lose faith. This leads to de-alignment and erosion of the regime. If niche-innovations are not sufficiently developed, then there is no clear substitute. This creates space for the emergence of multiple niche-innovations that co-exist and compete for attention and resources. Eventually, one niche-innovation becomes dominant, forming the core for re-alignment of a new regime.” *Technological substitution* is different: ”If there is much landscape pressure (‘specific shock’, ‘avalanche change’, ‘disruptive change’) at a moment when niche-innovations have developed sufficiently, the latter will break through and replace the existing regime.” And finally, *reconfiguration pathways*: “Symbiotic innovations, which developed in niches are initially adopted in the regime to solve local problems. Subsequently, they trigger further adjustments in the basic architecture of the regime.”

2.2.6 Analysis

Based on our system’s perspective, the definitions on transitions, the notions regarding transitions in the literature and the classifications, we built our perspective on transitions. Energy infrastructures are considered socio-technical systems. When discussing transitions in energy infrastructures, it is, therefore, a transition in a *system*. We coin the term *system transition*, to specify this perspective on transitions. In systems thinking, a crucial notion is the *system’s state*: the *components*, their *interaction* and the emerging *performance* of the system. In a large-scale socio-technical system this entails both social components (humans, businesses, governments) as well as technical components (physical installations), and possible interactions between them (ownership, communication, material flows). As Mulder (2007) claims: “New technologies always entail social change. The successful introduction of a new technology is, therefore, always a matter of socio-technical change.” This refers to our socio-technical system’s perspective.

Therefore, transitions are socio-technical changes. The literature explicitly dealing with transition focuses on the level of sectors and organizations. In the context of public policy, the sector level is the most relevant level. Therefore, we focus on this level. The sector-level and a focus on public energy policy necessarily implies a multi-actor setting with significant technological aspects.

Furthermore, we will conclude our elaboration with a definition for transition. As discussed in Table 2.1, we can include a number of components in this definition. Considering the *type* of change, our perspective points us to the fact that the *system state* must change. A transition implies that the components of the system, their interaction and, with that, the performance system changes. Related to the *size* of the change, transitions point to relatively large changes. Many terms such as ‘fundamental’ and ‘radical’ are, however, ambiguous: they *also* point to the type or speed of change. Therefore, we choose ‘substantial’ change, since this only regards the size of the change. We choose not to include a restriction on the *speed* of change, because there is huge variation in the numbers mentioned by authors who did include speed in their definitions. Additionally, there are quite a number of definitions without mentioning the speed of change. Consequently, a transition may be the result of a long process and slow change, or a shorter process and faster change. We claim that no restrictions for *before*, *during* and *after* the transition are necessary for the concept of transition itself. Most definitions do not include such restrictions. Consequently, the transition can be between every possible set of two points in time (if the other components correspond to our definition). We also claim that no restrictions are needed for the *reason* for transition. The reason for transition is unrelated to the general concept of transition. We propose the following definition:

> *A system transition is substantial change in the state of a socio-technical system.*

The *multi-phase perspective* (Rotmans et al., 2000) may help us recognize the different phases in transition, when we are able to visualize them. Based on our definition for system transition, we deduce, however, that it is not necessary for the *performance* to increase during a transition. The system state can change without affecting the performance. Furthermore, change in performance is biased by the selection of indicators. Therefore, performance improvement depends on the perspective of the analyst. As a result, the multi-phase perspective is mainly useful when performance is important and can be measured.

Transitions in the *multi-level perspective* (Geels, 2002b) come about by pressure that macro level exercises on the typically stable regime. When different elements align, breakthrough may become possible. The three levels in this perspective may contribute to our perspective in the sense that system components and interactions may be identified using these notions. Furthermore, this notion is important for public policy, as this perspective may lead to ideas how transitions can be steered (Smith et al., 2005).

From the various *classifications* we can distil the distinction between *planned* and *unplanned* transitions. We discourage using the term *emergent* in this context: each transition is emergent from a socio-technical system's perspective, and is, therefore, ambiguous, and not a synonym for unplanned. An additional useful distinction may be the difference between a process in which a transition leads to a different *performance* or in which only the *structural character* changes (meaning the components and their interaction).

2.3 What is transition management?

Since we need to shape/improve our energy infrastructures and design what public policies we need with respect to transitions, our focus shifts towards the *management* of transitions. But what is transition management? And, in the context of public policy, what has to be managed, who will manage it and how? A significant body-of-knowledge on transition management (TM) has emerged in the last decades (see Figure 2.8). It can be separated in two parts (recall the two blocks in the second level in Figure 2.3). The first part is on the organizational level, where it entails the management of transitions within organizations. This part contains the oldest transition management literature. The second part, described in detail below, encompasses transition management in a multi-actor setting, for instance a whole sector. In this section, the two parts of the

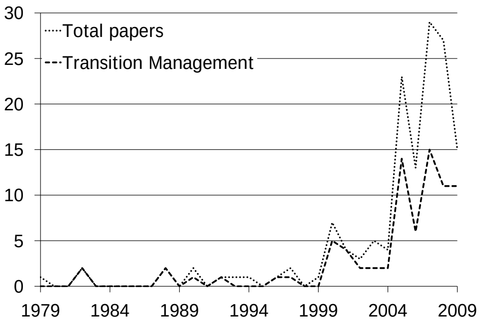

Figure 2.8 – Transition literature statistics: transition management

literature are discussed first. Afterwards, we analyse the most important transition management notions in the literature.

2.3.1 Intra-organizational transition management

In the 1980s, from the very beginning, the transition management literature has been two-sided. The first part dealt with transitions *within* organizations [3]. Several US publications dealt with how to act as a manager in order to achieve a successful transition to a new product line or organizational structure. Those publications dealt with the implementation of organizational transitions (Ackerman, 1982; Nadler, 1982; Hunsucker et al., 1988; Hunsucker, 1990), i.e. how to manage *changes* in the *structure* of the organization.

Management of organizations is rooted in the work on management, which Taylor (1911) defined as follows: "to secure the maximum prosperity for the employer, coupled with the maximum prosperity for each employé". Another definition of management is "the art of getting things done through people" (Barrett, 2003, 51). Fayol (1966) wrote about the five primary functions of management:

- Planning – The management decides what needs to happen in the future and comes up with plans for action.
- Organizing – The management optimizes the use of resources to enable the successful carrying out of plans.
- Staffing – The management takes care of job analysing, recruitment and hiring.
- Motivating – The management motivates participants to play an effective part in achieving the set out plans.
- Monitoring – The management monitors progress against plans and comes up with modifications.

The step from management in general to the *management of transitions*, requires a reflection of the actions of a manager of people in an organization into a manager of a

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[3] The second part of the transition management literature, inter-organizational transition management, is the topic of the latter part of section 2.3.

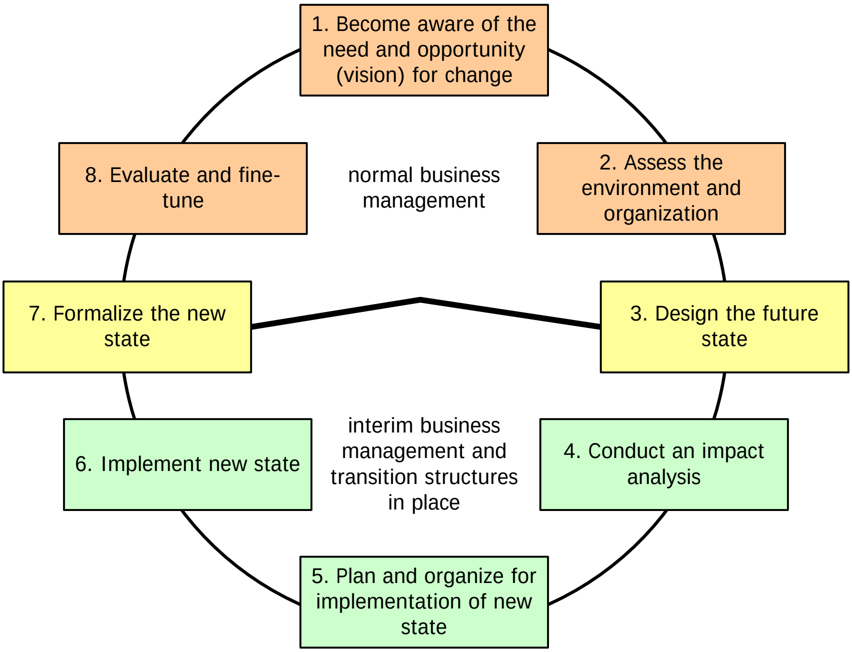

Figure 2.9 – Transition management activities, adapted from Ackerman (1982, p. 50)

system in transition. This implies, that the transition manager, whoever he is, needs to translate these five functions – planning, organizing, staffing, motivating, and monitoring – into a system in transition. In addition, the manager needs to select his/her strategy and behave in such a way that the functions are optimized. What can and should the transition manager do? How can transition management guarantee or even make likely that the transition will be properly managed, in terms that he/she directs the development of the system in transition?

Transition management was coined by Ackerman (1982) as "the systematic study and design of an organization's strategy and supporting structures, followed by the formal planning, implementation, and monitoring of the changes required". Ackerman (1982) owned a consulting company which aided companies in their organizational transitions. Based on their experience, they formulated a sequence of eight activities for transition management (see Figure 2.9). The top half of activities is executed by the normal business management, but starting with the design of a future state of the organization interim management is installed. They make the plan and implement the transition in the organization. After formalization, the normal management takes over again.

One could argue that Ackerman (1982) translates the *functions* of Fayol (1966) into a *design of a process*, as the five functions appear in the 8 subsequent steps, describing the process in which an organizational transition takes place. Next to the idea of a process design, the main addition to management functions is that an interim business management temporarily replaces normal management in order to execute a number of steps in the transition.

Regarding *implementation* of new systems, Bolesta et al. (1988, p. 848) define transition management activities as "the management of non-technical, non-system aspects of the implementation process". Bolesta et al. (1988) focus on the implementation of new information systems within hospitals and claims that both transition management, project management, and training are needed to accommodate a successful transition. They argue that transition management can be used in addition to common practices. In their view, transition management is a different method for *problem analysis*. A number of aspects of the organization under transition are considered important, such as commitment of management, whether people are willing to work together, current workloads and stress levels and cultural barriers (Bolesta et al., 1988). These appear to be reflecting the organization's *capacity* for change.

Langowitz (1992) from Boston College, Massachusetts, US, analysed two approaches for the management of the transition from mechanical to electronic technologies. He concluded that, in this case, a pro-active approach rather than a reactive approach leads to a smoother transition. In the most successful case, management was proactive in the sense that "new hires and acquisitions kept their vision current and contributed to a fluid and adaptable organization." (Langowitz, 1992, p. 84).

Duckney (1996), from 4C's Associates, argues that long-term and short-term visions of managers are important for successful transition management within organizations. He compares top-down changeover processes, initiated from the management level to bottom-up processes, emerging from the lowest levels in an organization. Furthermore, Marks and Mirvis (2000), organizational psychologists from San Francisco, California, US, focus on the transition of merging two large companies. They speak about temporary transition *structures* with teams that provide coordination and support during the implementation of change. 8 The older publications focus on transitions on the organizational level, formulating strategies for management of radical changeover processes within organizations. Let us see how these ideas on the management of transitions reflect on the ideas of transitions on a larger scale. They may lead to new ideas for transition management of sectors.

2.3.2 Inter-organizational transition management

Newer literature explicitly dealing with transition management focuses on the level of sectors (top part of level 2 in Figure 2.3). This branch of transition management literature follows the idea coined by Matthews et al. (1997) that transitions as outlined in the discussion above can be steered or shaped. Matthews et al. (1997) actually claim that "the importance of transitions is that their magnitude, and rate of change, can be significantly influenced by policy intervention" (Matthews et al., 1997). The idea of the connection between *transition* and *public policy* is, therefore, not new. However, we now acknowledge that no single actor in a socio-technical system has full control (see earlier this chapter). *Who* are transition managers? *What* can and should they do? *How reliable* can a transition management strategy be for a socio-technical system such as our energy infrastructures? Let us look into the ideas in the literature on shaping or managing transitions in this large-scale socio-technical systems.

Rotmans and Kemp (2008) see transition management as a *model* of how transitions in societal systems can be steered. In modern transition management literature, "transition management is based on a two-pronged strategy. It is oriented towards both system improvement (improvement of an existing trajectory) and system innovation (representing a new trajectory of development or transformation)" Loorbach and Rotmans (2006, p. 10). As the systems under study exhibit complexity, transition management argues, classical command-and-control management is not possible and one should aim for adjusting, adapting and influencing (Loorbach, 2007). Governments have been trying transition management (Ministry of VROM, 2001; Paredis, 2007) and results are promising in qualitative terms (Rotmans, 2003; Loorbach et al., 2008), although no quantitative results are yet achieved (Rotmans and Kemp, 2008).

In the literature, many transition management elements have been described (see appendix A for an overview). We will now describe the most important elements in the transition management literature and relevant links between them.

The first set of characteristics and stages Geels and Kemp (2000) provide input for the first main set of transition management elements, which were published by Rotmans et al. (2001). Postulating their relevance, these are called *characteristics* of transition management. Since, this list is the basis for transition management, which can mainly be seen in the number of citations.

- Long-term thinking for framing short-term policy
- Multi-domain, multi-level, multi-actor
- Learning-by-doing and doing-by-learning
- Trying to bring about system innovation alongside system improvement
- Keeping a large number of options open

Both the multi-level perspective and the multi-phase perspective together were the inspiration for this list (Rotmans et al., 2001). Central in these characteristics is allow the long term to connect to current actions, by allowing for learning, by not excluding options that may prove useful in the future, by including many issues, and by bringing many stakeholders to the table.

On the potential success of their transition management they mention the following: "the aim of transition management is not so much the realization of a specific transition: it may be enough to improve existing systems, or the problems may turn out to be less severe than at first thought" (Rotmans et al., 2001, p. 22). 'Successful' transition management is however ill-defined. Two possible definitions are 'transition was invoked' or 'problem was solved'. This ambiguity is easily connected with the abstract aspects in the transition definitions. How can we know whether, and under which conditions 'this' transition management is the best way to invoke transition in our energy infrastructures?

Vollenbroek (2002), from the Department of Strategy of the Dutch Ministry of Environment, adopts the same list of elements (although no reference to Rotmans et al. (2001) is provided). Vollenbroek (2002) is more modest in his claims, the elements are considered principles that 'seem to be important'. They describe transition management as a strategy where all relevant stakeholders are incorporated into a *process* in which many issues are on the table. This is similar to the recommendations of Ackerman (1982) on the transition management within organizations, and is also strongly connected with the body of knowledge on Process Management (de Bruijn et al., 2002). Additionally, they focus on the long-term and on learning.

Furthermore, Rotmans et al. (2001) mention a number of *stages*. Rotmans et al. (2001) describe that transition management consists of a *transition objective* that is adjusted over time according to the intermediate performance. The next stage is one in which *transition visions* are created for a sustainable future. These visions function as a roadmap towards system innovation. In that way, a set of visions of the far future is a means for communication between the actors involved in the process. The use of such visions explicates both the focus on long-term thinking and the strong connection with sustainability. The next stage is evaluating and learning, in which intermediate reflection of the achievements takes place. Finally, creating public support is advocated, by means of participatory decision-making or local support for new technologies.

Refinements of transition management elements Building on these publications and on experience in the Netherlands (Rotmans, 2003) and Belgium (Geldof, 2002), refinements and changes are made to the elements in transition management. Rotmans et al. (2005) acknowledge a coupling between transition management and complex adaptive systems (CAS) theory. A number of *assumptions* are presented regarding societal development, complexity, and options for steering and managing society. Many of the principles that follow, now reformulated as transition *instruments*, can easily be derived from these assumptions. They reformulate transition elements which are now presented as 'partially prescriptive'. Further refinements include renaming the characteristic identified as 'multi-domain' to 'integrated policy'. The principle keeping options open is further delineated, some form of selection is now advocated. Also Loorbach and Rotmans (2004) argue for learning about *a variety of options*, which is quite different from the general rule of keeping open a large number of options. The step *transition evaluation* is introduced (Loorbach and Rotmans, 2004). Rotmans and Loorbach (2009) introduce some new principles, rephrasing their ideas into complex systems terminology such as 'guided variation and selection'.

A useful new distinction is that between transition *paths* and transition *scenarios*. Transition paths are defined as by transition management affected trajectories; transition scenarios contain relevant uncertainties, in the literature generally referred to as *environment scenarios* (Fahey and Randall, 1998). Wiek et al. (2006), from ETH Zurich, bring in a different angle. They focus on the use of scenarios for transition management, but introduce an all-inclusive set of four requirements for transition management (see Figure 2.10). The first requirement is generation of knowledge on the system, the target, and the transformation. The second requirement is integration using backward planning and qualitative and quantitative data from different fields. The third is adaptation, which relates to learning by planning and learning by doing. The last requirement is transdisciplinarity. These four requirements are translated to activities, in which Wiek et al. (2006) introduce many elements mentioned in other publications, but also bring new concepts in the discussion. For instance, change management and transformation knowledge are introduced. This seems to be the first effort to aggregate previous work and give an integrative overview of what transition management should be. In addition, Wiek et al. (2006) provide underpinning of what the role is of scenarios in the requirements for transition management.

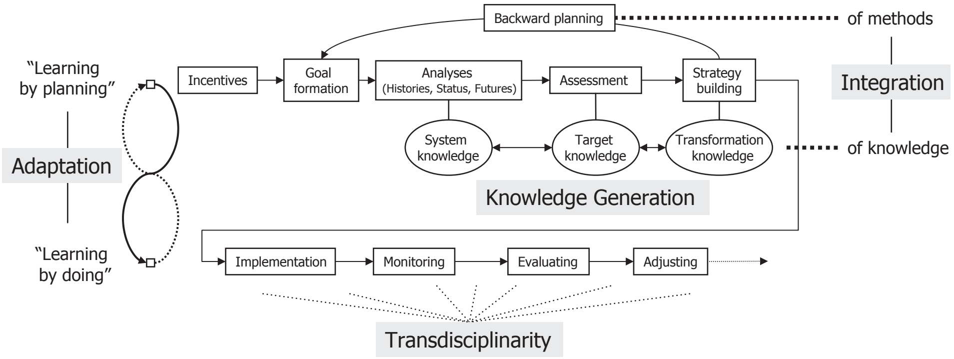

Figure 2.10 – Requirements for Transition Management, from Wiek et al. (2006)

Loorbach and Rotmans (2004) couple transition scenarios to the use of *visions*. Loorbach and Rotmans (2006) argue that visions are to be translated into multiple trajectories by which they can be realized. Transitions are linked even stronger to sustainability, by reformulating transition visions to *sustainability visions*. According to Loorbach and Rotmans (2006), the setting of short-term and longer-term goals should be based on long-term sustainability visions, scenario-studies, trend-analyses, and short-term possibilities; he calls this process back-casting and forecasting. Bruggink (2005), from the Energy Research Centre of the Netherlands (ECN) postulates that visions regarding transition management can be used to come up with a road map to reach that vision. In addition, he operationalizes the stimulation of niches (recall niche is the lowest level in the multi-level perspective) by claiming that the niche should be supported by means of participative involvement of companies, research institutes, and civil society. In the report by Drift (2006)[4], a number of already found elements are again rephrased into *rules of thumb*. In addition, one rule of thumb is newly introduced, namely to focus on *innovation and optimization*.

Hekkert et al. (2007) connect the field of transition management to *innovation systems* (IS). "The concept of 'innovation systems' is a heuristic attempt, developed to analyse all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation" (Hekkert et al., 2007, p. 414). Innovation (Freeman, 1987; Freeman and Soete, 2000) and, more specific, environmental innovation (Chappin, 2008) is an important aspect in both the literature on autonomous transitions and in the literature on transition management because of the strong link with sustainability. Therefore, Hekkert et al. (2007) discusses innovations in protected niches in the multi-level perspective from the perspective of innovation systems. A framework with seven functions of innovation systems is presented and later validated (Hekkert and Negro, 2009). From the seven functions, a number coincide with earlier ideas. First, knowledge development, i.e. mechanisms of *learning* are at the heart of any innovation process. This was indeed mentioned as a characteristic (in the form of learning-by-doing) by Rotmans et al. (2001) and as requirement by Wiek

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[4] The Dutch Research Institute for Transitions is part of the Erasmus University of Rotterdam and directed by Jan Rotmans.

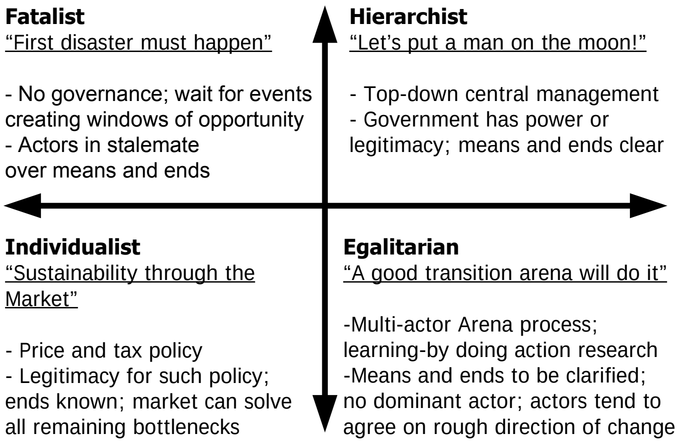

Figure 2.11 – Archetypes for transition management, adapted from Tukker and Butter (2007, p. 99)

et al. (2006). Second, knowledge *diffusion* is the essential function of networks. This is also important in the transition arena (Loorbach and Rotmans, 2004, described below). And last, a market needs to form, which may be initially protected or supported in order to let new technologies mature. This was also considered by Geels (2002b) and Rotmans et al. (2001).

In contrast with this there are a number of contradicting ideas and additions to the transition management elements. First, the existence of *entrepreneurs* in innovation systems is of prime importance. This is new in the sense, that in earlier literature, only protection of niches was discussed, and not the importance of such activities. Second, the search for innovations need to be *guided*, i.e. preferences of the intended users need to be visible and clarified. This function was not mentioned in previous literature on transition management. This is different from a lot of literature on transition management, which claim to keep all options open. Hekkert et al. (2007) clearly advocates to limit the number of options to allow for enough resources per option. Third, financial and human resources are necessary as a basic input for the activities in the innovation system. This implies more government action than we see in the other transition literature. And finally, legitimacy needs to be created and resistance to change minimized. Although this appears similar to the transition arena, there the advice is to leave the incumbents out of the arena, because they can block the process. Innovation systems are more explicit about how to deal with those incumbents.

In contrast to most of the literature in which little is mentioned on the role of *government*, Jacobsson and Bergek (2004) focus on *government mechanisms* either to induce or to block transition. R&D funding, investment subsidies, demonstration programmes, and legislative changes belong to the inducement mechanisms. Government policy in general could also be a blocking mechanism. Also uncertainty, lack of legitimacy of new technology, and ambiguous or opposing behaviour of established firms could block a transition. Elzen and Wieczorek (2005) look specifically at groups of *government instruments*, affecting transition. They discuss top-down instruments such as formal rules, bottom-up instruments such as financial incentives, and process-oriented instruments such as learn-

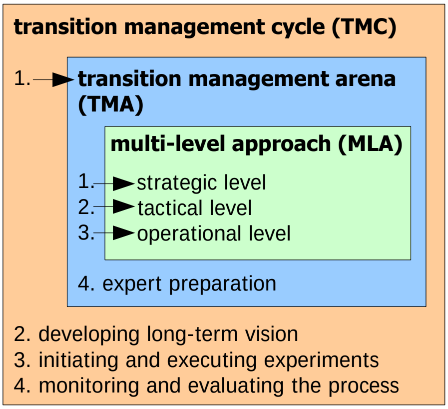

Figure 2.12 – Links between the transition management cycle, the transition arena, and the multi-level approach for transition management

ing processes and network management. Both Jacobsson and Bergek (2004) and Elzen and Wieczorek (2005) appear to be of the opinion that government should have a larger role in the process of transition than given in the before-mentioned literature. Also, Tukker and Butter (2007) are more elaborate on the role for government as they developed four *archetypes* of transition with different roles for government (Figure 2.11. Although one of their archetypes, 'Egalitarian', is strongly connected with Loorbach's notion of the transition *arena* (described below), two others provide a large role for the government.

The transition management cycle, arena, and the multi-level approach Strongly connected with Rotmans' stages are the transition *steps* by Loorbach and Rotmans (2004). These steps form the transition management *cycle* (TMC). In the transition management cycle, four activities take place in a cyclical process, each cycle being a *development round*. The TMC is interlinked with two other notions in the literature, i.e. the transition management arena and the multi-level approach for transition management. Their relations are depicted in Figure 2.12.

The elements in the TMC from the cycle are partly concurrent and parallel (Rotmans et al., 2005). Each development round consists of the following elements and takes two to five years (Loorbach and Rotmans, 2006):

- Establishing and further developing a transition arena for a specific transition theme. The transition management arena (TMA) is discussed below.
- Developing a long-term vision for sustainable development and a common transition agenda.
- Initiating and executing transition experiments.
- Monitoring and evaluating the transition process.

Two new aspects are introduced in the TMC. First, the introduction of the transition arena, an operationalization of the idea of an organized *process* with the actors involved.

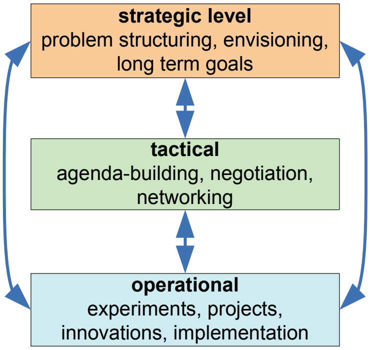

Figure 2.13 – Multi-level approach to transition management (based on Kemp et al., 2007, p. 83)

More details on the arena follow below. Second, the focus on performing transition *experiments*, which focus on creating conditions in which niche-technologies can mature. Recently, Rotmans and Loorbach (2009) pictured the transition management cycle, in which a selection step is introduced. Inspired by evolutions' 'variation and selection', the TMC description is augmented with the selection of promising niches. Furthermore, the activities in the cycle are strongly connected to the multi-level perspective (Geels, 2002b). These activities aim to manage transition by organizing support for niches that will break open the incumbent regime and take over its role, or the 'contestation and substitution' trajectory (recall Table 2.2). The transition management cycle has been adopted by some colleagues, Van der Brugge et al. (2005) and Van der Brugge and Rotmans (2007), in their case on water management in Holland and Europe.

The first step in the cycle refers to the *transition arena*, or transition management arena (TMA, Loorbach and Rotmans, 2004), which prescribes to incorporate the main frontrunners in a virtual network. Loorbach and Rotmans (2006, p. 9): "Transition arenas are networks of innovators and visionaries developing long-term visions and images which, in turn, are the basis for the development of transition agendas and transition experiments, involving growing numbers of actors." Rotmans and Loorbach (2009, p. 192): "The transition arena is best viewed as a virtual network, which is a legitimate experimental space in which the actors involved use social learning processes to acquire new knowledge and understanding that leads to a new perspective on a transition issue. Such a transition arena has to be supported but not dictated by political actors or regime powers – for example, through the support of a minister or a director. In general, around 15 to 20 frontrunners (i.e. pioneering individuals) are involved in the beginning of the transition arena, although, over time, only around 5 will become the core group."

A transition arena consists of four phases of activities. In each of the phases, activities on the process are distinguished from those on the content. Loorbach (2007, p. 137) considers them "the main activities involved in transition management". The first three phases in the transition arena equate the activities in the *multi-level approach* (MLA, Kemp et al., 2007). Rotmans et al. (2005) present assumptions and principles for transition management and translate them into instruments on a strategic, tactical and operational level. Those instruments are captured by Kemp et al. (2007) in the multi-level approach for transition management[5]. Kemp et al. (2007) contain the same levels as defined by Rotmans et al. (2005), on which transition management activities take place (see Figure 2.13). On the *strategic* level, the transition arena is developed. On the substance, the problem is structured and sustainability visions are generated. On the *tactical* level, the arena is split in arenas and coalitions are built. Target images and paths are developed together with a transition agenda. On the *operational* level, experiments are prepared, the actor network is developed and actors are mobilized to act. On the substance, this results in knowledge and experience.

This approach is an interpretation of the earlier mentioned activities in transition management, particularly the use of long-term thinking in visions, and learning from experiments. As is the case with the transition management cycle, transition arenas are adopted by colleagues in their work on water management (Van der Brugge et al., 2005; Van der Brugge and Rotmans, 2007; Loorbach et al., 2008). Van der Brugge and Rotmans (2007) base their management principles on Rotmans et al. (2005), but come up with a different list. For instance, van der Brugge and Rotmans (2007) explicate the opinion that long-term goals should be adaptive. In addition, they interpret multi-level governance as having varied but attuned objectives and instruments at the different levels so they reinforce each other. Also the management strategies and instruments should vary at the different phases.

The fourth level in the transition management arena is *not* in the multi-level approach. It is the newly introduced phase called *expert preparation*. In this phase, a process design is made and actors are selected that need to participate in the arena. In addition, a first integrated systems analysis is performed. This connects to the argumentation of Van de Kerkhof and Wieczorek (2005), from the Free University of Amsterdam. They apply the work on the arena and the cycle and argue that learning-by-doing needs to be further operationalized before it is useful: learning-by-doing needs to be arranged in the transition arena. They link transition management to the main components of process management: commitment of the actors in the process, fairness and transparency of the process, and competence of the actor constellation (de Bruijn et al., 2002).

Strategic Niche Management (SNM) The work on niches (section 2.2) was also developed into the notion of Strategic Niche Management (SNM, Caniëls and Romijn, 2008). SNM is a recently developed *method* designed to *facilitate* the introduction and diffusion of technologies (Elzen et al., 2004), with a focus on increasing sustainability (Hoogma et al., 2002). SNM uses "socio-technical experiments in which the various innovation stakeholders are encouraged to collaborate and exchange information, knowledge and experience" (Caniëls and Romijn, 2008, p. 246). In SNM, niche formation requires an actor network, not centred on short-term financial gains (Hoogma, 2000), with certain composition (Kemp et al., 1998), and a strong role for the user (Weber et al., 1999). Factors that strongly promote niche processes are technology-specific characteristics: protected niches are required (Kemp et al., 1998), continuous improvement should be likely (Elzen et al., 2004), there should be potential for survival after a period of protection (Kemp et al., 2001) and initially, there should be highly valued attractiveness (Kemp et al.,

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[5] The multi-level *approach* by Kemp et al. (2007) is not to be confused with the multi-level *perspective* by Rip and Kemp (1998); Geels (2002b).

1998). Attitudes, values and choices of actors also matter (Caniëls and Romijn, 2008). With these elements, SNM proved useful for the *analysis* of past sustainability-related experiments (Caniëls and Romijn, 2008). However, SNM is young and the potential for SNM as a tool for transition has yet to be proved (Hoogma et al., 2002).

2.3.3 Analysis

While description of past transitions indeed leads to increased understanding of transitions, transition *management* requires transitions to be directed and shaped. In a critical review of the transition management literature, Shove and Walker (2007) argued that it is unknown *who* is the transition manager. In addition, we found that 'successful' transition management is ill-defined: 'transition invoked' or 'problem solved'? Acknowledging this fact, how can we know whether and under which conditions transition management as described in the literature is the best way to invoke transition in our energy infrastructures?

We are dealing with complex socio-technical systems that evolve over decades. Typically, actors in these systems decide over installations that have a very long technical if not economic life-span. Elucidating transitions of energy infrastructure systems is not only difficult and maybe even impossible, to establish the *relation* between transition *instruments* and their *effect* is an even more daunting task. We conclude with a definition for transition management in socio-technical systems:

> *Transition management is the art*[6] *of shaping the evolution of socio-technical systems.*

This implies a combination of the content and the process of transition – changing the structure, content, and body-of-rules of a system; and a process whereby this change takes shape. It is this process that is managed, the process that is shaped through the collective actions of the actors in the social network. Their behaviour and decisions on the physical network can be influenced through policies, regulations, R&D strategies, financing etcetera.

In the old transition literature, transition management focused on changeover *processes* within organizations, like with process management and network management (de Bruijn et al., 2002). One of the strategies is installing temporary management executing the transition, using a *design of the transition process* (Ackerman, 1982). Other strategies include the organizations' *capacity for change* (Bolesta et al., 1988). The distinction between a pro-active and reactive approach has been put forward (Langowitz, 1992). Other relevant distinctions are long-term versus short-term management visions and top-down versus bottom-up processes of change (Duckney, 1996).

Also in more recent transition management literature, that deals with transition management on a higher level, i.e. the sector level, the focus is on managing the *process* of transition (Rotmans et al., 2000; Loorbach and Rotmans, 2006; Rotmans and Loorbach, 2009). Elements that are part of transition management deal with both the perspective of

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[6] In this definition, the notion 'art' refers to 1) the description of management by Henry Mintzberg, who points at imagination and creative insights as part of the core of decision making and management (cf. the lecture by Henry Mintzberg at http://www.youtube.com/watch?v=DyvXu3lSSGo), and 2) the definition by Stephen Sondheim: "art, in itself, is an attempt to bring order out of chaos".

the transition manager (for instance 'multi-domain'), as its activities (for instance 'keeping a large number of options open'). The focus on the multi-actor process of transition management can be seen in the literature on the transition *cycle* (Rotmans et al., 2001), focusing on the process surrounding experiments and the transition *arena* (Loorbach et al., 2008), which is part of that. In general, there is a myriad of elements of a more or less prescriptive nature. Many of those elements are debated on occasions. For instance, Hekkert et al. (2007) shows with Innovation Systems theory that the idea of 'keeping options open' (Rotmans et al., 2001) is generally not preferred as available resources per option become insufficient. It is however hard to choose between the elements, based on the given arguments. And what combinations would work?

Transition management has been strongly focusing on *sustainability*. All discussed management strategies, including the multi-level approach (Kemp, 1994), transition arenas (Loorbach, 2007; Rotmans and Loorbach, 2009) and strategic niche management (Caniëls and Romijn, 2008) explicitly focus on sustainability and/or relate transitions to sustainability in their analysis. This is interlinked with the many definitions of transitions including the type of problem they solve (as was discussed in section 2.2). Consequently, all other – unsustainable – transitions are neglected (e.g. diffusion of air-conditioning Shove and Walker, 2007, p. 767), in which other factors and mechanisms may play a role because of which specific transition management strategies may or may not work. We suggest to loosen the link to sustainability and open up the literature to other transition objectives.

In the literature, there is no agreement on the role of *government*. Generally, the government gets a relatively small role or remains outside the discussion (Loorbach et al., 2008; Rotmans and Loorbach, 2009). Some argue that the role differs between possible transition types (Tukker and Butter, 2007). Others claim that government has instruments that may induce (Elzen and Wieczorek, 2005) and/or block transition (Jacobsson and Bergek, 2004). We agree with the latter: while energy infrastructure systems are not planned in the sense of the primary function of management (cf. Fayol, 1966), governments represent a form of coordination through appropriate policies, taxation, rules, and regulations. As argued in the introduction, governments have to manage transitions in energy systems through the development, implementation, and use of their instruments.

2.4 The design of a system transition in energy

In the last section we identified a number of issues regarding the literature on transition management: what successful transition management is, the myriad of prescriptive transition elements, the strong focus on sustainability and the role of government. In the context of energy policy facing transition, how could 'we', i.e. who is responsible for it, choose from the myriad of elements? And, eventually, 'how could 'we' manage an energy transition successfully?' This question appears to be of the same type as: 'How could we choose from all the possible elements in order to be able to develop into a *car* that is both affordable, safe, economical, and attractive?' In other words, we face a *design problem*. But not the design of a system itself, such as a car, with the wheels, the engine etc. Rather the design regarding transition in a system: it is a metadesign. It should include the design of *how to get there*. In this section, we apply a *design approach* to energy transition. First, we explore the relation between energy policy and transition design. Next, we elaborate on the design approach. Finally, we will conclude this section with the identification of knowledge gaps resulting from the analysis.

2.4.1 Energy policy and transition design

In the context of the public policy, the role of the government is making *the rules of the game* using policy instruments and regulation. Such policies should make actors behave according to the policy makers' set of objectives, while actors realize their own goals. If policy intends to lead to structural change in an energy infrastructure – for whatever reason – it is likely that a system transition is needed. The policy needed for structural change is, therefore, only effective when it initiates a transition to a desired end state. In addition to requirements for the end state, there might be requirements or objectives for the pathway of the transition itself. Incorporating the transition pathway and end state adds a new dimension to the challenge of policy design.

Transition management hinges on the design of a *coherent set* of instruments, which we will call an assemblage:

> *A transition assemblage is "the all-inclusive set of transition instruments"* (Chappin and Dijkema, 2010a, p. 107).

Framing transition management as a design problem for government – 'what assemblage of transition instruments is required to initiate and manage the transition process?' – helps us to identify the problems in developing effective transition management. Ever design activity – a technical process system design, product design, policy or strategy design – typically starts with a problem exploration, system description and analysis, and (design) problem statement (Dijkema, 2004, p. 55). Subsequently, elements for design solution must be generated. Alternatives must be evaluated and 'the best' alternative must be chosen. This requires a statement of objectives, constraints, and tests (Herder and Stikkelman, 2004).

Success is typically viewed as 'are objectives achieved'. In projects, these are typically milestones and completion. In change management and governance, these also may be formulated as 'process objectives': has the process of change started, have the right actors been involved, have projects been launched to let the transition materialize? The effectiveness of any transition assemblage design then is expressed as the likelihood of meeting the designers' objectives – whether the transition assemblage design leads to system change and emergence of improved system performance. In order to do this properly, and to maximize their chance of success, transition managers require a basic understanding of the socio-technical design space, and of the complexities of and the uncertainties involved in bringing socio-technical systems, or parts thereof, into being. Upon such knowledge recipes, do's and don'ts for transition managers can be formulated, as well as guidelines for transition process management.

"Design generally is concerned with an artefact which purpose and system boundary are both well-known and static" (Herder et al., 2008, p. 18). Design of a *complex* system can be considered a contradictio in terminis (Herder et al., 2008), because these systems evolve as a never-ending series of discrete events and interactions, amongst themselves and their surroundings. Let us assume that we can position ourselves as an independent

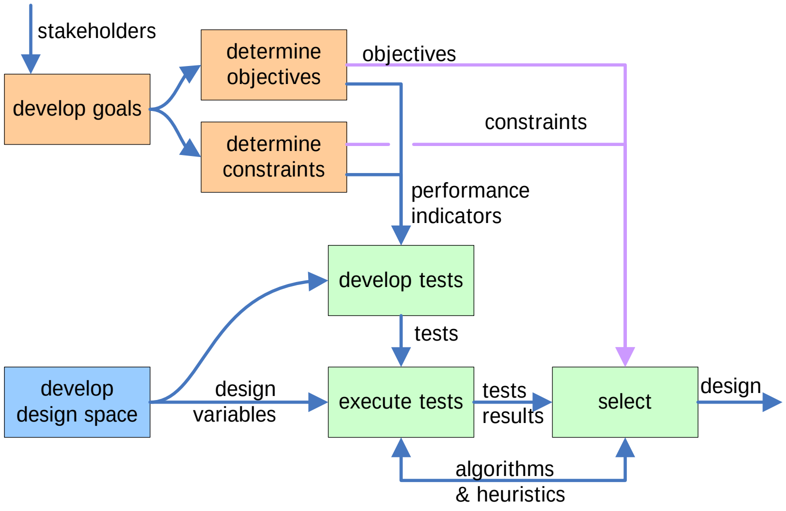

Figure 2.14 – Conceptual model of a design process, adapted from Herder and Stikkelman (2004)

high-level observer who is detached from this process. Subsequently, we may realize that the design of system elements such as individual power plants, and gas pipelines is led by single actors who want to benefit from these facilities. Meanwhile, other actors, governments and parts thereof are shaping the regulatory environment, allocate research funds, and develop public infrastructure. In summary, parts of the surroundings of the complex systems are subject to design efforts. Preferably, such design is done in concert with present technological capabilities while leaving options for innovation.

We conjecture that an energy system can at least be partly designed. The design process of a transition in energy systems may be seen as a *metadesign*: the design of a design process. A metadesign, therefore, differs from the designing of simpler systems (Maier and Rechtin, 2002; Dym and Little, 2004). In a metadesign, in addition to the technological system content, the process of bringing the system into being is designed (Herder et al., 2008). The system can be directed by affecting actors' actions through *designing* and *implementing* a transition assemblage. Using a designers' perspective, we will study transitions and transition management.

2.4.2 Designing energy transitions

In general, the methodology of a design study contains (1) the development of goals, objectives and constraints, (2) the specification of the design space and (3) the development of tests. The tests should be set up in such a way that by executing them the best performing design for implementation can be selected.

In order to develop such a metadesign in which a complex system undergoes transition, we will use the conceptual model of a design process (See Figure 2.14). Let us now assume we are a metadesigner who is again detached from the transition itself and who is in need of a metadesign for system transition. We may then proceed to apply the general design process to arrive at a suitable metadesign for system transitions in energy.

Develop goals The first step in the design process is the development of goals for the metadesign. Since eventually we want to select the best design, i.e. the metadesign that best fulfills these goals, goals should be unambiguous and complete, which clashes with transition management guidelines stated in the literature. In transition management it is preferred to state ambitions above objectives, to have qualitative rather than quantitative objectives and to recognize that all objectives may be subject to re-adjustment (see for instance Rotmans et al., 2001). In many design approaches, however, goals are formulated as functional requirements, must-haves and should-haves. For system transitions in energy, transition managers claim as main functional requirement that the energy infrastructure must be *sustainable* (Rotmans et al., 2000, see also above). A proper design of a system transition for energy should contain a comprehensive set of functional requirements for the metadesign wherein the system transition develops itself. Sustainability is both a goal for the metadesign of a transition, as for the system itself: it reflects what the outcome of transition should be as well as its pathway. As sustainability has been properly defined since 1987 (World Commission on Environment and Development, 1987) it can be operationalized in the design process.

However, in order to develop the goals for a system transition, transition managers involve many actors: it is a multi-actor process. It is highly unlikely that all involved actors agree that sustainability is the only goal. Other relevant stakeholders have different goals in this design process: the sustainability goal should be augmented with many more goals. Since more actors are involved, they will impact the goals resulting from this step. For example, companies strive for continuity of their business and want to make profit. In the analysis designing a transition, the set of goals should incorporate this as well. The full set of goals, therefore, includes for instance affordability and continuity for businesses.

Determine objectives and constraints In determining objectives and constraints one makes the previously defined goals explicit. For all objectives and constraints, performance indicators are identified whereby one can assess whether and to what amount the objectives and constraints are met. This is necessary to be conclusive on the performance of different designs of system transitions. Actors will put in effort to make sure that objectives and constraints which are relevant for them are put in or left out according to their own preferences and means.

Two notes should be made here. First, designing large-scale socio-technical systems results in a huge set of constraints and objectives, possibly including conflicting ones. That would complicate defining the design space. For the design of a system transition, this might be even more problematic, because not only the socio-technical system but also the transition process is subject to objectives and constraints. Second, objectives and constraints must result in measurable performance indicators. Indicators identified for system transitions are based on a top-down system's view as mentioned in the second section: the time period of a transition, the speed, and the size of the change. However, one could identify many more by analysing what the characteristics of a transition pathway means for the socio-technical system in which the system transition occurs.

For deriving objectives and constraints for sustainability one can distinguish three domains: economy, ecology, and equity. To come to explicit and measurable performance indicators, one can exploit and operationalize these three domains. For the economy domain, sustainability implies an objective and/or constraint on welfare: a constraint for a transition could be that a transition should lead to continuous welfare growth or to limited welfare decrease. Additionally, an objective for the economy domain could be that welfare should be maximized during the transition. Gross national product (GNP) is a well-defined and measurable indicator for welfare. For the domain of equity, a constraint is that during the transition welfare should be distributed more equally than it is now. An objective could be that the variance in welfare should be minimized. For the ecology domain, constraints could be that irreversible emissions with a global or local environmental impact should be avoided, which can be measured by emission levels of substances which are known to harm the environment, or by uptake of limited resources. Another could be that biodiversity should not go down, which is measurable as number of affected species. For the same goal, objectives could be that irreversible emissions harming the environment should be minimal or that negative biodiversity effects during the transition should be minimized.

Develop the design space Crucial in any design process is the development of a suitable design space. A design space is built-up from design variables that can be varied in order to come to the set of possible designs. A design space is n-dimensional.

The multi-level perspective (Geels, 2002b) and the four phases in a transition (Rotmans et al., 2001) structure how transitions come about. The key point in the multi-level perspective is that system innovations – that lead to system transitions – come about through the interplay between dynamics at multiple levels. Design variables should, therefore, impact the dynamics on those levels. The four phases imply that transitions follow a certain pathway. Designing a transition, therefore, implies designing this pathway and, according to that, design variables to do so. This transition path is, however, directly connected to indicators (recall the vertical axis in Figure 2.4): for the identification and use of transition pathways, unambiguous and measurable performance indicators are a necessity. Both the multi-level perspective and the four phases do not focus on how to impact system transitions. They are rather used for analysing and describing past transitions.

The transition management literature should provide the design variables. Methods for invoking transitions might be useful as design variables for system transitions. As discussed in section 2.3, there is a myriad of transition management elements. Some of them are considered *instruments*, but also mentioned are key elements, characteristics, principles, stages, steps, instruments, management principles, activities, and mechanisms. It is not straightforward to derive what the transition instruments are. Some of the other elements may be instruments as well. Let us, therefore, provide a first analysis, by starting with those elements that are explicitly named instruments. They are extracted from appendix A, Table A.2, page 227 and listed in Table 2.3. In the compiled list, three groups of instruments can be distinguished. First, instruments regarding the initiation of a transition process. Second, a number of instruments are relevant during the transition itself. Finally, there are instruments regarding public policy. Let us discuss each of these.

All instruments related to the initiation of a transition process should not be considered part of the design variables. Specifically, transition objectives and interim objectives belong to developing goals (and after that determining objectives and constraints), as discussed above. Transition arenas are also mostly applicable to the process of develop-

Table 2.3 – Transition management instruments

Element	Reference
Initiation of the transition process	
Transition objectives	Rotmans, Kemp and Van Asselt (2001)
Interim objectives	Rotmans, Kemp and Van Asselt (2001)
Transition agendas	Rotmans, Loorbach and van der Brugge (2005); Loorbach (2007)
Transition arenas	Loorbach and Rotmans (2004)
Innovation networks	Rotmans, Loorbach and van der Brugge (2005)
Transition visions	Rotmans, Kemp and Van Asselt (2001)
Scenario development	Rotmans, Loorbach and van der Brugge (2005)
Creating public support	Rotmans, Kemp and Van Asselt (2001)
During the transition	
Experiments	Rotmans, Loorbach and van der Brugge (2005)
Learning	Rotmans, Loorbach and van der Brugge (2005); Elzen and Wieczorek (2005)
Monitoring, evaluation	Rotmans, Kemp and Van Asselt (2001); Rotmans, Loorbach and van der Brugge (2005)
Public policy	
Formal rules	Elzen and Wieczorek (2005); Jacobsson and Bergek (2004)
Financial incentives	Elzen and Wieczorek (2005); Jacobsson and Bergek (2004)

ing goals. Transition visions and scenario development are not part of the design space too, because they are a means to explicate and visualize the result of a system transition and explicating relevant conditions for transition. These far-future visions can be used to derive transition steps that can lead to this result. Next, by creating public support (through the involvement of actors in decision-making and through education) one can create a momentum for change in the process. This also relates more to earlier parts of the design process, i.e. determining objectives and constraints.

During the transition itself, many transition management articles focus on the design and support of experiments, so learning can take place and technologies can mature. Under the assumption that technological niches can mature, they can diffuse into society and realize a transition. Basic underlying assumption is that the 'market' condition is sufficiently favourable for the technology to take over eventually. In this category, monitoring and evaluation are also mentioned. They should allow input for steering during the process of transition. But how the input is used to steer remains undefined.

Regarding public policy, some mention that formal rules and financial incentives are transition instruments. These work by affecting the 'market' conditions, so change can take place. These can be considered top-down instruments. However, they may also be seen as facilitating change processes, either by allowing for protected environment of technologies, or for giving possibilities or incentives to change.

Develop and execute tests All possible combinations of options for variables within the design space are potential alternatives that can be selected for implementation. If performance indicators are defined well, i.e. when they are measurable and unambiguous it is possible to develop and execute tests that can grade the performance of the design alternatives. Designs for system transitions cannot be tested in reality: only one test could be executed, afterwards the system was changed by the test itself. As a consequence, the transition management literature is thick on historic cases. Best practices are identified analogous to those cases rather than identifying design alternatives and tests for them. For real testing of design alternatives one can use the power of modern computers to simulate real systems. As we adopt a socio-technical system's perspective in those simulations, all essential components of the socio-technical system should be apparent. Rotmans et al. (2001): "The system approach implies thinking in terms of *stocks* and *flows*". They refer to the top-down systems view, which is only one of the possible system's views. When the object of study is transitions, a socio-technical system's perspective is more relevant, which is very different to stocks and flows. It is one of physical and social elements and links.

Simulation exercises (Birta and Özmizrak, 1996, goal-directed experiments with a computer program) need to be well designed experiments in order to come to results that are meaningful. This is especially true for models on system transitions, since the systems under study have many relevant components and are heavily connected to other systems. Relevant components include the technological system of apparatus and connections, the preferences of stakeholders and their social and economic behaviour, and policy. Simulations can be used to better understand the functioning of systems, to explore and identify determinant components and their interplay, and – given the main aim of this section – to test the impact of design alternatives without implementing them. Given a set of well-chosen assumptions, this can all be done without having the ambition to predict the future, rather to predict the variety of trajectories and future states for a system. To enrich the process of codifying actor behaviour (translating behavioural rules to computer-readable code), one can use serious gaming. By observing the outcomes and motivations of real players in a serious game, one can extract actors' behaviour and translate it to real situations. With these simulations and games, one can execute tests for design alternatives and gain their performance on the defined indicators.

Select In this step, the selection is made based on the outcome of the executed tests. If the performance indicators are well defined and the tests are well developed, one finds out which design alternatives meet all constraints. Those are still feasible. If there is more than one design alternative left, selection can be made based on the objectives. Comparing objectives is subjective and actors will probably weigh the objectives differently. Therefore, selection for a design of a system transition might prove very difficult. It is, however, crucial to indicate the performance of alternatives in this selection process so that a fair selection based on a discussion on objective importance becomes possible. In addition, advanced methods to visualize and present the outweighing different uncertainties and objectives are necessary to be able to choose more transparently between alternatives.

2.4.3 Analysis

We have argued for a design approach for transitions, in order to allow for true transition management. The design approach brings together many research domains, which fits the multidisciplinary approach needed to elucidate transitions and underpin transition management. By addressing transition management using a system's perspective and a designers' approach, three items have been identified for the transition management research agenda: the need for transition instruments, transition indicators, and tests.

The need for instruments The myriad of transition management elements, of which some are named transition instruments, should be translated into proper design variables for system transitions in the energy domain. It is ambiguous when, whether and in what combinations the explicitly mentioned instruments in the literature apply. In addition, further input for such instruments could be gained by using insights into technology, policy, and economy from literature on system transitions, design, complex systems thinking, energy technology and energy policy. In individual cases, transition instruments should be identified in order to develop feasible transition assemblages.

The need for indicators Since design teams need to assess the features of their design, the goals must be made explicit as objectives and constraints for which measurable performance indicators can be defined. As argued before, success and performance are ill-defined: indicators are lacking. Therefore, research is required on developing shared definitions of performance indicators of system transitions. With such definitions, one can assess when a system transition is started and completed and whether it can be called a system transition, and one can effectively share this information and over time create a body-of-knowledge on what works and what does not work for transition management.

The need for tests Third, tests should be developed whereby different system transition designs can be compared. The indicators are used as benchmark for transitions. We argue that simulation models and gaming are needed as tools to compare the performance of different designs. These tests should contain relevant elements in the large-scale socio-technical system under study by incorporating the interdependency of technology, policy and economy. This will be the topic of chapter 3.

We believe that these knowledge gaps can be filled by undertaking individual transition design approaches. In specific cases, transition instruments and indicators can be operationalized and tested, drawing from the available literature on transitions and transition management, but also from domain literature specific to the case at hand.

2.5 Conclusions

Energy infrastructures are true socio-technical systems. From a socio-technical system's perspective, transitions emerge out of the myriad of decisions of actors, their interactions and their behaviour regarding their physical assets. Based on this perspective and the many definitions of transitions, we derived the following definition: *A system transition is substantial change in the state of a socio-technical system.* Literature regarding unplanned transitions dominantly discusses qualitative transition case-studies. These have led to the recognition of *phases* in transitions (similar to innovation-diffusion patterns). Furthermore, three system *levels* are identified – niche, regime and landscape. A transition is depicted as a regime-shift.

Theory regarding unplanned transitions can be distinguished from theory regarding transition *management*. From our system's perspective, transition management is *the art of shaping the evolution of socio-technical systems*. In our view, public policy regarding energy infrastructures relates to transition management: transition management promises, and should allow us to improve our energy infrastructures substantially by invoking a transition when required. However, in the literature on transition management we found that 'success' and 'performance' of transition management is ill-defined. In addition, there are a myriad of prescriptive, and partially conflicting transition management elements. There is a strong focus on sustainability and the role of government is highly debated.

By rephrasing transition management into a *design* problem, we intended to shed light on these issues. This design approach led us to think in terms of *assemblages of transition instruments* that can be *tested for performance*. However, we identified three knowledge gaps in the existing literature that prevent us to do so: transition *instruments*, *indicators*, and *tests*. We argue that in specific cases, these knowledge gaps are filled by operationalizing domain-specific literature on this case and the instruments, named in the transition and transition management literature. By doing so, we *can* test transition management and validate it piece by piece.

Many of the articles on transitions and transition management could be considered a single school of thought. However, the literature on transitions seems to be currently in transition. In the last decade, the field grew rapidly with papers from authors from many countries and institutions. Many old ideas are now debated, they were never systematically *tested*. Waiting to see what the future will bring for this field of study is hard. There are recent attempts of simulation, which is an indicator that the earlier theory and claims will soon be put to the test (recall Figure 1.1 on page 2). Therefore, we need to select ideas that seem to be fruitful and test their merits in *concrete situations*, preferably using a *simulated environment*.

We see transition thinking as a *different perspective*, rather than as a school of thought. Therefore, transition research should not imply thinking about different things, but thinking in a different way, having a different perspective. Transition thinking is not thinking in terms of where to go, but in terms of how to get the most out of the journey. Or as Duckney (1996, p. 1-2) illustrates:

> "Some people think of the future as some fixed point in time. On arriving at their future they hope for a reprieve from the frenetic change process they have endured on the way to that future. This thinking can be compared with someone planning a journey. They know where they are today, the routes available to them to get to their destination, and they have some ideas on what they will do when they arrive. This model implies stability in the past, transition in the present and back to a stable state in the future.
>
> Perhaps a more realistic model would be that based on a group of gipsies. They have a similar concept of moving to some other place in the future, but a fundamental difference is that their future is seen as transitory. Their technologies are chosen with this thought in mind, (caravans replace houses). They have a strong sense of family or team spirit and a flexible attitude to doing whatever is necessary in their new location to succeed in business terms.

> They see an infinite range of futures in different environments, which they welcome, whilst making the most of their present position.”

With this perspective on transitions in socio-technical systems, we are ready to consider an environment in which we can come up with transition designs containing individual or sets of interventions and put them to the test. From our socio-technical system's perspective, we argue that simulation models of transitions should have a representation of the socio-technical system: the physical and social components and their interactions. Furthermore, the structure of the system should be emergent, so the performance and structure of the system can change over time and transitions can emerge. From the literature and the design approach, we can conclude that we need transition indicators to show transition and that the long-term effects of a variety interventions can be traced and assessed. Naturally, such tests need to result in specific new insights on the domain on energy transition and for specific interventions or transition instruments. Additionally, the general insights on transitions should be obtained, it should be able to connect to existing models, and models can be set up in a modular fashion. Let us continue to chapter 3 for the framework, so we can start simulating energy transitions.

3 Modelling for Energy Transition Management

> All models are wrong, some are useful.
> *George Box – Some Problems of Statistics and Everyday Life, 1979*

3.1 Introduction

In chapter 2 we have defined a system transition as a substantial change in the state of a socio-technical system[1]. Transitions emerge over time in large-scale socio-technical systems. During transitions, the structure and the content of the physical subsystem change. These changes are caused by the social subsystem, which comprises actors, their interconnections, and the body-of-rules and institutions that govern actor behaviour and decision-making. The mutual dependence of physical and social subsystems causes both to change in a complex web of interaction, feedback and feed-forward relations.

For successful transition *management* – the notion that actors could somehow *manage* the emergence of transition – a basic understanding of the socio-technical design space for transitions is lacking. The very complexity of many a socio-technical system may imply that we only have a certain chance of success to steer large-scale socio-technical systems towards some preferred state. In chapter 2, we showed that policy design and implementation is part of the socio-technical design space. Policy is a transition instrument if policy-makers implement it to cause structural change, in other words, if it is intended to invoke a transition. The policy is effective when it initiates indeed a transition and leads to a desired end state, while often additional requirements for the transition path exist. Elucidating suitable design variables for shaping transitions is difficult and may even be impossible. We argued that transition managers need to design a coherent *transition assemblage* of interventions (policies, regulations, R&D strategies, financing) and trace and assess their effects.

We need simulation models to assess the performance of individual or assemblages of interventions. A *model* is a simplified representation of (part of) a real-world system. Models are used for several purposes: to improve the *understanding* of existing systems,

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[1] This chapter is partly based on Chappin and Dijkema (2010a).

to improve the *performance* of existing systems, to *predict* the future state of existing systems, and to *design* new systems. *Computerized* models allow for simulation of the real-world systems captured in a simulation model: *Simulation* is "the activity of carrying out goal-directed experiments with a computer program" (Birta and Özmizrak, 1996, p. 77). Robinson (2004) focuses on existing systems in his definition of simulation: "Experimentation with a simplified imitation (on a computer) of a [. . .] system as it progresses through time, for the purpose of better understanding and/or improving that system" (Robinson, 2004, p. 4). In this thesis, we will use simulation models to assess the *performance of transition designs*. Those assessments are intended to inspire recommendations for policy design which structurally improve our energy infrastructures while acknowledging their complexity.

In this chapter we elaborate on a *framework* for the development of simulation models of transitions in energy systems. Before we do so, we discuss the requirements for the modelling framework and the simulations themselves that stem from the analysis in chapter 2. Afterwards, we describe several possible modelling paradigms and introduce Agent-Based Modelling (ABM) as our modelling paradigm. In section 3.4, the modelling framework is presented. Subsequently, we elaborate on a typology for categorizing models used to trace specific interventions. After providing an example, we end this chapter with a description of the software used throughout this work for the developments of the simulations.

3.2 Requirements for simulating energy transitions

Before simulations can be developed, we need to specify a number of requirements following from the perspective we adopted in chapter 2. This perspective builds upon complex socio-technical system's theory and a designer's approach on transition management. How this perspective can be translated to simulations models may be summarized in Figure 3.1. *Managing a transition* implies *diverting* system developments according to some need. When we apply this in a hypothetical system, one could think of the current state of a system, let us call it system state *A*. This state necessarily contains both technical and social elements: it is a socio-technical system. All possible combinations of decisions and events could lead to an infinite number of future possible states. However, we could imagine a 'characterization' of a system state called *B*. One could envision a possible transition as a *pathway* that could emerge over time between these two states of the system. In general, the notion 'transition' implies a *pathway* over time. Knowing that each decision creates a new pathway, one could come up with a whole number of possible pathways that link system state *A* to a system state, more or less like state *B* through time. One could also end up in many other system states if starting in system state *A*, as many interactions will lead to different directions.

The route of transition is influenced by changes in components, relations within the system, and external influences. Actors – components of the system – can use their instruments: governments can use their policies to influence the transition path and thereby alter the pathway – the evolution of the system as a whole – which is depicted as diverting the system towards system state *C* in Figure 3.1. Transition *management* could, therefore, be seen as diversion of the system's state towards a certain desired state. Acknowledging

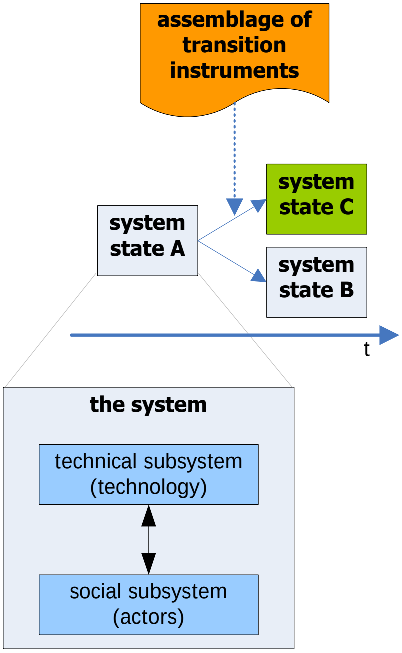

Figure 3.1 – A socio-technical system's perspective on transition management

the complexity of energy infrastructures, this line of thought leads us to all kinds of questions, such as 'What is the likelihood of this course of direction?', 'What circumstances make it probable?', 'For whom it is a desired future and for whom it is not?', 'What other transition pathways with a high potential are there?', etcetera.

It appears to be very complicated to develop simulation models that allow for 1) capturing a complex socio-technical system, 2) grasping how its evolution may be diverted, and 3) the development of insight that support energy transition management in the real world. What kind of simulation model should that be? A list of requirements reflecting this may help for the selection of a modelling paradigm, such that the simulations of energy transitions we can develop will fit their purpose and be useful. We have adopted the concept of functional requirements (Herder, 1999).

3.2.1 Requirements for the modelling framework

The following two requirements focus on the framework itself. These requirements focus on the fact that it should be useful: simulations developed should be supported by the framework.

Useful for development The framework has to be useful for the developer of simulations of transitions in energy systems. It should assist the modeller in developing models of transitions in energy systems. It should aid in the many choices made during the development of simulations. The framework should promote the selection of the most essential components and interactions and provide an overview of all modelling aspects that need to be considered.

Show potential of simulations The framework has to indicate whether specific simulation models can expected to be useful. It should ex-ante show whether the characteristics of the simulation model allow for insights in transitions and what kind of insights an existing simulation model could provide. A typology or classification is one way in which the framework can allow for a quick judgement of the use of a simulation model of energy transitions. That would aid a modeller in judging existing models in the literature and provides aid in initial design choices.

3.2.2 Requirements for the simulations

The other requirements focus on the simulations themselves. They stem from the system's perspective of section 2.2 and the design approach of section 2.4.

Physical and social components We have argued that our energy infrastructures are true socio-technical systems. From that perspective (see Figure 2.2 and Figure 3.1, simulations have to capture at least the essential physical and social components of energy systems. Physical entities of energy systems, such as power plants, consumer appliances, industrial facilities, grids, and physical infrastructures are important for the performance of these systems as they change during transition. Therefore, they need to be present so that transitions can be observed. The essential social entities are *actors*, such as governments, energy producers, consumers, and market places. The main features of these entities should be represented in simulations of energy transitions, because they make the decisions that prelude change in the physical subsystems and, eventually, may drive a transition. Therefore, they are required in these models in order to allow for the observation of system transitions in energy systems.

Interactions Energy infrastructures contain physical and social components that interact. As argued in chapter 2, change in a system is driven by decisions of actors. They may decide to change their physical assets, for instance. These interactions are, therefore, pivotal for grasping transitions. Interactions between physical components include material and information exchange. Interactions between social components encompass negotiation and information exchange. Socio-technical interactions include the control, ownership, and operation of physical components by social components. All these interactions need to be considered, since the aggregate of the interactions determine the state and evolution of the system. Moreover, the system's state and evolution determine whether a transition can be observed.

Emergent system structure Besides the fact that the essential components and interactions need to be grasped, it is also important *how* they are represented. The first requirement relates to the structure of the system, which we define as *the configuration of the social and physical components in the system and the interaction between those components*. Crucial to transition is that the state of the system changes substantially (recall the description of the definition for system transition in chapter 2). The state of the system changes partly by which components are in the system, and partly by the structure of the system itself that emerges out of the interactions between those components. Therefore, we require that the system structure emerges from the interactions during the simulations and evolves. In other words, the configuration of the components and interactions should not be predetermined or fixed. Only if the system's structure is emergent we can observe the structure changing. Only then we can observe transitions in simulations.

Transition indicators From the analysis using a designer's perspective, described in section 2.4, we derived that we are in need of indicators for transition. Therefore, we need our models to show indicators of transitions when the simulation is running. The simulations have to show indicators designed to measure change in the system's structure. When the indicators are well-designed, they indicate if and when a transition occurs in the simulation.

Tracing specific interventions Next to the indicators, the design approach of section 2.4 pointed us at the need for tracing specific interventions. In order to assess the effects of transitions, the simulation model has to be able to cope with tracing specific interventions. Therefore, individual interventions, or assemblages of interventions in a transition design, such as a set of certain public policies, should be modelled in such a way that it is possible to measure under what conditions that intervention leads to transition.

Specific new insights Simulations have to lead to new insights in specific transitions of energy systems. A crucial requirement of any simulation model of transitions in energy systems is that it brings new insights regarding transitions specific to the simulated energy system. That is the eventual purpose of the modelling effort. A range of types of insights could be envisioned, such as insights related to policy design in energy systems and insights in the dynamics of such systems. Such insights may well promote recommendations for the design of these systems and promote the debate surrounding possible actions in the real world.

General insights in transitions Simulations need to lead to general insights regarding transitions in addition to the insights in specific energy systems. That is a contribution to the body of knowledge on transition, which may lead to more general research on transitions.

Existing models Simulations should be able to connect to existing models of energy systems. Although those models were not designed from the perspective on transitions, many models may be relevant as components in bigger models. When successful, using the existing literature for this purpose could lead to a more efficient model development process. For instance, a CGE model could be used to model the economy around a modelled energy system.

Modularity Simulations should be setup in a modular fashion. Modularity allows for the reuse of parts of models and increases the efficiency over a number of model devel-

Table 3.1 – Properties of modelling tools, partly based on Chappin (2006), Schieritz and Milling (2003), and Borshchev and Filippov (2004)

Aspect	Abstraction	Building block	Mathematical formulation	Dynamics
Scenarios	Static relations	Scenario	None or static	None
Econometrics	Correlations	Parameters	Stochastics	None
CGE	Economic relations	Equation	Optimization	Lurching
ABM	Disaggregated decisions	Agent	Mainly logic	Emergent
SD	Dynamic relations	Feedback loop	Differential equations	Feedback
DS	Physical relations	Equation	Differential equations	Feedback
DES	Event system	Event	DEVS	Events

opment processes. In addition to specific model parts, practices from a successful model development process could be transplanted.

3.3 Modelling paradigm for simulating energy transitions

In this section, we give an overview of the relevant paradigms for modelling transitions in energy systems. Where policy support is quantitative, simulations appear at the scene. Econometric models, scenario analyses, and Computational General Equilibrium (CGE) models are dominant. However, we will also discuss Agent-Based Modelling (ABM), System Dynamics (SD), and Discrete Event Simulation (DES). Their main properties are summarized in Table 3.1. We stress the strengths and weaknesses of all of these, summarized in Table 3.2. Afterwards, we consider the advantages and disadvantages of the options and we explicate our choice for *Agent-Based Modelling* (ABM).

3.3.1 Overview of modelling paradigms

Econometrics and scenario analysis Econometric models use statistical fitting to show correlations. This points out which relations are significant and can be used to find key parameters that may be affected by public policy. Scenario analysis (cf. Fahey and Randall, 1998) fulfils a similar purpose. Scenarios are used to explicate a range of what-if cases. A number of internally consistent possible futures are defined. For each policy intervention, its effect in the set of futures is analysed. A variety of methods, both qualitative (narrative scenarios) and quantitative ('spreadsheet' calculations) for such an analysis exist.

An example of a quantitative scenario analysis of energy transitions is the *Energy Transition Model*[2] (Quintel Intelligence, 2010), which was developed by a Dutch energy consulting firm with the support of a wide range of Dutch governments and national and multinational companies. This advanced scenario tool has three levels of usage that allows the user to choose either 50, 100, or 250 parameters. The Energy Transition Model has a wide coverage in terms of energy use (households, the transportation sector, industry,

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[2] http://www.energytransitionmodel.com, the most recent version at the time of writing is the version of September 15, 2010

and agriculture), types of energy (electricity, natural gas, heat, fuels), development of costs (generation facilities, CO_2 market price), and policy objectives (renewables, CO_2 emissions, energy import, energy cost, and used area). A strength of the model is the ease of use: the tool can be accessed entirely through internet. Other strengths are its possibility to observe which of the policy objectives are met under which scenario, the fact that it is very detailed, and that it has a broad scope. Its weakness is, however, it cannot show how we can actually get there, because the dynamics are not simulated. To give an example, one of the parameters is how many wind farms will be built before the target year. The Energy Transition Model does not give insight in whether the selected set of conditions will actually lead to the investment by private companies in that amount of wind capacity. Therefore, it does not give an answer to questions related to the need for specific public policies to make that the transition is likely to occur. Similar arguments hold for many of the parameters. The Energy Transition Model presumes an 'engineered society' and underestimates the complexity involved in strategic decision making in energy infrastructures: it focuses on the *what?* question, and not the *how?*.

Another study regarding the energy transition using scenario analysis is the Roadmap 2050[3] (European Climate Foundation, 2010). A variety of back-casting analyses – which are essentially scenario analyses – underlie this report. The Roadmap is the result of a large collaboration of companies, institutions, and academia. It shows four 'possible' scenarios for achieving 80% reduction of CO_2 levels compared to 1990. In their analysis they show, for example, that in order to achieve European reduction targets the power sector needs to be decarbonized 90-100%. This is a valuable result, because it shows on what aspects public policy makers should focus. Similarly to the Energy Transition Model, we refrain from new insights in *how* to achieve this reduction due to the lack of simulation.

These tools cannot deal with the dynamics in the infrastructure systems under study. These dynamics are very important for transition: during a transition the structure of the system changes and, therefore, the dynamics change as well. That is why the complexity of the infrastructures makes it very hard to analyse the effects of public policy in a range of futures. As we will focus on the dynamics in infrastructure systems, we shall look at *simulation models*: models that simulate how a system changes over time.

Computational General Equilibrium An important class of simulation models used for public policy is Computational General Equilibrium (CGE) models[4] (de Melo, 1988; Devarajan, 2002). Although these models have strengths – they are data-rich, well understood and relatively fast – they also have inherent limitations. Typically, they are *models of the economy*, with parameters referring to macro-economic notions, such as labour, market prices, and demands for goods. CGE models are fundamentally based on balancing linear macroeconomic equations (Johansen, 1960). CGE models capture multiple-sector systems with aggregate top-down macroeconomic equations (Schäfer and Jacoby,

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[3] http://www.roadmap2050.eu

[4] The notions of Computational General Equilibrium (CGE) and Applied General Equilibrium (AGE) models are fuzzy. CGE models have first been formalized by Arrow and Debreu (1954). Although often reported otherwise, the mathematics of current CGE models are unrelated to that formalization. AGE models are based on foundations from micro-economics. Although both have different origins, throughout the years, research merged parts of both streams of models into both AGE and CGE models. In this thesis we will only refer to CGE models.

2006, p. 172). CGEs use a technology-matrix (Jones, 1965) or database (Lofgren et al., 2002) which generally contains the characteristics of technologies for the production of goods (Leontief, 1970, 1998). In essence, the variables in the equations of CGE models are aggregates (Lofgren et al., 2002) and CGE models are continuous. For instance the consumption by households of a certain good is aggregated into a single continuous parameter. Because of that, heterogeneity of households is neglected and strict assumptions are made for the decision making of these households. Furthermore, to be able to solve CGE models and find equilibria many variables need to be fixed exogenously. Therefore, aggregate variables defining technology, consumer tastes, and government instruments (such as tax rates) are usually exogenous.

Nowadays, CGEs use calibration and benchmarking of real-world economic data to fit an initial equilibrium data set (Kehoe et al., 2005). The effects of policies are estimated under exogenous changes of relevant economic parameters. At each time step, CGE models balance the same set of macroeconomic equations to "represent price-dependent market interactions as well as the origination and spending of income for various economic agents" (Böhringer et al., 2006, p. 407). In finding the equilibrium at a certain moment in time, "prices of inputs and outputs adjust until demands equal supplies. The interactions between markets are predominant" (Lejour et al., 2006, p. 13). CGEs typically assume that all relevant mechanisms underlying the working of economic systems are successfully captured and remain constant in the future, within the modelled time-frame.

The focus of CGE on the equilibrium of the economy is problematic when discussing the long-term effects of policy interventions. The technique imposes strong assumptions on the representation of *technology* and *decision-making*. In CGE models, technology is a very abstract means of production. Many technological properties and interlinks are not captured. Similarly, decision-making is aggregated with assumptions of homogeneity and rationality. Often the economy as a whole is 'optimized' for societal welfare maximization. How that level of social welfare works out for individuals is unknown, however.

A drawback of CGE models for studies with a long-term perspective is that they have a low capability of capturing *dynamics*. The technique assumes that in between two time steps the economy is able to stabilize in an *equilibrium*: a stable state of all parameters of the economy. The consequence is that "CGE models are not dynamic" (Mitra-Kahn, 2008, p. 71). CGEs try to deal with trajectories over time though. Despite the fact that they are often classified as dynamic, those models are actually *lurching*: an equilibrium is found for each modelled time step (Mitra-Kahn, 2008). The equilibrium can vary between time steps because it is solved under different exogenous conditions. Other solutions include the use of modules that work on different time scales. Each module is inherently static though and assumes it is realistic that an equilibrium would be reached within each time step. Consequently, it is important to note that CGE models do not model the dependence *between* time steps, and that the structure of the models is inherently static. Whether, why, and under what assumptions an actual stabilization of the economy can be taken for granted is unclear. It is difficult and may prove even to be impossible to understand truly what consequences both limitations impose on the conclusions drawn, and eventually, on the policy decisions made.

Many important institutes for policy support use CGE models, because of their focus on economic parameters. A classic example of a CGE model studies the effect of subsidies on trade (Taylor and Black, 1974). Another reason to engage in CGE modelling is that the modelling process is streamlined so that new results can be generated quickly. Amongst them are the World Bank (with their model LINKAGE, Van der Mensbrugghe, 2005), the International Energy Agency (IEA) and in the Netherlands, the Netherlands Bureau for Economic Policy Analysis (CPB) and the Energy Research Center (ECN). This shows that CGE has developed into the de-facto standard for supporting many policy decisions throughout the world. As, in general, the use of quantitative methods has increased with developments in computing, CGEs are increasingly used. With a modern desktop pc, running a reasonable CGE model is done in a matter of minutes.

IEA uses their *World Energy Model* to examine 20 years of future energy trends (IEA, 2008). Also this model is data-intensive, collected and updated by the IEA itself. The World Energy Model covers all energy markets and has a holistic, mono-actor approach. It is an interlinked set of models, of which some parts are modelled in different modelling paradigms to improve the model as a whole (IEA, 2009b). IEA presents results in relation to a *reference scenario*, which is an extrapolation and functions as "a baseline picture of how global energy markets would evolve if the underlying trends in energy demand and supply are not changed" (IEA, 2008, p. 52).

An example of the intensified use of CGE models can be found in the Netherlands, where the Netherlands Bureau for Economic Policy Analysis (CPB) is pivotal for CGEs for policy support (Don and Verbruggen, 2006b,a). Nowadays, CPB evaluates the political plans of many of the parties in times of national elections. The CPB predicts how their plans will affect economic growth and number of jobs and other macro-economic parameters. CPB has become the main organization that supplies such advice. For their long-term predictions, the CPB developed the *WorldScan* model (Lejour et al., 2006), fed by data from the Global Trade Analysis Project (GTAP) database (Hertel, 1997). Exogenous system drivers include labour supply, employment growth, population growth, and age distribution. Equations in the *WorldScan* model contain consumer goods markets, producer markets, capital markets, and the labour market. ECN has developed a portfolio of CGE models for policy support (Volkers, 2006) of which a few focus on medium to long term (e.g. Boerakker et al., 2005, a model of the energy use in buildings).

CGE models typically have a large number of equations and variables, for which common solvers (such as Excel or Matlab) are insufficient. Industry-standard software for CGE models is GAMS (GAMS Software, 2010), which is only commercially available. GAMS is able to solve very large algebraic problems.

Agent-Based Modelling Agent-Based Modelling (ABM) "takes agents (components) and their interactions as central modelling focus point" (Nikolic, 2009, p. 51). ABMs "emphasise modelling behaviour at the lowest practical level, with an interest in studying the emergence of [...] agent interactions, as well as the evolution of strategies for agent interaction with the environment and other agents. [...] Agent-based models are well suited to model strategies of different stakeholders, their interactions and the outcome of such interactions" (SAM Corporate Sustainability Assessment, 2010).

In general, ABMs provide us with a laboratory for capturing evolving systems in models. Therefore, an ABM is a *playground* for scientists, to *explore* emergent outcomes of the interaction of a set of autonomous agents. ABMs come into many flavours, for which the terminology used in the literature varies. We consider both Agent-Based Simulation and Individual-Based Modelling to be synonyms of ABM.

Traditionally, ABMs are applied in the social sciences (e.g. Axelrod, 1997b; Kohler and Gummerman, 2000; Gilbert et al., 2007), but more recently energy markets are modelled too. Applications related to technology and markets appeared as well, such as models of electricity markets (North, 2001; Guerci et al., 2005; Krause et al., 2006; Bunn and Martoccia, 2008; Chen et al., 2008; Ortega-Vazquez and Kirschen, 2008; Weidlich and Veit, 2008; Yu and Liu, 2008), and also the evolution of industrial clusters (Nikolic, 2009) and a model of the different departments of a refinery (van Dam, 2009).

In addition to general ABMs, a large body of literature emerging on Agent-Based Computational Economics (ACE) are essentially ABMs containing agents with rules from economic theory – a subclass of ABMs. ACE is "the computational study of economic processes modelled as dynamic systems of interacting agents" (Tesfatsion, 2006, p. 3). A relevant example of ACE is the EURACE project[5] in which a very large, policy-design oriented agent-based model of the European economy is being developed.

Very different in purpose from ABM is something called a Multi-Agent System (MAS). MASs de-facto are sets of software programmes on a disaggregated scale. The main purpose of each software program is to fulfil a certain (set of) objective(s) by interacting with similar programmes. All together, the software programmes or agents are performing tasks that are difficult to carry out in a centralized manner. The main difference with Agent-Based Models is that this is software for real-world applications. Therefore, in contrast to ABM which are rather simulation models of real-world systems, MASs systems in the real world. Examples of MAS are meeting planners, traffic control systems (Negenborn et al., 2008), cooperation in medical systems (Lanzola et al., 1999), and e-commerce (Lee, 2003b). When we refer to Agent-Based Modelling we exclude the notion of Multi-Agent Systems.

A large variety of software is available for developing ABMs. Common in the social sciences are Netlogo (Wilensky, 2010), REPAST (Repast, 2006), and MASON (MASON, 2010), all open source. Commercial tools are also available (e.g. Anylogic by XJ Technologies Company, 2010).

System Dynamics and Dynamic Systems System Dynamics (SD) is "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester, 1958). Typically, SD models are used to "understand the long term behaviour of states in a system for which there is a deterministic way rule for how a state evolves" (Robinson, 1998, p. 1). The stream of models called Dynamic Systems (DS) (Rosenberg and Karnopp, 1983) refers to system dynamic models applied to *physical systems*, but system dynamics is broader than that and includes non-physical system elements.

An SD model is defined by a set of differential equations. Each equation represents a process which is conceptualized as flows between stocks of, for instance, materials, energy, knowledge, people, or money. Additional parameters determine the values of the flows (Forrester, 1969). SD models are inherently continuous. SD models were originally coded in DYNAMO, commercial software, now unavailable. Although there are less common open source and/or freely available alternatives, common modern software

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[5] http://www.eurace.org/

for system dynamics such as PowerSim (PowerSim AS, 2010), Vensim (Ventana Systems, 2010), and iThink/Stella (ISEE Systems, 2010) are commercial. Much of the software is well developed in terms of GUIs, graphs, and built-in solvers. Modern software allows for some relaxation of the restrictions of the continuous domain such as step functions.

Typically, SD modellers intend to look at feedback loops and delay structures. SD does not model individual events, for instance the decisions of a person to become an adopter. Events are rather aggregated to flows. Therefore, in system dynamics a flow of people can refer to people changing their state, in this case the number of adopters of a certain technology (Sterman, 2000). This is not possible in the Dynamic Systems methodology – continuous models of physical systems – because only inherent continuous variables are allowed and no aggregates for multiple entities can be used.

System dynamics is used throughout many fields of research, such as studies related to populations and ecological and economic systems. In addition, SD is relevant for policy analysis: "Because dynamic behaviour of social systems is not understood, government programmes often cause exactly the reverse of desired results. The field of system dynamics now can explain how such contrary results happen" (Forrester, 1971a). The most important example is the model behind the *limits to growth* (Meadows and Club of Rome, 1972) that Forrester (1971b) further refined into the *World2 model*. Other SD studies have modelled the electricity market (Olsina et al., 2006).

Discrete Event Simulation In Discrete Event Simulation (DES) the operation of a system is represented as a chronological sequence of events (Gordon, 1978). Events occur in a system with a fixed structure. Such events change the state of the system, including the state of the entities in the system and these changes trigger new events.

Underlying DESs, is the discrete event system specification (DEVS), developed by Zeigler (1984, 1987). This specification allows for various discrete-event formalisms that can be adopted for developing DESs. DEVS represent events by defining how the system state changes based on a set of input and output events. Although it is only one possible formalism (Vangheluwe, 2008; de Lara and Vangheluwe, 2010), a typical DES application is represented as entities that "travel through the blocks of the flowchart where they stay in queues, are delayed, processed, seize and release resources, split, combined, etc." (Remondino, 2004, p. 27). The simplest form of a DES is a queue system that holds the entities. "Simulation progresses by repeatedly dequeueing events, computing their consequences, and reporting the consequences either by updating the global state of the simulated system or enqueueing notices of additional future events. Any number of events may be scheduled as a consequence of one event. Some events only change the global simulation state, while others schedule large numbers of new events." (Jones, 1986, p. 301). For example, customers passively reside in the system: they are waiting in a queue at a counter. Events triggered determine which consumer's state is changed.

A variety of software tools is available for DES (e.g. Arena by Rockwell Automation, 2010). DESs are mainly used to analyse and improve the design of handling systems. Examples of DESs are container handling in ports (Boer et al., 2002), global supply chains (Boyson et al., 2003; Corsi et al., 2006) and dynamics in electricity markets (Gutierrez-Alcaraz and Sheble, 2006).

Table 3.2 – Score on requirements for modelling paradigms

Requirement	Scenarios	Econometrics	CGE	ABM	SD	DS	DES
Physical components	?	?	+	+	?	+	+
Social components	?	?	?	+	?	–	?
Interactions	–	–	?	+	?	+	+
Emergent system structure	–	–	–	+	?	–	–
Transition indicators	+	?	+	+	+	+	+
Tracing specific interventions	–	–	?	?	?	–	?
Specific new insights	+	+	+	+	+	+	+
General insights in transitions	+	+	+	+	+	+	+
Existing models	–	–	+	+	+	–	+
Modularity	–	–	+	+	–	–	+

3.3.2 Choice of modelling paradigm

An indication of whether the simulation tools meet the requirements presented in section 3.2 is displayed in Table 3.2. As highlighted in Table 3.2, ABM is the modelling paradigm that has the largest potential for simulations of transitions in energy systems with the requirements we have discussed above.

First of all, we need *simulation* in order to be able to discuss *dynamics* of the system under study and allow for an assessment of the long-term effect of specific interventions. Within the simulation paradigms, the main argument for our selection is that it is the only simulation paradigm that allows for an *emergent system structure* (cf. Nikolic, 2009). For simulations of energy transitions, emergence implies that during and after a transition, the components and interactions are different; being-in-transition is one of the emergent system properties. If we want to gain insight in how we can manage this change – we aim to support transition management – it needs to emerge out of the interactions in the model. Observing a transition is difficult and subjective, and complete understanding and management of energy infrastructure transition may be impossible. However, Axelrod (1997b) already argued: “the simulation of an agent-based model is often the only viable way to study populations of agents who are adaptive rather than fully rational.” Although there are proposed examples of SDs with changing structures (Duggan, 2008), they have not yet matured: in SD the structure of the system is fixed (Yücel, 2010). In all simulation paradigms except ABM (and for other tools), the structure the modelled system is typically fixed by the equations of the model, or by the fixed set of elements in the model.

There are more arguments that favour ABM. The way in which social components and interactions are modelled in those paradigms may prove insufficient in other simulation paradigms. At the core of transition is the fact that the *decisions* made by actors drive change in the system and, possibly, the transition. This fits best with an agent-based paradigm. Other paradigms are not as focused on decisions, and/or they are not explicit. For instance, in SDs, only *aggregate* decisions can be modelled and assumptions in relation to how single decisions add up an aggregate are inherent. Although the benefit of an SD model could be that aggregation allows for more simple models (Yücel, 2010), the validity of the model depends strongly on the aggregation used.

It has also been demonstrated that physical subsystem models can be adequately incorporated in agent-based models to yield models that increase our understanding of energy infrastructures and industrial networks (Chappin, Dijkema and Vries, 2010; Chappin and Dijkema, 2009; Davis et al., 2009; Nikolic, 2009). ABMs can easily be made modular, for instance by adding agents, or adding behaviour to existing agents: all elements can be modules in themselves; pieces of behaviour can be exchanged for others. ABMs can be connected to other models by choosing a programming language that allows to do so. That may be more difficult with some of the other paradigms.

We conjecture that ABM is likely to be useful for tracing and assessing the effects of specific policy interventions on the long-term evolution of energy infrastructure systems. In an ABM, decision-making of relevant actors can be translated to behavioural rules of agents; technical subsystems are modelled as physical networks of equipment and flows. Therefore, we argue that Agent-Based Models (ABMs) are suitable to assess 'transition designs' in the energy domain. While we *do not* claim that ABMs will produce perfect predictions of these systems, we do believe, however, that it is possible to compile valid agent-based models that show transitions in energy systems. We deem such models to be valid if they are "fit for purpose" (Chappin, 2006). These models do not show what *will* happen, but what *may* happen in a delineated part of society, given a stringent set of assumptions and conditions. With the results generated by such models, the modellers can obtain insights in the long-term effects of specific interventions on the evolution of energy infrastructures and, ideally, it improves related strategic decisions made in energy infrastructure systems.

3.4 Modelling framework for simulating energy transitions

In this section, a framework for simulating energy transitions is presented. We will use the framework to develop Agent-Based Models (ABMs). Nevertheless, it is not limited to ABM: the components of the framework are applicable to any modelling paradigm. The framework provides a cohesive overview of the building blocks for simulations of evolving energy infrastructure systems and presents the choices that modellers need to make and the restrictions that apply. Thus, it aids in balancing model development of evolving energy infrastructures. In addition, the framework serves as a typology of transition models: it characterizes existing and new models in terms of their ability to trace specific interventions – and provide input to the assessment of the viability of transition management. As a consequence, the modelling framework structures the discourse on transitions. We demonstrate the usefulness of this framework by three applications in the following chapters.

The modelling framework is visualized in Figure 3.2 and contains five components. These are the system representation, exogenous scenarios, interventions, system evolution, and impact assessment. Let us have a closer look at each of these building blocks.

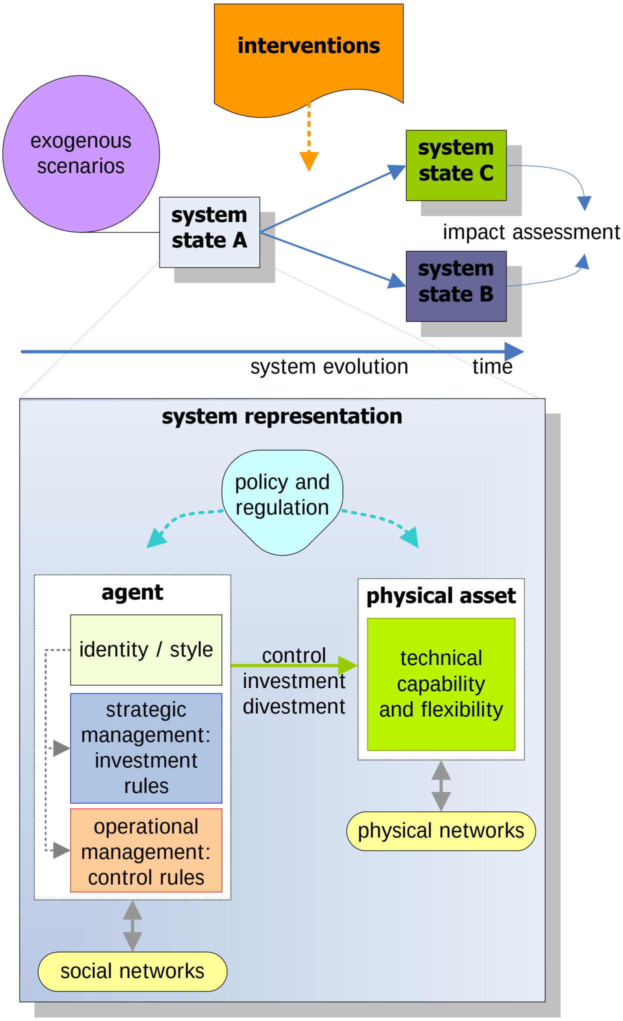

Figure 3.2 – Modelling framework for simulating energy transitions. Although the framework is not specific to a modelling paradigm, the system representation is made operational for the use with Agent-Based Modelling (ABM).

3.4.1 System representation

Our framework equips us with the possibility to use simulation models of evolving energy infrastructure systems. This implies that the simulation model represents the energy infrastructure system. Based on the concept of energy infrastructure systems as complex evolving socio-technical systems, we have selected agent-based modelling to make the system representation operational. We define the terms agent-based models and agents and provide the steps to come to agent-based system representations of evolving energy infrastructure systems. The framework can also be used to simulate evolving energy infrastructures using other paradigms by developing an appropriate system representation.

In general, all subsystems or elements under relevant influence by other subsystems or elements need to be included in the system representation.

ABM emerged from the fields of complexity, chaos, cybernetics, cellular automata and computers (Heath et al., 2009). A common definition for an *agent-based model* is "a collection of heterogeneous, intelligent, and interacting agents, which operate and exist in an environment, which for its part is made up of agents" (Axelrod, 1997a; Epstein and Axtell, 1996). In other words, "the components of an agent-based model are a collection of agents and their states, the rules governing the interactions of the agents and the environment within which they live." (Shalizi, 2006).

An *agent* is defined as "an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives" (Jennings, 2000). In other words, an agent is "a thing which does things to things" (From Stuart Kauffman, quoted from a talk in 2000 by Shalizi, 2006, p. 35).

An important design model for agents originates from artificial intelligence and is called the Beliefs-Desires-Intentions (BDI) model (Georgeff and Lansky, 1987):

- Beliefs are the agent's interpretation of its environment.
- Desires are the agent's general objectives.
- Interests are defined by agent's objectives that are, given its beliefs, translated into actions.

The BDI model was the origin of many properties that agents can have. These properties follow from how the agent's beliefs, desires, and intentions are conceptualized and implemented. For example, agents can be heterogeneous by modelling a variety of desires or beliefs. The beliefs are called the working memory of an agent. It contains information about the agent itself (the state of the agent). Knowledge or observations on the behaviour of other agents is also part of the beliefs. Therefore, beliefs are developed during interactions with other agents. These interactions lead to or are decisions made by these agents. They deliberately act on the basis of decision rules. Common properties of agents are that they are autonomous, flexible, learning, pro-active, and reactive. Summarizing, an ABM is a simulation of the interaction of a set of agents over time that make decisions based on their beliefs and desires.

Loosely based on the BDI model, the literature contains different sets of properties for agents (Weiss, 2000; Bussmann et al., 1998). The core of the discussion in the literature focuses on the following components:

- a set of goals
- a working memory
- a social memory
- a set of rules of social engagement

Agents have goals and can take actions to reach these goals. The set of goals are objectives the agent wants to accomplish. The working memory of an agent is a set of

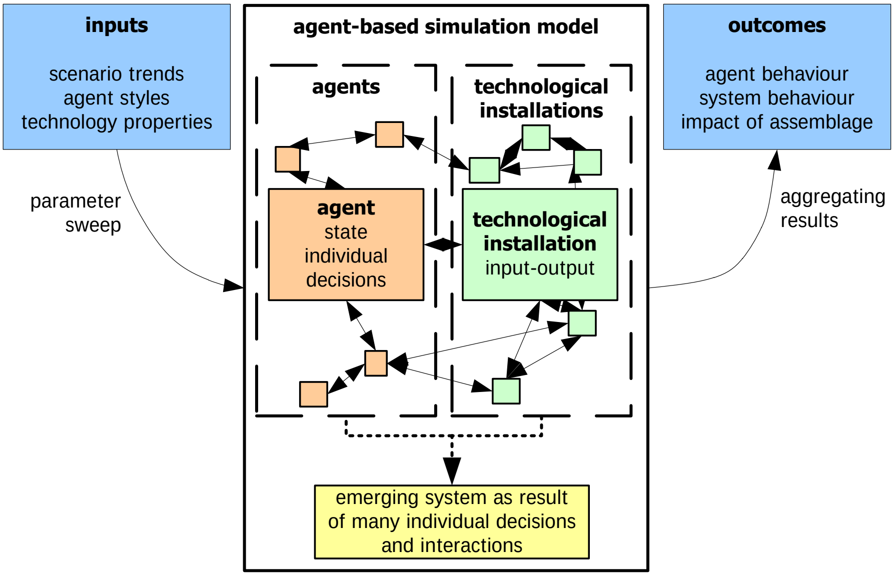

Figure 3.3 – The use of an agent-based model: from parameter inputs to outcomes

information about itself, called the state. The social memory is a set of knowledge regarding the behaviour of the agent and other agents. Past actions and interactions build this memory. Social engagement rules define the social behaviour of an agent. It contains the abilities of an agent to interact with others or make decisions. In other words, an agent-based model is a simulation of the interaction of a set of agents over time that make decisions based on their goals, exogenous parameters, and past interaction with other agents.

Figure 3.3 focuses on the model development process within the framework for simulating energy transitions. Agents – each making individual decisions – and technological installations make up the core of the model. The decisions of agents are made on the basis of the parameter inputs. Based on the decisions of individual agents, the system as a whole evolves. After aggregation of results, the outcomes can be analysed with respect to the behaviour of agents and system developments.

The agents in the model do strategic management; they have to make decisions which have a large and long-lasting impact. As they must deal with day-to-day operational decisions, the agents also do operational management. These two different types of decision making are modelled and discussed separately. The reasons for this distinct model setup and the implications for model implementation have been extensively documented elsewhere (Chappin et al., 2007).

Physical elements do not act themselves, they are not pro-active. Therefore, properties and capabilities characterize elements in the physical subsystem.

Many tools and methods exist for operationalizing the system representation. Developing a system representation is a process that combines the collection and interpretation of knowledge about the system. The framework prescribes the structure for the translation of this knowledge into the representation of the system. This follows from the combination of using agents in agent-based models and the chosen socio-technical system's perspective.

The model developer defines a conceptual model of the system, containing all relevant elements. Consecutively, implementation of those elements is formalizing the identity and decision-rules of agents and the properties and capabilities of physical assets. In addition, the definition of communication protocols for agent interaction allows for creating social and physical networks.

Within this framework, there are still many system representations possible. Further operationalization is a tailored design process, specific to the domain under study and the researchers' focus. Additional conventions or methodologies aid this process. For instance, one can use the System Decomposition Method (SDM, Nikolic et al., 2006, 2009) designed to capture tacit knowledge of actors in an agent-based model. This method prescribes the systematic gathering of data from actors and domain experts. A formal computer model contains a representation of the stakeholders' knowledge. This knowledge can be formalized and shared using ontologies (van Dam, 2009; van Dam and Lukszo, 2009). Next, many suggestions increasing the efficiency of a model development process are formulated (Chappin, 2006, chapter 9).

3.4.2 Exogenous scenarios

Useful models require strict delineation. Especially regarding the study of transitions, deciding what should be included and excluded is difficult. Inherently, not all relevant subsystems can be represented within the system. Therefore, assumptions need to be made on the relationships between subsystems. Where possible, we define parts of the system that are unaffected by other parts within the system; we exclude them from the system. Everything outside the system boundary is, therefore, *exogenous*. Everything relevant but exogenous makes up the scenario space (Fahey and Randall, 1998). The scenario space (or parts thereof) can be of various levels of complexity. In all these levels, relevant but unaffected components are modelled as exogenous parameters. Scenarios "are sometimes interpreted as providing a range of plausible developments, they are perhaps better viewed as worlds that will never materialize but are nevertheless realistic and internally consistent" (Lejour et al., 2006, p. 11). The task is to select a functional method for modelling exogenous scenarios. They can be static, be varied individually, and varied together.

Static parameter values The easiest way to vary parameters is between runs only. For instance, in each simulation run a particular value is assigned to the price for natural gas on the market, chosen from a number of predefined values. If the number of possible values equals one, this implies a static value for all simulations, which effectually excludes them from the scenario.

A range of values, sometimes with a non-uniform distribution, is most common. The need for data is limited: for each parameter, the minimum, maximum, interval values, and, possibly, the distribution need to be determined. The range of available values reflects the parameter's uncertainty.

Table 3.3 – Modelling individual interventions or assemblages of interventions

Level	Description	Level of complexity
1	Implicitly modelled	
2	Fixed system parameter	Model requires responsiveness
3	Exogenous scenario parameter	Model requires flexibility

Varying trends The modelling of scenario parameters as continuous trends is more difficult and data-intensive. At this level we require a representation of a price trend of, for instance, natural gas. One representation is a start value and a change pattern, which may be stochastic. Modelling scenario parameters as trends has two consequences. First, this requires the additional parameters: a probability distribution and its properties. Although more complicated to develop, this approach would enable the use of more realistic scenarios. The variability in the trends characterize the uncertainty in the parameter. This uncertainty can be time-related (uncertainty can grow or decline over the simulated time). Second, the model needs to adapt to changes of the value of this parameter. Since parameters are not static *within* one simulation, there is a need for taking this trend into account, for instance, by forecasting of agents. Therefore, the use of varying trends leads to very different models.

Coupling with other models Finally, one can develop or use existing models, such as system dynamics (SD) models or mathematical models, to provide for exogenous parameters. SD models – collections of differential equations – are often considered incompatible to ABMs, since ABMs are discrete and SD models continuous (Schieritz and Milling, 2003; Borshchev and Filippov, 2004). The *types* of assumptions often differ between modelling paradigms, which makes it hard to link them. We postulate, however, that we should combine various paradigms, such as ABM and SD into hybrids in order to use the best of both worlds. A single mathematical, CGE or SD model may generate multiple scenario parameters. Again, this may be more complicated than varying trends only, as this approach not only leads to software requirements but also requires more and different modelling skills. Using simulation models for exogenous scenario parameters should be considered if multiple scenario parameters are strongly related, especially when appropriate and validated models are available.

3.4.3 Interventions

Similar to exogenous scenarios, different levels exist for modelling individual or sets of interventions. Table 3.3 presents an overview of these levels. We postulate that for adequate assessments of individual or assemblages of interventions, one should aim at the highest level (level three), although it may be possible to start at level two and upgrade later. Level one should be avoided, since reusability in a higher level model will prove very difficult if not impossible. One should take notice that these levels are not exclusive and that different levels of policies and regulations can be simultaneously present in one model. The levels are now discussed.

Implicitly modelled In this case, the structure of the model accommodates a certain policy and regulation. The intervention is a fixed set of policy and regulation, the setting of which is implicit in the model. Since the set is fixed, it may prove hard or impossible to adapt to changes. System components do not have to be aware of the intervention. As a consequence, one could never assess the impact of the intervention. Therefore, using this level will not lead to models that contribute to the assessment of the viability of transition management. Consequently, we recommend not applying level one policy and regulation in transition models. The very selection and design of policy and regulation is de-facto a transition design variable. If policy is not modelled as such, alteration of policy is impossible without constructing a new model.

Fixed system parameter When policy or regulation is a fixed system parameter, the model needs to be able to respond to this parameter setting during the simulation. Translated to agent-based models, this implies that agents base their decisions on this policy setting and assume (or are uncertain about the) stability of this policy setting. Since the policy is unrelated to other system properties, it is exogenous to the model.

With level two, it is still impossible to assess the effect of interventions. The only advantage of using this level over making it implicit is that it may be possible to upgrade the model to the highest level in a later stage. Upgrading implies adding the responsiveness of the system to other policy values, while the model structure remains intact. Hence, we recommend starting at level two or higher.

Exogenous scenario parameter Third, policy can be a (set of) scenario parameters that is exogenous to the system in transition. In this set-up, policy is one of the three levels of scenario parameters – varying parameter values between runs, varying trends between runs, or based on system dynamic models – all with their advantages and disadvantages (see the previous section on exogenous scenarios).

Only at this level it is possible to vary the modelled policy or regulation in order to derive and test different transition assemblage design-alternatives. Therefore, this is the lowest level that a modeller should aim for when modelling interventions in this framework. However, as stated above, one may start with fixed system parameters (level two) as this will not limit model expansion.

3.4.4 System evolution

By the actions of agents the system will evolve over time. They act as part of the system, by reacting on exogenous scenarios and endogenous parts of the system. Since agents are interdependent, system level properties and *system behaviour* are emergent. Variety of parameter settings in input will provide differences in outcomes of simulation runs. Therefore, the evolution of the system in one simulation is not a prediction of the future of that system. In order to come to sound conclusions, an impact assessment by using different system evolutions at different locations in the parameter space is necessary.

3.4.5 Impact assessment

Together, the above notions are the necessary ingredients for the assessment of the impact of various modelled interventions: how to choose between (sets of) interventions? The impact assessment has to encompass a well-designed set of experiments and a solid analysis of their results.

Parameter sweep: experimental design In order to assess and compare the performance of different interventions, one can use literature on design of experiments (e.g. Kim and Kalb, 1996; Box et al., 2005; Goupy and Creighton, 2007). An experimental design is the way in which factors of the model differ between model runs.

Classical methods include factorial designs, in which the factors are varied independently (Iman et al., 1981). Within the class of factorial designs, the main design is full factorial, a design in which the experiments take on all possible combinations of the levels of the factors. Usually, each of the factors has only two different values.

If the number of factors is too high to be executed within a reasonable amount of time, given the available computational power, a fractional factorial design may be adopted. An efficient form of a fractional-factorial design is obtained by a technique called Latin Hypercube Sampling (LHS) (McKay et al., 1979). This technique allows selecting any preferred number of experiments where the resulting set has a uniform distribution over the multidimensional parameter space. Thus, the number of experiments can be set depending on time and available computing resources.

The use of environment scenarios (Fahey and Randall, 1998) leads to a different setup, although the experimental design can be seen as a different class of fractional factorial designs. Each scenario is a combination of values on a set of factors, modelled separately in the full and fractional factorial designs. In other words, parameters are grouped by their variation, which leads to a smaller number of possible combinations. To arrive at a suitable variation of the values of factors in scenario, one may again use one of the experimental designs described. For example, a scenario may have three groups of factors that are varied with a full factorial design. In such a design, you have eight distinct scenarios (the corners of a cube). Altogether, this is a fractional factorial design that is fundamentally different to LHS, because preselected groups of factors are varied in concert. As a consequence, the use of environment scenarios is based on the assumptions that the factors within each scenario are interdependent and that each factor is independent from factors in other groups.

Analysis of the results: assessment methods The raw simulation result is a full record of the state of the evolving system during all experiments in the parameter sweep. In order to allow testing for correlations, the recorded parameters should include not only the selected performance indicators, but also the input variables. Since the parameter space is large, and modern computational power allows large sets of runs to be completed in reasonable time, this full record often is a huge amount of data. One can use visualization methods to grasp some specifics hidden in the data, but this does not lead to real assessments. Instead, statistical methods for data analysis must be used for assessing and comparing the system *structure* and *performance* under different interventions. However, statistical methods are generally of a static nature and are not capable of adequately analys-

Table 3.4 – Typology for transition models

Ability of the model	Level 1	Level 2	Level 3
Captures system evolution	x	x	x
Observes impact of interventions		x	x
Tracing specific interventions			x

ing the results. There is a need for adapting and building statistical methods to assess and compare different designs by their variety and uncertainty in evolving performance. An example is, for instance, making series of Student-T tests over time, to assess differences in means (Chappin and Dijkema, 2008c).

3.5 Typology for transition models

We defined different levels for exogenous scenarios and interventions in the framework. Selection of these levels impacts the whole model: adopting higher levels means more requirements for other model components. In return, higher levels allow for a more realistic type of model dynamics, results and, in the end, better conclusions. While doing that, the framework nor the typology impose a restriction on the modelling paradigm.

By introducing the levels of complexity for how the specific interventions are modelled (as a transition assemblage or otherwise), the framework can be translated to a typology for transition models (see Table 3.4). The three levels in the typology are summarized below. More implications can be found in the description of the framework in the previous section.

Level 1 – Implicit On each level, the system should be adequately represented so the evolution of the system can be captured. On the first level, the model is implicit specific to a single set of one or more interventions, as it is implicitly part of the modelled system. The impact of interventions cannot be assessed, because in the evolution of the system the effects of the interventions cannot be distinguished from other effects.

Level 2 – Fixed system parameter The intervention is mentioned explicitly, as a fixed system parameter. The system, as represented in the model, has to be able to respond to this parameter: the modelled system needs to factor the parameter in somehow. The modeller is required to make choices regarding the *response* of the system to this specific system parameter. The effect of a single intervention can be *observed*. However, the effects cannot be compared to other interventions, nor to a no-intervention alternative. It may prove very difficult to attribute specific consequences to the intervention itself, because there is no comparison possible. A real assessment of the long term effects is, therefore, impossible.

Level 3 – Exogenous scenario parameters A variety of interventions are modelled as exogenous scenario parameters. In addition to the fact that the modelled system needs to capture system evolution and respond to the intervention, it also needs to be *flexible*:

the system needs to be able to respond to (and thus be flexible with respect to) a variety of possible interventions. The modelled system needs to be richer in order to be able to cope with all these interventions: actor's decision making needs to be more sophisticated to be flexible enough to respond adequately to all the modelled interventions. Then the effects of various interventions, or a lack thereof, can then be compared. Comparing interventions may point out effects and patterns that only occur as the consequence of some of the modelled interventions. Furthermore, comparing a single intervention to a no-intervention alternative allows to trace the effects of a single intervention on the long-term evolution of the modelled energy infrastructure.

Classifying models This typology allows for a classification of existing and new transition models, based on a conceptual description of the model. Therefore, the typology can be used to ex ante show the potential ability of the model in assessing the effect of individual interventions. In essence, the ability of the model, in the described sense, is mainly determined by *how* interventions are represented in the model. We have used this typology to classify the models in the literature (see appendix A, Table A.4). Most of the models do not deal with transition management, but merely with autonomous transitions. Consequently all models in the literature except one are on level 1. They are not intended, nor able to perform assessments of interventions. Therefore, they will not lead to insights into how transitions can be shaped and managed. A variety of methodologies is used. Exactly one includes Agent-Based Modelling. However, this model is in prototype stage and is not focused on transition management.

The typology shows that we have to aim to develop models on level 3. Our objective – assessing the long-term effects of specific interventions in the evolution of energy infrastructure systems – can be achieved by doing so. That may provide input in the assessment of the viability of transition management. Developing such models will be the objective of the coming chapters. Before we do so, we shortly explain how the framework can be applied with an example (of which the case is discussed in detail in chapter 4).

3.6 Example case: transitions in power generation

In this thesis, three cases were selected out of a vast range of possibilities. Two important dimensions can be distinguished (see Table 3.5): the focal point in the value chain (horizontal) and the type of government action (vertical). The cases in this thesis are a fractional factorial combination. For each of the other combinations, cases that bring new results could be imagined. It is likely that specific questions regarding the outlined cases can be modelled successfully with the modelling framework and the case descriptions in this thesis. Results of these cases will probably contribute to the knowledge on transitions in energy infrastructures. Below, the framework is illustrated with the example of transitions in power generation.

A quantitative agent-based model (ABM) was developed to simulate the evolution of the structure and performance of a hypothetical electricity market in the next 50 years using insights from microeconomics, market design, agent theory, process systems engineering, and complex systems theory (Chappin and Dijkema, 2009b,c). The main objective is to get insights into the potential long-term impact of policy interventions on the power

Table 3.5 – Cases for simulation models of energy infrastructures

Intervention	Production	Transport	Consumption
Policy measure	Case 1: Power generation		
Governance		Case 2: LNG market	
Regulation			Case 3: Consumer lighting

sector, such as a carbon tax or emissions cap. A detailed analysis of this case and its results have been the subject of publications Chappin et al. (2009); Chappin, Dijkema and Vries (2010). A schematic overview of how the ABM is set up is presented in Figure 4.3 on page 88. This model can be called a level three model: the model allows for evaluation and comparison of different transition assemblages.

System representation The model reflects the real-world situation of six independent electricity producers who have different generation portfolios and who make different decisions regarding the operation of their generators, investment, and decommissioning. As in the framework, the model contains subsystems for agents and installations. The agents in the model have operational behaviour: power producers need to negotiate contracts for feedstock, the sales of electricity and, in the case of emissions trading, emission rights. They also exhibit strategic behaviour: in the long-term the agents need to choose the moment of investment, the amount of capacity, and the type of power generation technology. Agents interact through negotiated contracts and organized exchanges and are subject to the physical flows, their characteristics and constraints.

Markets for CO_2 rights, power and fuels are modelled as exchanges in which 100% of the product is traded every time step. The time step of the model is one year and the simulations span a horizon of 50 years. A consumer agent is modelled to consume all electricity. To allow for correct mass and energy balances, an environment agent reflects all uptakes and emissions. The government agent implements policy interventions.

Exogenous scenarios A range of scenario parameters are level 1: they are specific to the Dutch market. In addition, the electricity demand profile consists of 10 steps per year which reflect a typical load-duration curve. Furthermore, demand increases over time as a level two trend. Fuel prices are modelled as a variety of level two trends as well.

Interventions The main options for emission reduction for government are called carbon policies. Therefore, they are selected as main design variables for system transitions. The two main candidates are emissions trading (ETS), implemented in the EU and carbon taxation (CT), implemented on a smaller scale in Norway. In addition to these two options, no intervention is chosen as a base reference. All policy interventions and implementations are modelled in the government agent.

The main policy variable of the ETS is the emissions cap. In the model the cap is set to reflect the likely design of Phase 3 of the EU ETS in which the CO_2 cap is reduced every five years by 3 Mton for a market the size of the Netherlands. With an initial cap of 50 Mton, a 50% reduction is achieved in little more than 40 years. Another important policy variable is how many emission rights can be obtained through the Clean Development

Mechanism (CDM)[6]. This is set to 5 Mton/year over the entire simulated time period. The main CT-policy variable is the tax level. To allow a fair comparison between ETS and CT, the tax level in our model has been calibrated to the average CO_2 price that emerges in the simulated emission market. The initial tax level equates to 20 €/ton, which reflects current CO_2 price under ETS. With time, tax level increases to 80 €/ton. These values were estimated based on the runs under ETS. Consequently, the transition assemblage is modelled at level 3, using exogenous parameters, leading to strong requirements for the other model components: the agents need to be able to act under ETS and CT policies.

System evolution The characteristics of the modelled system are emergent: the generation portfolio and merit order, fuel choice, abatement options, as well as electricity and CO_2 prices and emissions emerge as a result of the decisions of the agents. In the model, the following schedule of actions, which will be repeated yearly, is implemented.

- Purchase emission rights in the annual auction. The auction bids are based on the 'willingness to pay' per installation, which is determined as the expected electricity price less the marginal costs of each unit, divided by the CO_2 intensity. The bid volume equals the expected electricity sales volume times the CO_2 intensity of the power plants that are expected to be in merit.

- Offer electricity to the market (which is modelled as a power pool). Each plant's capacity is offered at variable generation cost (fuel cost, variable operating and maintenance cost, and CO_2 cost). The CO_2 costs of a generator equal the CO_2 price times its CO_2 intensity. In case insufficient CO_2 rights have been obtained, CO_2 cost equals to the penalty for non-compliance[7].

- Acquire the required amounts of fuel from the world market, which are calculated from the actual production and fuel usage.

- Pay the penalty in case there is a shortage of CO_2 rights. Surpluses and shortages are calculated from the actual production levels and the volume of emission rights owned by the agent.

Impact assessment Simulations have been done for the three transition designs: no carbon policy, ETS or CT. Impact assessment was made possible by making the pressure of the intervention of ETS and CT comparable (calibrating the average price). Many runs were done and plots were made of emission levels, emission intensities and power portfolios. Some included stochastic information. It was found that all three transition designs performed differently. CT outperformed ETS in the chosen scenario.

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[6] Under pressure of the industry, the Dutch government acquires additional emission rights through the Clean Development Mechanism. In the Dutch ETS allocation plan, it was announced that government reserved 600 million Euros for this purpose, the equivalent of 20 Mton CO_2 rights (Ministry of VROM and SenterNovem, 2005)

[7] When the CO_2 price exceeds the penalty level, agents will rationally choose to pay the penalty rather than purchase more CO_2 credits. Consequently, this penalty level functions as a price cap for the CO_2 market.

3.7 Hardware and software for implementing and running simulations

In this section, we discuss the hardware and software used for the development of simulation models and for running and analysing them.

3.7.1 Hardware stack

Hardware for model development Models are developed on a local, modern pc for which a modern office pc is typically sufficient. However, the development process is aided dramatically by having a multi-core processor (which has recently become the standard), by adding a second monitor and by a relatively large amount of RAM. These additions together allow for efficient multi-tasking, which is often necessary during the model development process.

In addition to the local PC, fundamental for developing simulation model is a so-called Subversion (SVN) server. This is the standard in software development for revision control. The SVN server we use is hosted as a virtual server in TU Delft's server farm, accessible under https://svn.eeni.tbm.tudelft.nl. The use of SVN will be discussed below under software.

Hardware for performing simulations In contrast to model development, running simulations is a task with high computational demand. Individual simulation runs can take a couple of hours/days on a modern pc. To prevent occupying the developer's computer and to increase the speed of a set of simulations, we make use of a High Performance Cluster (HPC) located at hpc07.tudelft.net. The computational capacity of the HPC used is in the order of 1,000 modern pc's and contains 60 nodes with each eight cores. The HPC can execute 480 jobs simultaneously and is managed and maintained externally. No physical access to the machines is necessary, since the HPC is controlled by connecting through a Secure Shell (SSH) connection to the so-called *head node*, which is a powerful server machine dedicated for interaction with the users. The head node forms the gateway to the machines performing the computations.

In addition to model development, a Subversion (SVN) server has proved its worth for facilitating the process of performing simulations. The SVN server forms a vital link between the model developer and the HPC and contains all models, the model results and all related scripts.

3.7.2 Software stack

The models have been implemented using a variety of software tools, of which the most important are mentioned in Figure 3.4. The software packages are bundled and connected into a so-called *software stack*. We use an earlier developed software stack (Chappin, 2006; Nikolic et al., 2009; van Dam, 2009; Chappin, Dijkema and Vries, 2010) and developed it to accommodate our specific needs. The software stack is basically used for two different purposes:

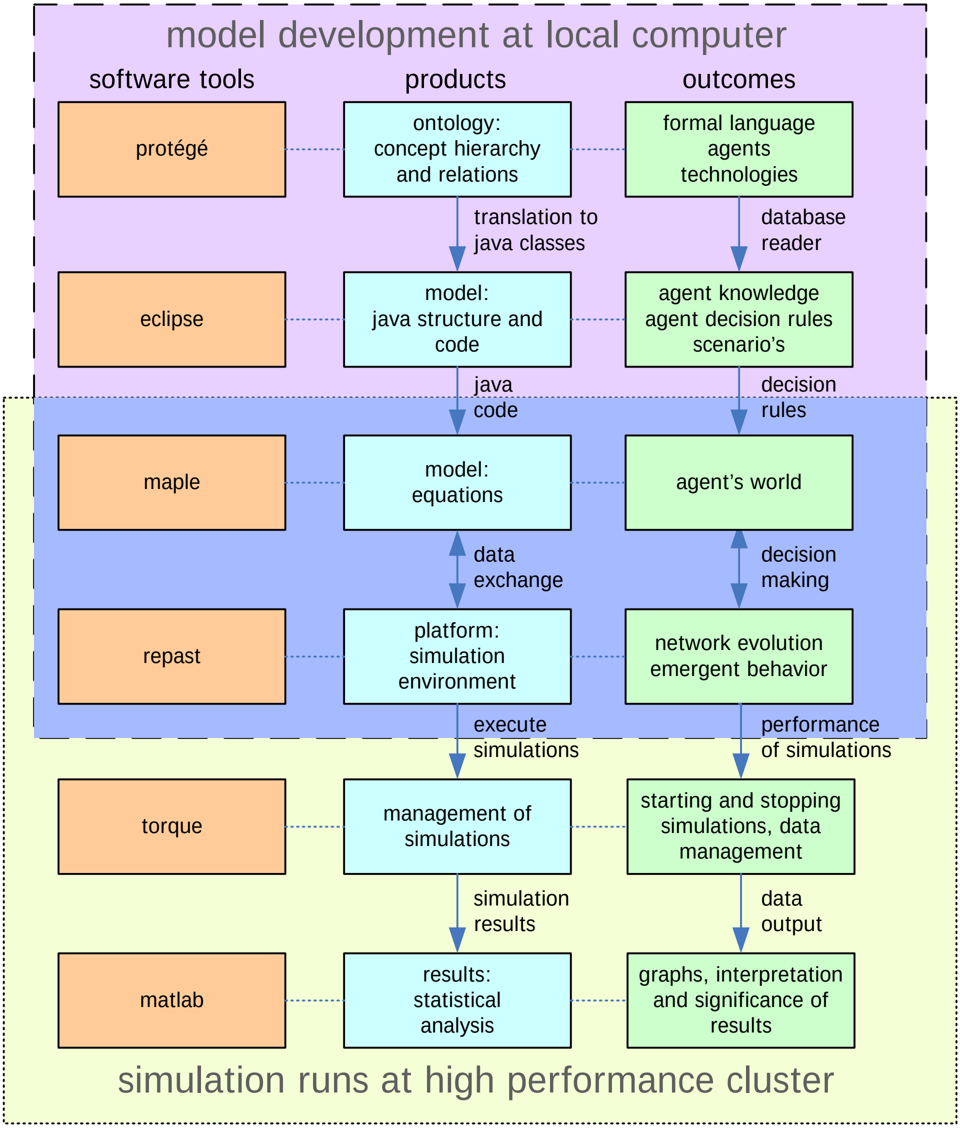

Figure 3.4 – Software for model development and running and analysing simulations

Software for model development The models are developed on a local pc and consist of many tasks, such as writing Java code, data collection and debugging. The software stack is not specific to the operating system in use, i.e. the modeller can choose to use Windows, Linux or Mac on the machines he occupies for model development. This allows the integration of modelling activities in day-to-day use of the pc. All software is available for all these platforms and, consequently, the software stack is platform-independent. Most software is open-source, making it available for anyone interested in engaging in these modelling efforts.

It is common practice to observe individual model runs regularly while developing it. The main software components used during model development are described below.

A structure of concepts is adopted by using an ontology in Protégé (2006). The ontology is shared amongst researchers and has proved to be useful for the development of a variety of agent-based models of different socio-technical infrastructure systems (van Dam, 2009). In this ontology, data regarding agents and technologies are stored. In addition, the concepts used in these models are formally defined and shared. This forces some modelling choices and, consequently, allows for the exchange and reuse of parts of models.

The agent-based model is essentially written in Java using Eclipse (2006), the de-facto standard for developing Java software. The structure of concepts is translated as Java classes and extensions, specific to these models, have been implemented. For each model a Java class to start and manage the model is developed. For each model, agents' decision rules are coded in additional Java classes. In addition, where required, extensions to the ontology are coded in Java classes.

All code is centrally stored, using the *Subversion* (SVN) server. Although a local copy of the code exists on the local pc, the central repository allows for sharing (parts of) code, it allows for version control. SVN provides a record of what when was contributed in order to be able to trace back problems. The documents on the SVN server are accessible through the internet. In our case, the server is accessible through a secure web connection[8]. All revision information and differences can be traced through the web by using Trac[9]. For all common operating systems, open source tools are available integrating the use of SVN into the operating system. For Windows TortoiseSVN[10] integrates well with Windows Explorer. For Linux, RapidSVN[11] is often used. In addition, server software is also freely available for all operating systems that allows for *hosting* SVN.

SVN is also useful for sharing many other types of documents. The use of SVN prevents the need for a variety of versions of a single document side by side. In addition, it allows for replacing the need for sending documents over email to sending links to the document on the server. This prevents bulk emails, but also prevents people from working with outdated versions of documents. Consequently, SVN can have a dramatic impact the organization of work flow, whether related to modelling, writing activities, collaboration or education. For many a modeller it has improved the efficiency of pc-related activities.

In some models, the agents implement an equation-based model, which was implemented in Maple (MapleSoft, 2010). The connection between the agents and the equation-based model is through *jopenmaple*, a Java library for Maple. Additional developments improved the usability of the interface between the Java code and the equation-based model (see appendix C, section C.3 for details). Integration with Maple is optional; integration with other software packages is possible.

The model makes use of libraries from REPAST (Repast, 2006), designed to run agent-based models in the social sciences. During model development we use REPAST for making graphs and running tests.

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[8] https://svn.eeni.tbm.tudelft.nl

[9] http://trac.edgewall.org

[10] http://tortoisesvn.tigris.org

[11] http://rapidsvn.tigris.org/

Software for performing simulations As said above, the simulations require high computational demand and are executed on a high performance cluster (HPC).

The Java code, including the libraries containing REPAST and *jopenmaple* are packed into a so-called *jar-file*. This jar-file is executable under Java. Information regarding which scenarios have to be run are contained in a parameter file.

Torque is used to execute and manage the simulations on the HPC. By using Bash scripts, Torque queues a set of simulation runs, distribute them over the nodes and start them when capacity is available.

When the simulations are done, the raw data are put in a database. The data are analysed using Matlab code (Mathworks, 2010) and statistical tests and graphs are the result. Again SVN is used to send the results from the analysis to the SVN server. The results are easily accessible to the modeller on its local computer by fetching the new items on the server.

A variety of scripts that automate the work-flow on the HPC have been developed[12]. Scripts start the process of queuing and execution, wait until all jobs are finished, collect the data into a database, perform the required analysis of the results using the data in the database, and commit the analysis to the SVN server, which is easily accessible from the local PC. The use of scripts dramatically simplified the whole process of executing simulations and allows for easy repetition of simulations.

3.8 Conclusions

Since transitions in energy infrastructure systems are to be 'managed', we developed a framework to develop simulation models that can trace and assess the effects of (sets of) interventions in the evolution of energy infrastructure systems. The framework allows for a structured discourse on transitions. Although the framework is applicable to any modelling paradigm, we have used the concept of socio-technical systems to select agent-based modelling (ABM).

The proposed framework consists of five parts. First, the system needs to be represented using a socio-technical systems perspective. We have shown how to make such a representation operational for ABM. *Agents* represent the actors, which are pro-active components in the system. Physical elements are represented as objects. Second, exogenous scenarios need to be developed using scenario analysis or other models. Third, possible interventions need to be selected and implemented. Fourth, the system evolution needs to be monitored and recorded. Fifth, the effects of interventions on the long-term evolution of energy infrastructure systems need to be determined by performing an impact assessment.

By classifying the way in which the interventions are modelled, this framework serves as a typology for existing and new transition models. On level 1, interventions are implicit, which, although often used, disallows the assessment of the effects of the interventions. On level 2, interventions are modelled as fixed system parameters. It is possible that such models can be upgraded to level 3, in which interventions are modelled as exogenous system parameters. Only models on level 3 are able to trace the long-term effects of interventions on the evolution in energy infrastructure systems.

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[12] The scripts for automated workflow are located at https://svn.eeni.tbm.tudelft.nl/HPC/scripts

4 Transitions in Power Generation

Global warming is the greatest market failure the world has ever seen.
Nicholas Stern – The Economics of Climate Change: The Stern Review, 2007

4.1 Introduction

Currently, electric power production is largely based on the combustion of fossil fuels, predominantly coal and natural gas, except in environments with abundant hydropower[1]. This inevitably leads to the emission of carbon dioxide (CO_2), as carbon capture and storage and renewable energy sources are not yet feasible or available on a large scale. In Europe, electricity generation accounts for one third of CO_2 emissions (Cozijnsen, 2005; Cozijnsen and Weijer, 2005). Global climate change caused by CO_2 and other greenhouse gases (IPCC, 2007) can be considered a *Tragedy of the Commons* (Hardin, 1968) for which no effective global coordination, regulation and enforcement has yet been developed. Global warming may be "the greatest market failure the world has ever seen" (Stern, 2007).

In the realm of sustainability and the potential severeness of global warming, a *transition* to a low carbon society is necessary. The success of a transition in emissions depends for a significant part on the reduction of emissions from the electricity infrastructure. Can such a transition be invoked? Who should do that? By what means? Because of multiple reasons, insufficient measures have been taken so far. First, CO_2 is a global, not a regional pollutant such as SO_2 or NO_x, which implies that the regulation of local emissions needs to be coordinated worldwide. Second, fossil fuels have become the lifeblood of developed economies: reducing or replacing their consumption is difficult and expensive, while the practical potential of renewable energy sources is, for the time being, not enough to sufficiently limit CO_2 emissions. While the cost of abatement is high, doing nothing will eventually be much more expensive (cf. Stern, 2007).

The growing consensus that CO_2 emissions need to be stabilized and then reduced in the course of this century has led to much interest in achieving cost-efficient emission

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[1] This chapter is partly based on Chappin and Dijkema (2009), Chappin, Dijkema and Vries (2010) and Chappin, Dijkema and Vries (2009).

reduction through incentive-based instruments, rather than command-and-control regulation. Incentive-based policy instruments use market signals to influence decision-making and behaviour (Egenhofer, 2003). The best known incentive-based policy instruments that can be used to reduce CO_2 emissions are an emissions trading scheme (ETS) and carbon taxation (CT).

Under the Kyoto Protocol, governments accepted CO_2 reduction targets in order to counter climate change (UNFCCC, 1998). In Europe the EU emissions trading scheme (EU ETS) was implemented as from January 2005 (CEC, 2003, Directive 2003/87/EG, see Box 2 on page 84 for an overview of the experience so far). In the EU ETS, companies active in specific sectors must be in the possession of CO_2 emission rights that equals the amount of emitted CO_2 (EnergieNed, 2006). Any surplus can be sold; any deficit must be compensated for by acquiring rights. Effectively, by economic pricing of CO_2 emission the external effects are partly internalized to the economy. By limiting the total amount of rights – the cap – the EU and its Member States must make sure that a suitable price of rights is formed and that trade amongst the parties involved emerges. The magnitude of the CO_2 cap determines the scarcity of rights. An emissions trading scheme is based on the assumption that the *invisible hand of the market* (Smith, 1776) would lead to emission reduction by those who can achieve reduction at the lowest cost (Ehrhart et al., 2003; Svendsen, 1999; Svendsen and Vesterdal, 2003). However, "abatement investments remain dependent on an elusive carbon price-signal which has failed to emerge" (Escalante, 2010). In contrast to expectations, the first trading period of the EU ETS did not result in "radical change in the development and use of generation technologies" (Hoffmann, 2007).

The main alternative pricing mechanism to an emissions trading scheme is carbon taxation (CT), in which certain activities can be taxed for its CO_2 emission. Pricing CO_2 emission gives incentive for CO_2 abatement. Besides pricing mechanisms, subsidizing measures can be used. In a feed-in tariff (FiT) the government pays a fee for electricity produced by clean technologies.

For sustainability, CO_2 reduction is only one indicator and *renewables* is another. Since our resources are finite (Meadows and Club of Rome, 1972), we have to reduce our dependency on oil, coal, natural gas, and metals in order to maintain or increase our quality of life in the long run. Although investments in renewables are increasing (e.g. IEA, 2009a), no trend-break has been seen in the use of fossil resources for power generation.

CO_2 reductions and renewable targets are new requirements of our electricity infrastructure augmenting affordability, security of supply, and safety. This requires that we think about *transition* in and *transition management* of our electricity infrastructure. We need to find out *how* and *when* a transition to a low CO_2 may occur. And at what cost to consumers, producers, and government. Rephrased in the terms of chapter 2, will we be able to come up with a set of *designs* for transition and will we be able to assess their potential effectiveness and robustness in decoupling CO_2 from economic growth and welfare?

These questions have made us explore the power generation system (section 4.2, explore the effect of emissions trading on emissions by power generation (experiment 1, section 4.4), explore a comparison between emissions trading and a carbon tax (experiment 2, section 4.5), and evaluate additional policies to the emissions trading scheme

Table 4.1 – Characteristics of energy sources and their adoption in the Netherlands

Energy source	Availability	Energy density	Carbon-intensity	Fuel costs	Adoption
Natural gas	decreasing	low	low	very high	47%
Coal	high	high	high	low	45%
Uranium	high	very high	none	very low	2%
Wind	uncertain	n/a	none	none	5%
Biomass	increasing	medium	short-cycle	medium	1%

as it is in place (experiment 3, section 4.6). Afterwards, conclusions are drawn on the transition to a CO_2-extensive power generation infrastructure.

4.2 Decarbonizing the electricity infrastructure

In this section, we describe the electricity infrastructure from a socio-technical system's perspective (Ottens et al., 2006). In this perspective, the sector is viewed as a single system consisting of a technical and a social subsystem. The technical subsystem contains physical apparatus, such as power generation facilities, electricity grids, and consumer equipment; the laws of physics apply to this subsystem and its components. The social subsystem contains actors who engage in contracts with each other on the exchange of fuels and electricity. Some of these actors own and operate components of the physical subsystem. The social system is subject to a regulatory regime and market competition. Actors are active on markets, decide on the investment in and operation of their assets. We analyse the potential for CO_2 emission reduction and outline the policy options available to achieve structural reductions.

4.2.1 The electricity infrastructure

In Figure 4.1 an overview is given of the electricity generation system from a socio-technical perspective. The organization of our electricity infrastructure has been changed dramatically in the past decade. In the realm of liberalization, power generation, transport over the national grid, regional distribution, retail, and supply have been unbundled (de Vries, Correljé and Knops, 2009). This affects the organization of the sector. A limited number of companies are active in (large-scale) electric power generation: in many a country a tight oligopoly is in place (Chappin, Dijkema and Vries, 2010). Electricity is transported long-distance over a high voltage transport grid that is owned and controlled by system operators. Medium voltage distribution grids are used for local distribution. Ownership and control of these networks vary throughout Europe. Households buy electricity from retail companies that are active on power markets in order to buy the contracted electricity. Some large industrial consumers buy their electricity on the market themselves, mainly through engaging in bilateral contracts with electricity generators. It is this bilateral market which is the main power market in the Netherlands, where 80% of the electricity is exchanged. The rest is sold on the spot market.

In the Netherlands, natural gas and coal are dominant. To a lesser extent other sources are used, such as nuclear, wind, and biomass (EnergieNed, 2006). Portfolio diversification

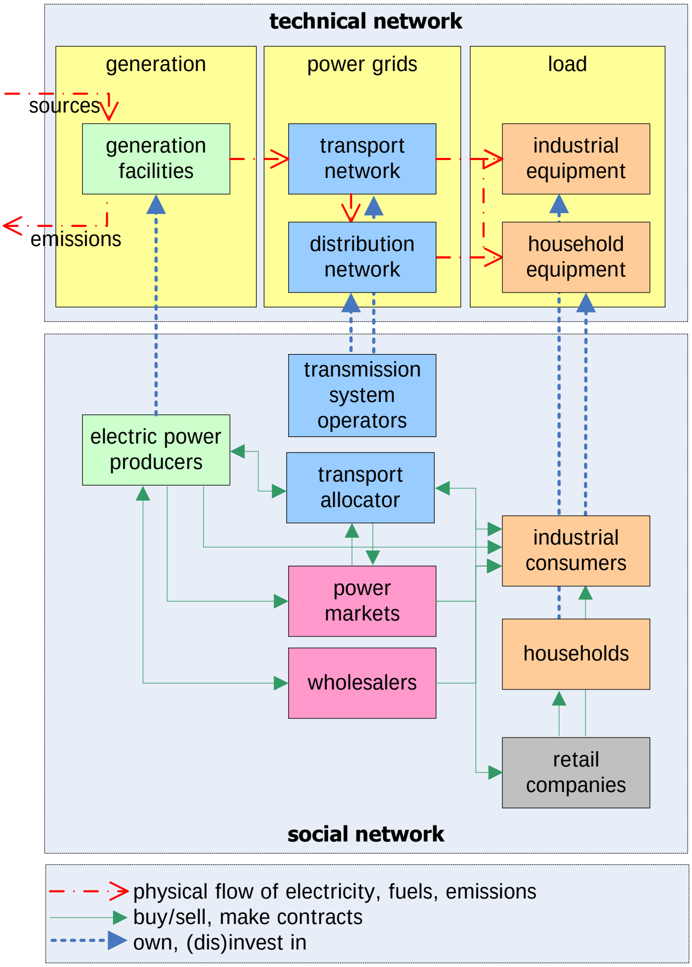


Figure 4.1 – Socio-technical system of electricity production

is required, because of the variety of characteristics of the different energy sources and their respective power generators (please refer to Table 4.1 for an overview of those properties). Coal is, compared to natural gas, a relatively cheap fuel. If compared on an energy basis, uranium can be acquired at even lower cost. When it comes to investment, a world-scale gas-fired power plant has the lowest investment on a per MW basis; the investment for a modern coal plant doubles this, and a modern nuclear plant is more than 5 times as expensive as a natural gas plant. Coal and nuclear facilities are of their economic and technical characteristics typical base-load facilities. Natural gas plants take up peak-load.

4.2.2 CO_2 emissions reduction by power generation

CO_2 is emitted when electricity is generated. A *net* CO_2 emission reduction is very hard to achieve. Emission reduction by fuel switching, reduction of demand, investment, and innovation will be discussed below. We conclude that we rely on investment in CO_2 extensive power generation facilities to bring down CO_2 emissions.

Reduce electricity demand For the last decades, electricity demand has been rising steadily by 2% a year on average. The continuous increase in population and living standards are the main underlying reasons (cf. IPAT, Ehrlich and Holdren, 1971, 1972). The growth reflects the ongoing electrification of society. Electricity demand is relatively inelastic to price changes (Lijesen, 2007), both on short and long term. On short term, consumers do not know the electricity price, so they are unable to respond.

Also on long term, the elasticity of electricity demand is relatively low, although the recent financial crisis caused electricity demand to drop significantly. Such a response stands not on its own: "We need only look back to the oil price shocks of the 1970s to see how well the price mechanism works. Higher fossil fuel prices dampen total energy consumption" (Manne and Richels, 1993). However, also on long term, consumers have little knowledge of the electricity cost for individual appliances and consumers are known to have a very large discount rate when purchasing goods (Hausman, 1979; Kooreman, 1996). Therefore, the purchase price is dominant in its purchase decisions. Outside exceptional conditions, the incentives for consumers to invest in low-energy devices or sustainable distributed generation are not attractive enough and consumers act as price-takers. This also points to the fundamental importance of electricity in our society. The potential for demand reduction alone is limited compared to the CO_2 emission reduction needed.

Switch to CO_2 extensive fuels Of all energy sources, coal is the most CO_2 intensive; natural gas is less CO_2 intensive, nuclear and wind are essentially CO_2-free. Biomass is the subject of an intense debate wherein its carbon-neutrality is questioned (van Dam et al., 2008). Under the current EU ETS biomass is considered to be carbon-free, on the basis of the argument that firing biomass only uses short-cycle carbon and the carbon uptake of the biomass chain equals the carbon emission. Recently, however, it has been concluded by a variety of researchers (cf. Cramer Commission, 2006) that first generation biomass use does have a carbon footprint of 30-70% of the carbon in the biomass used.

Although emission levels are strongly dependent on energy source, the potential emission reduction from fuel switching is limited. At the sector level, fuel switching takes place through changes in the merit order: plants moving from base load towards peak load and vice versa. Technical constraints limit the options for fuel switching at the level of individual power plants. The technical designs differ too much to make a switch from coal to, for instance, natural gas in an existing installation economically attractive. Many natural gas plants have the possibility to switch to diesel or fuel oil, but this is mainly for the purpose of reliability, as the use of diesel or fuel oil is more often than not uneconomic. Currently, the main option is co-firing biomass in a coal plant. The only technology with significant fuel flexibility is coal gasification. Apart from a single demonstration facility, to date, these facilities exist on the drawing board. Fuel flexibility via gasification can only be realized at the expense of significant investment cost. Therefore, the fuel flexibility of current power plants is limited to 10-15%.

Innovation of CO_2 extensive technology CO_2 intensity of electricity generation (in Mton CO_2 per kWh electricity produced) is strongly connected to the electric efficiency of power generators. Therefore, many incremental innovations drive-down CO_2 intensity of electricity generation. Innovative power generation technologies that have both lower operational costs and CO_2 intensity could outcompete the existing portfolio and bring about structural CO_2 emission reductions, but it is unlikely that such an innovation will emerge within a reasonable amount of time.

Investment in CO_2 extensive technology Significant CO_2 reductions in the medium term can only be achieved by investment in CO_2 extensive generation capacity. The main options for investment are major retrofitting of existing installations, the extension of existing installations with carbon capture and sequestration (CCS) and investment in new, more efficient facilities or carbon-free technologies, such as wind. If successful, over time, investment decisions will tend towards less CO_2 intense technologies, gradually lowering the average CO_2 intensity of the electricity generation portfolio. However, electric power generation is a capital-intensive industry and assets have life cycles of decades. The capital cost of a full scale, state-of-the-art coal-fired power plant in the EU is around 1000–1200 €/kW_e, which means more than a billion Euros for a 1040 MW plant such as currently planned by E.On. A coal gasification plant cost another 600-800 €/kW more. Less carbon-intensive power generation technologies are technologically proven and commercially available, but on what conditions do power companies invest in these technologies? The dynamics of process innovation in mature capital-intensive industries are characterized by high risks and long time spans (cf. Dijkema, 2004)). Power companies take the investment decision under deep uncertainty of policy, fuel prices, competitors' investments, and technological development. Therefore, it is incredibly difficult to predict what power producing companies will do and whether our emissions will actually go down. However, the main source for emission reductions are investments by electricity producers.

4.2.3 Policy options for CO_2 reduction

As argued above, structural CO_2 emission reduction in the long run is only possible through investment in CO_2 extensive power generation facilities. An important observation is that transition to a low-carbon electricity infrastructure will not prevail without government intervention. Therefore, we need to outline the options that provides us with means for transition *design*. Let us briefly analyse carbon policies and their effects. Two types of effects of incentive-based carbon policy instruments can be discerned.

Table 4.2 presents an overview of the main types of policy options for emission reduction. Three types of policy options can be discerned: price/quantity-based mechanisms, subsidy-based mechanisms, and direct intervention. They will all be discussed below.

Price/quantity based policies Pricing carbon is the essence of carbon taxation, cap-and-trade and performance-standard-rate. Both cap-and-trade and performance-standard-rate are forms of emissions trading. In the European ETS, which is a cap-and-trade system, the total amount of rights granted is capped to reach a certain emission target. This cap has been divided between Member States. As of January 2008, trade between Member

Table 4.2 – Policy options for CO_2 reduction

Policy instrument	Price	Volume of emissions	Allocation of emission	Implemented in practice
Carbon taxation	Set by government	Not limited	Can shift between sectors	Yes
Cap-and-trade	Market-based	Capped	Grandfathering or auctioning	Yes
Performance-standard-rate	Market-based	Not limited	Benchmarking & performance	No
Feed-in tariff	Subsidize production	Not limited	Per source	Not for CO_2
Command-and-control	No price	Regulated per source	Per source	Not for CO_2

States is possible. Member States can also increase the volume of rights via the Clean Development Mechanism. An alternative strategy is to ration carbon allowances per capita. Box 2 presents an overview of the experience with the European ETS.

Economic theory tells us that if cost and benefit functions are known for certain, tax and tradeable permits are equivalent in terms of efficiency (Hovi and Holtsmark, 2006). However, one of the key issues in climate policy is that cost and benefit functions are uncertain. Weitzman (1974) argued that given uncertainty, the slope of the supply and demand functions should determine the choice. Grubb and Newberry (2007) summarize his argument and apply it to CO_2 policy. They conclude that in principle taxes are superior, but they observe practical obstacles such as political acceptability. An important advantage of a tax is that – if it can be made credible that the tax level will not be reduced during the economic life of investments in abatement – it reduces investment risk significantly as compared to the price volatility that is apt to develop in a CO_2 market.

Carbon taxation provides a clear price signal by increasing the variable costs of fossil fuel-based electricity production (Lowe, 2000). It is a classic Pigouvian tax, the ideal level of which should be equal to the marginal social damage (Pigou, 1947). The positive cost of CO_2 emissions provides a monetary incentive for reducing emissions (Pizer, 1999, 2). An issue with a carbon tax is that the total emissions volume is not constrained. A tax is expected to shift the portfolio balance from coal to more natural gas and perhaps renewables and CCS. Such a shift is the aggregate result of many separate investment decisions regarding the choice of energy source, electricity generation technology, plant scale, and CO_2 abatement technology. A possible second-order effect of a carbon tax is that it reduces the demand for coal and increases the demand for alternatives such as natural gas, which could cause coal to become relatively cheaper, partly undoing the effect of the tax. It is difficult to predict at what level fuel prices, volumes of CO_2 emission rights, and CO_2 emissions the market would stabilize, because they not only depend on the fuel markets dynamics but also on the availability and price of alternatives such as CCS and renewable energy sources. This is one of the reasons why the effect of a tax upon the CO_2 emission level is difficult to estimate *ex ante*.

This would not be a problem if we knew the optimal tax level; then, by definition, In January, 2005, the European emissions trading scheme (ETS) was implemented (CEC, 2003). In the ETS at least 90% of CO_2 emission rights are grandfathered: they are allocated to emitters for free, in volumes based on past emissions. This led to a highly politicized process in which companies, industrial sectors, and European countries vie for CO_2 emission rights in order to minimize the financial consequences of the CO_2 cap. Over allocation of CO_2 emission rights was the consequence. Initially, market parties did not know this, but when in April 2006 the European Commission communicated that they had issued too many CO_2 emission rights, the price collapsed to nearly zero (Cozijnsen, 2005). Between 7 and 8 billion Euros in CO_2 emission rights value vaporized overnight. The grandfathering of CO_2 emission rights also led to substantial windfall profits for power producers. They passed the marginal costs of CO_2 on to the consumers (in perfect accordance with economic theory), which they had obtained largely at zero cost. In addition, with respect to emission reduction, the low-hanging fruit could still be picked at no or limited cost. To solve this issue, all CO_2 emission rights for the power sector (and a portion of the CO_2 emission rights for the other sectors) will be auctioned in the third phase of the ETS (2013–2020).

In the first phase of the ETS (2005-2007), the prices of tradeable CO_2 emission rights were highly volatile. In retrospect, this was due to the limited time horizon of this phase, the highly politicized process for determining the emission cap, uncertainties regarding the cost and availability of abatement options, the mismatch between the actual and forecast demand for CO_2 emission rights, and the inelasticity of the supply of CO_2 emission rights. Using the first phase as a learning period, the European Commission proposed improvements to the ETS. The most important change is to set a predictable cap that is to be reduced by 1.7% each year to achieve a 20% reduction between 2013 and 2020. The Commission also made it clear that ETS will continue beyond 2020 and at least become more stringent. Meanwhile, an extensive program to develop and demonstrate CCS is being developed. Funding of R&D on innovative energy technologies has been increased, and regulation and research to reduce energy consumption is back on the agenda. As in any market, a certain amount of price volatility remains inevitable, but both the design of the ETS and its context are improved to reduce uncertainty.

Box 2 – Experience with the European Union's Emissions Trading Scheme (EU ETS)

the resulting emission level would also be socially optimal. However, a fundamental problem with a Pigouvian tax is that we do not have a reliable measure for the social damage, so it is impossible to establish *ex ante* the correct level of the tax (Bimonte, 1999). As Grubb and Newberry (2007) argue, we do not know which tax level would reduce CO_2 emissions sufficiently to stabilize the atmospheric concentration at a certain level. A possible solution is to start with a relatively low tax and to adjust it over time in response to observed emission reductions. If a firm commitment is made that the tax will not be lowered during the life span of existing investments in less carbon-intense power generation or CO_2 abatement, this would provide investors with significant certainty regarding the minimum level of return on their investment. This way, investment risk can be limited while preserving policy flexibility.

Emissions trading relies on a price signal for internalizing a negative external effect of production (Ekins and Barker, 2001). A major argument for tradeable emission rights

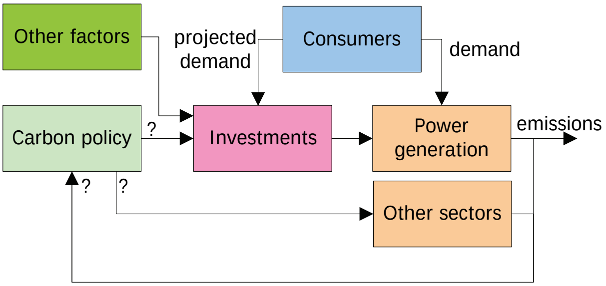


Figure 4.2 – The effect of carbon policies on electricity generation is mainly through investment by power producers

is that "the invisible hand" of the market would lead to emission reduction at the lowest cost possible (Smith, 1776; Svendsen, 1999; Ehrhart et al., 2003; Svendsen and Vesterdal, 2003). Both within a sector and between sectors transactions will occur until a CO_2 price develops which, corresponding to an emission level, is just equal to the emissions cap and no emitter is interested in investing in further emission reduction. "There is a broad consensus that the costs of abatement of global climate change can be reduced efficiently through the assignment of quota rights and through international trade in these rights" (Manne and Stephan, 2005). The main difference between trading and taxation can be summarized as follows: with trading, the total volume of CO_2 emissions is set but the CO_2 price is unknown and volatile. Under taxation, the price of CO_2 is fixed, while the volume of emissions is not.

Subsidy-based policies Subsidizing measures are an alternative to price and quantity based mechanisms. Essentially, these policies do not work by means of punishing an activity emitting CO_2, but through promoting activities that emit no or little CO_2. Most common in this category is a feed-in tariff (FiT). A FiT consists of a fee which consumers or producers get from government for the *use of clean technologies*. In this way, the government guarantees the technology user a certain utility that may promote him to make an investment in that technology. FiTs have been successful in promoting renewables in for instance Germany (Stern, 2007) and the Netherlands (van Rooijen and van Wees, 2006). Box 3 describes the Dutch and German feed-in tariffs. Feed-in tariffs have not yet been adopted with CO_2 reduction as main purpose.

Direct intervention Government can also take measures directly intervening in the activities of consumers and producers; banning CFKs and CKCs altogether proved to be effective in countering the depletion of the ozone-layer. This had a farfetching effect on the production of, amongst others, fridges and aerosols. A ban can, therefore, be effective if it is politically feasible. As argued above, a ban on CO_2 is not considered likely.

The Netherlands implemented its first feed-in tariff (FiT) in 2003. The 'environmental quality of electricity' (in Dutch: Milieukwaliteit van de Elektriciteitsproductie, MEP) policy was financed by a levy on electricity connections of Dutch households (van Sambeek and van Thuijl, 2003), entailed a ten year lasting feed-in tariff, intended to reduce investment risk and to improve the cost-effectiveness of renewable energy. The MEP regulation was popular for investment in large-scale electricity generation from wind and projects using biomass. Although the MEP regulation was considered successful, the policy was cancelled out by the Minister of Economic Affairs in 2006. The regulation became too expensive to maintain and lost its political support.

Recently, in 2009, another feed-in tariff policy, called 'Incentive for renewable energy production regulation' (in Dutch: Stimuleringsregeling Duurzame Energieproductie, SDE) was implemented, which is still ongoing and has a broader scope, including renewable technologies for households. In contrast to the MEP regulation, there are limited budgets available for specific technologies: solar photovoltaics (PV)s, biomass, hydro, on-shore wind, off-shore wind, and combined heat and power (CHP). Similarly to the MEP regulation, the SDE regulation proved to be very popular. The requests for grants on the first day of the regulation exceeded the total budget. Grants are provided at random within the budget.

Germany is famous for its success with its feed-in tariff called the 'renewable energy sources act' (German: Erneuerbare Energien Gesetz EEG), which was enacted in 1991 and replaced in 2000 to meet Germany's renewable energy consumption targets (12.5% in 2010, 20% in 2020 and 50% in 2050 Lauber and Mez, 2004). Already in 2005, 10% of the electricity production in Germany was renewable. Because of its feed-in tariff, Germany has a significant proportion of the global market for PV (58% of globally installed capacity Stern, 2007, p. 367).

Box 3 – Experience with Feed-In Tariffs (FiTs) in the Netherlands and Germany

4.3 Overview of experiments on transition in power generation

A myriad of policy options appear to exist to let us invoke a transition, decarbonizing our electricity infrastructure. How to choose one or more of these options? And in terms of chapter 2, how can we design the optimal transition policy? What is the likelihood that the policy is effective, both in the short run and the long run. In other words: what is the effect of carbon policy on the emissions, emerging from the interactions in complex socio-technical electricity infrastructure? As argued in chapter 3, we have to develop suitable simulation models to explore the options and find out whether we can assess the effect on transition. Based on the analysis above, our focus is on the impact of carbon policy on CO_2 emissions through power producer investments (see Figure 4.2). In that journey, we have designed and executed three extensive experiments on transition in the electricity infrastructure.

Experiment 1 – Impact of emissions trading In the first experiment, we have explored the potential of emissions trading. This leads to the alarming conclusion that although capped, emissions reduction targets are not achieved by definition under a cap-and-trade scheme. Some argued that the way in which the interaction between the power market and the CO_2 market was modelled could be improved. The conclusion, however, holds since the cap-and-trade system is open (both in relation to CDM/JI and the concept of carbon leakage).

Experiment 2 – Comparison of emissions trading and carbon taxation In the second experiment, we came up with a new design that allows a stricter emissions trading scheme which is more close to reality. In this experiment, we compare emissions trading to its main alternative: a carbon taxation scheme. It proved to be hard to make these two instruments comparable, but we did find a solution. This experiment leads us to the conclusion that a fundamental investment risk exists under an emissions trading scheme which is an inherent flaw. A carbon taxation scheme was found to be outperforming the emissions trading scheme.

Experiment 3 – Towards the design of EU ETS+ The main criticism on experiment 2 was the political difficulty in getting such a tax into place. Consequently, we designed a final experiment, in which we opted for improving the current system by way of *combining* it with either a tax, a feed-in tariff or a carbon price floor. In this experiment we really opted for testing a policy assemblage.

4.4 Experiment 1: Impact of emissions trading

4.4.1 Introduction

To elucidate the impact of emissions trading on the CO_2 emissions of the power generation sector an agent-based model (ABM) was developed. In the model, actors are represented by agents that live in a simulated world driven by exogenous forces. The agents represent companies active in electricity production. They own and operate a set of power generation facilities, the technical system. Each generation facility is represented in the model by a set of equations that respects the Law of Conservation of Mass and Energy. The agent's behaviour is modelled by a set of rules, reflecting the way of operating and (dis)investment decisions are made in the power industry.

We will now describe the model developed to execute this experiment. Afterwards, validation and assumptions are discussed, results are presented and conclusions will be drawn.

4.4.2 Model description

An *agent-based model* (ABM) was developed to simulate the evolution of the structure and the performance of a hypothetical electricity market in the next 50-75 years using insights from microeconomics, market design, agent theory, process system engineering, and complex system theory (Chappin, 2006; Chappin and Dijkema, 2008a,c). The ABM represents a set of interacting agents with certain properties that live in an external

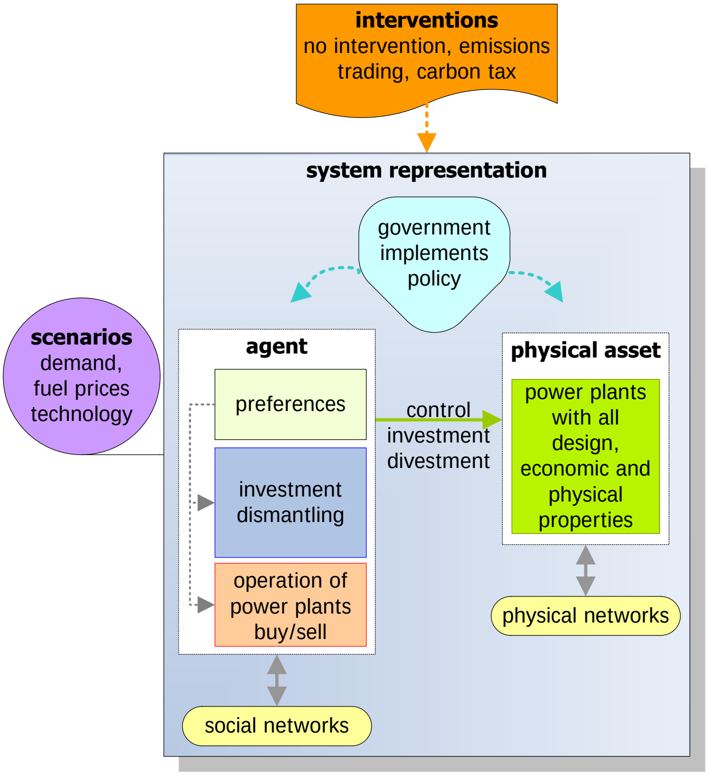


Figure 4.3 – The modelling framework applied to carbon policies and power generation

world whereupon they have no influence – a modelling paradigm that matches the electric power production sector, where independent power producers, governments, and consumers can be considered agents that compete and interact via markets. The model is described according to the five components, defined in the framework (please recall Figure 3.2 on page 62). A schematic overview of the ABM, presented as application of that modelling framework, is drawn in Figure 4.3.

System representation In all experiments, agents, physical installations, and markets are represented in the system. The agents in the model, the power producers, negotiate contracts for their fuel supply, the sales of electricity, and CO_2 emission rights. The agents also need to choose when to invest, how much capacity to build, and what type of power generation technology to select. The agents, markets and physical installations are discussed below.

Agents The main agents in the model are *power producer agents*. To reflect the tight oligopoly, their number is set to six. Each of them has the same decision making structure, but differ in management style (see below). The agents have strategic management in which they decide on divestment and investment.

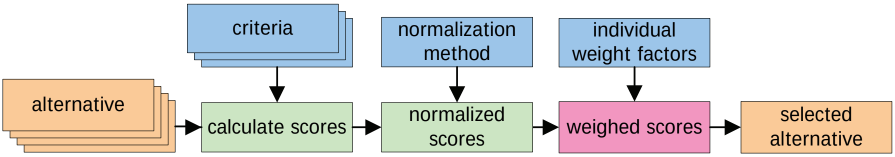


Figure 4.4 – Investment algorithm using MCA

- Divestment. The agents decide what power plants should be dismantled. Two reasons for divestment are modelled: (1) reaching the technical lifetime of existing power plants and (2) for a long time (5-9 years, depending on the agents' management style) the marginal revenue has been smaller than the marginal costs.

- Investment. The agents decide whether investing in a new power generation facility is sufficiently attractive to them. The reasons for investment are (1) to-be-expired capacity will be replaced and (2) identification of an opportunity for capacity expansion.

- Technology type. If agents decide to invest, they will also decide on the preferred technology type for investment. In the simulation model, their decision is assumed to be based on a multi-criteria analysis (MCA, see Figure 4.4). Therein, criteria used for selection of the electric power generation type include hard and soft criteria. The lifetime cost-benefit expectation is a hard criterion, for which all anticipated costs and revenues are modelled: investment cost, fuel, CO_2 and other variable operational and maintenance costs, and revenues from power generation. Soft criteria such as a dislike of nuclear power plants and conservativeness are also taken into consideration. The performance of all possible alternative technologies on all criteria will be calculated for each agent using score weights that reflect the agent's management style. The analysis leads to a single best alternative. An elaborate description of the implementation of MCA in the agents is in appendix B, section B.2.

As stated, apart from strategic management, the power producing agents have operational management. Short-term, they must make decisions on:

- Selling of electricity. Based on marginal costs bids, agents sell electricity through the spot market for electricity; the spot market, the APX, is represented as another agent in the simulation, which is described below. Marginal cost bids are based on expected fuel costs, other variable costs, and CO_2 costs. The expected CO_2 costs are based on past CO_2 prices on the CO_2 market (see below).

- Acquiring fuel. Based on actual electricity production, the needed fuel is determined and acquired.

- Acquiring CO_2 emission rights. Based on actual electricity production, the needed CO_2 emission rights are acquired.

In the simulation model there is one *government agent* that makes policy related decisions. Under the emissions trading scheme, it decides on allocation: whether and how to distribute CO_2 emission rights at no cost, so called grandfathered rights. Through the following formula, grandfathered rights are allocated for a single installation, when the emitting agent demands them:

$$g_i = t \times \frac{r}{100} \times \frac{e_i}{\sum_{j=1}^{m} e_j} \tag{4.1}$$

Where g_i is the number of grandfathered rights for agent i in ton/year, t is the total cap in ton/year, r is the percentage of total rights that are grandfathered, e_i is the actual emission by the installations of agent i in ton/year and m is the number of agents. The allocation scheme limits the total amount of rights – a cap-and-trade system – and the part of the total that is grandfathered (for instance 90%, the rest should be acquired from the market). The available rights are divided amongst the electricity producing agents on the basis of actual emissions. Therefore, each agent gets its share. This reflects the arrangement for grandfathering adopted in the first and second phase of the EU ETS.

One *consumer agent* corresponds to the aggregate demand of all domestic consumers for electricity. The yearly demand is determined in the scenario (see below).

The *environment agent* will supply all environmental uptakes, e.g. air, and consume all environmental emissions, such as CO_2. This agent is required to ensure that mass and energy balances are correct.

Markets All electricity is sold through the *power exchange*. This is an agent that represents the combination of an ordinary day-ahead spot market, such as the Dutch APX market and the longer term bilateral contracts. The agent collects all bids from electricity producers. In addition it collects information related to import from the world market agent (see below) and demand from the aggregate consumer agent (see below).

The electricity spot market agent's decision-making comprises the market clearing process. In reality, spot markets operate on a very short transaction horizon, e.g. a quarter of an hour. To limit the required computational time, this is aggregated to a yearly clearing process. The clearing process implemented takes into account the variation of demand over the day and the year, i.e. it reflects the price-differences for base-load and peak-load electricity. Yearly output and prices are calculated based on yearly bids that power producers make for its installations and the yearly demand, import price and capacity, and the aggregate demand by using the following formulas:

$$s_i = c_i \times \frac{d}{\sum_{j=1}^{n} c_j} \times \frac{\sum_{j=1}^{n} (c_j \times p_{b,j})}{\sum_{j=1}^{n} c_j \times p_{b,i}} \tag{4.2}$$

$$p_{a,i} = 40 \times \frac{d}{\sum_{j=1}^{n} c_j} \times \frac{\sum_{j=1}^{n} (c_j \times p_{b,j})}{\sum_{j=1}^{n} c_j \times p_{b,i}} \tag{4.3}$$

Where s_i is the actual supply of power plant i in MWh$_e$/year, c_i is the capacity power plant i in MWh$_e$/year, $p_{a,i}$ is the actual price for power plant i in €/MWh$_e$, $p_{b,i}$ is the bid for power plant i in €/MWh$_e$, d is the total demand for electricity in MWh$_e$/year and n is the number of power plants.

The first formula determines the actual yearly supply per installation, by using bid price and capacity. Since bids are based on marginal costs, as stated above, relatively low bids already result in relatively high actual supply offers: these bids will be for base load. The reason behind this is that by accepting these low price – high volume bids, an installation will be *in merit* (below the market clearing price) for a greater part of the year and will thus produce more. Please note that actual supply s_i for each power plant i is capped at maximum capacity c_i. The second formula determines the price, also according to the bid. Relatively high bids lead to a higher price. The reasoning for this formula is that at a high bid the average selling price is higher, because the market prices, under which you were in merit, are only the high prices. A validation of these formulas can be found in (Chappin, 2006, appendix E).

After market clearing, contracts are signed and finalized. The agents involved in a particular bid ensure themselves that the actual electricity is supplied according to the contract and that the financial transaction is completed.

The *CO$_2$ market agent* represents trading platforms for CO$_2$ emission rights. Since it is often the case that agents need more rights than they obtain from grandfathering, additional CO$_2$ emission rights can be acquired from the CO$_2$ market agent. Yearly clearing is based on the demand for and the supply of rights. Prices are equal for all parties and are based on the following calculation:

$$p_{CO_2} = 10 + 40 \times \left(\frac{\sum_{j=1}^{n} e_j}{t} \right)^2 \tag{4.4}$$

Where p_{CO_2} is the price of CO$_2$ rights in €/ton, e_j is the emission of power plant j in €/ton, n is the number of power plants and t is the total cap in ton/year.

The price is based on ratio of supply and demand for CO$_2$ emission rights and the total emission of the sector. The price is calibrated at a base price of 10 €/ton CO$_2$ and a price of 50 €/ton CO$_2$ when using all rights assigned for the power generation sector. The main assumption in this setup is to reflect the main idea of ETS, namely that inter-sector trade should be possible to achieve emission reductions in sectors that incur the lowest cost. The implication is that a reduction of the sector emission to comply with the amount assigned for the sector is not necessary: rights can be acquired from other sectors or 'imported' from other countries. This choice has consequences for the impact of emissions trading, both in reality and in the simulation, because it is possible for the sector to grow beyond its cap.

The *fuel market agent* allows the electricity producers to acquire all fuels needed for their electricity production. This agent sells the fuels available in the model – coal, natural gas, biomass, and uranium – at an exogenous price that is determined in the scenario (see below). Since the world market agent is the only agent that offers fuels, the electricity

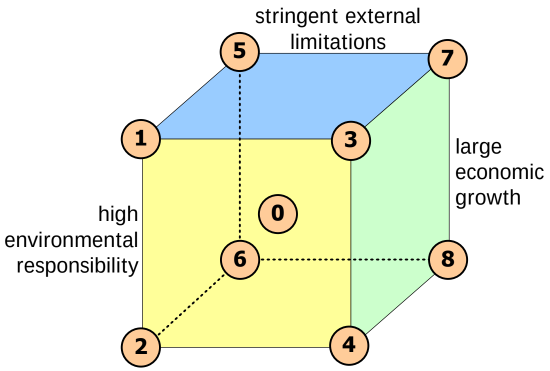


Figure 4.5 – Scenario space

producing agents will buy from this agent at the scenario price. In addition, the world market agent allows for import, but the import capacity is limited. The capacity and import price are set in the scenario.

Power generation technologies Power plants can be characterized by their fuel-type, costs, lifetime, and fuel usage. In appendix B, section B.1 the main characteristics of the used power plants in the Netherlands are listed. For coal two types are listed, a conventional coal fired steam power plant and a coal power plant with CCS (Carbon Capture and Storage), i.e. a clean coal power plant. Today, CCS is not yet proven technology, but seen as one of the most promising technologies (Task Force Energietransitie, 2006a). Technological innovation is not modelled, except for the possibility of CCS. In reality the operational flexibility of power plants is limited. In the model, operational flexibility is assumed to be negligible. Reductions by operational changes in existing power plants can safely be assumed to be of limited impact. In the model, emission reduction can only be realized by a shift in the power generation portfolio employed.

Exogenous scenarios As pointed out earlier, agents decide based on their style and in response to exogenous factors. All exogenous factors are bundled in so called environment scenarios (Enserink et al., 2002). Three driving forces are defined that have an effect on relevant and uncertain factors surrounding the agents, namely world economic growth, environment mindedness, and external limitations. The factors influenced include potential developments in fuel prices, electricity demand, and changes in the cap. For all factors, data were collected for initial values and trends (Chappin, 2006), reported in Table 4.3. The three scenario axis together build a scenario space – a cube – in which each point represents a set of values of trends, in other words, a scenario. A total of 9 scenarios are selected: all combinations of extremes on the axis and one in the centre of the scenario space Figure 4.5. Note that subsidies are enabled in some scenarios. Therein, subsidies are provided for the use of technologies that use renewable resources, i.e. wind farms and biomass power plants.

Table 4.3 – Scenario data values and trends

Scenario axes	Factors influenced	Initial value	High trend	Low trend
World economy	Aggregate electricity demand	106 TWh_e	+4 %/year	+0 %/year
	Average margins in supply bids	constant	15%	5%
	CO_2 demand other industry	constant	10 Mt	0 Mt
	Natural gas price	0.144 €/m^3	+6 %/year	+2 %/year
	Coal price	52.6 €/ton	+5 %/year	+1 %/year
	Uranium price	40 €/kg	+2 %/year	+1 %/year
	Bio-fuel price	66 €/ton	+0 %/year	+0 %/year
Environment mindedness	JI/CDM allowances bought	constant	10 Mt/year	0 Mt/year
	Technology specific subsidies	constant	100 €/MW_e	0 €/MW_e
External limitations	Cap width	50 Mton	-2 %/year	+0 %/year
	Part of rights grandfathered	constant	70%	90%
	Electricity import price	15 €/MWh_e	+2 %/year	+0 %/year
	Inter-connector capacity	20 TWh_e	+0 %/year	+2 %/year
	Types of power plants available	constant	no cln coal	all

Intervention The design of transition assemblage in this experiment follows the design of the EU ETS of phases I and II (2005-2007 and 2008-2012 respectively). The main design elements are discussed in the model description above.

In addition to the simulation of the EU ETS we also simulate the power generation system without intervention. In this way, one can gain insight into the added value of the EU ETS.

System evolution The time step in the model is one year and simulations span a horizon of 75 years to allow for exploration of long-term dynamics in the system. Although the agents are central in the model, there is a simulation schedule that aligns the agents in their actions and interactions. The simulation schedule consists of four steps:

- Model initialization. Model initialization determines whether a single run or a set of batch runs is performed and which output is selected. When single run mode is selected, model parameters can be adjusted. When batch run mode is selected, the variety of parameters must be selected to define the particular scenario-space for this set of runs. After run type selection, the model dataset is loaded from the knowledge base (see below for more details and implementation issues).

- Run initialization. In this step, the dataset is used to initialize the run, whether single or one of a set of batch runs. The selected parameters together with the data from the knowledge base determine which agents and technological installations are created. Among other things, this means that the initial portfolio of power plants is created in this step. The initial scenario parameters are selected and applied as well.

- Simulation. The agents evolve over time through action and interaction and through exogenous change. The total simulation run length of 75 years is sliced into steps of one year. In each step, the model procedure is repeated until the end of the simulated period is reached.

- Next run. If a set of batch runs is to be completed, then the next run is initialized, i.e. the run initialization step is executed again and a new simulation is completed.

In each simulation run, the system behaviour emerges out of the myriad of actions of the agents. For instance, the electricity prices and supplied amounts from the installations are the result of the electricity trading step. Based on the bids of all electricity producing agents, the market clears (see explanation below). The simulation is essentially demand driven. Since there is demand for electricity, there is demand for fuels and CO_2 emission rights. As time passes, installations reach the end of their technical or economic lifespan and a demand for new investment emerges. In case demand grows rapidly, opportunities for investment arise earlier in the simulation run. The choice of the demand pattern over the simulation run basically determines the order of actions and interactions and how they are aligned. The evolution of the simulated system is a sequence of activities that take place. The following activities are repeated each time step:

- Update exogenous scenario parameters.
- Electricity trading
- Emissions trading
- Fuel trading
- Investment and divestment
- Record data and update graphics

4.4.3 Model validation and main assumptions

Validating ABMs is not straightforward. There are no generally accepted validation methods for ABMs in the literature. Key in this discussion, therefore, is the definition of a valid model. Validity will throughout this thesis be defined as the extent to which it satisfies its purpose (e.g. Holling, 1978; Forrester and Senge, 1980; Forrester, 1985; Barlas and Carpenter, 1990; Qudrat-Ullah, 2005). Therefore, one can distinguish two parts to the validity of the model.

The first part of validity is what we normally refer to as verification, i.e. whether the model is consistent. A consistent model is a model in which the objects are modelled free from errors. The second part of validity is on the structure of the model and on conceptual choices and assumptions, i.e. whether the model spans the objects needed and whether it includes a sufficient representation of these objects and their interaction in order to answer the research questions the model was built for.

Extensive validation was performed during and after the model development. For validation of agent-based models many of the same tests as developed for System Dynamics models (Qudrat-Ullah, 2005, p. 2) are used. Even a broader range of validation methods for System Dynamic Models than suggested has been used in order to validate both on consistency and conceptualization. Where applicable, the tests described by Barlas (1996) are used. Our validation approach included direct structure tests, such as tests on empirical structure and parameters, direct extreme conditions, boundary adequacy of structure, dimension analysis, and face validation. Also structure oriented behaviour tests were successfully completed: these comprise tests for extreme conditions, qualitative future analysis, comparison with accepted theory, and an extensive sensitivity analysis. The model outcomes were not sensitive to most parameters, including agents' management style parameters. The model seems to be quite sensitive to fuel trends though. It is concluded that except for fuel price trends, the model is not very sensitive to any parameter, since the number of parameters is rather large.

Note that the goal of the model is not to provide absolute numbers and predictions, but rather to get insight in the potential of emissions trading as instrument to influence the emissions by power generation through a technology-portfolio-shift over time. Having said that, the main assumptions in the model and their consequences are the following:

Significant technological breakthrough is absent, except for carbon capture and sequestration (CCS) technology. The consequence of this assumption is twofold.

First, the overall picture can improve by incremental technological innovations, meaning that both under emissions trading and under a no intervention strategy the emissions might be lower. So the additional insight in the impact of emissions trading is limited. Implementing incremental innovation is on our research agenda in order to be able to model the feedback of higher technology adoption to learning curves, i.e. applying endogenous learning curves (Martinsen, 2008, e.g.). Results would change though, if this feedback was significant. Both exogenous and endogenous learning curves are easy to implement within the current framework. This is easy to implement, as it will only require small changes in the model's code. Learning curves have been implemented in the other experiments. The results, in portfolio terms, would not change more than a few percent, because both scenarios with and without emissions trading would be impacted similarly. It would improve results in absolute terms though.

Second, a dramatic technological innovation could occur, the breakthrough of nuclear fusion, for example, could mean a dramatic decline in emissions and outperform all other technologies. Such an outcome is not modelled, since the occurrence of such an innovation is not significantly impacted by the emissions trading scheme and falls beyond the scope of the modelling exercise, i.e. it is not what we want the model to do. What we rather want from the model is to envision the impact that emissions trading has under a realistic set of circumstances. Does emissions trading lead to selection and use of technology which is known and proven today? And does the instrument have sufficient merit – is its impact large enough to prefer it over alternative policy instruments or over not intervening?

The model is based on and delineated to the Dutch power and CO_2 markets. Some parameter settings are specific to the Dutch situation. The main features specifically Dutch are the starting portfolio of technologies, the number of power producers, electricity demand, import capacity, and the general attitude towards nuclear. Obviously, the model would generate different results for parameters corresponding to other countries. The Dutch case is a only a suitable illustration, however. By changing the above mentioned settings and by incorporating the appropriate datasets, all liberalized European power markets that have limited or no import capacity can be simulated. The Dutch

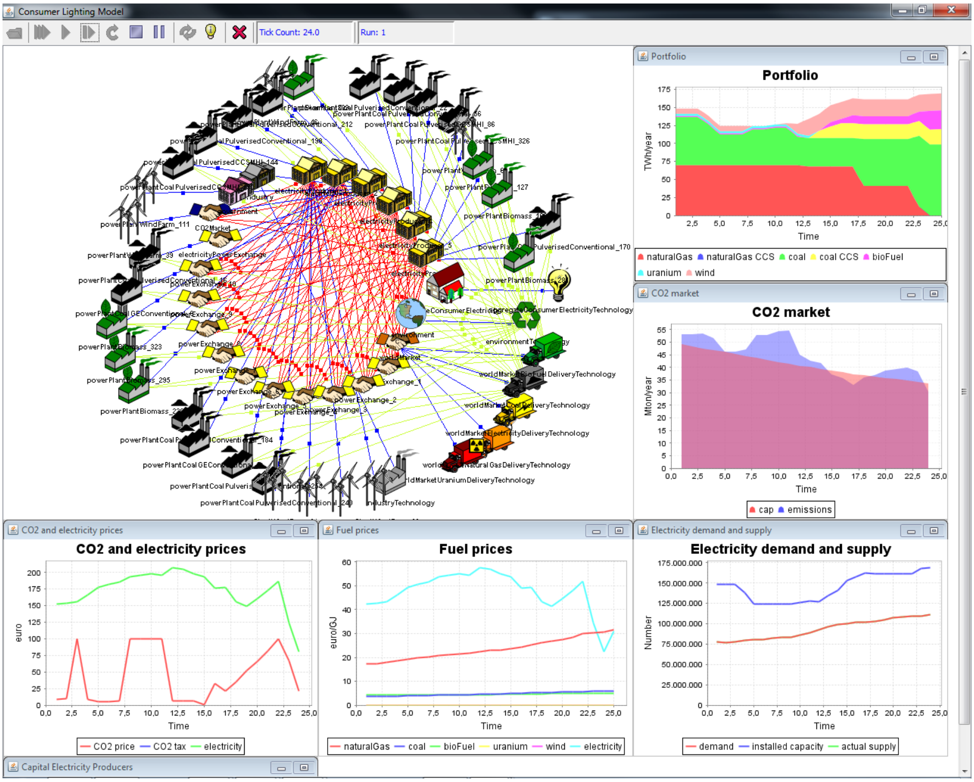


Figure 4.6 – Snapshot of the Power Generation Model

situation is, in that sense, not more than an exemplary case.

CO_2 emission rights can be exchanged between sectors and countries. It is assumed that there are rights available from other sectors and from other countries, basically corresponding to the rules in phase II that started in 2008. One has three options: invest in order to reduce emissions, acquire rights from the outside, and pay the penalty.

4.4.4 Simulation results

3600 simulation runs have been executed over the extensive scenario-space described earlier, each for a time period of 75 years. Initial conditions for all simulation runs are equal, but both the modelled variation in scenarios and stochastic parameters in the model lead to variation in the output. In all of the model runs, the system emerges out of the interaction of individual decisions and the system evolves over time. A snapshot of the evolution of the power generation system can be seen in Figure 4.6. The agents are drawn in the inner circle, with the contracts they negotiated between them. The technological elements are in the outer circle with physical flows of goods in between them. Ownership of technology is drawn between agents and technological elements. During the model, this picture changes by change in contracts and by investments and dismantling.

Since the system in the model evolves – by the myriad of decisions – we need to

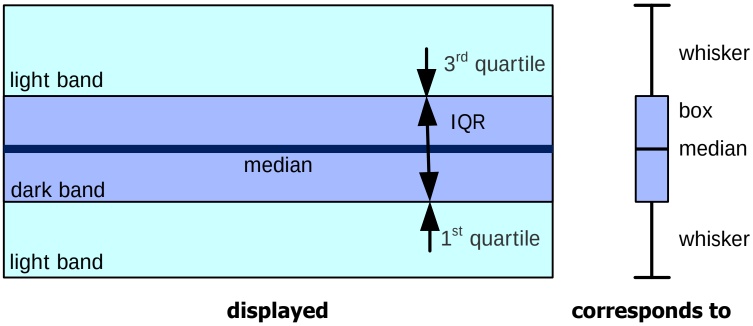


Figure 4.7 – Explanation of the graphs that show the median, a dark band, and a light band

look at indicators *over time*. For most graphs in this thesis, insight in the location and spread of the data over time is relevant. In those graphs, we display a number of lines for each variable, using statistical notions that are also captured in a so-called *box plot*. The meaning of the different lines is visualized in Figure 4.7. Essentially, for each time step a box plot is made and the result is connected: all the boxes become the dark band, and the whiskers the light band. In some graphs in this thesis, only the median and the dark band is displayed.

The median refers to the middle value, so at a certain moment in time 50% of the values are above this line and 50% are below.

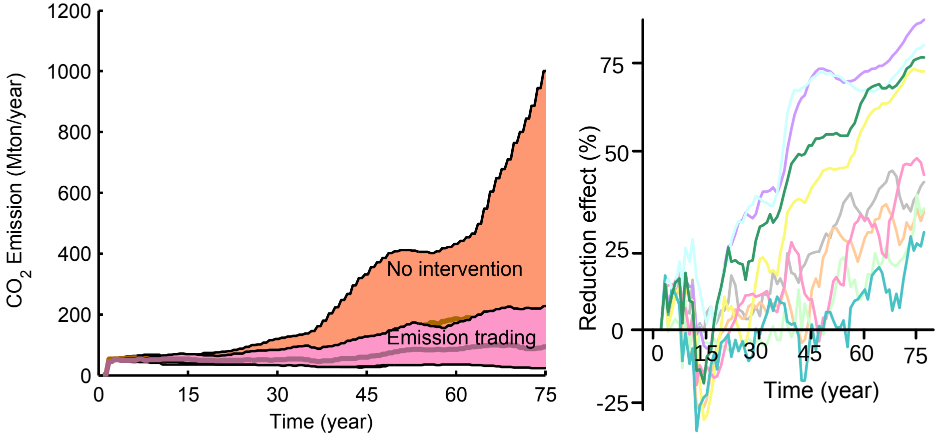
The dark band refers to the inter quartile range (IQR), i.e. the size of the box of a box plot. At a certain moment in time 50% of all the values fall within this band.

The light band contains all the values found at a specific time step that are not considered to be outliers (see below), i.e. the size of the whiskers of a box plot.

Outliers are values that are further than 1.5×IQR away from the dark band. Outliers are usually removed from the plot in the graphs shown in this thesis. When they are relevant, they are displayed as dots.

In order to compare emissions trading with no-intervention the same number of simulation runs have been completed for both cases. This is crucial in interpreting and assessing the relevance of the results: these simulation outcomes are compared; the focus is not on interpretations of the absolute numbers. Rather, the simulation results for emissions trading and no intervention are statistically analysed and aggregated to enable interpretation of the results and comparison of these two cases.

The impact of CO_2 emissions trading on emissions is shown in Figure 4.8. The absolute emissions still rise in most scenarios, because total electricity demand rises (see Figure 4.8a). Next, the emission reduction over time that is depicted shows the direct consequence of implementing emissions trading (see Figure 4.8b). A value of 25% for scenario x at year y means that when during the time up to year y emissions trading had not been implemented, the emissions by electric power generation would be 25% higher on average for scenario x. Therefore, each deviation from 0% is a consequence of emissions trading. As shown, the impact in the first two decades is small: for some scenarios



(a) CO_2 emission levels

(b) Impact of emissions trading in different scenarios

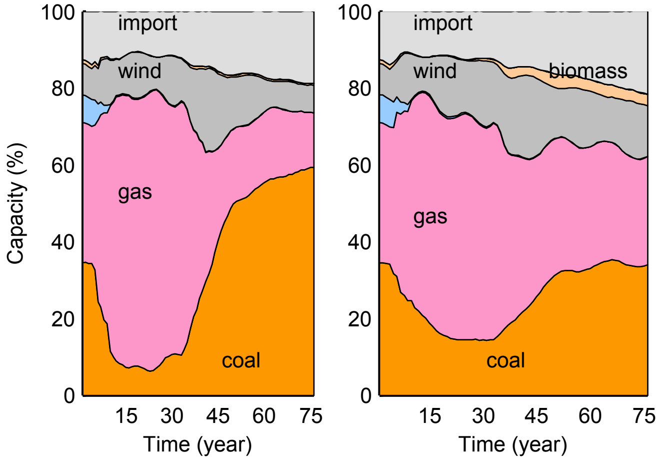
Figure 4.8 – Experiment 1: The impact of CO_2 emissions trading on CO_2 emissions

a reduction and for others an increase of up to 25% is noted. After twenty years, a significant reduction is reached in most scenarios. Reductions can reach even 80% on the long term. Please note, however, that these are reductions compared to no intervention.

In Figure 4.9 the composition of the electricity generation portfolio over time is displayed. Again, this is the statistical average over all scenarios and runs; implicitly, this assumes that all scenarios have equal probabilities to occur actually. The portfolio development under no intervention is displayed on the left and the development under emissions trading on the right. An impact of emissions trading is clearly discernible: the development of the composition of the electric power generation portfolio differs. In the first decades the impact is minimal: current standing installations are not replaced until their technical lifetime has passed and electric power producers just accept the costs for CO_2 rights. Even the current run for natural gas power plants is slowed down. After the first decades, coal is quite dominant in both policy settings. The relative amount of coal does decrease under emissions trading though, as it starts at a 45% share and ends at a 30% share. However, coal is not banned.

Note that clean coal technology is not displayed: it is not adopted in significant amounts. That is caused by the assumption of high variable cost for transport and storage of CO_2 and the higher investment cost for the capture technology and connection to a suitable infrastructure. Therefore, the shift to coal is not a shift to coal with capture and storage, but rather a shift to conventional coal. Although we see this shift, it would be far stronger without emissions trading, in other words, it is partially prevented by emissions trading. Without any carbon policy, coal appears to dominate the energy sources for power generation. Emissions trading leads to increased use of both renewable sources in the model, but power producers withhold to adopt them in dramatic amounts.

Given a dramatic increase in demand and assuming that rights are available in other sectors and countries, conventional coal is necessary in the portfolio and still competes with the other energy sources: it is even a relatively attractive option for power producers.



(a) No intervention (b) Emissions trading

Figure 4.9 – Experiment 1: The impact of CO_2 emissions trading on portfolio

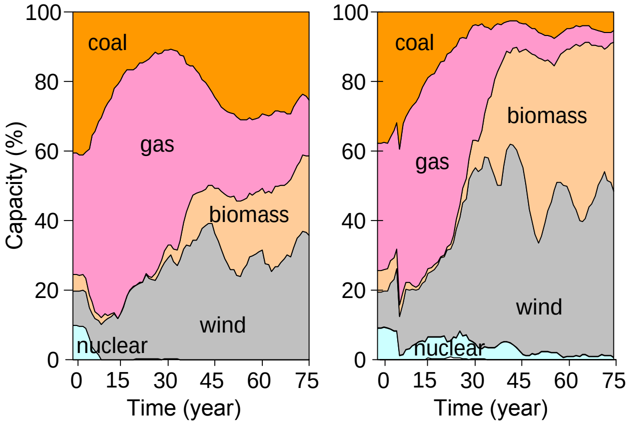
At reasonable CO_2 prices, it has low variable cost (especially fuel cost) and is, therefore, part of base load: capital utilization is relatively high. Since electricity prices rise, power producers still make a profit.

Under these assumptions, the effect of emissions trading is thus not strong enough for power generation to reduce actual emission levels. Although more realistic assumptions would change this result, the findings are insightful: the effectiveness of this policy is strongly dependent on technology and economy. Cost levels for CCS technology, learning curves, and decrease in demand are crucial for its success and these three are not directly impacted by the policy itself!

As was mentioned, unique sets of investment decision criteria were selected for six electric power producer agents in the model. At this moment, the criteria are fixed (within and between runs). The examples in Figure 4.10 show that the portfolios of the agents develop differently – note that, on average, they possess equal initial portfolios. It was found that electricity producer 3 had the highest power generation capacity at all times and was also most profitable. Since this producer is also the largest emitter in the model – it uses the most coal of all agents and only little amounts of renewable sources – and the most profitable (!) it appears, it continues to pay to burn coal. Apparently emissions trading does not generate a sufficiently strong price-signal to induce a total shift, especially since in reality the management style and associated decision criteria might change over time towards the criteria of the more successful power producers.

4.4.5 Analysis

In comparison with no intervention, the impact of emissions trading on CO_2 emissions by Dutch power production and its generation portfolio is relatively small and late: absolute emissions by electricity generation rise under most scenarios. On the longer term conventional coal is still adopted: driven by low coal costs and an increase in electricity



(a) Producer 1 (b) Producer 2 (c) Producer 3

Figure 4.10 – Experiment 1: Portfolio developments of individual agents.

demand, coal use appears to be unavoidable. The share of coal is found to be more in balance with the other energy sources under emissions trading.

From these results it should not be interpreted that the presented portfolio developments will be the most likely to occur. Large differences between scenarios are found, technological innovation will drive down fixed and/or variable costs for alternatives and new alternatives might be developed, and new power producers can come to the market and existing power producers can merge or adapt their strategies. Although these are reasons why the adoption levels of coal might be lower in reality, coal is attractive for its flexibility: when using coal technology, one can co-fire biomass and one has option to capture and store the CO_2 later.

Interestingly, the findings correspond to the dominant part of current capacity expansion plans in the Netherlands and Germany. An overview of plans for new power plants in these two countries is given in Table 4.4, presented per fuel type. It is possible to co-fire biomass with the coal for some coal power plants planned for the Netherlands. The biomass figures are calculated with a maximum of 15% co-fired, on basis of energy content. In the coming years, much capacity for natural gas will become operational in the Netherlands. However, starting from 2010, large coal power plants are planned – modernized, but still the most CO_2 intensive option available. With a 46-52% share of total capacity planned, coal is likely to expand the most. In Germany this is even worse: 68% of capacity expansion is planned to be coal-fired power plants. This equals 30 GW_e which corresponds to 1.5 times the presently installed Dutch power generation capacity. Also in the UK, the first coal power plant in 20 years is planned to be built after 2010 (The Parliamentary Office of Science and Technology, 2007). It seems surprising that even after the introduction of emissions trading current power generation capacity expansion plans indicate a preference for coal. Coal has even more advantages than was reflected in the models. Apparently, the economic effect of CO_2 emissions trading is not sufficient to outweigh the incentives to choose for coal. As also comes out of the model, such a shift is not easily reversed: power plants have lifetimes of decades.

Table 4.4 – Plans for new power plants in the Netherlands and Germany (based on data from RWE, 2007; Seebregts, 2007)

Country	Energy source	Capacity MW_e	% of plans per country	Operational in
The Netherlands	Natural gas	4,390	45.6%	2008–2010
	Coal	4,415–5,000	45.9–52.0%	2011–2012
	Biomass	<685	<7.1%	2008–2013
	Offshore wind	228	2.4%	2006–2007
	Total	*9,618*		
Germany	Natural gas	12,830	29.7%	2007–unknown
	Coal	29,245	67.6%	2008–unknown
	Nuclear	60	0.14%	2007–unknown
	Other	1,102	2.55%	2007–unknown
	Total	*43,237*		

4.5 Experiment 2: Comparison of emissions trading and carbon taxation

One could argue that the amount of rights available for this sector – the imposed sector's cap – is strict and emission reduction should be reached within the electricity sector, and, therefore, the dynamics found in the first experiment would not hold. CO_2 emission rights will be limited and the only alternative to achieve reduction by investment is paying the penalty. One can have strong arguments for both settings. Therefore, we now model a strict cap, which is reduced by 1.7% each year, and where rights are not grandfathered but will have to be acquired by auctioning. This reflects the current thoughts of the European Union on the post-2013 ETS. In such a model, the power generation sector is expected to incur much larger costs for the emission-rights. The available amount gets smaller each year.

4.5.1 Introduction

In this experiment, we will compare two policy instruments, addressing the following question: What are the effects of taxes and emissions trading upon CO_2 emissions, electricity prices and the technology portfolio for electricity generation and CO_2 abatement? We address this question by developing and using an agent-based model of a competitive electricity production sector in which non-coordinated decisions are made within a common framework of an electricity market with either no carbon policy, with emissions trading (ETS), or with a carbon tax (CT).

First, we will describe the model. The main differences with the first experiment are the decision making of the electricity producers and the combined clearing of the power and CO_2 markets. Next, we provide information on model validation and the main assumptions behind this experiment. Results are presented and conclusions are drawn.

4.5.2 Model description

The model developed for this experiment is based on the model described above. We have refined the model in many respects and added a number of components. Therefore, the description below focuses on the components changed from the model used in the first experiment.

System representation The power generation system is represented in agents, physical installations and markets. The agents in the model, the power producers, need to negotiate contracts for feedstock, the sales of electricity and, in the case of emissions trading, CO_2 emission rights. In the longer term, the agents need to choose when to invest, how much capacity to build, and what type of power generation technology to select. Agents interact through the markets to negotiate contracts. The agents, markets and physical installations are discussed below.

Agents The key agents in the model are the power producing companies which exhibit tactical and strategic behaviour.

Their *tactical decisions* consist of operating on CO_2, power, and fuel markets. The scenario determines which markets are active and also accommodates for the order of the activities.

Offers of electricity to the power market are based on variable cost per generator (the expected fuel, variable operating and maintenance, and CO_2 cost). Note that CO_2 cost under carbon taxation equals the taxation level, under no intervention equals zero and under emissions trading equals the CO_2 market price.

If the CO_2 market is active, the agents bid for CO_2 emission rights in the annual auction. The auction bids are based on the “willingness to pay” per installation, which is determined as the expected electricity price less the marginal costs of each unit, divided by the CO_2 intensity. The bid volume equals the expected electricity sales volume times the CO_2 intensity of the power plants that are expected to be in merit. Surplus CO_2 rights are banked and penalty is paid in case there is a shortage of CO_2 rights. Surpluses and shortages are calculated from the actual production levels and the volume of CO_2 emission rights owned by the agent. The interdependence of the CO_2 and power markets is discussed below in the paragraph Markets.

Agents can acquire the required amounts of fuel from the fuel market based on the actual production and fuel usage.

Besides these tactical decisions, the *strategic decisions* concern investment in and decommissioning of power plants. Each agent’s strategic decision process is as follows: First, agents decide per power plant whether it should be *dismantled*. The decision to dismantle is taken when the technical lifetime of a power plant has expired (after 20 years for wind farms, 30 years for gas and coal plants and 40 years for nuclear) or if the plant caused continuous operational loss for over 5-9 years, depending on the preferences of the agents. Second, the agents estimate whether there is a need for *new generation capacity* in three years. The estimate of the demand for capacity in three years is based on an extrapolation of the electricity demand trend of the past three years. Capacity expansion decisions take into account investments and decommissioning already announced by competitors. Continuous operational losses will cause unannounced decommissioning;

thus the planning of agents is not perfect and investment cycles can occur. Limited overinvestment is modelled to dampen those investment cycles. If investments are needed the agent needs to select a technology for its new plant. Its decision is based on the life-cycle cost per MWh_e produced. The life cycle CO_2 cost is based on current CO_2 taxation levels or, under emissions trading, the three year average CO_2 auction price. The total life-cycle cost must be recovered by electricity income or else the investment is cancelled. In addition to financial aspects, an agent's conservativeness, aversion to nuclear power, and risk attitude affect its decisions. Despite the large weight of financial considerations, these individual style aspects have an effect, especially when financial differences between options are small. Conservativeness is modelled as 'preferring more of the same'; risk attitude translates to different responses to historic variance of CO_2 and electricity prices.

Markets The electricity demand profile consists of 10 steps per year that reflect a typical load-duration curve, in order to reflect the different emissions levels, costs, and operating hours of the different power plants. Therefore, bidding on the electricity market is modelled as bidding on ten smaller electricity markets, each with a different demand. Since the supply curve is the same on these markets, higher demand will result in the same or a higher price.

Both in the case of no intervention and carbon taxation, there is no CO_2 market. For no intervention, no CO_2 cost is taken into account. For carbon taxation, the bids on the electricity markets are increased by the CO_2 cost times the CO_2 output per MWh_e electricity produced.

A difficulty arises when incorporating the CO_2 market under emissions trading where CO_2 and electricity markets are mutually dependent. The 10 different electricity prices *and* the CO_2 price need to be determined together: the markets are to be cleared simultaneously. Since this is not possible, we need to model arbitrage between these 10 periods and the CO_2 market. We had to develop an iterative process, visualized in Figure 4.11, in which arbitrage between the demand for CO_2 in these markets takes place in such a way that total annual demand for CO_2 satisfies the emissions cap and a single annual CO_2 price develops.

Since the outcome of the CO_2 market is input to the power market and vice versa, the electricity and CO_2 markets are iteratively cleared and this is complete when stable prices have been established for the entire year. In each simulation interval, we start with the prices of the previous year. In each iteration, first the CO_2 auction is cleared, which results in a fictive CO_2 price (p_{CO_2})[2]. This price is then used by the electricity producing agents to calculate power market offers. For each of the ten sections of the load-duration curve this market is now cleared, assuming this CO_2 price. This results in 10 electricity prices ($p_{e,1} \dots p_{e,10}$). The new clearing prices for electricity are fed into the next iteration of the bids for the CO_2 auction as the expected price of electricity and so on. Upon completion of this iteration, emissions trading has effectively been completed. The main difficulty is that it is not guaranteed that the optimum will be reached. Especially since there are hard constraints, (e.g. the penalty level) and all bids are of a relatively large

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[2] When the CO_2 price exceeds the penalty level, agents will rationally choose to pay the penalty rather than purchase more CO_2 emission rights. Consequently, this penalty level functions as a price cap for the CO_2 market.

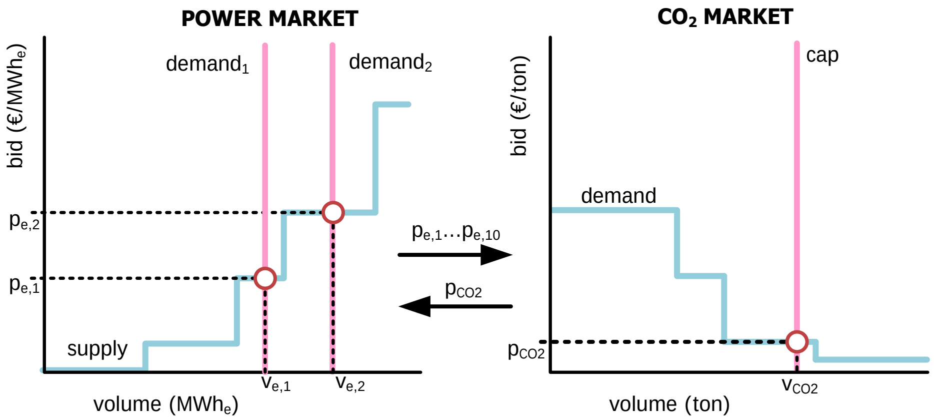

Figure 4.11 – Experiment 2: Iterative clearing of power and CO_2 markets

volume it is possible that the procedure results in flipping sets of price levels on the power and CO_2 markets. In that case, one of those is selected at random.

Power generation technologies In the model, power plants are characterized by their fuel type, costs, technical life span, and fuel usage (conversion efficiency). The model includes an extensive set of 'state-of-the-art' power generation technologies as well as technologies that are expected to be commercially available within 10 years time, most notably CCS. The data in Table B.3, in appendix B, section B.1 on coal and gas plants – with and without CO_2 capture – are taken from Davison (2007), the other data are published in Chappin (2006). Yearly modifiers for the efficiency and the investment costs are applied to reflect learning curves and incremental innovation. Carbon capture and storage options are only available after the first ten years of the simulation.

Exogenous scenarios The electricity producers – the agents – operate in a dynamic world which is represented as exogenous trends: time series of fuel prices, electricity demand, and carbon policy parameters (emission cap or tax levels). We assume that the electricity producers have no market power, neither in fuel markets nor in the electricity or CO_2 markets. In Table 4.5 an overview of the scenarios and carbon policy parameters, values, and used trends is provided.[3]

The fuel prices in the simulation start at current market levels (October 2008) and develop as depicted in Figure 4.12. The figure presents the average fuel prices used. In individual runs, fuel prices vary randomly around these averages.

The rationale for these choices is as follows:

- Natural gas is and remains relatively expensive because it is a clean fuel, the conversion efficiency (MWh produced per GJ fuel) is high (55-60% for new plants), the capital costs of natural gas plants are relatively low, and natural gas can be used

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[3] World average gas price in 1984-2007 (BP, 2008). World average coal price in June 2008 (Global Coal, 2008). World average uranium price in June 2008 (UxConsultingCompany, 2008). Taxation level rises from 20 to 80 €/ton CO_2 with the average equal to the average CO_2 price in emissions trading.

Table 4.5 – Exogenous parameters: scenario and carbon policy settings

Domain	Parameters	Initial value	Trend
Fuel markets	Natural gas price	0.61 €/Nm^3	+2 %/year
	Coal price	103.3 €/ton	+2 %/year
	Uranium price	17 €/kg	+1 %/year
	Bio-fuel price	120 €/ton	+1.5%/year
Power market	Electricity demand	140 TWh/year	+2%/year
Emissions trading	Cap	50 Mton CO_2/year	-3 Mton/5 year
Carbon taxation	Taxation level	20 €/ton	20–80 €/ton

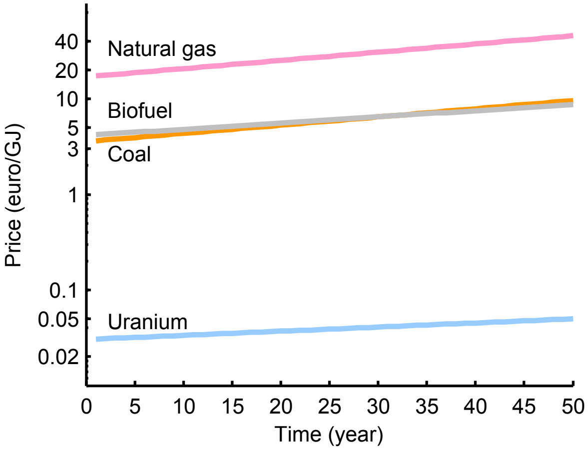

Figure 4.12 – Experiment 2: Average development of fuel prices

for home heating and combined heat and power generation, also in small facilities. With increasing demand, the production of existing fields levelling off, and a limited amount of new production underway, an increasingly tight supply-demand balance is expected for the coming decades, which leads to continuously increasing prices.

- Coal has a much lower price per energy unit than natural gas, because it is a polluting fuel that can be used only in large power plants or gasification units at relatively high investment costs, while the conversion efficiency (MWh produced per GJ fuel) is relatively low (40-45%). World coal resources suffice for over 400 years of present consumption, or even 2500 years of present consumption if all known coal deposits are developed. Therefore, the marginal cost of coal production will only gradually increase and average prices are only expected to rise moderately.

- Biomass for use in power generation is expected to be traded at a somewhat higher price than coal, because while biomass can be fired in similar installations as coal, it is a more desirable product as we assume that it does not lead to net CO_2 emissions.[4] On the other hand, biomass demand is limited by the higher handling costs, the more expensive installations and the fact that it is converted at a lower efficiency (35–40%). We assume that biomass production can keep pace with demand, so price reflects costs rather than scarcity. The possibility of switching from biomass to coal is an effective cap on the biomass trading price.

- Uranium costs per GJ are assumed to remain near their current low levels.

The following assumptions underlie the models:

1. Fuel is always available. There is an unlimited supply of biomass and natural gas.
2. Fuel prices are exogenous and reflect the relative scarcity of fuels. The modelled system is too small to impact world fuel prices.
3. Biomass is assumed to be 100% carbon-neutral. In our model, biomass represents the general characteristics of renewable energy: carbon-free, but more expensive.
4. The main characteristics of Phase 3 of the EU ETS (2013 and beyond) are included: 100% of CO_2 emission rights are auctioned and the cap will decrease over time.
5. The effect of inter-sector emissions trading is assumed to be negligible compared to intra-sector trade.
6. Innovation is limited to learning; available technologies gradually improve in terms of cost and performance, entirely new technologies do not become available in the model.
7. The generation portfolio, size of the market, CO_2 cap, the number of players, and the attitude towards nuclear power reflect the current (2008) Dutch power sector.
8. All costs and prices are in constant 2008 Euros. Electricity prices are wholesale prices; taxes and network fees are not included.

Design of transition assemblage The main objective of the modelling exercise is to compare and evaluate the different policies for CO_2 reduction: carbon taxation (CT), emissions trading (ETS), and no intervention. The objective is to compare the merits of those three strategies in the best possible way. However, how can we make the intervention of carbon taxation and emissions trading comparable? They are fundamentally different, in terms that the level of intervention is dependent on different aspects (the tax level for carbon taxation and the cap under emissions trading). With the objective of fair comparison in mind, we argue that we should impose *comparable system pressure* with both carbon policies and compare the effects of those pressures. In order to do that, we have to define the system pressure that we can calculate with both instruments. The main

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[4] Currently, the net CO_2 emissions associated with biomass production are heavily debated. Some biomass sources appear to have a negative CO_2 impact – the emissions associated with the production chain exceed the emissions avoided. In its advice to the Dutch Government the high-level Cramer committee concluded that 30 to 70% of the direct CO_2 emission from burning biofuel is compensated for in the biological cycle (Cramer Commission 2006).

indicator for system pressure by either carbon taxation or emissions trading is the *CO_2 price*. Therefore, we want to have a similar CO_2 price for the two policies.

Under emissions trading, however, we cannot set the price: this is an emergent property, an outcome of the model. The main policy variable of the ETS is the emissions cap. In the model the cap is set to reflect the likely design of Phase 3 of the EU ETS in which the CO_2 cap is reduced every five years by 3 Mton for a market with the size of the Netherlands. With an initial cap of 50 Mton, a 50% reduction is achieved in little more than 40 years. After we completed the simulations with emissions trading, we analysed the results and calculated the average CO_2 price.

We used the CO_2 price from the emissions trading simulations to determine the tax level. To enable comparison with the ETS, the average tax level is calibrated to the average CO_2 price in the CO_2 market. It is, however, not useful to have the same price during the whole simulation. A tax would not be as volatile. Therefore, we decided to let the tax level increase in such a way that the average tax level equals the average CO_2 market price. Calculations showed that the tax level trajectory, from 20 €/ton at the start up to 80 €/ton towards the end, will suffice for this condition.

System evolution The time step of the model is one year and the simulations span a horizon of 50 years.

In each time step agents are allowed to perform their tactical actions, given the carbon policy active. In addition, agents will get the opportunity to invest. The order in which the agents make their investment decisions varies randomly and the decisions are modelled to match the expected demand growth.

The characteristics of the modelled system are emergent: the generation portfolio and merit order, fuel choice, abatement options, as well as electricity and CO_2 prices and emissions emerge as a result of the decisions of the agents. The structure in which the simulations are run is similar to the first experiment.

Impact assessment Using statistical analysis, the impact of the different transition designs is assessed. We highlight the model results in the next subsection of the chapter.

4.5.3 Model validation and main assumptions

However complex a model is, it remains to be a stark simplification of reality. The results are influenced by the following types of assumptions:

- The way in which the carbon policies are modelled;

- The assumptions regarding the model's inputs: the (relative) prices of natural gas, coal, biomass and uranium, the set of available generation technologies, and the demand for electricity;

- The structure of the energy market that was modelled;

- Assumptions regarding investment behaviour and the way in which prices are formed in the market.

As it involves more design variables a cap and trade scheme is more complicated than a carbon tax. Choices need to be made regarding the method of allocating the CO_2 emission rights (auctions are theoretically superior but not always politically favoured), credit issuing and continuous registration, banking and borrowing CO_2 emission rights, and whether to issue negative rights to CO_2 sinks. In both systems, emissions must be monitored and verified, the scope of the system (which sectors and countries to include) must be selected, and the obligation to obtain CO_2 emission rights or pay tax (at the consumer, the power producer or further upstream) must be determined.

A difficult choice is how to model fuel prices, because structural changes (such as China's economic emergence) may create lasting price effects. We assumed prices to be exogenously determined. This assumption holds for a small system, e.g. a single country or state, but if carbon policies are widely implemented, this may decrease the demand for carbon-intensive energy sources worldwide, making them cheaper and hence economically more attractive, reducing the effectiveness of the reviewed carbon policies.

We did not assume any technological revolutions. The existing technologies, including carbon capture and sequestration (CCS), would continue to be available and gradually improve in terms of cost and performance. We assumed that a technology's maturity determines its pace of improvement, with learning being exogenous to the market. In reality, adoption and improvements reinforce each other, so technological learning is endogenous. A second technical issue is that most existing coal plants are not suitable for running peak load (in case high carbon prices cause them to shift their position in the merit order). This could lead to block bidding and reduced flexibility of the power system. Future technologies, such as coal gasification, will probably be more flexible.

The abatement options differ per country. In most countries, only a limited amount of CO_2-free generation options such as hydropower or geothermal energy are available. In these countries, the options that were reviewed in this chapter are the main ones. But there are exceptions, like New-Zealand, Canada, Brazil and Norway, since they have an abundance of hydro.

Electricity demand is modelled exogenously, without price elasticity. One may assume that there is, in reality, some price elasticity, which would dampen price swings. Perhaps price elasticity will be improved through applications that make use of the digital electricity meters that are beginning to be installed across the world. Finally, it may not be a correct assumption that electricity demand will grow perennially; perhaps there is a saturation point, or conservation efforts may outweigh natural demand growth.

The acceptance of a carbon policy by society may be affected by the way in which the revenues are spent. Stoft (2006) favours returning revenues (both from a tax or an auction of emission rights) to the people on a per capita basis. This avoids a net income transfer from consumers to government while maintaining the incentive to reduce emissions. The revenues may also be returned to the affected industry sector to maintain an international competitive position. Other options are to use the revenues to finance CCS infrastructure, support R&D or to let them flow to the treasury. This question of political acceptability and allocation of the revenues, however, is outside the scope of this chapter.

The electricity market The model starts with the Dutch generation portfolio, which is not optimal in either of the three policy scenarios. The long time, needed to reach a new generation mix, creates a certain path dependence, but the generation mix in the second half of the modelled period hardly depends on the initial generation portfolio. The market is modelled with a limited number of generating companies, which is realistic, but they act as perfect competitors, which is not realistic. Oligopolistic behaviour is likely to be observed in electricity markets, given the regional nature of the product, and may lead to different investment behaviour. Oligopolistic rents may offset investment risks, allowing companies to invest more pro-actively in a CO_2 market than the model suggests, but it remains uncertain whether they will choose to do so.

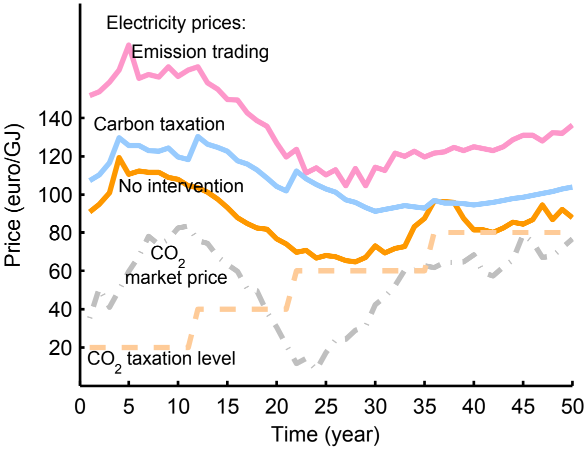
CO_2 markets have no physical limitation and may, therefore, span a continent or even the world and cover a multitude of industrial sectors. Market power is less likely to develop when markets grow in size and diversity and the impact of individual investment decisions becomes much less significant than in our relatively small, closed system. This would cause CO_2 prices to develop in a smoother way than in the model. On the downside, a global, diverse trading system may leverage global effects to individual operators and include unanticipated feedback loops that may result in larger volatility and system crisis.

Decision making will also be more sophisticated in reality, with investors making better projections, which will also reduce price volatility. However, high CO_2 price volatility has been observed in the EU ETS, which contributes to the risk of an investment cycle. In reality, the cycles might be smaller than in the model, but it may still be an inherent problem with emissions trading.

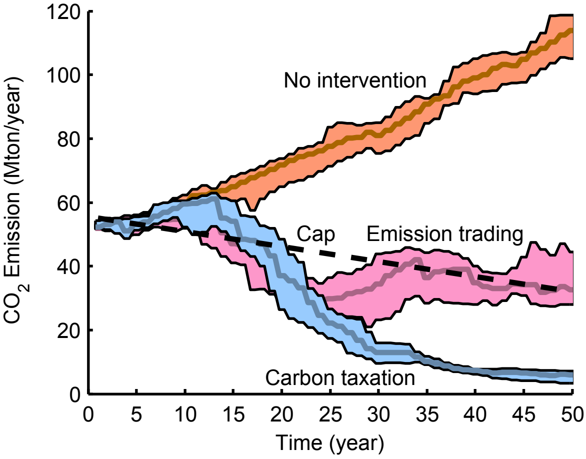
The technological options At each point in (simulated) time, an agent may prefer to invest in a different technology. Especially when the costs of options do not differ much, secondary criteria such as greenness (measured in CO_2 intensity) and conservativeness (measured as current adoption level) can be decisive. The adoption of wind – in continuous but limited amounts – is a typical example of this feature: there is one agent that is relatively conservative and green and as wind is often close to the cheapest option, it is sometimes adopted. When the scenario run leads to early adoption, the agent's conservativeness will cause it to adopt wind again. In other runs, wind gradually disappears because of the same mechanism. Averaging the wind adoption levels over the scenario runs then results in a gradual and limited amount of wind farms in the portfolio. The example represents the reality that decisions are not fully rational, but are also driven by a collective mindset that determines preferences.

4.5.4 Simulation results

While the design of the model and the technology representation are generic, the CO_2 market is modelled after the European ETS and Dutch portfolio and market data are used in order to provide a suitable reflection of reality. Carbon policy is only one of several factors that affect emissions. The evolution of the system is also determined by: (1) the scenarios (exogenous factors such as fuel prices and electricity demand), (2) the system's components and properties, (3) and the starting conditions. To provide a good impression of the possible development of the system over 50 years, we present the aggregated results of 60 simulation runs in which the scenario parameters were varied evenly across the



(a) Electricity and CO$_2$ Prices



(b) CO$_2$ emission levels

Figure 4.13 – Electricity and CO$_2$ prices and CO$_2$ emission levels for three carbon policies

entire scenario space and the initial set of power plants is randomly distributed amongst the agents.

Average total CO$_2$ emissions Figure 4.13 shows that carbon policies deliver in the long run. Emissions are lowest under the carbon tax. In the long run, emissions trading generally leads to emissions close to the cap. This may not come as a surprise, but in some simulation runs the cap is not met at all. In these cases abatement investments are made too late, given their long lead time and the fact that the cap continues to decrease. High CO$_2$ prices result. Despite the spread in outcomes (indicated by the band in Figure 4.13, the difference between the trajectories caused by the three carbon policies is statistically significant.

Without intervention, emissions rise continuously, as expected. Neither carbon policy guarantees a continuous and rapid decrease of emissions. To the contrary, due to the technological path dependence in the system emissions increase in the first 10-15 years in all scenarios: even at high CO_2 prices, it is not attractive to replace relatively new power plants, even if they emit much CO_2. The initial increase is highest under carbon taxation as scarcity of CO_2 emission rights drives up the CO_2 price.

Electricity prices The pressure that carbon policies put on the power generation system is reflected in the electricity prices (see Figure 4.13), since power companies pass through their CO_2 costs to consumers in a closed, competitive market. The prices shown are outcomes of the simulated negotiation between the six operating companies and simulated demand. Three important observations can be made:

- The three carbon policies cause significant, structural differences in the electricity prices.
- Under emissions trading, CO_2 prices are highly volatile for the first three to four decades.
- Under emissions trading, the CO_2 price is strongly correlated with the electricity price, while the correlation between a carbon tax and electricity prices is much weaker.

Without intervention, the electricity prices drop during the first decades as the starting portfolio is not optimal. Coal becomes increasingly dominant because it is more attractive. Innovation leads to further cost reductions. Towards the end of the modelled period, electricity prices begin to rise again due to the assumption that fuel prices will gradually increase. In the case of an emissions trading scheme, both the price of CO_2 emission rights and the CO_2 emissions remain high for the first 15 years, which leads to extremely high electricity prices. The reason is the path dependence of the generation portfolio (the economic rationale for keeping existing power plants, plus the lead time for new ones), combined with risk aversion towards capital-intensive investment in CO_2 abatement technology due to the volatility of CO_2 prices. The high prices lead to an abatement overshoot in most runs, which causes a CO_2 price collapse in the third decade. This discourages further abatement measures and emissions creep back to the cap and stabilize.

Under emissions trading the CO_2 price is volatile (see Figure 4.13). It contributes to an already high investment risk. The consequences for abatement efforts are a delay and bias towards less capital-intensive abatement technology efforts, many of which are more costly in the long run. A carbon tax does not have this disadvantage and minimizes the price risk of abatement measures, provided there is no regulatory uncertainty about the tax level. Regulatory uncertainty – the risk of later governments backtracking on earlier carbon policy decisions – also is a potential risk with emissions trading, however, as the cap may be loosened. Thus regulatory uncertainty can increase investment risk under both policies.

The impact of carbon taxation on the electricity prices is relatively small. The tax starts at a fairly low level of 20 €/ton. When the tax level rises, investment in abatement reduces the CO_2 intensity of electricity generation, which reduces the impact of the tax upon electricity prices. Clearly, one cannot simply add the cost of CO_2 under the two carbon policies to the electricity prices under no intervention. The price is determined by the CO_2 price, and the CO_2-intensity of the portfolio, which evolves differently under each policy option.

CO_2 intensity Given the continuous rise in electricity demand, CO_2 emissions can only be reduced significantly by changing the generation portfolio, i.e. by shutting down existing facilities and by investing in new ones. The absolute emission levels shown in Figure 4.13 are achieved via a dramatic reduction of the CO_2 intensity of the generation portfolio. Without intervention, CO_2 emissions rise, but the CO_2 intensity is relatively stable – natural gas is replaced by coal while its fuel efficiency increases through innovation.

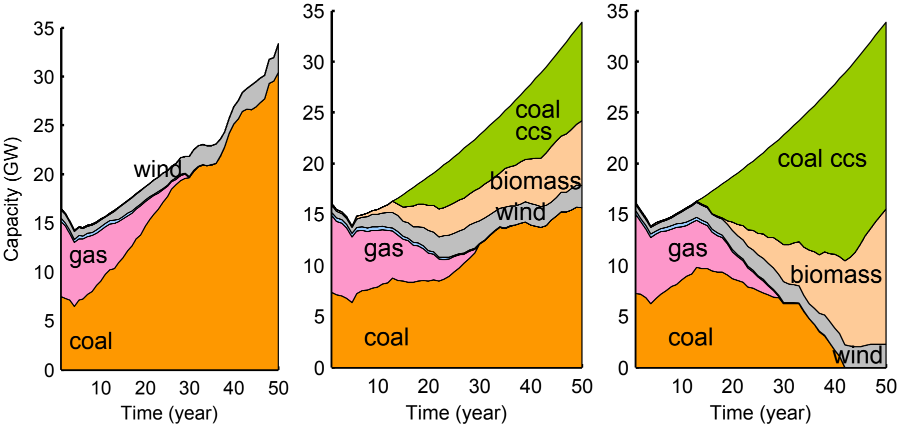
The impact of CO_2 prices on the variable cost of installations may change the merit order of generation. At higher CO_2 prices, CO_2-intensive installations may move from base load to peak load. Under all scenarios, including no intervention, a merit order shift takes place from CO_2-intensive towards CO_2-extensive base load facilities.

Generation portfolio development The different policies profoundly affect the generation portfolio. Without a carbon policy, the economics favour coal, which replaces natural gas, nuclear and biomass. Under emissions trading, the generation portfolio becomes more diverse. Coal without CCS remains important, but its share stabilizes. Coal with CCS emerges in the second decade and replaces natural gas, because of the declining cost of CCS and the increasing price of natural gas. Biomass is the second largest source of emissions reductions. An increasing carbon tax prompts an almost complete switch to carbon-free electricity generation in the long run. Coal with CCS first replaces natural gas capacity and later coal without CCS. Biofuel plays an even larger role than under emissions trading. Traditional coal is phased out. The volumes of wind energy are stable and small under all three policy instruments. In Figure 4.14 the evolution of the average portfolio of technologies is displayed.

4.5.5 Analysis

We formulated the need for a model that can analyse the merits of CO_2 taxation and emissions trading in terms of realizing a transition in emissions from power generation. Earlier we developed a framework for models of transitions in the energy domain. In this case, we analysed the effects of taxation and CO_2 emissions trading schemes in an agent-based model of the power generation sector. The model contains the main characteristics of the power sector, such as policy uncertainty, risk aversion by investors, and long construction lead times. We explored the long-term effects of a carbon tax and emissions trading upon CO_2 emissions, electricity prices, and preferred technologies for electric power generation and CO_2 abatement.

Taxation and CO_2 emissions trading schemes yield similar results in theory. In this chapter, we analysed, for a hypothetical electricity sector, the effects of both instruments in less than optimal but more realistic circumstances, such as policy uncertainty, risk aversion by investors, and long construction lead times. Using a quantitative agent-based model, we explored the long-term effects of a carbon tax and emissions trading upon CO_2



(a) No intervention (b) Emissions trading (c) Carbon taxation

Figure 4.14 – Experiment 2: Average generation portfolio evolution for the three scenarios

emissions, electricity prices and preferred technologies for electric power generation and CO_2 abatement.

Both carbon policies are effective in reducing CO_2 emission in the long run, provided that the tax or cap level is set at an ambitious level. The first 10-15 years, CO_2 emissions from power generation continue to increase under all three policies (no intervention, CT or ETS). Operational adjustments – which both CT and ETS can be expected to invoke in the short term – do not have sufficient potential. A substantial change in the generation portfolio is needed to obtain the policy goals for emission reduction. Under emissions trading, natural gas is replaced by coal with carbon capture and sequestration (CCS) and biofuel, while for conventional coal (without CCS) some share remains. An increasing tax leads to a complete phasing out of natural gas and conventional coal, leading to a portfolio with almost only coal with CCS and biofuel. In the absence of intervention, absolute emission levels grow dramatically (50%), even though the CO_2 intensity of electricity generation is stable due to technological improvements.

A key result is that given a certain CO_2 cost to producers – whether it be due to a tax or the price of CO_2 emission rights – carbon taxation leads to lower electricity prices than emissions trading. The main reason for this is the difference in investment risk, as – in our model – a tax is predictable, whereas CO_2 prices are volatile. This uncertainty leads to an investment cycle under emissions trading which is absent under carbon taxation. This cyclical behaviour is a significant disadvantage of emissions trading. Because of this cycle, high CO_2 prices frequently occur when the CO_2 intensity of electricity generation is high. In contrast, under taxation, high tax levels occur only in the second half of the simulated period. At that time, they do not cause large income transfers, because the CO_2-intensity is already low, so the impact upon the electricity price is limited. Predictability is a key advantage of taxation, which allows investors to minimize cost over a longer time horizon. Given the capital-intensiveness of many of the abatement options, this leads to substantially lower overall costs as well as lower emissions in the long term. This confirms the ideas of Grubb and Newberry (2007). Both trading and taxation are instruments that create pain today, while yielding significant results in only 15 to 20 years. When these policies are kept in place for decades, their long-term impact is significant. From the modelling exercise, however, we also conclude that, in order for both instruments to have effect, affordable and competitive low-CO_2 electricity generation options must become available on a large scale. In our simulations, these were biomass firing, wind and CCS; in practice, nuclear power, wind or other technologies may also be part of the solution. While from these results it cannot be concluded that the portfolio shifts in the model are the most likely to occur, it is safe to conclude that carbon policies do deliver in the long run.

4.6 Experiment 3: Towards the design of EU ETS+

4.6.1 Introduction

In the last experiment, the main finding was that in the current emissions trading scheme the *volatility* in the CO_2 price is cause for concern regarding a strong and inherent investment risk weakening the signal for abatement. This mechanism may have severe consequences for the performance of the EU ETS in terms of actual emission reduction, both on short and long term. We showed that this problem does not occur in a carbon taxation scheme.

Critics to this conclusion claim that it is politically infeasible to strive for a carbon taxation scheme. Therefore, we have designed this third experiment, in which we opt for *improvements* of the current system, rather than *redesigning* current emissions policy.

4.6.2 Model description

The structure of the model is similar to that of the last experiment. The main differences will be discussed in this section. At the core is the description of the electricity producer agents: this has been altered specifically for this experiment. Furthermore, the CO_2 market has been set up differently and new transition instruments have been introduced and implemented. In addition, scenarios and data on power generation technologies are updated.

The changes to the model will now be described in terms of the modelling framework, i.e. the system representation (agents, markets, and power generation technologies), exogenous scenarios, design of transition assemblage, and system evolution.

System representation Essentially, the system contains the socio-technical power infrastructure: agents represent the actors in the system of which the power producers are the most important. Power facilities are represented as technological components, operated by the agents that own them. Agents sell their electricity on a power exchange, acquire their CO_2 emission rights on a carbon market and buy fuels on a fuel market. The agents make their decisions under a variety of conditions, as is explained below.

Agents As in all experiments of the power generation model, *power producer agents* are at the core of the model. They invest in, own and operate power plants. As we

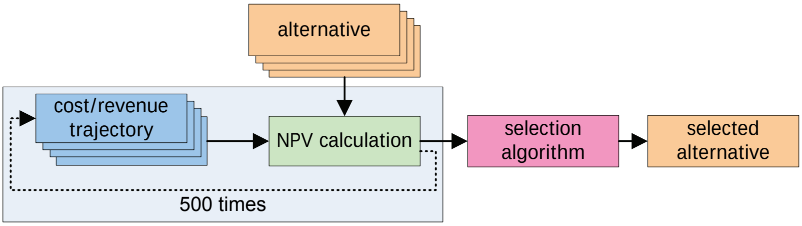


Figure 4.15 – Investment algorithm using LCOE and NPV

discovered that *risk* is crucial in the investment decisions of power producers, we looked more focused for a good way to represent the way these decisions are made in an agent in the real world.

Based on this analysis, discussed in detail, we came up with a new method for evaluating investments, which uses the notion of levelized cost of electricity LCOE and net present value (NPV). Levelized cost of electricity is widely used and adopted by the IEA, US Department of Energy and the UK government (Gross et al., 2007). Typically, an LCOE is measured in €/MWh_e, taking into account all costs throughout the life cycle of each possible power plant.

The structure of the developed algorithm can be found in Figure 4.15. We have made enhancements to the general LCOE concept, also taking the revenues throughout the lifetime of a plant to allow for choosing a technology type. Additionally, the expected capacity factor (or rate of usage) is included in the analysis. These are updated, based on actual market results of existing installations. In this way, agents learn how their past decisions worked out in the marketplace.

A variety of price projections are input to the analysis. They relate to the costs and the revenues. For uncertain price developments – expected fuel and carbon prices – we generate projections. The agent generates fuel and carbon price projections in order to simulate the uncertainty surrounding its decision in its own calculations. Pindyck (1999) showed that geometric Brownian motions successfully replicate oil and coal prices. Therefore, we have implemented an algorithm to simulate such Brownian motion projections. Revenues and operating and maintenance costs are expected constant throughout their lifetime. Investment costs are assumed due at the moment of investment.

As Brownian motions for fuel and CO_2 prices are used, every time it is calculated the NPV is different. Therefore, per technology type a whole range of NPVs is needed. For each investment decision, agents perform 500 NPVs per technology type to prevent bifurcations. The prices are generated using the parameters in Table 4.6.

In the model, the different agents will choose one of the following algorithms to select a technology for their investments:

- Maximize expected profit – agents select the technology with the highest average of the NPVs.

- Maximize most likely value – agents select the technology with the highest mode of the NPVs.

- Maximize expected profit, being risk averse – agents select the technology with the highest ratio average over standard deviation of the NPVs.

- Maximize return on investment – agents select the technology with the largest average expected revenues over investment.

After selecting the preferred technology the investments can still be cancelled if the technology is not expected to be profitable. Please note that more information on this investment algorithm can be found in appendix B, section B.3.

Other agents include a *government agent*, which performs all the duties regarding the policy in place. For instance in a carbon taxation scheme, the agent collects taxes, and, if a feed-in tariff is implemented, it pays the subsidy to the power producers. Furthermore, a *consumer agent* brings demand for electricity in the market.

Power generation technologies We have introduced new data on power plants from the IEA (2010), which are listed in Table B.4, in appendix B, section B.1. Power plants are modelled as converting certain inputs into outputs: at a fixed efficiency, electricity is generated. A number of economic, physical, and design properties are used by the agent in investment decisions, bids on the market, acquiring fuels, etcetera. The properties taken into account are efficiency, investment cost, operating and maintenance (O&M) cost, maximum load, lifetime, and construction time. New power plants improve over time in terms of efficiency (resulting in lower fuel consumption and CO_2 output per MWh_e produced) and become also investment cost decline.

Markets The *power market* is modelled as an exchange where all the power is sold. Demand is divided in 10 different parts per year, similar to experiment 2.

A crucial difference to the last experiment is the way the *carbon market* is modelled. Although power producer agents are not programmed to realize it, the carbon price is actually *generated* by a Brownian motion. In contrast to the past experiments where the CO_2 price emerged from the market, we want to specifically address the effects of the *volatility* in the CO_2 price. Therefore, we specify the volatility and trend and generate it. More details are discussed in the description of the scenarios. The market provides information regarding price level and volatility the agents use in their decisions.

As the price is not directly reflecting actual demand levels, emissions could rise above the cap set for the sector. When emissions rise above the cap, this can be interpreted as CO_2 emission rights flowing into the power market (for instance in the form of JI/CDM allowances). As this would be limited in reality, the results are no predictions. We conjecture that the model is sufficient to draw conclusions the way additional measures would improve the EU ETS.

Exogenous scenarios Both CO_2, fuel, and electricity prices are exogenously generated. Therefore, the scenario is unique in each simulation run. Initial values and trends are transcribed in Table 4.6.

Design of transition assemblage In all simulations, the EU ETS is implemented with a generated price, using a prescribed annual trend and volatility. Three secondary policies

Table 4.6 – Scenario of exogenous parameters (based on Escalante, 2010; Pindyck, 1999)

Parameter	Initial value	Annual growth	Volatility
Fixed values			
Annual inflation	2%	—	—
Cost of capital	7%	—	—
Trends			
Coal price	50 €/ton	1%	7%
Natural gas price	0.25 €/m^3	3%	11%
Biomass price	60 €/ton	2%	7%
Uranium price	1865 €/kg	2%	5%
CO_2 price	12,92 €/ton	2%	11%
Electricity demand	93 TWh$_e$/year	2%	0%

which intend to increase the performance of the EU ETS are modelled. Therefore, the transition assemblages are as follows:

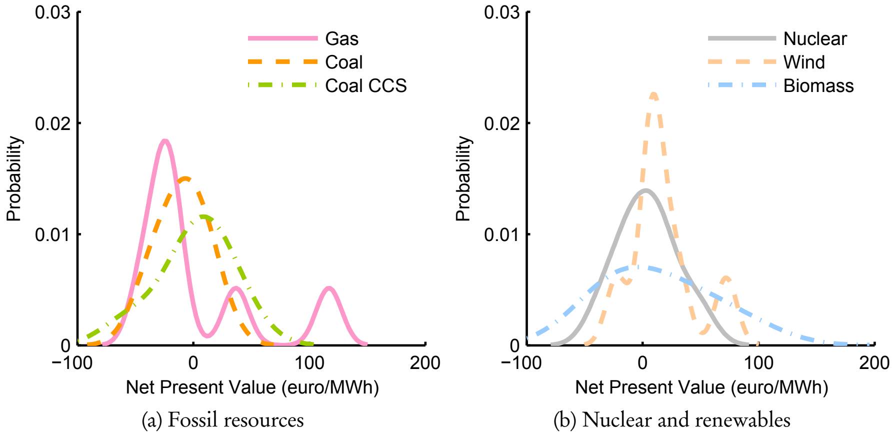
1. Emissions trading only. The market price needs to be paid for emitting CO_2.
2. A price floor on the CO_2 market of 15 €/ton CO_2.
3. In addition to emissions trading, a feed-in tariff of 15 €/MWh$_e$ is paid to electricity producers using wind, CCS technologies and biomass, for the first 20 years of the lifetime of the plant.
4. In addition to emissions trading, emitting carbon is taxed by 10 €/ton.

System evolution Evolution of the system is similar to experiment 2. We perform simulations of the coming 50 years, with a time step of one year. The electricity producers make their investments and sell electricity on the market.

4.6.3 Simulation results

The *investment decision* is at the heart of the agents: it has been explored separately from the rest of the model – outside regular simulations. This is a 'cheap' way of performing experiments: no full simulation runs have to be executed and analysed. Therefore, a vast parameter space can be covered and analysed. During the simulations, many individual decisions are made, from different perspectives and with different agent preferences. Therefore, it is hard to judge the validity of the individually made decisions. This is a way to achieve such judgement before performing the actual simulations. It is also a tool for exploring decisions under specific conditions.

Individual investment decisions make use of a) fuel, electricity, and CO_2 price predictions – each of them different every time a projection is made and b) capital cost, capacity factor, CO_2 intensity, and fuel intensity – all typically fixed within a certain time step. When an agent performs an investment decision, a variety of *iterations* results in a variety of *NPVs*. Iterating many times leads to a probability distribution of the NPV of each



(a) Fossil resources

(b) Nuclear and renewables

Figure 4.16 – Experiment 3: NPV distribution for technologies using 50,000 iterations

possible technological option. An example temporary result is displayed in Figure 4.16, using 50,000 iterations[5].

In the example, the most likely values of the NPV for wind, nuclear, and coal are positive, the others are not. It can be noted that biomass and gas have relatively wide distributions. In spite of these remarks, we found that these distributions strongly depend on conditions (Escalante, 2010). Therefore, the drawn distributions should not be interpreted as a result. In spite of that modesty, this method allows for producing NPV distributions under any condition required, which can be quite insightful. This can be done quite easily using Matlab. For this purpose, we have developed a Matlab script that executes the analysis and creates the graph. This script uses the latest version of the model in a Java jar file. In the model itself, in Java, we have written components that allow for the execution of individual decisions and can supply the intermediate result. The decisions are performed by way of the same code used by the agents during regular simulations. Therefore, it is a validation of the decisions of the agents as it is an exploration of NPV calculations of individual technologies.

These distributions are input for the actual investment decision. One of the four algorithms described above is used to judge the distributions and decide which of them is preferred. We have performed over 30,000 decisions like these under a variety of conditions and denoted how often each technology was chosen in Figure 4.17. The following conditions are varied:

- The fuel prices are individually varied. The coal and biomass price is varied between 2, 6 and 10 €/GJ. Natural gas price between 5, 10 and 15 €/GJ. The uranium price is varied between 1, 2.5 and 4 €/GJ.
- The CO_2 price is varied between 0, 30 60 €/ton. The volatility in the CO_2 price is set to 11.2%.

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[5] To show patterns more clearly we have used a vast number of iterations for this graph. In the algorithm, many random numbers need to be drawn, and, therefore, it is rather slow (~ 15 seconds). During regular simulations, we use 500 iterations.

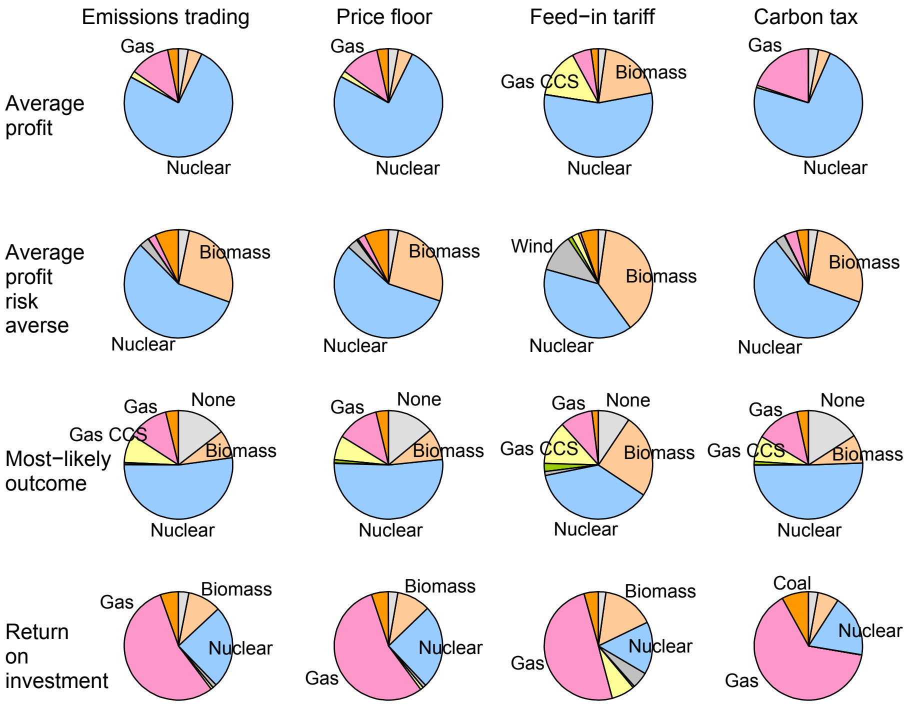


Figure 4.17 – Investment decisions using various decision algorithms, carbon policies, and conditions

- The electricity price is varied between 10 and 100 €/ton, in steps of €25.
- The interest rate used is varied between 5%, 7% and 9%.
- Three secondary policies are modelled. A price floor on the CO_2 market of 15 €/ton, a feed-in tariff of 15 €/MWh_e and a carbon tax of 15 €/ton CO_2.

All decisions use 500 NPV iterations. The results are grouped per secondary policy (columns) and per decision algorithm (rows). Of the modelled conditions, many favour nuclear technology. Especially when being risk averse, the limited expenditures on nuclear fuel are important. When the investment cost is certain, there is little risk because the amount of fuel used is low. The feed-in tariff strongly promotes biomass. With these numbers, the feed-in tariff is likely to overcome the extra expenditures on biomass. Gas is more prominent when the return on investment algorithm is used. This makes sense, as it is more dependent on fuel prices and less on capital cost. Natural gas technology with CCS is sometimes the winner with the feed-in tariff. Using the most-likely outcome algorithm, on some occasions not any of the technologies have a positive NPV. A more detailed analysis showed this is the case under higher interest rates.

These results, however, are no prediction for the future portfolio. These were done using a variety of conditions – a fundamentally different setting from a simulation *over time*. The simulation over time shows intractability and lock-in, because current and past

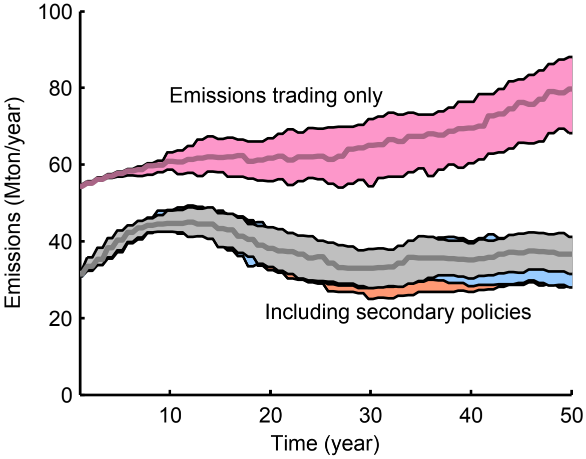


Figure 4.18 – Experiment 3: Developments in CO_2 emissions under the policy scenarios

performance impact decisions made. Furthermore, multiple agents depend on each other. Results from such simulations are displayed in Figure 4.18 and Figure 4.19.

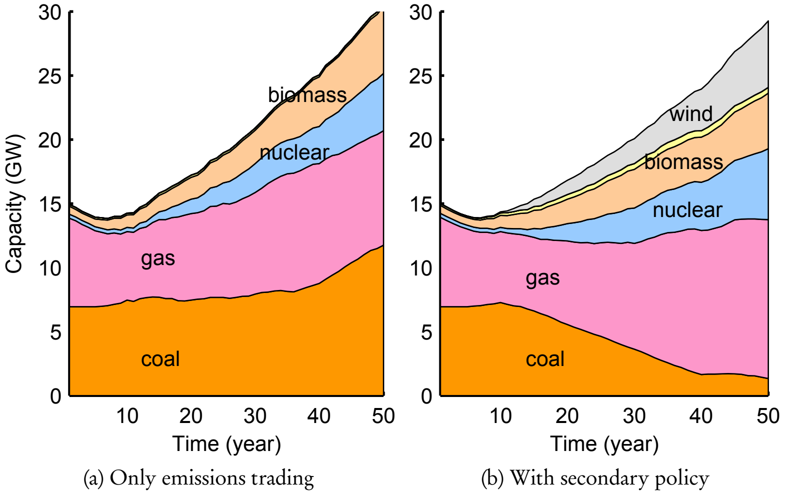
All secondary policies improve the effectiveness of the EU ETS. Emissions are significantly lower under each of the secondary policies. This is caused by a transition from coal to gas and wind. Also the role of nuclear increases. The secondary policies cause stabilization of current emission levels. The differences between the secondary policies are quite small. Looking in detail allows for small differences in performance, but on the whole they are overshadowed by other factors. Adopting any of the secondary policies is expected to help in reducing emissions.

4.6.4 Analysis

This experiment has led to two new products. First, a revised algorithm for investment adopting ideas from NPV, levelized cost of electricity, and Brownian motions, *and* heuristics for judging these results. Second, we showed that we can develop models in which emissions trading and secondary policies are combined.

New from this experiment is the result from a separate investment analysis that takes place outside the regular simulation. Through analysing a vast number of investment decisions of specified agents and not unlikely conditions, we gain insight into the room for transition. As private actors make these decisions in the real world as well, conditions need to be shaped so that our preferred change confers with their optimal choice. By simulating an assemblage of transition instruments we gain insight in the way the conditions need to be shaped so that we may meet our emission reduction targets. Combining emissions trading with secondary policies allows for a holistic analysis of transition management in this case.

There are likely conditions under which many of the options present themselves as the ‘optimal choice’ for an electricity producer. Nuclear is the most robust option under the conditions we simulated. Natural gas is optimal when optimizing for return on investment. Biomass and wind are relatively profitable options when emissions trading is



(a) Only emissions trading

(b) With secondary policy

Figure 4.19 – Experiment 3: Portfolio development under the different policies

combined with a feed-in tariff. Under some conditions, CCS technology is profitable in combination with natural gas. In contrast, the potential of coal technology is limited, also when including CCS. It is not only important that the result from each of the algorithms is explainable, but also that the algorithm can deal with the uncertainties electricity producers face regarding fuel prices, electricity prices, and carbon policies. Therefore, these decision rules may be input for more experiments under specific conditions of interest for an electricity company or a policy maker.

From the results of the simulations over time, we can conclude that secondary policies will assist in emission reduction by reducing the effect of the fundamental flaws of emissions trading schemes. The trends in those results are, however, strongly affected by modelling choices. In contrast to the previous experiment, the emissions trading scheme was modelled as an *open* system, where unlimited CO_2 emission rights will flow in if required by the companies. The emission reduction targets are not met in this experiment, nor when secondary policies are enabled. However, we have seen that, because of the nature of an emissions trading scheme, secondary policies help to reduce the problem of *investment uncertainty*. As this was the aim for this experiment it is useful. Either a carbon tax, a feed-in tariff or a price floor on the CO_2 market can be used to reduce this uncertainty.

4.7 Conclusions

Significant emission reduction in power generation needs to come from *investment* by private actors in CO_2-extensive technologies, such as wind, biomass, nuclear, and coal or natural gas with CO_2 capture and sequestration (CCS). So far, emissions have continuously risen as did electricity demand. The electricity sector has been unbundled: power generation and retail is now a competitive activity. Therefore, the *market* drives investment decisions. Consequently, decarbonizing the electricity infrastructure requires public policy to be in place, promoting investment in 'clean' technologies or punishing 'dirty' alternatives. The electricity industry is capital-intensive: it is about a lot of money and these plants have a long technical lifespan. Therefore, the transition to a low-carbon electricity infrastructure needs to be designed properly.

Public policy options for emission reduction have led to the implementation of the EU ETS. Will the transition to a CO_2-extensive power generation sector be successful? We have performed three experiments to gain insight in different aspects of the transition in CO_2 emissions by power generation. These experiments were designed to answer new questions that popped up and to refine previous answers. Together, they outline the potential for transition and transition management in the case of decarbonizing the power infrastructure.

Based on the experiments we conclude that the transition to a low carbon electricity can indeed be managed, but it requires significant change of the current policy. The two extreme settings we used for simulating an emissions trading scheme are a fully open setting in which unlimited numbers of CO_2 emission rights are available (experiments 1 and 3) and a fully closed setting in which CO_2 emission rights are limited to the modelled sector (experiment 2). An open setting allows for specifying more of the conditions during the simulation, i.e. explicating the annual trend and volatility of the CO_2 price. However, in an open setting, part of the dynamics inherent to the emissions trading scheme are lost. The cap is not pressing on the system because the trend and volatility in the CO_2 price are a given. In spite of these disadvantages, it gave us the insight that if many escape routes in the emissions trading scheme are institutionalized in the real world, its performance will be poor. More advanced and realistic is a closed setting, as the number of CO_2 emission rights that can flow in from the outside is limited in reality. The closed system is especially valid if it is arguable that patterns in the modelled country also occur in the other countries. In that case, in time of scarcity of rights, no other countries exist with a surplus that can be imported. In a closed system, the performance of the ETS is much better. In the long run, emission reductions will follow the set cap on CO_2 emission rights more or less. However, such a setting leads us to a fundamental flaw of the emissions trading scheme regarding investment risk.

The fact that the CO_2 price on the market is *volatile* introduces a fundamental *investment risk*. As the CO_2 price is highly unpredictable, investors become risk averse. As a consequence, investment in CO_2 extensive installations is lower than optimal. Therefore, the transition under an emissions trading scheme is partially held back by this volatility. We found that a carbon taxation scheme does not have this drawback and can be designed to achieve a smoother transition trajectory. One can argue that a taxation scheme using a relatively low tax level at the start and rising over time can be implemented. Overall, a taxation scheme with an average level equal to the CO_2 market price leads to a far smoother transition. Emission reductions are faster and further and income transfer from consumers to producers is also lower.

Although not impossible, replacing the EU ETS by a carbon taxation is highly unlikely from a political point of view. Therefore, we experimented with assemblages including the current EU ETS. A first analysis showed that augmenting an emissions trading scheme with either a taxation scheme, a feed-in tariff or imposing a floor on the carbon price will improve the transition to low carbon electricity supply.

5 LNG Markets in Transition

> Imagination equals nostalgia for the past, the absent; it is the liquid solution in which art develops the snapshot of reality.
> *Cyril Connolly*

5.1 Introduction

Supply chains for Liquefied Natural Gas (LNG) represent an option to monetize remote natural gas reserves by converting gaseous natural gas to a liquid that condenses to 1/600th its original volume[1]. This volume reduction makes it suitable for long-distance transport and connects otherwise stranded gas with the markets of the Atlantic (US and EU) and Asian Pacific Basin. The LNG value-chain comprises three segments: upstream (production, transportation to liquefaction, liquefaction), midstream (LNG sales and shipping), and downstream (LNG regasification, storage and transportation to the market, consumption). The realization of a single LNG supply chain requires a multi-billion dollar investment. Initially, upstream, midstream and downstream were vertically integrated, while today the partners in LNG projects arrange contracts covering the entire lifespan of these high volume, capital-intensive operations. Already from the early project phase, project development, transport, and capacity commitment are negotiated and secured through long-term contractual arrangements to reduce financial risk. Declining natural gas reserves combined with increasing demand in the OECD countries have raised concerns on security-of-supply. The availability of favourably priced and abundant gas reserves in remote locations have increased interest in and global importance of LNG. This prospect attracts new players, accelerates technological developments and could fundamentally change the way LNG is traded.

We postulate that the recent changes in the LNG market initiated by the aforementioned trends are the prelude to its transition, a departure from the *traditional* LNG market, which is governed by long-term high-volume project specific Sales and Purchase Agreements (SPAs), towards a *global* LNG market where actors engage in flexible spot trading models, and which is governed by Master Sales Agreements (MSAs). In order to validate this conjecture we address the research question:

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[1] This chapter is partly based on Chappin, Praet and Dijkema (2010) and Chappin, Preat and Dijkema (2010, submitted).

How can we simulate the LNG sector and let the transition to spot trade in the LNG market emerge?

First, we elaborate on the transition perspective section 5.2 and identify the perceived drivers of the LNG market transition. Second, we present a simulation methodology which combines Agent-Based Modelling (ABM) and Computable General Equilibrium (CGE) modelling. We present the structure of an LNG-model that enables the exploration of an evolving LNG market which is subject to the actions of the market participants. The strategic and managerial decision making of the agents is based on an adaptation of the Diamond model, which was originally presented by Brito and Hartley (2007).

Two experiments have been developed that are described in section 5.4 and section 5.5. We conclude this chapter in section 5.6.

5.2 Transition and Drivers of the LNG market

Various changes are simultaneously affecting the global LNG sector and its market structure, including: volume growth, new technologies, and new players. It may thus be seen that a transition is unfolding in the *socio-technical system* (Dijkema and Basson, 2009) that is the global LNG sector. The social subsystem or network thereof is the market; LNG facilities are the technical subsystem. Using this socio-technical system perspective, we set out to define the LNG market transition before focusing on its key drivers, as there is no universally accepted definition of a market transition.

5.2.1 Defining the LNG Market Transition

Since the first commercial shipment in 1964 delivered Algerian gas to the UK and France, LNG has rapidly become a mainstream natural gas market alternative, which in 2008 accounted for 28% of the global trade movements of natural gas (BP, 2009). While the LNG market evolved out of a series of independent regional projects in which the risks were covered by SPAs, the situation changed in the early 2000s when the cost price balance broke the so-called ‘tyranny of distance’ and connected the largest gas market (US) with the largest stranded reserves (Middle East) (Baily, 2007). The increasing international trade and price connectivity of LNG (Cook, 2005) suggests that its strongly related regional pricing will develop in the same way as benchmark crude oils (Tusiani and Shearer, 2007). The current expansion of LNG infrastructure and resulting increase in trade volume and flexibility gradually establish international price references which, in turn, facilitate the use of more elaborate trade instruments. The arrival of Floating Liquefied Natural Gas (FLNG), Floating Storage and Regasification Units (FSRU) and the planned creation of LNG storage and trading hubs will accelerate this development. It took the crude market time to move away from long-term bilateral contracts towards today’s flexible liquid market and we believe that LNG could undergo the same transition. BG (2007) claims that crude markets moved away from long-term bilateral contracts towards a truly fungible market because of excess ullage in the system that acted as a safety valve for unexpected supply or demand swings.

Capitalizing on these technical developments, the spot market for LNG has grown from being virtually non-existent in the early 1990s (1.2% of total trade in 1992) to 16%

of the total LNG trade by 2005 (Morikawa, 2008). This growth is widely expected to continue and increase the relative importance of the LNG spot market to 30% "within the next decade" (NGI, 2007; Aissaoui, 2006) or, less specifically, "in the future" (IEA, 2004; Financial Times, 2004).

5.2.2 Identifying Key Market Drivers

All LNG actors (the social system) are bound together in 'the market'. When its environment and portfolio of options change, this market may depart from a *traditional* LNG market governed by SPAs, towards a *global* market characterized by a palette of trading models, including spot trading governed by MSAs. In order to identify the key market drivers of this transition it is necessary to know the characterizing conditions of both the *traditional* and *global* LNG market. The *traditional* LNG market is an oligopolistic market that is dominated by few vertically integrated and interrelated companies. Its transition towards the *global* LNG market will require new market structures and institutions.

We argue that the development of a spot market for LNG is critical to such a transition and distinguish between fundamental or structural conditions that contribute to its realization and conditions which are more facilitative and less restrictive in nature. An effective functioning market with "high liquidity in terms of traded volumes, and sufficient capacity in terms of physical availability of natural gas, transport, flexibility in terms of storage, line-pack, production swing, quality conversion, interruptible customers, and imports" (Jepma, 2005) is a prerequisite to the development of any spot market. This aligns with Treat (2004), who argues that a successful futures market requires 'sufficient deliverable supplies', 'market concentration', and 'product homogeneity'.

Together these conditions resemble the "physical and structural market characteristics determining the flexibility, tradeability, transportability, and efficiency and in essence determine the potential liquidity of the market" (Jepma, 2005). While the liquidity of the wholesale natural gas market is determined by the number of market participants, price transparency, traded volumes, and the number of trades (Patel, 2007), the availability of sufficient (spare)capacity is related to the global LNG technology and the participants' accompanying trading models.

Other conditions such as 'high transparency', 'non-discrimination', 'product perishability', or 'availability of price information' can be enforced by the respective regulatory regime and are of a more informational nature. With regards to the 'large competition' condition it is noted that although this is indicative for a market with perfect competition, it is certainly not a prerequisite for the well functioning of a spot market.

As the *global* LNG market is not likely to satisfy all the conditions of a *perfect* spot market in the near future, we adopt a qualitative test of trading liquidity to determine whether portfolio imbalances may reliably be resolved in the traded market. Global Insight (2007) notes that "For functional purposes, the qualitative test of trading liquidity is whether or not a market participant with a portfolio imbalance of a 'normal' size can reliably be expected to be able to clear this imbalance in the traded market, over the space of at most a few days, at prices essentially in line with reported market prices at the time". This is important because it enables market participants to eliminate surpluses, acquire additional supplies, ameliorate shortages or sell excess supply. Pirog (2004) notes that these activities are central to the market process and the key to achieve lower prices and drive down costs while market determined prices will also help to shape future investment decisions in LNG capacity in a more efficient way.

5.2.3 Key Market Drivers Explained

By using the effective functioning of the market condition we were able to identify the following key market drivers of the LNG market.

Market Growth According to PWC (2007) the traded volumes of LNG will increase from 89 BCM in 2005, to 459 BCM in 2015. The number of market participants is also growing and has quadrupled from 8 to 32 between 1992 and 2004 (Boyoung, 2006). An important indicator for the liquidity of the market is the *churn* which is the ratio between the traded volumes over the consumed volumes. Keyaerts (2009) notes that liquidity in general is associated with churn factors above 15. "Spot trading liquidity exists to varying degrees in different commodity markets, from essentially none at all (churn factors < 1×) to 'perfect markets' (churn factors 40× or more)" (Global Insight, 2007). The US natural gas market, where the Henry Hub trades with a churn factor of 100 and NYMEX natural gas contracts trade with a churn factor of 30, is by far the most liquid gas market in the world with a significant lead over other markets, including the UK-based National Balancing Point (NBP), the Belgium based Zeebrugge Hub, and the Dutch Title Transfer Facility (TTF) with churn factors estimated at maximally 10-15, 4-6 and 4-6 respectively (Keyaerts, 2009).

Capacity Developments In addition to the overall size of the market it is important to look at the relative capacities of liquefaction, shipping and regasification. The transition towards a *global* LNG market is facilitated by the availability of sufficient ullage in the system. For the midstream segment of the market this implies sufficient uncommitted transport capacity. Griffin (2006) notes that the world LNG fleet is expected to reach 450 vessels by 2015 (from 350 vessels by 2009), a development that leads LNG shipper BW Gas (2008) to the conclusion that the expansion of the LNG fleet will outpace the growth in traded volumes of LNG. Another important driver towards more flexible transport is the current sub-optimal economic performance of LNG tankers which hold dedicated cargoes and follow point-to-point routes. This severely undermines the possibility to optimize transport of LNG by deviating from fixed routes or taking advantage of arbitrage possibilities. The possibility to turn to transport of LNG under charter makes the need to make long-term commitments avoidable. Tusiani and Shearer (2007) note that "for transient business opportunities, not controlling shipping and incurring the attendant fixed costs may in fact be an advantage".

Another important enabler of LNG spot trade is the trend to construct new liquefaction plants with the sale of anticipated production not yet completely contractually covered. This development appears to have two root causes: 1) technical system development; the pursuit of economies of scale leads to a continuous increase of the size of liquefaction plants and 2) social system developments; changes of markets and companies behaviour, e.g. smaller volume commitments from buyers because of the liberalization process of electricity and gas markets. This trend is illustrated by recent examples such as Malaysia LNG Tiga, Australia's NWS Train 5 (Tusiani and Shearer, 2007), and the Sakhalin II Phase 2 project (Ball et al., 2004) for which the go-ahead for construction was given, despite a significant volume of uncommitted production capacity.

Innovation Technological innovation could greatly increase the capacity of the global LNG infrastructure in all parts of the value-chain. Floating regasification units, for instance, could increase market flexibility because of shorter construction times and the possibility to changing the location and feed-in point of the domestic gas grids. Douglas-Westwood (2010) predicts that more than 100 floating production systems will be installed worldwide over the 2010-2014 period at a total value of approximately US$45 billion. Innovation could also equip the market with new opportunities for storage and, in doing so, enhance the spot trade of LNG. The establishment of LNG trading hubs is an interesting development in storage that offers its users the ability to store, trade, and plan supplies of LNG over an extended period of time. Memorandums of Understanding exist for both the creation of LNG hubs in Dubai (Business Wire, 2007) and Oman (APS, 2006). These innovations offer new players the opportunity to enter the market and create new business opportunities that require a reassessment of current business and decision models.

Self-reinforcing Expectations Although the future of the LNG market will be strongly influenced by the development of the above-mentioned exogenous market drivers, we postulate that these drivers alone will not suffice to invoke a transition. It is likely that there will be a substantial endogenous component as well, through which the momentum of the LNG spot market can reinforce its own development. This self-reinforcing loop incorporates the fact that market players' expectations about the future development of the spot market influence their decisions on whether or not to become active on the LNG spot market. This is indeed the central claim of Brito and Hartley (2007) who state that "while exogenous changes in costs or demand are critical to promote a change in market structure, there is also a substantial endogenous component. Expectations about the evolution of the market influence investments and trading decisions can make the change in market structure much faster and more abrupt". It is our firm belief that the interplay of exogenous forces and endogenous expectations can move the market along the pathway of transition towards the breakthrough phase in which visible structural changes are the forerunner of a new stable market equilibrium.

5.3 Overview of experiments on transition in LNG markets

The modelling framework, applied to the LNG model (Figure 5.1) depicts the LNG market as a socio-technical system that consists of social components (agents), physical components (technologies) and their interactions (projects and contracts). *LNG Agents* represent companies that are active on the LNG market through investment in and operation of *LNG Technology*. *LNG Projects* represent the investment of the agent and the contractual strategy through which technologies are constructed and operated.

The decisions that cause these interactions to occur are driven by developments in the world external to the agents and the options that are available to them. The former

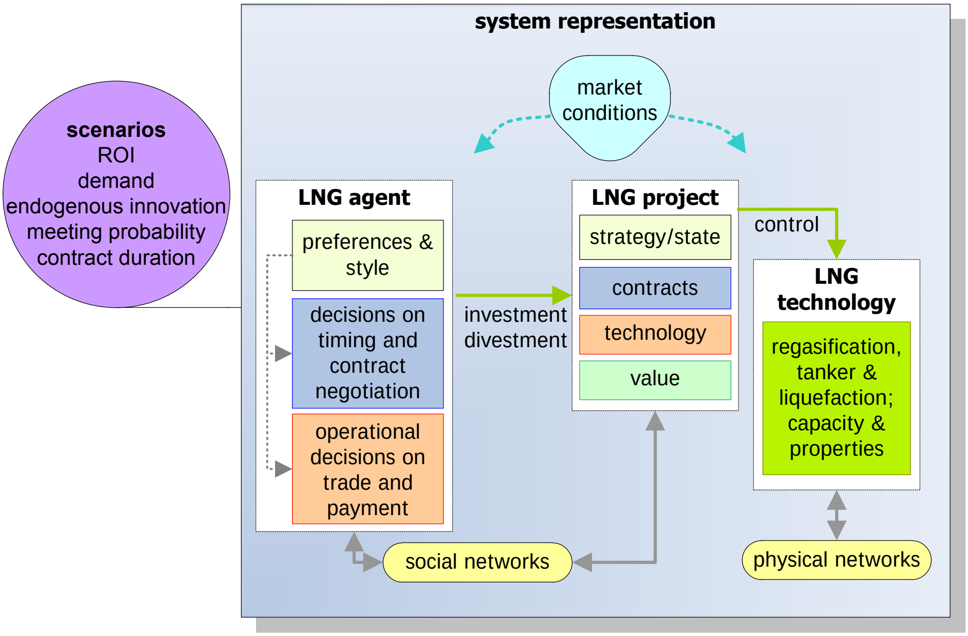


Figure 5.1 – The modelling framework applied to LNG markets in transition

are represented in the form of *scenarios* and the latter in the form of *transition design*. *System evolution* comprises of the emergent behaviour of the LNG market as a whole by all the decisions that are made by the heterogeneous set of agents, i.e. investment and contract negotiations. *Impact Assessment* is obtained by performing simulation runs for all scenarios and by collecting and exploring the data. By analysing the data, we intend to obtain new insights into the impact of the key market drivers and their potential to realize a transition in the *real-world* LNG market.

Two experiments have been executed with variations of this agent-based model.

Experiment 1 – The transitional spot market The first experiment describes the evolution of expectations of the LNG market. The agent-based model is interlinked with an equilibrium model already available. This eluded interfacing to modelling paradigms. With this experiment we assessed whether the drivers for transition can be expected to impact transition in the LNG market. A main conclusion was that the spot market is not self-reinforcing, but, functions as a *transitional* market.

Experiment 2 – Emergent expectations on the spot market One of the main criticisms regarding the first experiment was how agents were thinking about their expected returns on investment on the sport market. The second experiment was executed to show a subtle difference in the way the spot market was modelled. In contrast to the last experiment, now the expected return on investment of the spot market is changeable over time, reflecting that companies benefit from more potential trade on the spot market. Results show a different potential for the spot market. This is interesting, because the conclusion drawn from the first experiment, that the spot market is not self-reinforcing, still holds.

5.4 Experiment 1: The transitional spot market

5.4.1 Introduction

This experiment was designed to *explore* transitions in the LNG market. This needed a large number of activities: identifying all the relevant components in the socio-technical LNG infrastructure, gathering data, and identifying previous work on the LNG sector. In the remainder of this section, the model used in this experiment is described and simulation results are shown. Conclusions are drawn before going on to the second experiment.

5.4.2 Model description

An agent-based model has been developed to elucidate the mechanisms behind LNG trade. In the model, agents represent companies active in the LNG market. The agents' take a number of decisions, coded in java. In order to optimize their behaviour, the agents use their own *model of the LNG market*. While working on this experiment, an inspiring article by Brito and Hartley (2007) popped up that described the *Diamond model*. The authors presented an equilibrium model of the LNG market, and took a system's perspective relatively close to our ideas regarding the model we wanted to develop. The Diamond model used the concept of *expectations* of players in the market. Notions as 'the probability of meeting', 'the number of potential partners', and, 'the possibility of a successful partnership', all with respect to the LNG market, sound much like *agent-based* terminology. Therefore, we saw the potential for synergy between the existing equilibrium model and our agent-based model. The agent-based paradigm arranges for disaggregated decision-making in agents, and the interactions between agents. The equilibrium model functioning as a part of the *brains* of the agents – thinking and estimating expected values of their opportunities. This combination proved useful for advanced agent reasoning, agents optimizing their own behaviour.

System representation The agent-based model of the LNG market contains only one type of agents, which are companies active in LNG liquefaction, shipping and/or regasification. There is a market for LNG with simulated demand. Agents define new projects and negotiate contracts (vertically integrated or not) and because of all the agents acting, the LNG market emerges. A variety of exogenous scenario parameters can be set.

Agents The core of the model is the codification of the *LNG agent*. These agents make autonomous strategic, managerial, and operational decisions by applying coded decision rules on a number of topics, i.e. investment, strategy formulation, negotiation, project realization, and operation. Their decisions are based on their own abstraction of the world – their *belief-system* – represented by an adapted version of an equation-based model (EBM) called the *Diamond model of LNG market evolution* of Brito and Hartley (2007), Diamond and Maskin (1979, 1980), and Diamond (1984). This equation-based model of the 'world' forecasts the perceived effects of different decisions and is used to select the optimal strategy (details of which follow in section C.1).

Strategic decisions are made with a long-term perspective in mind and concern the investment and trade decisions. Both the technology selection and the timing of investment are important strategic decisions with the latter being considered by Brito and Hartley (2007) as the characterization of change in the LNG market which refers to a transition from their *traditional* to the *alternative* market structure. "In the traditional LNG market, firms search for trading partners and sign long-term contracts before investing in infrastructure. In the alternative market structure, producers invest in infrastructure before they have buyers for all their anticipated output, and buyers invest in infrastructure without having firm contracts for all their expected gas needs. Substantial sales and purchase are also made on the spot market or using short-term contracts, and multilateral trades, swaps and switches in trading partners are more common" (Brito and Hartley, 2007). Managerial decisions involve contract negotiations and the search for improved partnerships which are required to develop profitable LNG value-chains. Each partnership contains two complementary projects (liquefaction, regasification or tanker). For example, an agent who invests in a liquefaction plant will try to form a partnership with another agent (or even himself) who owns a regasification terminal and one who owns a tanker. It is also possible for agents to develop a portfolio of projects that includes liquefaction, shipping, and regasification. The operational decisions of the agent refer to the day-to-day operations of LNG-technology. In the model this means that LNG technologies meet their design objectives. The indicator for success of the LNG agent is measured in monetary terms or credit.

Before the realization of the project, the agent needs to select one of the following strategies for all three of the components of the value-chain, i.e. with respect to a potential 1) liquefaction plant, 2) tanker, and 3) regasification plant:

0. Initial situation deciding whether to search or invest first;
1. Searching for a long-term partnership, delaying investment;
2. Investing without searching for a long-term partner and operating on the spot market.

Agents who initiate strategy 1 projects will search for complementary strategy projects until a partnership is formed, in which case the partnership can be successful (good partnership) or not (poor partnership). Agents that decide to initiate a strategy 2 project can partner with other strategy 2 and 3 projects and are guaranteed a good partnership with the latter, just as two strategy 3 projects. The newly established partnership thus results in one of the following strategies for both partners:

3. The long-term partnership turned out to be a poor match, so the search for a new long-term partnership continues;
4. The long-term partnership turned out to be a poor match, but the search for a new long-term partnership is stopped;
5. The long-term partnership turned out to be a good match, so the search for a new long-term partnership is stopped.

Table 5.1 – Normalized data for LNG technologies

Type	Investment cost (K/BCM)	Capacity (BCM)	Lifetime (year)	Net-back good match u_1	Net-back poor match u_2
Liquefaction	2.75 (55%)	5 or 10	20	0.55 (50%×K)	0.16 (15%×K)
Tanker	1.35 (27%)	5 or 10	20	0.27 (50%×K)	0.08 (15%×K)
Regasification	0.90 (18%)	5 or 10	20	0.18 (50%×K)	0.05 (15%×K)

When agents form their long-term partnerships, they can also become an 'indirect' partner, i.e. a partner through other contracts their projects connect to. An example is displayed in Figure 5.2. To accommodate this structure, we introduce strategy 6 for indirect partners:

6. An indirect partnership has been established, so no search for a partnership is required.

Projects and Technology Based on data from EIA (2006), Peru Petro (2009), and Platt (2005), a list of technology parameters was used and normalized for the model (see Table 5.1). For each technology a big and a small version are available in the model. Note that the technologies are modelled as passive objects and are references in projects. The normalized investment costs of a complete LNG value-chain are equal to the upfront infrastructure investment costs of a firm that wants to generate a return. Brito and Hartley (2007) assume a *present value* of infrastructure investment costs of 4.0. Because we differentiate between the various components of the LNG value-chain we looked at the investment costs per unit of capacity [$/MMBTU] for each component of this value chain first and subsequently we averaged the data and normalized it to ensure that the total investment for a LNG value-chain equals 4.0. Accordingly, liquefaction accounts for 55% of the total investment, shipping 27% and regasification 18%. The status refers to the construction of the LNG technology and distinguishes between projects that are unavailable (not yet constructed), operational (constructed and active) or under construction.

The LNG project constitutes the link between agents and their technologies and contains information about the LNG technology, status, ownership, and strategy. To demonstrate how the LNG Project setup works out in the model, we visualized an example of a functional value chain in Figure 5.2. Three agents each own a project which is contracted by two contracts: *c*1 and *c*2. The first partnership is between agents 1 and 2 and is formalized with contract *c*1. This partnership constitutes a poor match as a result of which both agents continue their search (strategy 3). The second contract, *c*2, between agents 2 and 3 constitutes a good match which is exemplified by the fact that both agents have stopped searching (strategy 5). The indirect relation in this example is between project 1 and 3 because these are not connected through a contract, but rather through *c*1 and *c*2 respectively. Strategy 6 is used to denote such an indirect relation. There is also a reference to the agent owning the project as well as the associated contracts and the selected strategy (described in detail above).

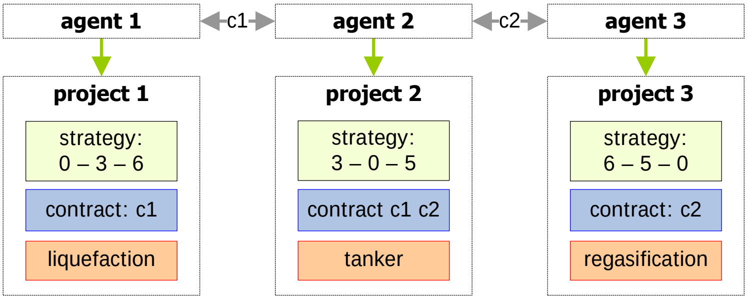


Figure 5.2 – Example of a value chain with 3 projects and the strategies of agents

Table 5.2 – Scenario parameters for the LNG model, adapted from Praet (2009)

Category	Driver	Traditional	Global
Economic	LNG demand	+5.7%/year	+7.7%/year
	Capital cost	constant	-0.25%/adopted plant per type
	ROI liquefaction; shipping; regasification	0.55; 0.175; 0.0225	0.45; 0.0135; 0.0275
Technical	Availability of innovative technologies	after 20 years	after 5 years
Institutional	Expected duration partnerships	20 years	10 years
	Expected probability of meeting	0.002 for all projects	0.002 & 0.006 for (un)contracted projects)

Exogenous scenarios The LNG Scenario module contains factors we modelled under a variety of conditions that drive or inhibit the transition of the LNG market. We varied the identified exogenous drivers including market growth, uncommitted capacity, and technological innovation independently and we distinguished economic, technical, and institutional parameters to monitor their impact. Table 5.2 illustrates these parameters and their settings for a LNG market that favours the status-quo (Traditional) and a transition (Global). Market growth is directly incorporated in the LNG-model while uncommitted capacity is expected to be stimulated by decreasing capital costs, contract durations, and a higher ROI on the spot market. The introduction of technological innovation concerns the speed of introduction for floating regasification and liquefaction. Finally there is the endogenous self-reinforcing loop that is expected to be influenced by a varying probability of meeting between simulation runs. Note that the model setup allows for the exploration of additional parts of the parameter space through a larger variation of existing parameters or for the introduction of new transition drivers.

5.4.3 Simulation results

We performed simulations in which the scenario parameters were independently varied (Table 5.2) for a period of 20 years (40 time-steps of half a year) using 20 repetitive runs for each parameter setting. Although we have 32 scenarios we mainly discuss two scenario extremes that equate with favouritism towards the *traditional* and *global* LNG market.

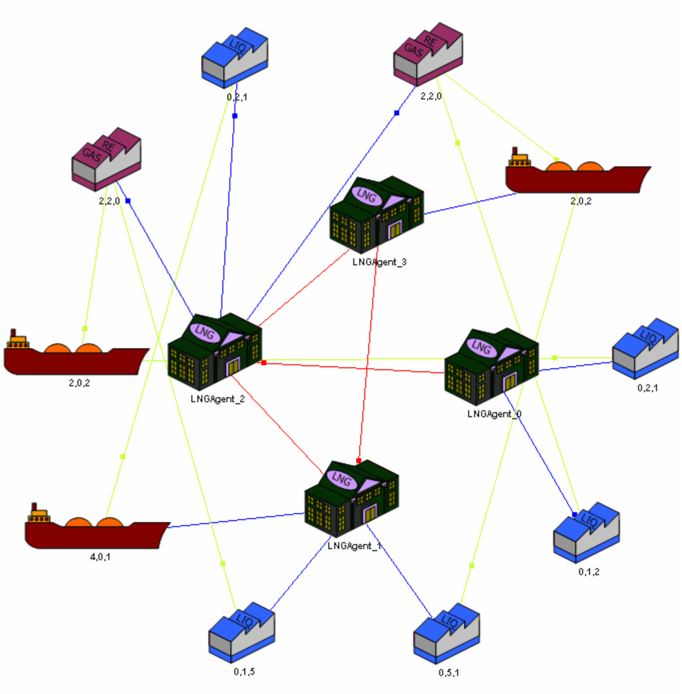
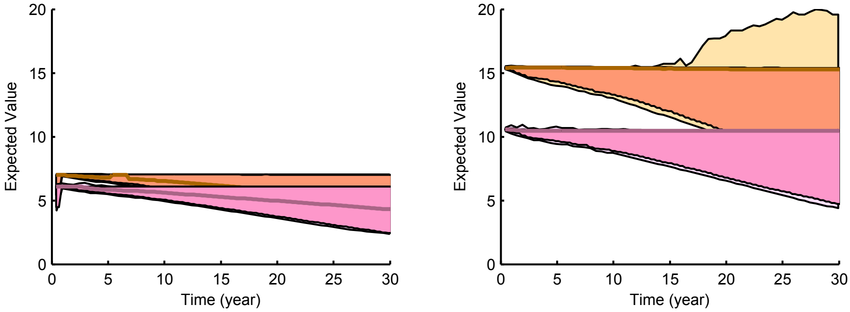


Figure 5.3 – Snapshot of the LNG model after the first time step

The evolving LNG infrastructure A snapshot of the LNG model can be found in Figure 5.3 which depicts the system's state after two years. The inner circle represents the social system while the technological system is represented by the outer circle. Agents in the inner circle own LNG projects (and their respective LNG technologies) that are drawn in the outer circle to which they connect (dark links). Agents that have partnerships are linked together in the inner circle while LNG projects that form a value chain on the long-term market are linked by in light grey. Figure 5.3 shows that four agents have entered the market, defined LNG projects, planned or constructed LNG technologies and established partnerships.

Similar snapshots of the LNG infrastructure become cluttered when the market expands which necessitates the use of indicators to assess the LNG market evolution. In general, two types of indicators can be distinguished. First, indicators that describe *actual developments* in the LNG market can be formulated. Examples of such indicators are the number of LNG projects in the market, the number of partnerships, and the capacity of liquefaction, regasification, and shipping on the spot market. Second, indicators can give insight in *expectations of agents* in the market. Such indicators describe how the market is perceived and primarily concern the expected ROI of certain technologies and strategies.

Agent expectations Figure 5.4 shows the evolution of expectations of the agents in the market under the two different scenarios, defined above. The first scenario (see Figure 5.4a) contains values favourite to the long-term market. The second scenario (see



(a) Expected values for the *traditional* scenario (b) Expected values for the *global* scenario

Figure 5.4 – Experiment 1: Development of expectations for strategies of agents under two scenarios. The upper band is the expected value of the strategy to search for long-term partnership; the lower band is the expected value of the strategy to operate on the spot market. For both, the variability is measured according to the description in Figure 4.7 on page 97.

Figure 5.4b) is expected to favour trade on the spot market. In both graphs, the developments of agent's average expectations are plotted over time. The upper band contains the average expected value for all agents searching for a partnership to invest and operating on the spot market afterwards. Contrastingly, the lower band, describes the average expected value for all agents operating on the spot market and not searching for a long term partnership.

Since the values vary between runs of similar scenarios, we have used notions from the so-called *box plot* in many of the graphs in this chapter, visualized and explained in Figure 4.7 on page 97. The lines indicate the median, the dark band contains 50% of the data, and the light band the other values that are not outliers. In some graphs, the outer band is not plotted for reasons of clarity. Outliers are not plotted when they are not significant.

The graphs show that the evolution of expectations is structurally different under the two scenarios. Looking at the axis, all expected values are much lower in scenario 1. In addition, the median is declining in scenario 1 and flat in scenario 2. Finally, only in scenario 2 an increase occurs in some simulations.

A number of implications can be made. First, these results imply that, under both scenarios, investing in the LNG market is expected to provide return on investment at all times. Agents are willing to invest in the LNG infrastructure. The certainty of a long-term partnership *on average* is preferable to the spot market. However, as we will see further in the discussion (see Figure 5.5), some agents prefer to use the spot market.

Second, the starting conditions, under which the expectations initially are calculated, are too optimistic. As discussed in section C.1, in order to solve the equation-based model that the agents use for determining their expectations needs initial values that do not coincide with the actual simulation. One driving force of the change in expected value of investments over time is just the fact that more "real" data for the analysis of the agents are available. Although the expectations are often declining, an investment for any strategy remains attractive.

Third, the expectations of agents are affected by system developments. By investing in LNG infrastructure, expectations are more and more based on what occurred during the simulation. And, as the system developments emerge from the interactions of agents, we have grasped some of the complexity of the LNG infrastructure.

Fourth, a variety of pathways are observed for both scenarios. In some simulation runs, expectations move only little, in others they decline. The expected value for long-term partnerships increases in the second half of some simulations under spot-favoured conditions. A detailed analysis of all the developments of expectations under different scenarios leads to the following observations: Under endogenous innovation, capital costs decline significantly during the simulation. As a result, the expected values decline with it. This explains the drop in expected values of some of the simulations. Next, an increase of the expected values is noted in some simulations. This is only the case in some simulations where there are both no endogenous innovation, low demand growth, and relatively short long-term partnerships. Furthermore, only at the scenario with high returns on investment, a decline in expectations is noted for the spot market but not for the expected value of a long-term partnership. Finally, only under the scenario that long-term partnerships last 20 years, expected values decline. When a period of 10 years is assumed the average trend is stable.

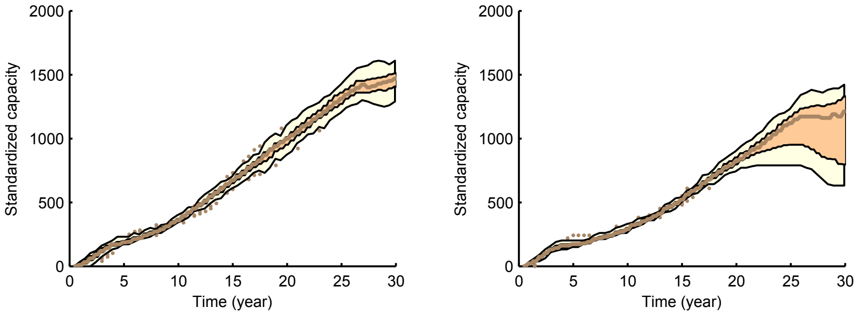
LNG capacity developments Apart from expectations, we also capture actual simulated developments, which result from the myriad of decisions taken by agents. In Figure 5.5 developments of capacity in liquefaction facilities are displayed. The capacity developments for regasification and shipping are similar.

A number of observations can be made from these graphs. First, the size of the long-term market differs from the spot market. As can be seen in Figure 5.5, at every moment in time, and for both scenarios, the capacity on the long-term market is bigger than the capacity on the spot market.

Second, the long-term market and the spot-market are very different in nature. The long-term market grows more or less with a linear trend. For both scenarios, the differences between the various simulation runs is relatively small. Only in the last decade of the spot-favoured scenario, the spread increases at a fast rate. In some simulations, a decline in capacity can be observed. On the spot market, there is no linear growth in capacity. In the first decade, the capacity is very spiky. Afterwards, capacities are more or less stable on average. In the final couple of simulated years, the spot market shrinks.

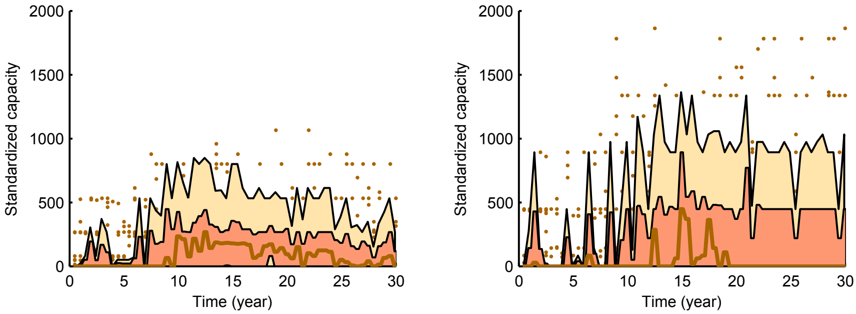
The spread in capacity difference between simulation runs on the spot market is relatively large. This implies that it functions as a transitional market: from the agents operating on the spot market, some eventually choose to contract a suitable partner in a long-term partnership and leave the spot market. In the intermediary period, this leads to a profitable situation. Please note that this strategy is only possible if the agents first decide to operate on the spot market. In contrast, when agents initially decide to operate on the long-term market, they delay the investment until a suitable partner is found. In the meantime, no investment has been made yet and the capacity is unavailable.

Third, several conditions influence the potential for a spot market. The spot market is bigger under spot-favoured conditions, as was expected. Under a scenario of endogenous innovation, the capacity on the spot market declines fast at the end of the simulated time, faster than can be observed from the displayed graphs. However, in some simulations



(a) Long-term market capacity for the *traditional* scenario

(b) Long-term market capacity for the *global* scenario



(c) Spot market capacity for the *traditional* scenario

(d) Spot market capacity for the *global* scenario

Figure 5.5 – Experiment 1: LNG capacity developments for liquefaction on the long term market (see Figures 5.5a and 5.5b) and the spot market (see Figures 5.5c and 5.5d) under two scenarios.

when LNG demand is surging and when the duration of partnerships is relatively short, the spot market is in the same order of magnitude (in volume) as the long-term market.

5.4.4 Analysis

A spot-market for LNG trade is found to have a significant potential. In our simulations, the spot-market peaks at 60% market share. Market shares of 10-25% are common. This appears to be rather consistent with expert opinions. These results are not extremely sensitive to a variety of conditions.

The analysis leads to an assessment of the drivers for transition:

Growth of the market for LNG has an effect on the potential on the spot market. Under faster growth, the capacity traded on the spot-market is larger.

Uncommitted capacity is crucial for the spot-market. The agent-based model shows that the strategy to trade on the spot-market is often superseded by a long-term partnership when a suitable partner is found. This holds under the assumption that companies could opt for investing before a partner is found. When the construction is finished but the search process is ongoing, trade on the spot-market occurs. Given that this is a possibility in reality, uncommitted capacity is crucial for trade on the spot-market.

Innovation in the form of reduced capital cost by learning-by-doing is found to promote trade on the spot-market. We observed that expected values between the different strategies are closer when endogenous innovation is enabled. Consequently, innovation drives more agents to trade on the spot-market.

A self-reinforcing loop in the spot market could not be observed. The spot market is found to function as a transitional market, where agents still searching find a temporary platform to use their equipment. However, we used the assumption that agents can leave the spot market when they find a partner. In contrast we did not include a possibility for agents to appear on the spot-market by breaching an existing partnership. Given those assumptions, the spot market does not drive itself.

5.5 Experiment 2: Emergent expectations on the spot market

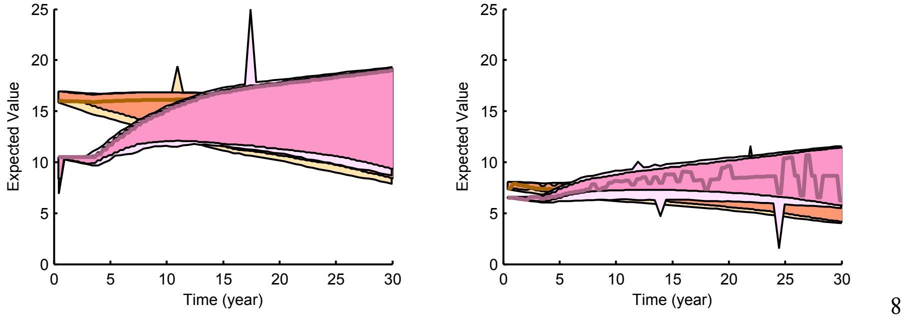
5.5.1 Introduction

The model is only marginally different from the last experiment. The differences can be found inside the *agent*: the equation-based model, used by the agents to determine the value of their options.

The main difference between the two experiments in the LNG case is how the expected return on the sport market is modelled. The difference can be found in the determination of parameter u_{spot}. In the second experiment, the surplus of trading on the spot market u_{spot} is made to *emerge* in the model, while it was fixed before. This is explained in more detail in appendix C, section C.2.

5.5.2 Simulation results

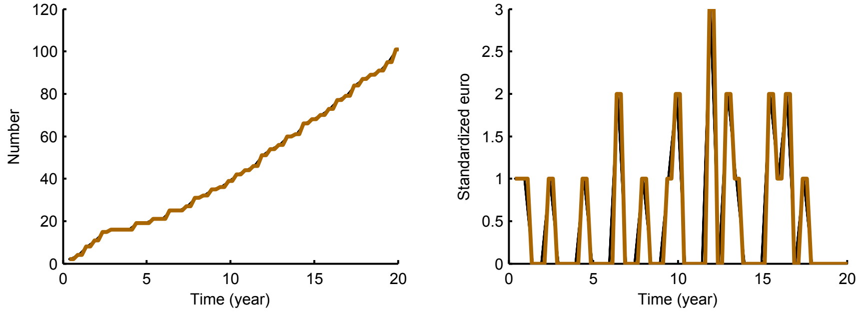
Agent expectations Figure 5.6 shows the evolution of expectations of the agents in the market that favours the continuation of the *traditional* LNG market (see Figure 5.6a) and a transition towards the *global* LNG market (see Figure 5.6b). Both graphs plot the development of agents' average expectations over time. The upper (light) band contains the average expected value for all agents who search for a partnership first and invest afterwards while the lower (dark) band, describes the average expected value for all agents who invest first and operate on the spot market afterwards. The graphs show that the evolution of expectations is structurally different under the two scenarios. Looking at the axis, all expected values are much lower in the *global* scenario when compared with the *traditional* scenario. Another distinction concerns at what speed agents expect a higher ROI from initiating LNG projects without a suitable partner, which is both faster and more erratic in the *global* scenario. We observe that:



(a) Expected values for the *traditional* scenario

(b) Expected values for the *global* scenario

Figure 5.6 – Experiment 2: Developing expectations for investment strategies of agents in the *traditional* and *global* scenario. Orange represents the expected ROI of the strategy to search for long-term partnership, purple (lower) the expected value of the strategy to operate on the spot market.



(a) Number of breached contracts

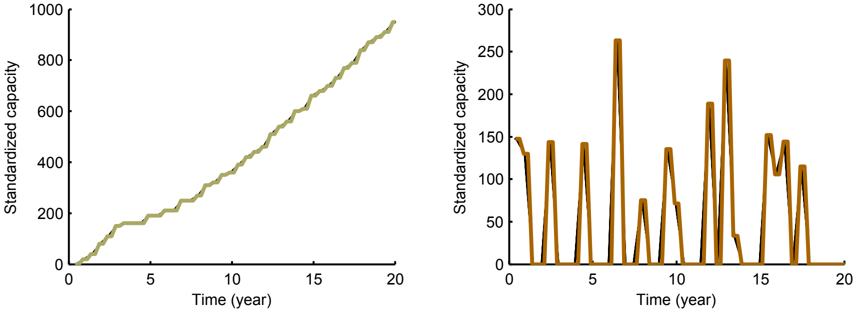
(b) Compensation fee for contract breach

Figure 5.7 – Experiment 2: Number of contracts breached during the simulation and the compensation fee that is required for each breach.

- Investing in the LNG market is expected to provide a positive ROI at all times under both scenarios implying that agents are willing to invest in LNG infrastructure.

  The certainty of a long-term partnership *on average* is preferable to the spot market. However, as we will elaborate further in the discussion (Figure 5.8), some agents prefer to use the spot market.

- The starting conditions, which determine the initial expectations, are too optimistic. As discussed in section C.1, the EBM that the agents use for determining their expectations needs initial values that do not coincide with the actual simulation in order to be able to solve. As such, one driving force of the change in expected value of investments over time is just the fact that more “real” data are available for the analysis of the agents. Although the expectations are often declining, an investment for any strategy remains attractive.



(a) Capacity development long-term market

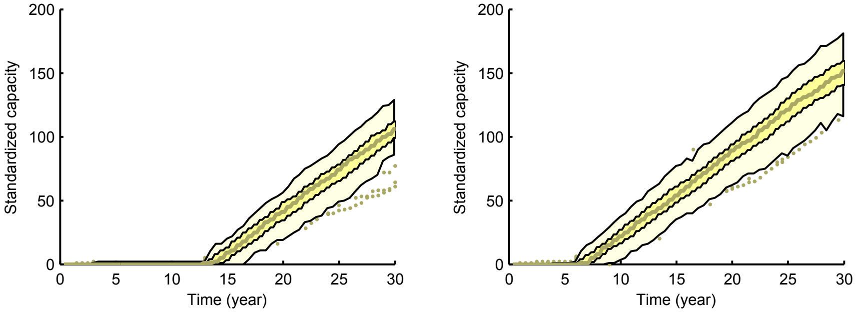
(b) Capacity development spot market

Figure 5.8 – Experiment 2: LNG capacity developments on the long term market and the spot market

- Contracts are breached (see Figure 5.7a) and compensations paid (see Figure 5.7b) during the simulation as agents in a poor match continue to search and negotiate with each other in an attempt to improve the ROI of their LNG projects.
- A detailed analysis of the developments of expectations under different scenarios lead to the following observations: Longer contract durations increase the expected ROI for both long-term partnership and spot market strategies. Under endogenous innovation, capital costs decline significantly during the simulation. Consequently, the expected values decline with it.
- Expectations of agents are affected by system developments. By investing in LNG infrastructure expectations are more and more based on what occurred during the simulation. And as the system developments emerge from the interactions of agents, we have grasped some of the complexity of the LNG infrastructure.

LNG capacity developments Apart from expectations, we also capture actual developments of the market, which result from the myriad of decisions taken by agents. In Figure 5.8 developments of capacity are displayed. We observe that:

- The size of the long-term market differs from that of the spot market at any moment in time (see Figure 5.8). Furthermore, the long-term market and the spot-market are very different in nature. The long-term market grows more or less with a linear trend whereas the spot market is more erratic in nature.
- The creation of the spot market differs between the scenarios. While it takes the spot market approximately 13 years to develop in the *traditional* scenario, this is only 8 years in the *global* scenario. The spot market is also bigger under spot-favoured conditions, as was expected (see Figure 5.9).
- The spread in capacity between simulation runs on the spot market is relatively large. This implies that it functions as a transitional market: from the agents operating on the spot market, some eventually choose to contract a suitable partner



(a) Capacity developments tanker spot market in the *traditional* scenario

(b) Capacity developments tanker spot market in the *global* scenario

Figure 5.9 – Experiment 2: LNG capacity developments on the spot market for both scenarios

in a long-term partnership and leave the spot market. In the intermediary period, this leads to a profitable situation. Please note that this strategy is only possible if the agents first decide to operate on the spot market. In contrast, when agents initially decide to operate on the long-term market, they delay the investment until a suitable partner is found. In the meantime, no investment has been made yet and the capacity is unavailable.

In the second experiment, it has been verified that a spot market for LNG has significant potential. In our simulations, the spot-market peaks at a market share of 35% , while market shares of 20% are common and not extremely sensitive to a variety of conditions. The analysis led to the following assessment of the drivers of transition:

Growth of the market for LNG has an effect on the potential of the spot market. Under faster growth, the volumes traded on the spot market are almost twice the number of those in the case of more modest growth.

Uncommitted capacity is crucial for the spot market. The LNG-model shows that the strategy to trade on the spot market is often superseded by a long-term partnership when a suitable partner is found. This holds under the assumption that companies could opt for investing before a partner is found. When the construction is finished, but the search process is ongoing, trade on the spot-market occurs. Given that this is a possibility in reality, uncommitted capacity is crucial for trade on the spot market.

Innovation in the form of reduced capital cost by learning-by-doing is found to promote trade on the spot market as the expected value of trading on the spot market overtakes that of the long-term market when endogenous innovation is enabled. Consequently, innovation drives more agents to trade on the spot market.

A self-reinforcing loop in the spot market was not observed. The spot market is found to function as a transitional market, where agents who are still searching find a temporary platform to use their equipment. However, we used the assumption that agents can leave the spot market when they find a partner. In contrast, we did not include a possibility for agents to appear on the spot market by breaching an existing partnership. Given those assumptions, the spot market does not drive itself.

5.6 Conclusions

We addressed the following research question: *How can we assess to what degree and under which conditions a Spot Market for LNG materializes?* We have identified four key market drivers for transitions in the LNG market: growth of the market, uncommitted capacity, technological innovations, and self-reinforcing expectations. Subsequently, we have developed a hybrid simulation model to explore the impact of these drivers in a model where LNG agents represent market participants who decide on strategies regarding investments and the formation of partnerships. We have compared circumstances that show favouritism towards maintaining the status-quo and the *traditional* market to circumstances that favour a transition towards the *global* market. As such we were able to observe the market evolution that emanated from autonomous agent decision making based on an EBM component that calculated the expected value of proposed strategies. In order to do so we made the following adjustments in circumstances: a change in demand growth, the inclusion of endogenous innovation, different returns on investment for technologies, different expected duration of partnerships, and different probabilities of meeting other agents.

We have developed a hybrid simulation model to explore transitions in the LNG market. The model is essentially agent-based, i.e. agents represent LNG companies that decide on strategies regarding investment in the liquefaction, shipping, and regasification. Strategies include operation on the spot market or delayed investment until a suitable long-term partnership has been formed. We have let the market evolve under different circumstances and observed the myriad of decisions of the agents. The agents use an equation-based model to evaluate the expected value of their potential strategies. Based on the outcome of this model, agents select a strategy and act accordingly. Our hybrid LNG-model is able to draw on the strengths of both ABM and EBM and should be seen as a first step to integrating both modelling paradigms. It enables EBM to utilize the dynamics of ABM, while ABM is able to integrate optimization problems in the decision making of autonomous agents. We have observed the evolution of the LNG market under different circumstances: a variety in demand growth, the inclusion of endogenous innovation, different returns on investment for technologies, different expected duration of partnerships and different probabilities of meeting other agents. Since we expect some of those circumstances favour long-term partnerships and others trade on the spot-market, we can explore the potential of spot-trade.

In future research, the model can be further explored by adapting it in a number of ways: first, we would like to allow the agents to switch back to the spot market by breaching an existing partnership. Second, we would introduce partnerships in which only part of the capacity of a project is in a long-term partnership; then the remainder can be traded on the spot market. Third, new technologies, such as floating regasification and liquefaction, can be included and existing technologies may be differently sized.

6 Transitions in Consumer Lighting

How far that little candle throws his beams! So shines a good deed in a naughty world.
William Shakespeare – Merchant of Venice, 1598

6.1 Introduction

Lighting is essential for modern living – it enables mankind to do many things that would otherwise be impossible[1]. For example, lighting is essential for education, which is a first requirement for economic development. Whereas humanity has used artificial lighting for millennia, the last two centuries have seen dramatic increases in the use of lighting. From medieval candles to today's highly efficient gas discharge and solid state lamps, the lighting technology has progressed greatly, contributing to a large decline in cost of lighting service (Fouquet and Pearson, 2006).

Electric lighting really took off after 1879, when Thomas Edison demonstrated his durable, well-performing incandescent light bulb, by using it to light his Menlo Park laboratory complex (NPS, 2007). During the last decades of the 19th century, electric power stations were erected in major cities around the world, supplying current for up to a thousand of incandescent glow-lamps per electric station (Forbes, 1889), marking the beginning of the electric power infrastructure.

Edison's first carbon filament glow bulb had a lifetime of 45 hours and an efficiency of 2 lm/W[2]. Many gradual improvements in electric lighting technologies (Gendre, 2003) increased the lifetime of the bulbs and the electric efficiency. By 1912, the glow bulb's efficiency had improved to reach a light output of 12 lm/W of electricity. Technological progress in incandescent bulbs stopped at that point. Presently, almost 100 years later, the incandescent lamps are hardly more efficient: even now, over 98% of the electricity used is converted into heat and not into light.

For the Netherlands alone, the yearly electricity usage in consumer lighting equals 3.8 TWh_e, comparable with the output of one large coal power plant (800 MW_e) (Afman,

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[1] This chapter is partly based on Chappin and Afman (2011) and Afman, Chappin, Jager and Dijkema (2010).

[2] Light output is measured in lumen (lm). An ordinary incandescent 75 W bulb (which is now banned in the EU) emits more or less 900 lumen at 12 lm/W. The theoretical maximum is 683 lm/W, which makes it $< 2\%$ efficient (Azevedo et al., 2009)

2010). Consumer lighting, therefore, contributes significantly to the ecological footprint of households and it is an important sector for energy saving.

More energy efficient alternatives have been developed, for example the compact fluorescent lamp (CFL, Azevedo et al., 2009). The CFL was first introduced by Philips in 1980, and offered four times energy savings and a much longer lifetime, with some disadvantages (size, weight). Subsequently, the CFL was much improved in the decades afterwards, and was known as the 'saving lamp'. The CFL enables a dramatic increase in the energy-efficiency of lighting while, partly being a screw-in/plug-in replacement, it retains an amount of compatibility with existing luminaires. CFLs offer clear benefits for many applications, and many governments tried to stimulate its use (see e.g. Mills, 1993; Martinot and Borg, 1998), but these stimulus programmes have only seen limited successes, and presently, CFL saving bulbs are present only in 55% of European households (Bertoldi and Atanasiu, 2007).

Another exciting development is solid-state lighting: the Light-Emitting Diode (LED). General Electric introduced the first commercial (red) LED's in 1962 (Azevedo et al., 2009). Since then, the developments in LED technology has continued, and these days, LED lamps are a very promising alternative. In the laboratory, LED designs achieve unparalleled electric efficiencies compared with other light sources (Dupuis and Krames, 2008). Proponents consider the LED as the ultimate lamp of the future, because it is very suitable to a wide range of applications, and because it will continue to achieve significant gains in electric efficiency (Curtis, 2005; U.S. Department of Energy, 2009; Holonyak, 2005; Azevedo et al., 2009).

Consumers have adopted CFL and LED technology only partially because of a number of obstacles (Menanteau and Lefebvre, 2000). CFL and modern LED saving lamps are characterized by high up-front cost for consumers and poor light quality, which serve as a barrier for adoption. Consumers implicitly use high discount rates when purchasing energy efficient durable goods (Hausman, 1979; Kooreman, 1996). Halogen lamps proved more attractive because they fitted in popular designs and do not have the disadvantages that CFLs have.

In consumer lighting, changes are forthcoming. The European Union's phase-out of incandescent lighting is a clear strategy that will change the sector, it involves regulation designed to remove from stores the cheapest forms of inefficient household lighting (CEC, 2009). Although implied, it is uncertain whether the lighting sector will become efficient overnight; consumers may switch to forms of inefficient lighting that are exempt from the phase-out; or consumers' behaviour will change. The precise dynamics induced by the phase-out are unknown.

Not only display consumer markets complex behaviour (Gilbert et al., 2007), the myriad of decisions and interactions of consumers and light bulb producers (purchase, marketing, product innovation), the interactions between consumers themselves (word of mouth, fashion), and those in the technology (incompatibilities between lamps and luminaires), determine the short and long run impact and effectiveness of policy. From the perspective of transitions (Chappin and Dijkema, 2010a; Geels, 2002b; Rotmans, 1994), governmental policy, such as the EU ban on bulbs, can be viewed as an instrument to manage a desired transition. This transition-policy should be ex-ante tested for effectiveness (Chappin and Dijkema, 2010b). General linear or system dynamics models are rather useless to determine which and whether consumer-oriented policy will be effective. Instead one must study the underlying complexities in a market to reveal crucial processes and possibly effective strategies to manage this market. Framing the system as a complex socio-technical system (Dijkema and Basson, 2009), agent-based modelling (ABM) offers a useful modelling paradigm to do this (Nikolic, 2009). ABM allows for modelling interactions within a network of consumers and producers. Rather than a static general linear model, an ABM is capable of exploring the dynamical properties of such a complex system. The more adaptive a system, or the more heterogeneous individuals in the system, the greater the opportunity to learn from ABMs (Garcia, 2005).

In this chapter, we present an agent-based model of the socio-technical consumer lighting system. Policy makers and other players in the sector can use the simulation model to test their strategies, learn to understand patterns that appear, and design a feasible transition oriented policy. The research question of this chapter is:

What are the effects of government policies on the transition to low-electricity consumer lighting?

The structure of this chapter is as follows. First, an overview is given of the two experiments with the consumer lighting model. Afterwards, the models of both experiments are described and results are presented. We end the paper with conclusions.

6.2 Overview of experiments on transitions in consumer lighting

For transitions in consumer lighting, two (sets of) experiments are executed (see Table 6.1 for an overview of the differences).

Experiment 1 – Transition by purchase of lamps The first is the most extensive and contains household agents purchasing lamps of certain brands and having certain technologies. Agents know other agents by their (scale-free) social network, in which they influence each other's decisions by looking around. The distribution of socket-specific luminaires – that allow only for certain lamps to fit – is exogenously determined and static throughout the simulation.

Experiment 2 – Revisiting the 1980s In the second experiment, we aim for confirming and further substantiating the conclusions from the first experiment by replicating the consumer lighting system from the 1980s onwards. We experiment with settings replicating naive expectations (a fast penetration of CFLs), and with settings showing more realistic patterns (dominance of incandescent lamps and upcoming halogens). A number of small changes to the consumer's purchase decision have been made, regarding the influence of the social network, perceptions and heterogeneity. The experiments will now be subsequently discussed.

Table 6.1 – Differences between consumer lighting experiments

Property	Experiment 1 *What may happen*	Experiment 2-a *'Naive' expectations*	Experiment 2-b *'Realistic' expectations*
System			
Start year	2009	1980	1980
Luminaires	static	replaced slowly	replaced slowly
Social network	included	excluded	included
Households			
Criteria	all	price, life time, and efficiency	all
Perceptions	included	excluded	included
	neutral at the start	continuously neutral	varied from the start
	includes technology	excludes technology	technology dominant
Heterogeneity	included	excluded	included

6.3 Experiment 1: Transition by purchase of lamps

6.3.1 Model description

An agent-based model of the consumer lighting system is developed, which incorporates 250 household agents as consumers, a manufacturer as retailer agent, and a portfolio of lamps and fixed luminaires (lighting fixtures) as consumers' lighting technology. In Figure 6.1, we present the modelling framework of chapter 3 applied to this model.

System representation The consumer lighting sector is a true socio-technical system. The social subsystem contains a network of consumers, who purchase and dismantle lamps. Consumers communicate with other consumers about their purchases and they have a memory retaining knowledge on lamps. Consumers form opinions about individual lamp models, technologies and brands. When lamps fail, the consumer acquires replacement lamp(s) from a retail store that matches the socket of the failed lamp's luminaire.

The technical part of the system consists of the lamps people have in their homes. In the model, a consumer owns a number of fixed luminaires, with attached to these a number of light bulbs that match in socket type and wattage. Usage for each lamp is related to the location in the house: some lamps are used more often than others.

The retailer has 70 different lamp models for sale, amongst which incandescent, CFL, halogen and LED bulbs. The model allows for assessing the consequences of innovations in the simulated technologies (such as performance improvements and declining prices of recent technologies).

Consumers: Household Agent Consumers are heterogeneous in their initial portfolio of lamps (total number of luminaires, socket types, and the specific lamps installed initially) and in their preferences for light colour, colour rendering, and light output. Consumers start with neutral opinions (to become negative or positive in simulation).

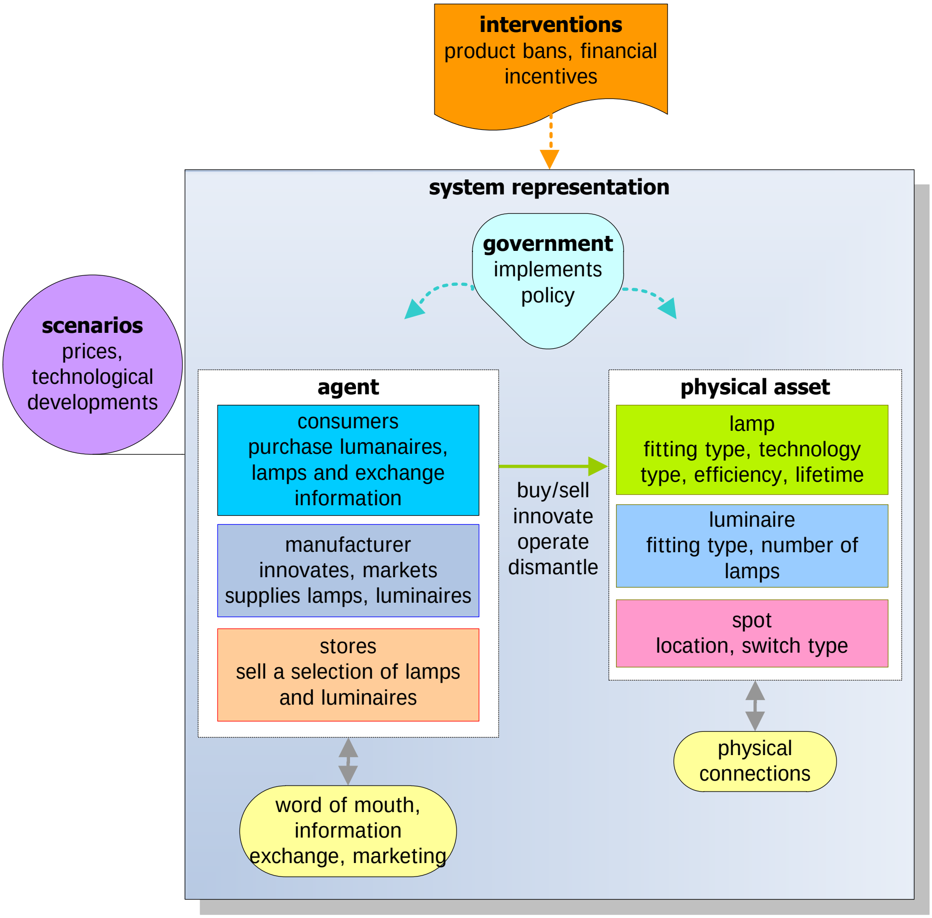


Figure 6.1 – The modelling framework applied to transitions in consumer lighting

The consumers' lamps purchase decision is modelled using multi-criteria analysis incorporating a number of criteria. The criteria relate to aspects of the lamps (purchase price, efficiency, and lifetime), preferences for subjective lamp qualities (colour, colour rendering index (CRI), light output), and opinions (perceptions) on the lamp's aspects (lamp model, brand, and technology type). A final criterion relates to what other consumers do (normative influence / fashion).

A number of important behavioural assumptions underlie the criteria weight factors that determine the relative importance of the normalized scores. As the purchase price needs to be the most important criterion (Menanteau and Lefebvre, 2000), it is assigned a high weight factor of 4. Then lamp efficiency, colour rendering, light colour, the household's opinion of lamp technology type, and normative adaptation (fashion: imitating neighbours) are assigned a weight factor of 2: important, but not as strong as the purchase price. Last, the lamp's light output, lifetime, and the consumer's opinions on brand and lamp model are even less important, they get a weight factor of 1. Between household agents, weight factors differ by +/– 50% to make them heterogeneous.

Consumers' opinions change autonomously on a [-1… 1] scale as a result of own experiences with bought lamps and through information it receives from neighbours in the social network (word of mouth). Parameters and increment values used for autonomous opinion change are:

- if positive experience: + 0.1
- if negative experience: – 0.3
- if positive experience, contrary to existing opinion: + 0.2.

When a consumer communicates its opinions, the opinions of a neighbour are averaged between its old value and the other consumers' opinions.

Social network The household agents are in a scale-free network, with 250 agents, which is typically considered sufficient (Barabási and Albert, 1999; Barabási et al., 2002; Nekovee et al., 2007). In the network, agents know at least 15 others.

Lamps Empirical data on the 70 modelled lamps were collected in a variety of lighting stores (see appendix D.2). For the modelled lamps, the following characteristics are implemented and used in the consumer's purchase decision: lamp technology, expected life time, uncertainty of lifetime, light output, electricity consumption, colour rendering index, colour temperature, voltage, shape, socket, and purchase price. Furthermore, survey data on the number and usage of lamps in consumers' homes were used (see appendix D.1). In addition, luminaires are modelled (see appendix D.3), which are specific with respect to sockets. In this version of the model, households do not change their luminaires. Therefore, the options to change lamps are limited to socket-compatible lamps.

Exogenous scenarios Technological improvement is modelled exogenously. Although the prices of all lamp models differ (see appendix D.2), the lamp technology determines the decline in price over time. Examples of the decline in purchase price for each technology are displayed in Figure 6.2. Newer technologies – LED and CFL – are modelled to improve faster than proven technologies (halogen and incandescent). Many of the other necessary parameters, such as the electricity price are held constant.

Design of transition assemblage We have modelled a base case, with no governmental policy and three possible policy interventions, i.e. the ban on bulbs, an incandescent bulb taxation scheme and a subsidy scheme on LED lamps. They are formalized with the following parameters:

This first policy entails a complete ban on the standard incandescent light bulb, phased in between years 2 and 5 (relative to the start of the simulation). This policy is comparable to the EU ban on household light bulbs: first the incandescent bulbs with the highest wattages are removed from the stores, after which progressively the lower wattages are removed.

The second policy scenario introduces a taxation on the sale of incandescent light bulbs that increases progressively during the first five years of the simulation to a maximum of €2,00 per lamp (which is relatively large compared to a purchase price of €0.35 – €1.50).

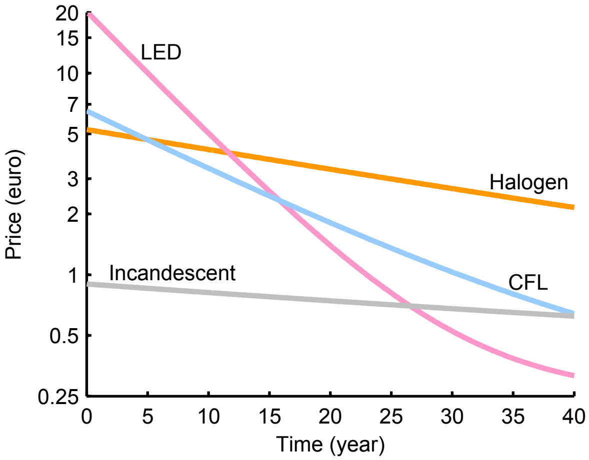


Figure 6.2 – Exogenous decline of prices of lamps are based on a technology-specific decline curve

The third policy is a subsidy on the purchase price of LED lamps. The subsidy is a discount of 33% of the purchase price. After five years, relative to the start of the simulation, the subsidy is slowly removed until year ten, when it is zero.

System evolution The system evolves because of the demand for lighting. Lamps fail after usage surpasses the lifetime passed. When a lamp fails, a consumer goes to buy a new one that fits the luminaire. His decisions are based on the perceptions of the alternatives available and its individual preferences. In consumers' decisions, past experiences with lamps of a certain kind are recorded in memory, influencing the decision. Consumers also influence each other by communicating their experiences.

Impact assessment The model allows for testing governmental interventions. The model is set up in a modular way, allowing for the introduction of new policies, next to the ones formulated above. On the other hand, also marketing strategies of manufacturers can be tested. First, different individual runs will be analysed. Later on, parameter sweeps will be executed to test the robustness of the strategies of the agents in the model.

6.3.2 Validation

A model is considered valid when *fit for purpose*. As the purpose of this model is to find out the effects of government policies on the transition to lower-electricity consumer lighting, we need to show whether this is the case. We come up with results that are useful for understanding transitions without claiming that the results are perfect predictions. These insights are scientifically useful: results have gained positive attention, mainly within the social simulation community. In addition, the results are of societal use as well, since the Dutch government found them useful. Therefore, the model is primarily valid.

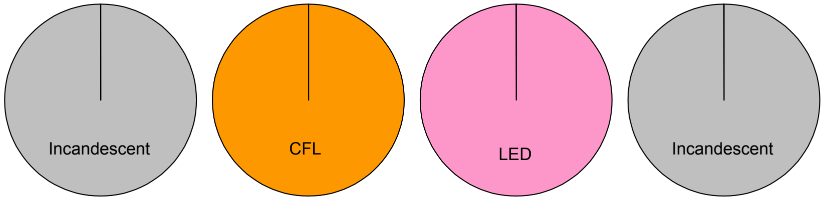
To further underpin these results, and assess their use, direct empirical validation of the model's outcomes is not possible as some policies have not and will not be implemented in reality. A number of verification and validation checks were done as a proxy of such a validation. These included a range of structure-behaviour tests that focussed on the outcomes of purchase decisions by consumer agents. As the lamp purchase decision is at the core of the model, we have tested a set of simulations of purchase decisions while changing 25 model parameters (of which 14 full factorial). A little over 10 million purchase decisions were analysed. Of these decisions, the result of each purchase decision – the preferred lamp – was recorded. It was verified whether these could be explained within the logic of the model. Overall, there is no single dominant lamp. The large variety of conditions tested showed that there are conditions for many of the lamps to be the best option. The top ten selection of lamps throughout these 10 million purchase decisions contains lamps of all technologies (2 incandescent, 2 halogen, 4 CFL and 2 LED), so the model is not biased towards one technology. In addition, valid reasons were found for all particular lamps that are popular. We looked more closely at different partitions of runs. Figure 6.3 shows the distribution of the lamps selected when only one of the criteria is used by an agent. Not the individual lamp models, but the lamp technologies are plotted. In those charts it can be observed that when only purchase price or light colour are considered, incandescent bulbs are fully dominant. When only efficiency is considered CFL is dominant and when only lifetime is considered LED is preferred at all times. It is different for the other individual criteria, i.e. colour rendering index, light output, lamp type perception, and brand perception. For those criteria, lamps with different technologies are competitive. In addition to these pie charts, we have looked at considering all criteria except one and we have looked at individual lamp models. Based on those analyses, the validation of the lamp purchasing part of the model is confirmed (see Afman, 2010, chapter 6).

6.3.3 Simulation results

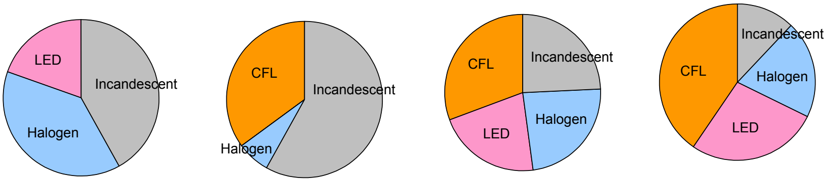
We explore potential transition to the use of more efficient consumer lighting by capturing a number of indicators. The myriad of individual decisions of agents to purchase lamps drives the system as a whole: system level adoption of the technology types, average electricity consumption levels, and average money expenditure on lamp purchases are important transition indicators. An individual run is shown in Figure 6.4. The social network is plot in the left top, each node representing a household. The colour represents the electricity intensity of its lamps. Some indicators are visible in the graphs on the right and bottom of this snapshot.

For each policy case, the simulation is repeated a number of times (100) to increase the probability for different possible bifurcations. In each model run, results are recorded on the transition to the use of more efficient lighting, which is captured through a number of indicators. The main indicators are the adoption levels of the different lamp technology types, household electricity consumption, and money expenditure for lamp purchases.

Since the values vary between runs of similar scenarios, we have used notions from the so-called *box plot* in many of the graphs in this chapter, visualized and explained in Figure 4.7 on page 97. The lines indicate the median, the dark band contains 50% of the data, and the light band the other values that are not outliers. In some graphs, the outer band is not plotted for reasons of clarity. Outliers are not plotted as they are not



(a) Price (b) Efficiency (c) Lifetime (d) Light colour



(e) CRI (f) Light output (g) Lamp type perception (h) Brand perception

Figure 6.3 – Lamp technology of the best choice when only one criterion is considered. All exogenous scenario parameters have values equal to those at the first time step of a simulation run.

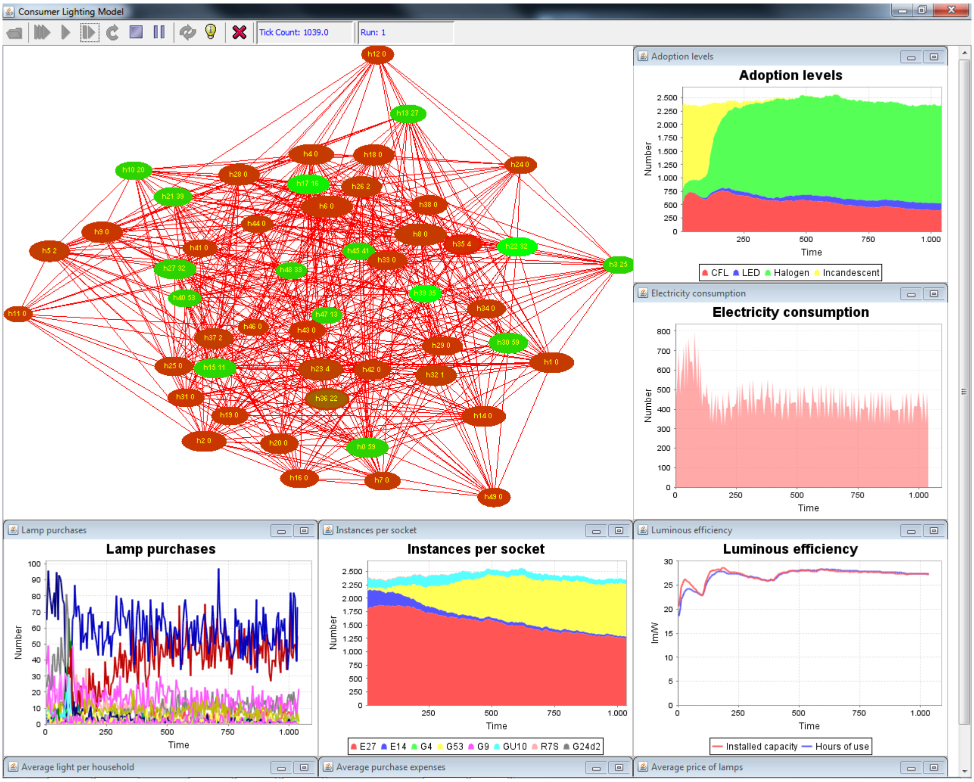
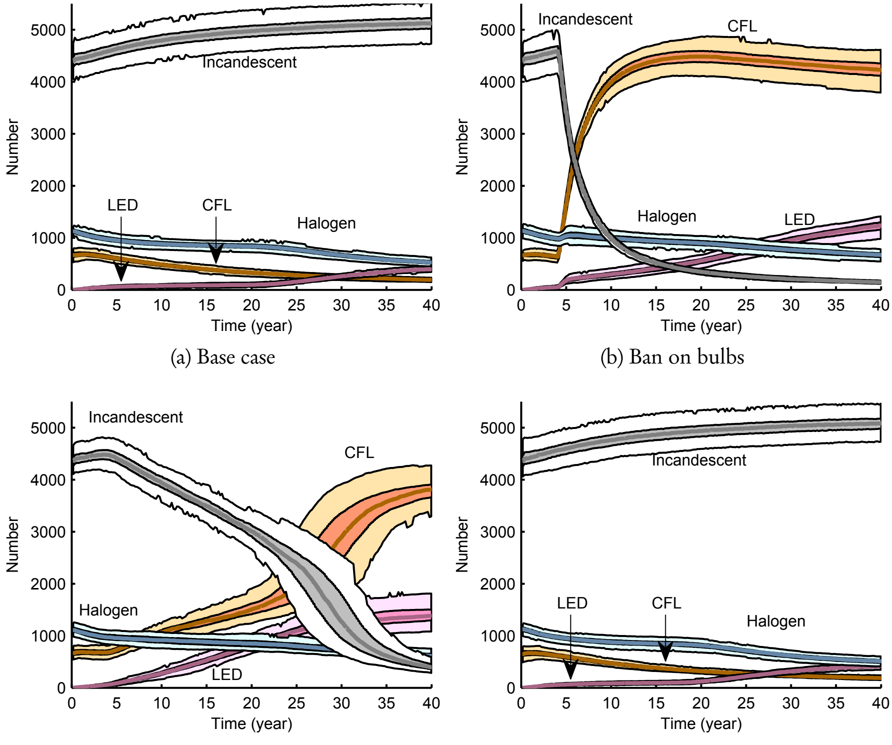


Figure 6.4 – Snapshot of the Consumer Lighting Model



(a) Base case

(b) Ban on bulbs

(c) Incandescent bulb taxation

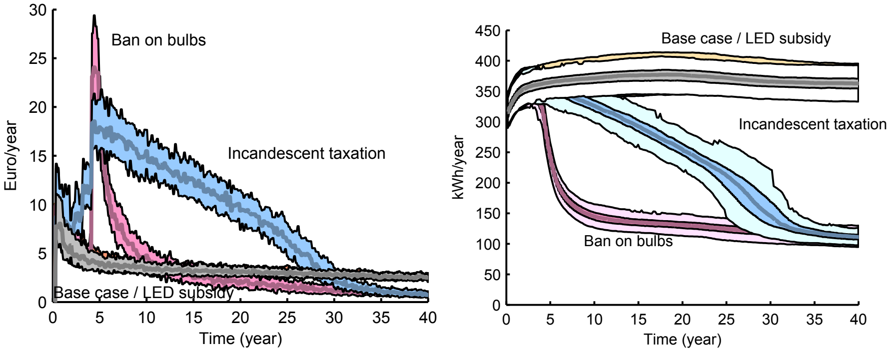
(d) LED subsidy

Figure 6.5 – Experiment 1: Adoption levels, measured as the sum of the working lamps per lamp technology of all households in the simulation. Per technology, the variability is measured in a dark and a light band, according to the description in Figure 4.7 on page 97.

significant.

Adoption levels of lamp technology In Figure 6.5 the adoption of the four different lamp technologies is plotted over simulated time (40 years), a sub graph per policy scenario. The results show that both the ban on bulbs and the taxation scheme on incandescent bulbs are probably effective to phase out the incandescent bulb in the long run. The ban on bulbs has a faster and more prominent effect. Without policy and with the LED subsidy the incandescent bulb remains dominant.

Cost for consumers Figure 6.6a displays simulation results of the yearly amount of money spent on lamps purchases, averaged over all households. Under the ban on bulbs scheme, consumers' investment costs peak in the first decade with an average of €28 per year to replace their broken light bulbs. With the taxation scheme this is less (€18 per year). The financial pressure on the consumers is much lower without policy or with the LED subsidy (€4 per year). For both the ban on bulbs and the taxation scheme, the total costs will drop in the long run, because electricity costs go down and the lifetime of



(a) Money spent

(b) Electricity intensity

Figure 6.6 – Experiment 1: Electricity intensity of consumer lighting

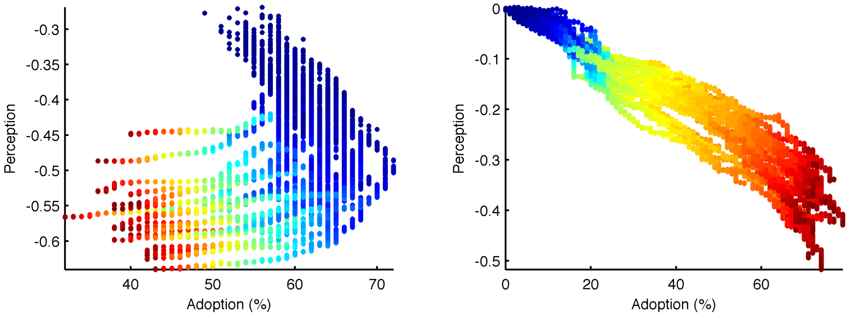
efficient lamps is longer.

Electricity consumption Figure 6.6b shows results of the average yearly electricity consumption of lighting. In both the ban on bulbs case and under the taxation scheme, electricity consumption declines significantly to reach a level of about a third of what it is in the base case and the subsidy for LED scheme. The decline is quickest under the ban on bulbs policy, where results are reached within the first decade of simulated time.

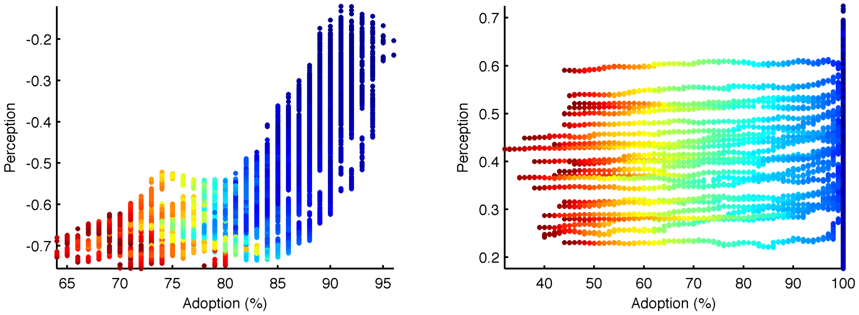
Perception and adoption The difference between the adoption levels (Figure 6.5) and the number of adopters is remarkable. Even without any policy, 70% of the consumers have at least one LED lamp in their house at the end of the simulation and are, therefore, considered adopters of LED lamps. However, the total share of LED lamps remains very small.

In Figure 6.7, the perception is drawn in relation to adoption levels, for each of the technologies for one of the scenarios. In this graph it can be seen that positive average perceptions of consumers do not directly lead to higher adoptions. For LED lamps, adoption levels are rising when perceptions get more negative. These observations can be explained through putting it in its context: adoption of LED rises because it is becoming cheaper. However, the LED experience is not good: lamps fail early and the colour temperature is bad. This deteriorates its perceived performance. For incandescent bulbs it is even more striking: the perception of incandescent light bulbs under the ban on bulbs appears to be irrelevant: perception levels hardly change at all when adoption levels drop from 100% to 40%. However, this is simply caused by the unavailability of incandescent bulbs after some time in the simulation. But from a system's perspective perceptions for incandescent bulbs are hardly related to actual adoption (and this also holds in other scenarios). This gives us reason to believe that affecting the perceptions by means of providing information on incandescent light bulbs is not a useful strategy for energy saving.

The simulation results indicate that the normative influence is of importance. Further research to which extent word of mouth effects influence the system evolution is needed.



(a) CFL (under no intervention) (b) LED (under no intervention)



(c) Halogen (under no intervention) (d) Incandescent (under ban on bulbs)

Figure 6.7 – Experiment 1: Adoption and perception of consumer lighting technologies are related in counter-intuitive ways. Except for LED, time increases with values from right to left.

It is expected, that, although light bulbs are products characterized by low-involvement of consumers, the social network is very relevant, if only to change the level of involvement.

6.3.4 Analysis

From the simulations, we conclude that it is likely that the EU's ban on bulbs policy is a very effective way to curb the use of incandescent lamps for consumer lighting. The adoption declines because of the purchases of more energy efficient lamps. The ban on bulbs is likely very effective at reducing the electricity consumption of the consumer lighting sector, and this effect is quickly realized.

The incandescent bulb taxation is also likely to be effective at reducing the use of the incandescent lamp and decrease the household's electricity consumption. However, it may well take a lot longer to reach similar consumption levels as under the ban on bulbs policy. In contrast to the other policies, the subsidy for LED policy is unlikely to achieve much effect, compared to no intervention.

6.4 Experiment 2: Revisiting of the 1980s

The ban on bulbs is expected to be a drastic input driver transition in consumer lighting. When one would over-rationalize how consumers make decisions, the transition could have been expected in the 1980s or 1990s. The 'superiority' of the saving bulb (at least at some of the characteristics), should have overflowed the market, dramatically reducing power consumption of consumers. Of course, this is not what happened. The incandescent bulb remained dominant and halogen became the main competitor. It is interesting to show which key drivers in the consumer lighting system could have been overlooked. Next to the previous experiment, showing what the likely effect is of the policy options we have *now*, we aim to grasp why the expectations were so far off. It is a means of validation as the experiment will indicate how close we may be to show what may happen.

6.4.1 Model description

The model was extended in a number of ways to be able to perform this experiment, but the basis has remained the same: a network of households purchasing new lamps when their lamps fail. We start the model in the situation of 1980, when the saving bulb was available and try to replay the past – 'predict' what has happened. Details on extensions and adaptations are highlighted below.

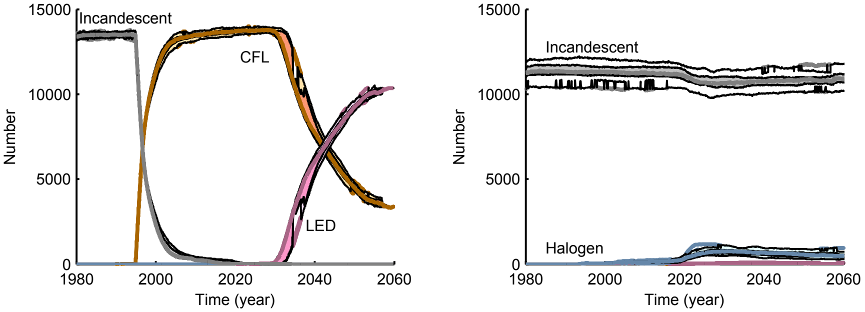
System representation In 1980, households only had incandescent lighting systems. Therefore, households start on average with 90% E27 and 10% E14 sockets. As from 1980, many new sockets entered the market. Agents now slowly replace their luminaires. In addition, we have made it possible to disable a number of basic functionalities of the model. This allows for experimentation of how the consumer lighting system was perceived at the time. More details are given below.

Consumers: Household Agent The household agent was expanded with a behaviour for choosing luminaires. Every time a new light bulb is purchased, there is a 15% chance that the household also replaces the luminaire with one that matches the light bulb of its preference. In this way, new socket types can enter the market.

Lamps and luminaires The set of lamps has been extended with some older CFLs (see appendix D, Table D.3). In addition, the price at the year of introduction, and of the year of introduction itself have been added as properties for all the lamps in the model. The newly introduced lamps do not affect the results of the previous experiment, because they are outperformed by other lamps that were introduced later (but before 2009).

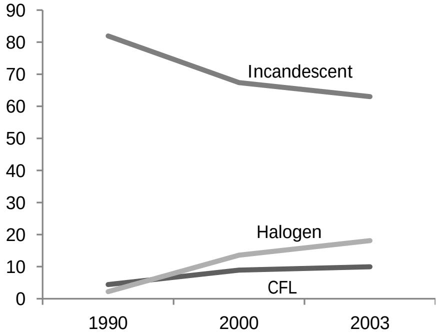
New is a basic set of luminaries (see appendix D, Table D.2). For all the sockets that are common nowadays, luminaries have been defined. In addition, assumed levels of adoption in 1980 and in 2005 are denoted.

Exogenous scenarios This experiment contains two basic settings, which are denoted as experiment 2-a and 2-b (please recall the main differences between experiment 1, 2-a and 2-b in Table 6.1 on page 146). Different from the first experiment is that, next to lamps,



(a) Experiment 2-a: 'naive' expectations

(b) Experiment 2-b: 'realistic' expectations



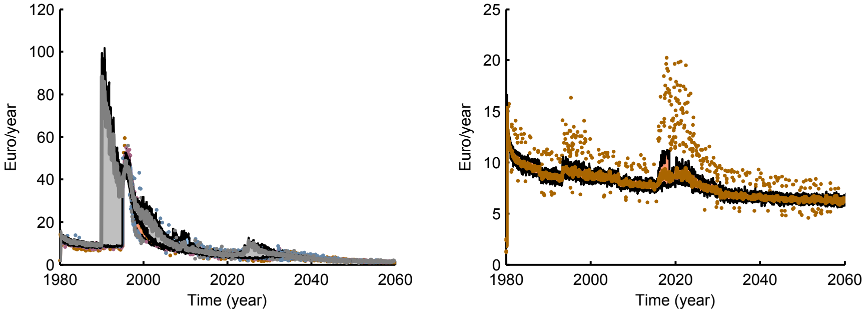
(c) Real values (source: EnergieNed)

Figure 6.8 – Experiment 2: Adoption levels of lamp technologies and real values for the Netherlands

luminaries are replaced slowly through matching a luminaire to the lamp of choice. On average, in 15% lamp purchase decisions, the luminaire is also replaced. Experiment 2-a can be characterized as what 'naive' expectations businesses could have been in the 1980s. We have disabled some of the features in this experiment to match the assumptions underneath these ideas. The households are not in a network, are relatively homogeneous, and have no perceptions. Experiment 2-b is similar to experiment 1: the social network is included, and heterogeneous agents make their decisions, using a variety of criteria and perceptions. Some important differences are that the perceptions at the start are not neutral. CFL starts with a negative perception and halogen with a positive. Furthermore, in the purchase decision, the perception of the technology type is considered very important.

6.4.2 Simulation results

Let us first look at the simulations of experiments 2-a and 2-b in which no policy instrument is implemented. The simulations of experiment 2-a show the 'naive' autonomous transition to CFL. Around the year 2000, all incandescent bulbs are replaced by CFLs. In addition, the transition to LEDs also occurs: within a couple of decades, large numbers



(a) Experiment 2-a: 'naive' expectations

(b) Experiment 2-b: 'realistic' expectations

Figure 6.9 – Experiment 2: Money consumers spend on average

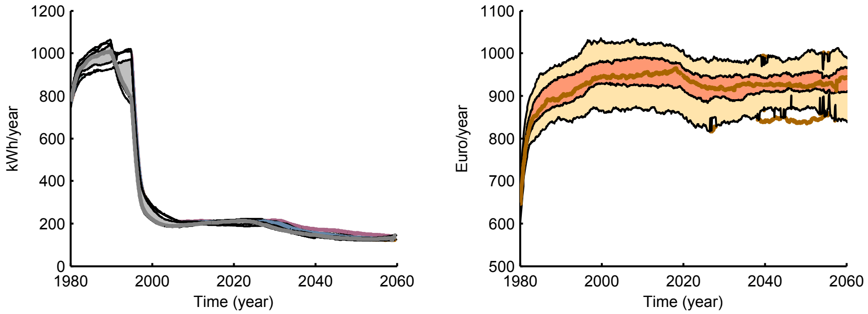
of CFLs are replaced by LEDs (see Figure 6.8). The classical innovation-diffusion pattern, therefore, emerges when important aspects of household decisions – heterogeneity, individual perceptions, technology type, and secondary criteria – are neglected.

In contrast, when these important aspects are included – see experiment 2-b in Figure 6.8 – this transition does not occur. The perceptions around incandescent outweigh the incentive to acquire CFLs or LEDs. In contrast, the positive perception around halogen made this the main competitor. The difference to experiment 2-a is striking, since only a few aspects of the consumer agent have been changed. Other simulations have showed that if the perception of technology type is less important, incandescent stays dominant if no policy is implemented.

Comparing this to what did happen in the past decades, (see Figure 6.8, 6.8c), the *pattern* is similar: incandescent is dominant and mainly attacked by halogen lamps. CFL is used marginally. The deviation in *time* is caused by the modelled trends in prices for the lamps in this experiment. With improved data on lamp prices of the 1980s and 1990s, this could be improved, but these data are hard to come by. For the conclusion they are not relevant either.

In experiment 2-a, there is a spike in consumer spending when CFLs enter the market. Later on, when LEDs are introduced, there is an additional but low spike. This second transition is more gradual and the cost difference is smaller at the time. In experiment 2-b, expenditures typically decrease over time. There is a slight increase when the adoption of halogen lamps, which are more costly then incandescent bulbs, increases. This indicates that the scenario outplaying, which was foreseen, experiment 2-a, bares an unacceptable cost to consumers. Reality proved that it is unlikely that such a burden is accepted. Rather, consumers put aside CFLs and continue to acquire their preferred incandescent lamps. This is not only due to price, since important secondary criteria were neglected as well: perceptions of colour temperature, technology type, whether friends have it, and colour rendering index.

In experiment 2-a, the electricity intensity of consumer lighting is lowered, too, through the penetration of CFLs. From 2000 on electricity intensity is ~200 kWh_e/year which can be considered a good result. After the introduction of LEDs, the electricity intensity drops further, to ~150 kWh_e/year, similar to the results of experiment 1, but



(a) Experiment 2-a: 'naive' expectations (b) Experiment 2-b: 'realistic' expectations

Figure 6.10 – Experiment 2: Average electricity intensity of consumer lighting

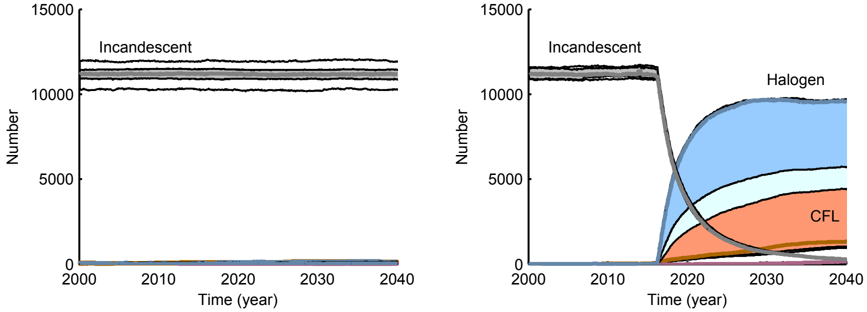
only under the ban on bulbs and the incandescent bulb taxation. This experiment shows that policy is unnecessary when important aspects, regarding how consumer purchase decisions are made, are neglected. Experiment 2-b shows much more of what actually happened and confirmed experiment 1. In contrast to the experiment 2-a, the electricity consumption in experiment 2-b is *not* lowered without government intervention (see Figure 6.10).

Other results of a slightly adapted version of experiment 2-b are displayed in Figure 6.11. The experiment is adapted in the sense that the importance of the perception of the technology type is not dominant. In this case, halogen is not adopted when there is no government intervention and incandescent lamps are dominant throughout the simulation. An important observation is that *halogen* is the most important alternative in this experiment. This can be seen when government intervenes and bans or taxes incandescent bulbs. In these policy scenarios, not the CFL or the LED, but the halogen lamp forms the dominant replacement for the incandescent bulb.

This result did not appear in experiment 1, because luminaires were not replaced *and* there were no halogen lamps taken into account that fit into the traditional E27 and E14 sockets. Therefore, there were no halogen lamps available to fit as replacement for incandescent bulbs. In experiment 2 we enabled the replacement of luminaires. Therefore, the adapted experiment 2-b, in which we model similar policies to experiment 1, shows that halogen replaces incandescent bulbs because consumers will replace their luminaires in order to make halogen fit. This is a clear suboptimal result, as halogen is generally *not more efficient* than incandescent bulbs.

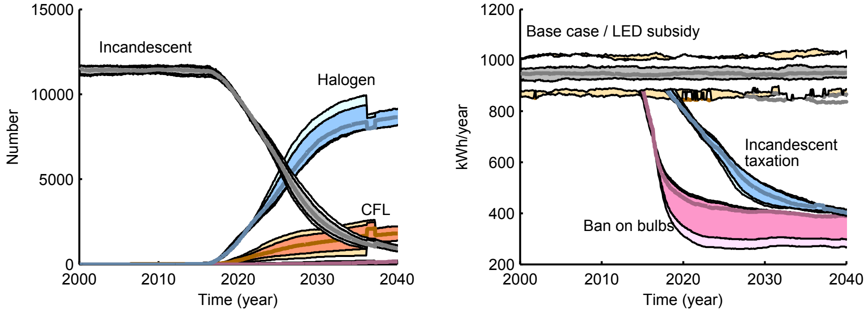
6.4.3 Analysis

In order to validate our conclusions regarding transitions in consumer lighting, we have performed simulations of the consumer lighting system from 1980 onwards. Since consumers were allowed to replace their luminaires and since 'old' lamps were included, the model shows patterns not equal but similar to what happened in reality (experiment 2-b). Without intervention, incandescent bulbs remained dominant. The main alternative technology is halogen, and not CFL. By adapting a small number of parameters



(a) No intervention/LED subsidy

(b) Ban on bulbs



(c) Incandescent bulb taxation

(d) Electricity intensity

Figure 6.11 – Experiment 2-b (adapted): Adoption levels of lamp technologies and electricity consumption under the ban on bulbs and the incandescent bulb taxation. Perceptions of the technology types are less relevant in this adapted experiment

used in the lamp purchase decisions made by households we were able to show what would happen when consumers were over-rationalized in the analysis (experiment 2-a). In these experiments, influences through the social network were neglected, perceptions were not included as criteria for the purchase decision, and heterogeneity of households was decreased. Under these assumptions, which apparently were behind the projections in 1980, CFLs would have penetrated the market fully around the year 2000, even in the absence of government intervention. Afterwards, a transition to LED is predicted under these assumptions.

6.5 Conclusions

A transition in consumer lighting can be expected. It is a primer example in which direct regulation forces the transition. It will be effective and rather efficient. The simulations and the discussion around it show that – if politically feasible – a transition policy which *limits* the options for consumers can be a way to overcome the lock-in effect of, in this case, socket-specific luminaires.

The simulation model confirms that, in the long run, the ban on bulbs is the most *effective* way of achieving a lower electricity usage for lighting. A tax on bulbs of €2 is also effective. In contrast, a subsidy on LEDs at acceptable levels is not effective. An important disadvantage of a ban is the burden on consumers: expenditures spike during the phase in of the ban. This might be considered unacceptable. In contrast to the ban, a tax could be made income neutral. Whether it is a ban or a tax, it is crucial to attack all unwanted products. In this case halogen is *not* more electricity extensive then incandescents, but is not banned or taxed. If the penetration of halogen proceeds, it hampers the transition to lower electricity consumption in the sector.

We have shown that these conclusions are robust. In additional experiments we could replicate patterns from the 1980s and 1990s. From the 1980s onwards neglecting important parts of the consumer decisions lead to 'naive' and unrealistic results. It is important to note that settings replicating realistic behavioural patterns lead to similar conclusions on the effectiveness that government policy will likely bring about from 2010 and onwards.

The agent-based model of transitions in consumer lighting can be improved further by way of gathering experimental data regarding perceptions and importance of the criteria used by households in their lamp purchase decisions. Such a project would lead to a further specification of the model and lower the bandwidth in the results and would probably lead to additional confirmation of the conclusions that were drawn. The insights from this model imply that for other sectors – where consumers are not particularly involved with the product and where better alternatives which are not adopted are available – a ban on or a tax on unwanted products is a good measure. In order to substantiate such a conclusion, the model can be adapted to simulate other sectors and products, which will prove to be relatively straightforward.

7 Analysing Simulations of Energy Transitions

Anything that, in happening, causes itself to happen again, happens again.
It doesn't necessarily do it in chronological order, though.
Douglas Adams – Mostly Harmless, 1992

7.1 Introduction

In the empirical sciences, one starts with a hypothesis that has to be proven or falsified[1]. This hypothesis describes the nature of a relation between two or more variables. In analogy, in simulation studies a *causal diagram*[2] describes the relations between variables observed in reality, grasped in the simulations. Depending on the nature of a simulation study its goal can be reformulated, from the specific modelling question to verifying the relations in the causal diagram by executing simulations[3].

Typical analyses of simulation data comprise plotting and investigating individual relations. As we will argue, such analyses may lead to faulty conclusions, because a) the strength of relations may be time-dependent and b) there are many relations, each of which partly explains the results. Therefore, we require a complementary approach that is able to estimate whether a causal diagram fits the data from simulations. The *strength* of a relation is measured with the partial correlation between two parameters. The partial correlation is the correlation between the parameters corrected for correlations with other parameters. A significant (partial) correlation is one of the requirements for a causal relation, but the strength of a relation refers to the partial correlation between the parameters and *not* to the causality. In this chapter, we will investigate which method can be used to confirm a causal model by means of adequately representing the strength of multiple time-dependent relations between parameters, captured in data from simulations.

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[1] This chapter is partly based on Chappin and Heijnen (2009).

[2] A causal diagram is a drawing of parameters and their causal relations as directed arrows, for instance the diagram of Figure 7.1

[3] There are also simulation studies with a more exploratory nature. It may be that for such studies the modeller has no causal diagram in mind, but we conjecture that it is fruitful for such a study to make at least some hypothetical causal diagram, in order to benefit from the comparison of the modellers' conceptual ideas and the simulation results.

First, we shortly introduce the case on power generation and carbon policy that is used to illustrate the developments in this chapter. Based on an exploration of the mentioned issues regarding the analysis of simulation data, we derive a list of criteria for a method that is resilient to these issues. Subsequently, we will give an overview of the methods from the literature, relevant to this problem. Based on this analysis, we conclude that a different approach is needed. Therefore, we present the developments of the so-called tool that adopts a *dynamic path approach*. We illustrate the tool and the approach through the case on power generation and carbon policies (described in chapter 4).

7.2 Introduction to the case: power generation and carbon policy

In this chapter we will use the case on transition in CO_2 emissions from power generation, as discussed in chapter 4. To move the power sector towards sustainability, it is now widely understood that we need to reduce CO_2 emissions. In Europe, governments have committed to ambitious targets, up to 50% reductions of CO_2 in 2050. Two key policies to do this are carbon taxation (CT) and emissions trading (ETS). There has been a lengthy debate in the literature on what is better, in general economic terms: price or quantities (Coase, 1960; Pigou, 1947; Bimonte, 1999; McChesney, 2006) and applied to the energy case: tax or trading (Ekins and Barker, 2001; Hovi and Holtsmark, 2006; Stoft, 2006; Grubb and Newberry, 2007). From the literature it is not clear whether these policies will lead to a timely shift in power generation technologies and fuel choice to meet the ambitious CO_2 targets. We postulate that this requires a transition (Geels, 2002b, 2005d) that needs to be managed (Rotmans et al., 2001; Loorbach, 2007). To enable such a transition, the policy needs to be an effective transition instrument (Chappin and Dijkema, 2008c). We made a causal diagram of the relevant relations (see Figure 7.1). Fuel prices and electricity demand are exogenous to the system. Depending on the scenario, also the CO_2 price is exogenous: it is zero under no intervention, exogenously determined by government under carbon taxation, but an endogenous outcome of the market under emissions trading. The electricity price is a real endogenous parameter: it is the result of the complex interaction of fuel and electricity markets, the actions of the agents in the model and, if apparent in the scenario, the CO_2 market. The portfolio of installations is a combination of the contributions of all possible technologies (coal, coal with carbon sequestration and storage (CCS), natural gas, biomass, and wind). They change by investment or dismantling decisions of the agents. Investment decisions have a significant construction time. Therefore, these decisions are based on *the past* of many parameters in the model. The dependence on the past of electricity, fuel and CO_2 prices is relevant. The main indicator of progress is the level of CO_2 emissions, which is mainly determined by the portfolio of power plants. These relations were the basis of the development of the simulation model. However, the strength and significance of those relations, and whether they change over time, is unknown ex-ante.

The agent-based model (ABM) that was developed to compare the effect of the two carbon policies on power generation was presented in chapter 4. The ABM paradigm matches the structure of the electric power production sector, where independent power producers, governments, and consumers are represented agents who compete and interact

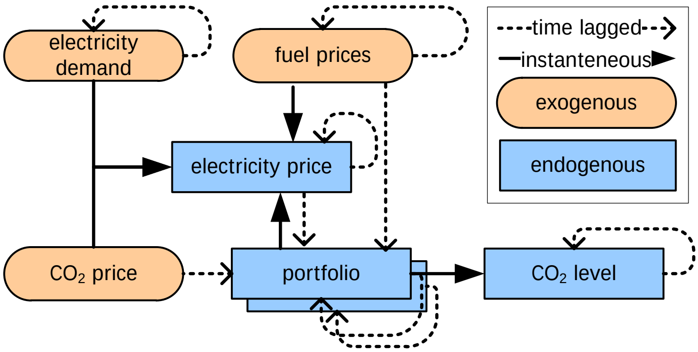

Figure 7.1 – Conjectured causal diagram, containing relevant and important relations in the simulation model. An instantaneous causal relation refers to a relation for which the cause and effect occur within the same time step.

via markets. The model contains a social subsystem that contains these agents and their interactions. In addition, the physical subsystem is modelled to contain installations, their physical connections, and the flows of physical goods.

Six independent electricity producing agents have different portfolios of power generation facilities. The agents negotiate contracts for feedstock, the sales of electricity and, in the case with emissions trading, emission rights. On a strategic level, the agents need to choose when to invest, how much capacity to build, and what type of power generation technology to select.

The external world is represented by exogenous scenarios. The characteristics of the modelled system are emergent: the generation portfolio and merit order, fuel choice, abatement options, as well as electricity and CO_2 prices, and emissions emerge as a result of the decisions of the agents. The model has been run for three cases: no carbon policy, emissions trading, and carbon taxation. As such, a transition in emissions would also be an emergent property of the model.

The outcomes of this simulation model have been presented in several ways. In general, we aimed at finding patterns in the output of simulation by comparing different groups of runs, each group representing one of the policies. The different groups are compared on one parameter at a time. In order to make such graphs, average values and a measure for the spread are calculated, so that the results can be interpreted. Emergent patterns in a number of different indicator parameters were presented as outcomes of the above mentioned model: CO_2 emission levels, electricity and CO_2 prices and the portfolio of power generation facilities (see Figure 7.1, and recall Figure 4.13, and Figure 4.14).

7.3 Drawing conclusions based on simulation data

In this section, two pitfalls regarding the analysis of the simulation results are addressed. The pitfalls are illustrated by examples from the case described in the previous section. A list of criteria is derived, preventing the mentioned pitfalls in the analysis of simulation data. Of the relevant methods we found, the weaknesses and strengths in terms of those criteria are discussed. It is concluded that none of the methods prevent these pitfalls in their current state.

7.3.1 Pitfalls regarding conclusions from simulation data

First, there is the pitfall of *claiming causalities*. One could, for instance, come to the counter-intuitive conclusion that higher natural gas prices lead to higher adoption of power plants running on natural gas. This can, of course, be caused by one or more other factors: coal prices went up more than natural gas prices, technology improvements, governmental subsidies, expectations of future natural gas prices, and availability. In this example, it is obvious that if there is a direct relation between natural gas price and the related adoption of power plants, it can only be negative. However, when analysing simulation outcomes it is not always as transparent. In general, one can only claim causality between A and B if (1) there is a statistical relation found in the data, (2) A happens before B in time and (3) there is no other variable explaining both A and B (cf. Aldrich, 1995). How can we prevent this pitfall in the analysis of simulation results if we can only plot one or two parameters at a time and base our conclusions on combining the several graphs? Therefore, we need to explicitly address all relevant parameters at the same time.

Second, there is the pitfall of *independent observations*. Many statistical techniques require independent observations to be valid. For instance, if you want to predict next years electricity prices, you would make a regression model with as dependent parameters all fuel prices, since they are known to impact the electricity price. In this case you use a fundamentally flawed approach, since the electricity price is dependent on its history: it is *autocorrelative*. Data analysis techniques either assume independent observations (e.g. regression analysis) or they are not able to show how relations change over time (e.g. time series analyses). How should we draw solid conclusions based on time dependent data, without using classical statistical methods that require independent observations?

We face the combination of both pitfalls. We have a conceptual causal model in mind of how parameters affect each other and with or without a time delay[4] and we want to test the validity of such a conceptual model on the basis of simulation results. We might presume in such a conceptual model that one parameter is causal to another, but that the causal effect takes some time: the delay may be larger than the length of a time step. On the other hand, there is more than one parameter affecting others, so we need to take more factors into account at the same time. If we manage to do that, we can get insight in contributions of individual parameters, for instance in order to weigh the impact of exogenous and endogenous parameters.

7.3.2 Criteria for the method needed

The described problems lead to a set of criteria for an analysis method that allows to deal effectively with simulation data. The criteria for the method needed should be able to analyse successfully the simulation results of the case presented. The method should allow for time delayed and instantaneous causalities to occur between endogenous and

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[4] A requirement for a causal relation is that the cause precedes the effect in time. When we consider instantaneous relations, we refer to causes and effects that occur *within the same modelled time step*.

exogenous parameters. In addition, the strength of multiple relations should be clarified in order to confirm a causal model, containing the parameters.

Some criteria are on the type of parameters (exogenous, latent, discrete), some on the relations (dynamic, autocorrelative, indirect, multiple), and some on the type of analysis (quantitative, confirmatory, comparative, and exploratory). The criteria are strict requirements except when noted otherwise.

Criteria regarding the type of parameters *Exogenous* – The method must be able to distinguish endogenous from exogenous parameters. An exogenous parameter is not influenced by other parameters. Endogenous parameters are influenced by other parameters. In the presented case, fuel prices are exogenous parameters.

Latent – It would be nice if the method discerns *unmeasured* variables, based on indicator variables from measured variables. For instance, we could use indicators to estimate underlying concepts, such as greenness of the power generation portfolio and the speed of transition, without explicitly measuring it.

Discrete – The method must be able to deal with discrete data, taken at a regular time interval.

Criteria regarding the relations between parameters *Dynamic* – The method must be valid for instantaneous relations and time-lagged relations. It takes at least three years to build new power plants after the investment decision has been made, so the impact of parameters on portfolio changes is by definition time-lagged. However, the impact of the CO_2 price on the electricity price is within the same year. The modelled time step is one year, so in the model outcomes, it is instantaneous.

Autocorrelative – The method must be valid for parameters depending on themselves in the past, such as prices for fuels, electricity, and CO_2.

Indirect – The method must be able to discern direct relations between parameters and indirect relations, where two parameters depend only on each other through a third. For example, the impact of CO_2 price on actual CO_2 emissions, which is only through the power market.

Many-to-many – The method must be able to deal with the fact that more than one independent variable is affecting more than one dependent variable.

Multiple – The method must be able to deal with multiple relations between parameters. One could argue for repeating a method capable of single relations, but it is intended that several relations are modelled and assessed simultaneously. Where a parameter is one of the dependants in one relation, it might be an independent in another.

Cyclic – It would be nice to allow for the possibility of cycles in the set of relations ($X \rightarrow Y \rightarrow Z \rightarrow X$). For this criterion, the multiple criterion is a requisite.

Variable relations – The method must be able to deal with relations that appear and disappear and change in strength over the simulated time.

Criteria regarding the type of analysis *Quantitative* The method must be able to quantify the strength of relations[5].

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[5] The statistical strength of a relation is measured in partial correlation

Table 7.1 – Overview of how the methods for data analysis score on the identified criteria

	Parameter		Relation						Analysis			
Method	Exogenous	Latent	Dynamic	Autocorrelative	Indirect	Many-to-many	Multiple	Cyclic	Quantitative	Conformatory	Comparitive	Exploratory
Static methods												
Partial correlation	+	–	–	–	+	–	–	–	+	+	+	+
Regression analysis	+	–	–	–	–	–	–	–	+	+	+/–	+/–
Canonical regression analysis	+	–	–	–	–	+	–	–	+	+	+/–	+/–
Factor analysis	+	+	–	–	–	+	–	–	+	+	+	+
Principle component analysis	+	+	–	–	–	+	–	–	+	+	+	+
Independent component analysis	+	+	–	–	–	+	–	–	+	+	+/–	+
Decision trees	+	–	–	–	–	–	+	–	+	–	+	+/–
Path analysis	+	–	–	–	+	+	+	?	+	+	+	–
Structural equation modelling	+	+	–	–	+	+	+	?	+	+	+	–
Dynamic methods												
Graphs over time	+/–	–	+/–	+/–	–	–	+/–	–	+	+/–	+/–	+/–
Tables	+/–	–	+/–	–	–	–	+/–	–	+	+/–	+/–	+/–
Time series modelling	+	–	+	+	–	–	+	–	+	+	+	+/–
Dynamic structural equation mod.	+	+	+/–	+	+	+	+	–	+	+	+	–
Dynamic path analysis	+	–	+/–	?	+	+	?	–	+	+	+	+/–

Confirmatory The method must be able to confirm or reject a conceptual model of the relations of parameters.

Comparative The method must be able to compare the performance of alternative models, for instance comparing the effect of two possible governmental strategies, emissions trading, and carbon taxation.

Exploratory It would be nice if the method is applicable for exploration of interactions of parameters and by means of this for the development of new conceptual models.

7.3.3 Most relevant methods

We will now elaborate on the most promising methods in the literature that are applicable to these criteria or to some of them. An overview of the methods is given in Table 7.1. As can be seen from the table, none of the methods is applicable to our problem. They all lack one or more of the criteria. Still, they can provide input to a new approach which has to be developed. For each of the methods, the main issues in this respect are highlighted.

Static methods The main disadvantage of static methods is that they are only applicable for time-independent data. Therefore, the methods described below are not useful as such. Since they can be a potential candidate for further development, we introduce them shortly. *Partial correlation* corrects a correlation of two variables for the movement of other parameters. In other words, the movement of two variables is isolated from the other parameters. *Regression analysis* models the relation between one or multiple independent variables and one dependent variable. *Canonical regression analysis* extends the concept of linear regression allowing it to deal with multiple dependent variables y (Hair et al., 1998, p. 442).

Factor analysis is a set of methods which can capture 'underlying factors' that are impossible to measure directly. These methods aim for finding underlying mechanisms or latent variables, based on multiple indicators. If several indicator variables stem from the same underlying concept, they will have shared variance. Factor analysis uses the shared variance of all indicator parameters and finds an appropriate number of underlying mechanisms. The latent variables can, but do not have to be independent. *Principle component analysis*, from this family of methods, finds underlying mechanisms in a different way. In its analysis it focuses on all the variance, not only the shard variance. This makes factor analysis better equipped for summarizing data then finding underlying theoretical concepts. The latent variables can, but do not have to be independent. *Independent component analysis* also stems from this family (Hyvärinen and Oja, 2000). One dependent variable is a mixture of an unknown number of latent variables. In addition, it is not known how the variables are mixed. The latent variables are assumed mutually independent. The analysis aims to find these independent components that lie under the observed outcomes through maximizing the statistical independence of the estimated components (Hyvärinen, 2009).

Decision trees stem from data mining (Hair et al., 1998, p. 681). Decision trees are used to divide a set of cases in a tree of groups, based on its outcome on a dependent variable. Typically, the objective is to find the largest separation. A tree is drawn based on iterating over all the separations. *Path analysis* estimates multiple linear relations simultaneously. A path of relations among a set of variables is defined, resulting in a set of linear regression equations. The complete set of relations is estimated at once, which is different to normal regression. *Structural Equation Modelling* (SEM) is often referred to as a synonym of path analysis. However, it is a method that builds upon path analysis, by including latent variables in the analysis (ref. by using factor analysis). The method estimates a series of separate, but interdependent, multiple regression equations simultaneously through specifying the structural model (Hersberger et al., 2003). The main problem with applying path analysis or SEM is that both assume time-independent data.

Dynamic Methods Dynamic methods are aware of time-dependent observations. The most used dynamic method is using *graphs with time* on the x-axis and another parameter on the y-axis. Sometimes a third parameter is introduced on the z-axis. This is an informatory method and it works well for presentation. Its main disadvantage is its limitation to two or three dimensions. In addition, causalities are left implicit: analysis of the graph will include this. Spread in outcomes are often covered by different lines or in areas which get wider over time. An example of a two dimensional graph is the dynamic box plot, which has been used throughout this thesis (e.g. Figure 4.13). In such a graph, the boxes of a box plot are drawn and connected for each time step. This results in areas in which 50% of the values lie. *Tables* can be used to display data over time. However, tables allow only for presenting data. They are no techniques for analysis.

Time series can estimate parameters that gives the best prediction of time series of one dependent variable (Yaffee, 2000). These parameters can be a combination of the past of the variable itself (that is called autoregressive) and other variables. The parameters are estimated for a single dependent variable and for one set of data at a time. Time series analyses are not applicable to our problem, because they do not allow for relations to appear, disappear or change in strength over time. An additional problem is that time series analysis does not allow for estimating multiple relations at once. *Dynamic structural equation modelling*, an expansion of structural equation modelling, includes a time dimension by distinguishing all parameters in each time step (Reinecke et al., 2005). It is, therefore, possible to include time-dependence and a time lag between parameters. The main disadvantage however is similar to time series modelling: the strength of relations is assumed to be constant: "if there is no coherence between time interval and causal lag, parameter estimates of the structural equation models can lead to wrong substantive conclusions" (Reinecke et al., 2005). *Dynamic Path Analysis* uses time-indexed directed acyclic graphs (Fosen et al., 2006). Two outcomes are gained at: (1) to find adequate path diagrams reflecting the data at all points in time and (2) to distinguish direct and indirect effects and their contributions over time. Latent factors are not included yet, but could be a possible extension. This method however does not allow for cycles.

7.3.4 Analysis

We have identified two pitfalls that occur when conclusions are drawn based on simulation data. One is related to claiming causalities and the other is related to the assumption of independent observations. After listing the criteria that prevent these pitfalls, we found that none of the methods common in the literature meets all criteria. Many cannot properly deal with *dynamics*, because they require time-independent observations. Also the more advanced and less common methods in the literature (dynamic structural equation modelling and dynamic path analysis) are inappropriate, since both assume the strength of relations to be constant over time. In contrast, methods that allow for dynamics are not able to consider a *set* of relations. Therefore, we postulate that a new approach is needed, combining the approaches of the methods discussed. Such a method would meet all the must-haves and would therewith prevent the two pitfalls. This method would be complementary to the more common types of analysis.

For our new approach, we coin the term *Dynamic Path Approach* (DPA). Using discrete time points as input collected from simulations, we intend to estimate a network of relations, with time dependent data, allowing for change in strength and significance of each relation over time. As such, this approach should allow for confirmation of the before stated causal diagram. It should be dynamic, in the sense that relations may change over time (in strength and significance). In addition, the whole network – or path – of relations is estimated at once.

7.4 Experiment 1: Exploring the potential for a new approach

In a first set of experiments, we explore the usefulness of a new approach. In this section, therefore, we will perform experiments in which some of the requirements are met. We will use existing software to show whether it is worth to pursue a dynamic path approach.

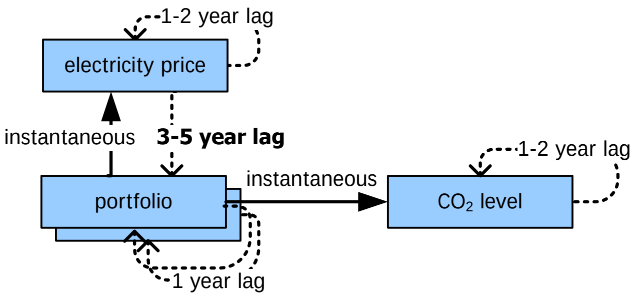

Figure 7.2 – Simplified causal model containing relations used in experiment 1

For this experiment we have used Amos (SPSS Inc., 2009), which is part of SPSS. Amos is developed for structural equation models (SEMs). Amos is not able to generate the lags needed to represent lagged relations, nor is it able to split datasets, according to the scenario. Data preparation for this experiment was done using other tools. A complete set of data, including lags was the input for Amos.

7.4.1 Experimental setup

Dataset Our dataset is that of experiment 2 in chapter 4, described in section 4.5. We delimit our analysis to a smaller set of variables in order to have a practical example while developing the approach. The dataset contains yearly data points with values on all relevant exogenous and endogenous parameters. Each simulation run has 50 data points, one for each simulated year. We have three scenarios, one related to each of the government interventions that was modelled. The governmental scenarios are: no intervention (NOI), carbon taxation (CT), and an emissions trading scheme (ETS). For all scenarios 20 runs were completed. Therefore, for all parameters the dataset contains 50 years $\times$ 20 runs $\times$ 3 scenarios $= 3{,}000$ data points.

Relations to be estimated Figure 7.2 gives an overview of the modelled relations and their characterization. Please note that the relations modelled are instantaneous and/or lagged. For parameters that autocorrelate we introduce a lag of 1 and 2 years as new parameters. Some other relations require a larger time lag. We will discuss all modelled relations below. Before we do that, we give a notion why we do not take any exogenous variables into account first. In the model, electricity demand and fuel prices are modelled as exogenous trends *without stochastics*. Therefore, the variance within each year for the exogenous parameters equals 0. As a consequence, any analysis that takes into account a single year at a time cannot incorporate these exogenous variables, it would just have no explaining power. The underlying idea was that we could isolate the main parameters from exogenous trends, without being unrealistic. In the future we intend to include these variables, by including a variety of values in the parameter sweep. For now we exclude all exogenous variables from the analysis.

In setting up the experiment, there is a trade-off between the number of lagged years one takes into account and the amount of data, left for analysis (see Figure 7.3). On the

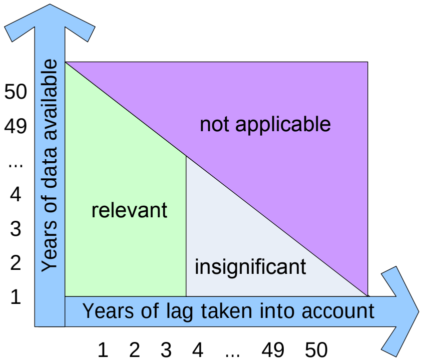

Figure 7.3 – Trade-off between years of data available for analysis and years of lag taken into account

vertical axis the amount of data available for analysis is denoted (in simulated years). Assuming each run has 50 simulated years, the maximum number of years that is available equals 50, the minimum is 1. On the horizontal axis the number of years of lag that is taken into account is depicted. A model with a lag of 0 assumes only instantaneous relations. Since there are no data available regarding the time before the simulation started, a time lag larger than the simulated time is not applicable (the area at the right top). For variables that autocorrelate or depend on other parameters in the past, not all of the past is relevant. Higher time-lagged terms will be less significant for most parameters, except when long time-cycles are known to exist. Therefore, there will be some area (at the bottom right) with insignificant parameters. In addition, there are less data available when taking lags into account. There are, therefore, two reasons for limiting the number of lags: the dataset shrinks and the parameters become insignificant. Part of the exploration may be devoted to the selection of lags.

Following the causal diagram, we selected 9 parameters from the dataset (reflecting the power generation portfolio (one for each technology type), the electricity price and the CO_2 emission level, see Figure 7.1). New parameters are introduced that are time-lagged. Therefore, the size of the model increases to some 40 parameters. Because it is needed to estimate models for each time step, the scripting facilities of Amos (SPSS Inc., 2009) are used where applicable.

Three experiments We perform three experiments. First, we estimate experiment 1-a, in which we only included the instantaneous relations. Therefore, this model is a typical Structural Equation Model (SEM). In the other experiments we deal with the time dependence of the data. In experiment 1-b, we introduce one of the key additions from our new approach. We have added the *time lags* as shown in Figure 7.2. The first years of the simulation data are removed, as the lagged variables in the dataset are incomplete. Finally, in experiment 1c, we introduce the other important time-related aspect. We now start estimating the parameters *per simulated year*. In such an experiment, the relations can change: they can even appear and disappear over time. To use existing software, we had to create 50 datasets, one with the data for each simulated year.

Table 7.2 – Result of experiments 1-a and 1-b: standardized regression weights of all relations. Time dependent relations are taken into account only in experiment 1-b, as time lagged parameters, a one year delay is noted as L^1. Electricity price is abbreviated as e-price.

Category	Independent	→	Dependent	Experiment 1-a			Experiment 1-b		
				NOI	CT	ETS	NOI	CT	ETS
Portfolio	natural gas L^1	→	natural gas				**0.974**	**1.013**	**0.969**
	e-price L^3	→	natural gas				0.001	-0.02	0.006
	e-price L^4	→	natural gas				0.003	0.027	-0.002
	e-price L^5	→	natural gas				0.003	-0.054	0.009
	coal CCS L^1	→	coal CCS					**1.002**	**1.007**
	e-price L^3	→	coal CCS					0.002	-0.003
	e-price L^4	→	coal CCS					0	0.023
	e-price L^5	→	coal CCS					0.011	0.028
	coal L^1	→	coal				**0.99**	**0.973**	**0.939**
	e-price L^3	→	coal				0.055	0.009	0.022
	e-price L^4	→	coal				-0.009	-0.002	-0.037
	e-price L^5	→	coal				-0.014	0.026	-0.073
	biofuel L^1	→	biofuel				**0.935**	**0.993**	**0.997**
	e-price L^3	→	biofuel				0.009	-0.002	-0.005
	e-price L^4	→	biofuel				0.024	-0.009	0.012
	e-price L^5	→	biofuel				-0.016	0.009	0.03
	uranium L^1	→	uranium				**0.94**	**0.914**	**0.933**
	e-price L^3	→	uranium				0.021	0.061	0.019
	e-price L^4	→	uranium				0.01	-0.014	0.039
	e-price L^5	→	uranium				0.01	0.025	-0.008
	wind L^1	→	wind				**0.903**	**0.934**	**0.958**
	e-price L^3	→	wind				0.026	0.037	-0.004
	e-price L^4	→	wind				-0.014	0.005	0.02
	e-price L^5	→	wind				-0.015	-0.031	0.008
CO_2 emissions	natural gas	→	emission	0.121	**0.675**	**0.638**	0.041	*0.171*	**0.553**
	coal CCS	→	emission		0.071	**-0.391**		0.084	**-0.29**
	coal	→	emission	**1.029**	**0.566**	**0.934**	*0.317*	*0.148*	**0.81**
	biofuel	→	emission	-0.014	0.049	**-0.405**	0.001	0.051	**-0.309**
	uranium	→	emission	-0.106	-0.023	-0.009	-0.041	-0.009	-0.012
	wind	→	emission	-0.185	-0.049	-0.261	-0.092	-0.008	-0.196
	emission L^1	→	emission				**0.808**	**0.967**	**0.253**
	emission L^2	→	emission				-0.113	-0.125	-0.032
Electricity price	natural gas	→	e-price	**0.689**	**1.407**	**1.077**	*0.187*	**1.263**	**1.111**
	coal CCS	→	e-price		**0.685**	-0.021		*0.91*	*0.061*
	coal	→	e-price	-0.077	**0.499**	**0.621**	-0.13	*0.742*	**0.701**
	biofuel	→	e-price	-0.073	**0.339**	-0.106	-0.005	**0.477**	-0.038
	uranium	→	e-price	-0.238	0.006	-0.045	-0.176	-0.003	-0.05
	wind	→	e-price	*0.011*	0.172	-0.079	*-0.018*	0.158	-0.012
	e-price L^1	→	e-price				**0.638**	**0.354**	-0.046
	e-price L^2	→	e-price				-0.015	-0.043	**0.221**

7.4.2 Results

Experiment 1-a: Structured Equation Model could be estimated The first model, which is an ordinary Structural Equation Model (SEM), resulted in the regression weights, displayed in Table 7.2. Each of the regression weights is, in itself, explainable. Overall model fit statistics were high. This is measured with a variety of fit indices that can vary between 0 and 1, where 0 implies a non-fit and 1 a perfect fit. In appendix E, the fit indices are described. For this experiment we found a goodness of fit index (GFI) of 1.000, and an adjusted goodness of fit index (AGFI) of 0.841. This indicates that the path model explains the data well.

Experiment 1-b: Path model with autocorrelations and lags could be estimated Next, we included all time lags as shown in Figure 7.2. We were again able to estimate models for all three scenarios. We removed the years for which no time-lagged data are available (the first years of the simulation). The model fit statistics were again good, i.e. a GFI of 0.799, and a AGFI of 0.810. Although these numbers are lower than those in experiment 1-a, they are high enough to be confident. The regression weights are presented in Table 7.2 and show quite different results.

Experiment 1-b: Autocorrelations are significant We found that autocorrelation of the portfolio components (each technology type) is very high (standardized regression weights vary between 0.9 and 1.0) and that the differences in autocorrelation between scenarios are very small. Also emission levels and electricity prices autocorrelate, but the results from the emissions trading case are quite different from the other two: the second order time lag of the electricity price is more relevant under emissions trading than the first order time-lag. The electricity price is predictable under no intervention, which is shown in a high autocorrelation (0.638). The contributions of the portfolio composition are significantly different under the scenarios. They can be explained when we take the patterns in portfolio compositions into account.

The very contrast of the autocorrelation of the emission levels is striking. It shows how different (and unpredictable) the impact of the emissions trading scheme is: only under this scenario, autocorrelation is almost absent (first order 0.253 and second order -0.032). Under the other two scenarios this is very high (first order 0.808 and 0.967 and second order -0.113 and -0.125). This finding can also be explained by earlier results: the emissions are only volatile under this scenario. Under the other two, they go down far more steadily.

This implies that in the case of emissions trading the electricity price and emissions are less predictable. This information is only available in experiment 1-b and this leads to an additional conclusion.

Experiment 1-b: Including lags affects the result Some of the strengths of the relations are quite different in experiment 1-b, compared to experiment 1-a (see the italics in Table 7.2). How in experiment 1-a the coal price affects the actual emissions is overestimated in the case of no intervention and carbon taxation, but not in the case of emissions trading. Experiment 1-a overestimates the impact of the natural gas price on the electricity price, but only in the case of no intervention. And even worse: experiment 1-a estimates the relation between coal CCS and the electricity price to be negative instead of positive, as it is in experiment 1-b.

These results clearly show that – only taking into account constant relations over time – the dynamic path approach leads to more and different results and, therefore, also to different conclusions. The advantage of using the approach will only grow, when we further develop it and arrange for more data from simulations. For instance, we expect the importance of specific portfolio parameters to change over time: coal with CCS is only available after the first 10 simulated years and, therefore, can only be apparent in the latter part of the simulation. In contrast, conventional coal disappears in the simulations with carbon taxation and emissions trading, so we must be able to see that in the strength of the relations of coal with other parameters. It is likely that if we can analyse the change in these parameters *in combination with* the strength of the impact of exogenous parameters, such as fuel prices, we will gain new insights in the dynamics of the possible transitions in the power generation sector.

Experiment 1c: Year-specific parameters could not be estimated In our final trial, we took subsets for each year. We were not able to estimate the models, because the available dataset, 20 cases, is too small. Therefore, we are not yet able to show how the relations change over time. We are confident, however, that we will be able to do that with a bigger dataset. Using such models is however fruitful. Therefore, we intend to adapt our simulation setup and increase the number of simulation runs.

7.4.3 Analysis

By the first set of experiments, we have identified two main arguments that underpin the need for a new approach for the analysis of simulation data. Two main observations can be made, which are strong arguments in favour of the dynamic path approach. First, only with the improved approach, results on autocorrelation can be obtained. The autocorrelations in our dataset proved to be significant. Second, introducing lags and autocorrelations results in different strength and directions of some of the relations. Therefore, the improved approach will lead to different conclusions. The last experiment was unsuccessful with our dataset. In order to make a similar experiment successful we need a bigger dataset. In addition, improving the usability of the approach, by means of developing a tool, may well prove highly valuable. Therefore, we have sufficient signals to start both the development of a tool and the generation of a bigger dataset that makes it possible to perform such experiments successfully.

7.5 Experiment 2: Using the Dynamic Path Approach (DPA)

In the second set of experiments, we use both a different dataset and a different tool.

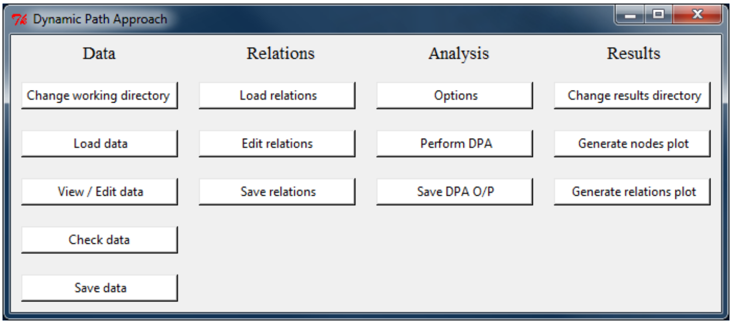

Figure 7.4 – Main screen of the DPA module in R

7.5.1 Development of the tool for the Dynamic Path Approach

Based on the experience in the first set of experiments, the analysis in appendix E, we have selected R as platform to develop the tool. Only in R, the basic functionalities for structural equation modelling are available, a graphical user interface can be created by using available modules, *and* scripts can be used to automate many of the required tasks.

Of the software packages available, only R is open source and free to use on all commonly used operating systems (Windows, Mac and Unix). R has a very large extension base, i.e. 2,500 user-contributed modules, available through the Comprehensive R Archive Network (CRAN)[6]. This is an indicator of the large and active user community that R has. Within R, we select several modules that are needed and we connect, extend, and use these in a new module, as is common in R. Our new package is called *dpa*. Functionality is written in methods within this module, but the user interaction is mainly through the user interface that is developed with it. The DPA module is released as an open source R package on the Comprehensive R Archive Network (CRAN). It is publicly accessible under http://cran.r-project.org/web/packages/dpa. The functions in the DPA module are related to data, specifying relations, performing the analysis, and analysing the results.

The tool can be used through its user interface (see Figure 7.4). In addition, small scripts can be used to automate all steps: importing data, specifying the relations, performing the analysis, and saving the results in the form of graphs and a movie. In appendix E, the basis of such a script is explained.

7.5.2 Experimental setup

Dataset To overcome the limitations found in the analysis before, a new dataset was generated. Fuel prices were generated using stochastic, rather than deterministic price trends. Furthermore, a much larger dataset was generated, containing 1,000 runs per scenario. Therefore, for all parameters the dataset contains 50 years × 1,000 runs × 3 scenarios = 150,000 data points.

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[6] As of 13 October 2010, http://cran.r-project.org/

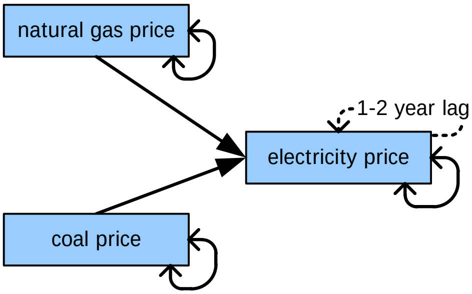


Figure 7.5 – Simplified causal model containing relations used in experiment 2

To be estimated relations Similarly to the first experiment we would like to estimate the relations in the causal model visualized in Figure 7.2. However, we were not able to estimate these relations with the new tool. This is probably caused by the SEM module and/or solver that R provides, but it can also be related to the dataset used. We will reflect on this fact later. For now, we introduce a more simple causal diagram in Figure 7.5.

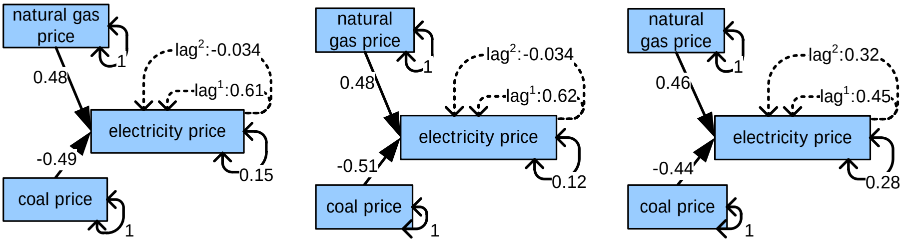
Both the coal price and the natural gas price are assumed to affect the electricity price instantaneously, because electricity producers use both prices in their bids on the market. Eventually the market price is based on all bids. However, there are many other factors, determining the electricity price. Many of these change over longer time than the coal and gas price. Therefore, such parameters can be explained by way of including the electricity price of the last two years in the analysis.

Two experiments In this experiment we will not do a similar analysis as experiment 1-a, in which we only included the instantaneous relations. We already showed the benefit of including lagged parameters and autocorrelation, which was the difference between experiments 1-a and 1-b. Experiment 2-a will be similar to experiment 1-b. Time lagged parameters are included in this experiment, as shown in Figure 7.5. Experiment 2-b goes one step further, as was intended as experiment 1-c. We introduce the other important time-related aspect and estimate the parameters *per simulated year*. In such an experiment, the relations can change over time, appear, and disappear.

7.5.3 Results

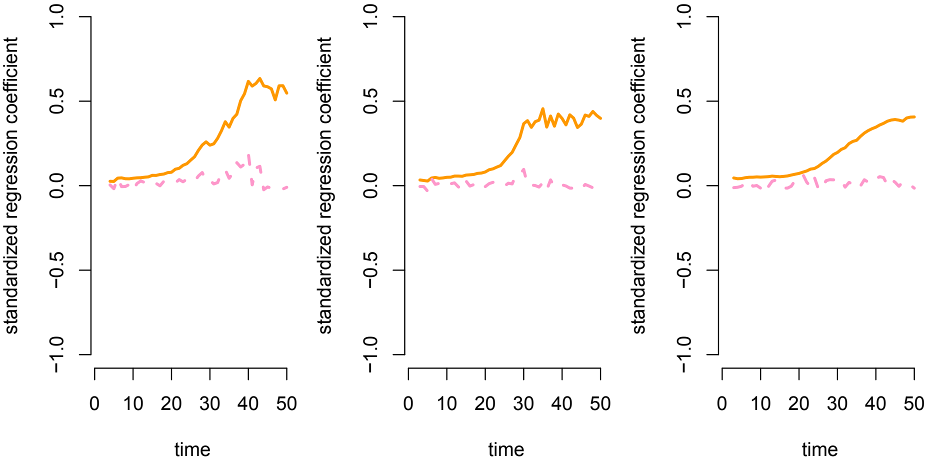
Experiment 2-a: Path diagrams with lags differ for the three scenarios The results from experiment 2-a are displayed in Figure 7.6. Similar to experiment 1-b, the path diagrams could be estimated and the standardized regression coefficients show the relative strength of each relation. Some differences are relevant. Specifically, the 2 year lag of the electricity price is close to 0 under the no intervention and carbon taxation scenarios, but 0.32 under the ETS scenario. Furthermore, the variance of the electricity price is also larger under only the ETS.

Experiment 2-b: The relations change significantly over time In experiment 2-b, we observe that the strength of relations change over time. This can be observed in a plot with the two main coefficients, drawn in Figure 7.7. In the first two decades of



(a) No intervention (b) Carbon taxation (c) ETS

Figure 7.6 – Experiment 2-a: Path diagram with estimated coefficients

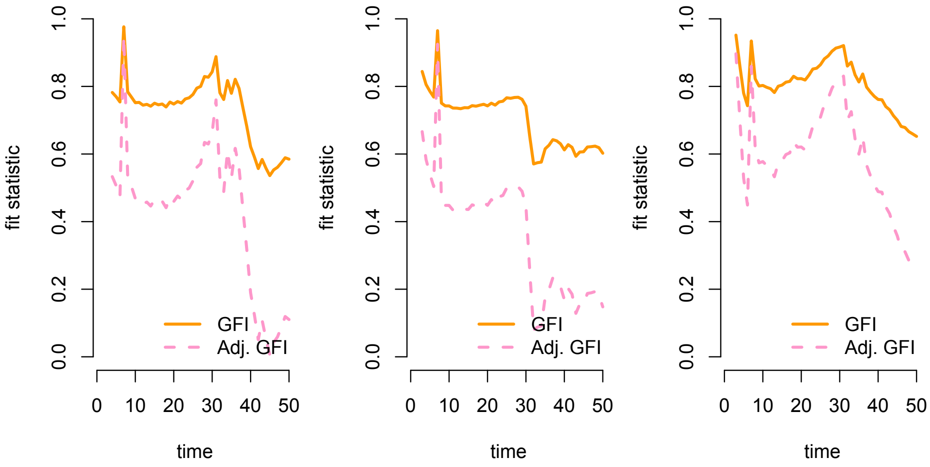


(a) No intervention (b) Carbon taxation (c) ETS

Figure 7.7 – Experiment 2-b: Main regression coefficients over time. Solid lines: natural gas price → electricity price. Dashed lines: coal price → electricity price.

the simulation, the natural gas price has only a marginal impact on the electricity price. However, the impact grows afterwards and it peaks around 0.5. The trajectories of the scenarios are slightly different: under no intervention, the impact of the gas price is a little bit higher than under carbon taxation and under the ETS. Under carbon taxation, the effect stabilizes after 30 years. In contrast to the natural gas price, the impact of the coal price on the electricity price is close to zero throughout the simulation, for all scenarios.

Experiment 2-b: The quality of the model changes significantly over time and is lower than in other experiments Next to the fact that individual parameters change over time, so does the fit of the model as a whole. This is depicted in Figure 7.8. The goodness of fit index changes over time and is quite different for the three scenarios. Typically, the goodness of fit index is high in the first half of the simulation, with values around 0.8. In the second half of the simulated time the goodness of fit index drops, to



(a) No intervention (b) Carbon taxation (c) ETS

Figure 7.8 – Experiment 2-b: Fit statistics over time. Solid lines depict the goodness of fit index (GFI). Dashed lines depict the adjusted goodness of fit index (AGFI).

levels round 0.6. This drop is steep under carbon taxation and more smooth under no intervention and the ETS. The adjusted goodness of fit index gives a similar, but amplified result. Values start high (between 0.5 and 0.8) and drop significantly in the second half of the simulated time. Low values, even lower than 0.2 are denoted especially under no intervention and carbon taxation.

These values for goodness of fit point at a potential problem. Important parameters are missing in the analysis, especially in the second half of the simulated time. This was not noticed in the other experiments. It also points at the fact that a high goodness of fit does not necessarily equate to a good causal model. It is only one indicator that shows whether the set of specified relations fits the data well or not.

Experiment 2-b: Including change of relations over time affects the result What could have been expected is that the estimated relations of experiment 2-a are more or less the average of the range of values found in experiment 2-b. When we turn to experiment 2-b, however, we find that the estimations are very different. The result is striking: the strength of impact of the coal price and natural gas price on the electricity price is greatly overestimated in experiment 2-a. This can be discerned from Table 7.3. In this table, the estimated strengths of the relations of both experiments 2-a and 2-b are denoted. The values for experiment 2-a stem from Figure 7.6. For experiment 2-b, the range of values found are indicated. The numbers displayed in bold font stand out and are discussed here.

The impact of the natural gas price on the electricity price in the experiment 2-a is in all scenarios close to 0.5 However, in experiment 2-b, the impact increases from 0.0 to 0.5 during the simulation. The difference is large and significant, particularly when one realizes that the goodness of fit is especially low when these values are close to 0.5. The average impact of the natural gas price on the electricity price of experiment 2-b is far off the value found in experiment 2-a. For the coal price the difference is even larger. The

Table 7.3 – Result of experiments 2-a and 2-b: standardized regression weights of all relations. Time lagged parameters are denoted with as L^1 for a one year lag.

Independent	→	Dependent	Experiment 2-a			Experiment 2-b		
			NOI	CT	ETS	NOI	CT	ETS
natural gas price	→	electricity price	**0.48**	**0.48**	**0.46**	0.0–0.5	0.0-0.5	0.0-0.5
coal price	→	electricity price	**-0.49**	**-0.51**	**-0.44**	≈ 0	≈ 0	≈ 0
electricity price L^1	→	electricity price	0.61	0.62	0.45	-0.2–0.8	-0.3–0.8	-0.3–0.8
electricity price L^2	→	electricity price	-0.034	-0.034	**0.32**	-0.1–0.1	-0.1–0.1	-0.1–0.5
variance electricity price			**0.15**	**0.12**	**0.28**	0.2–0.8	0.2–0.8	0.4–0.8

impact of the coal price in the experiment 2-a is in all scenarios close to -0.5. However, in experiment 2-b, the impact of the coal price is close to 0. At some points of time, the value is even above 0. Consequently, the range of values are different: experiment 2-b points at the fact that the coal price does not affect the electricity price, while experiment 2-a points at a strong negative relation.

The dynamic path approach solves the problems in the analysis of simulation data

The large differences between experiments 2-a and 2-b can be explained. The most important assumption underlying structural equation modelling is that all data points are independent. The data points in the analysis of experiment 2-a (similarly for 1-a and 1-b) are not. The fact that data points are related in time make them interdependent. And this interdependence may explain the difference in results.

This line of thought is illustrated in Figure 7.9. In experiment 2-a, a strong negative relation was estimated between the coal and electricity price. This is depicted in the left graph. The strength of the relation is a little bit exaggerated in the graph to make it better visible. Underlying this estimation, there must be data points with a low coal price and a high electricity price and the other way around. What cannot be depicted in the left graph, nor in experiment 2-a is the time aspect.

The right graph shows how *time* affects these results. At earlier times, we find ourselves on the top-left and, at later times, on the right bottom. When we look into one of the time steps or a short interval, and zoom in, there is no relation at all. The correlation is now close to 0. This clearly shows the pitfall of dealing with time dependencies in simulation data. The estimated relation in experiment 2-a was caused by time and the correlation between coal and electricity price is no valid relation in itself.

7.5.4 Analysis

In the second experiment, we have explored the dynamic path approach further by using a new dataset and a more advanced tool. Although it proved impossible to estimate a similar causal model with this tool, we have found important results that are strong arguments in favour of the dynamic path approach. We were able to estimate the relations of a simple causal model 1) for all time steps together *and* 2) per time step. We found that the relations change significantly over time. This points at the fact that the system changes in structure: the mechanisms change over time. This is a strong indicator for transition.

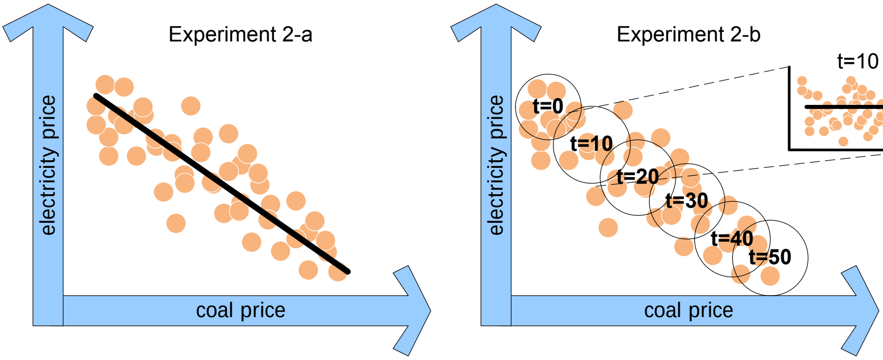


Figure 7.9 – The reason for the differences between experiment 2-a and 2-b

This argument is strengthened by the fact that the goodness of fit changes as well. This means that important indicators are neglected during parts of time in the simulation, which is another indicator for transition.

An important observation is that the results of the experiments were very different. The final experiment, in which models were estimated for each time step, showed more realistic relations than the previous experiment. The cause for this was identified as well. Neglecting the time dependence of individual data points leads to overestimating a relation between parameters that move *together over time*. The movement of either or both parameters needs to be sought in other mechanisms. Only the final experiment is able to show for which relations this problem occurs.

This experiment shows that more work is needed with respect to the strengths and weaknesses of the approach. By systematic assessments, more insight could be gained regarding the conditions that allow the tool to provide good estimations. In addition, the relevance and value of goodness of fit measures should be researched in the context of simulation data. We are confident, however, that difficult lines of thinking that originate from intensive discussions about results from simulations can be assisted by the dynamic path approach.

7.6 Conclusions

We have identified two important pitfalls with typical analyses of data from simulations. First, the strength of relations may be time-dependent. Second, many relations exist, each of them partly explaining the results. A new perspective on the analysis of simulation data is a conceptual causal model of how parameters affect each other, with or without a time delay. By analysing the results of simulations, we need to test the validity of this conceptual model. Some relations may have be delayed, other may change in strength, and even appear or disappear.

Criteria for a method that is able to deal with these pitfalls relate to the type of parameters that can be used, others to the nature of the relations, and some to the type of analysis. We found no existing tools to meet all our requirements. However, we found that structural equation modelling (SEM) is a promising technique. A first set of experiments was performed using SEM software. The developments are coined as the *Dynamic Path Approach* (DPA).

Two main arguments from this experiment underpin the need for this dynamic path approach. We need to be able to include autocorrelations and lagged relations, because they have proved significant. Based on the experience in the first set of experiments, we have selected R as platform to develop a new tool. We selected several modules that are connected and extended them in a new R module, called *dpa*. This module is available as open source software under http://cran.r-project.org/web/packages/dpa. The functions in the DPA module are related to data, specifying relations, performing the analysis, and analysing the results. The tool can be used through its user interface and small scripts can be used to automate all the steps required for the analysis.

We have found additional important arguments that show the use of the dynamic path approach. With the dpa module we were able to estimate the relations of a simple causal model for both for all time steps together, *and* per time step. We found that the relations and the quality of the model (in terms of the selection of relevant parameters) change significantly over time. This is an indicator that crucial mechanisms are changing over time, which indicates a transition. Furthermore, we were able to show that neglecting the time dependence of individual data points leads to overestimating a relation between parameters that move *together over time*. The movement of either or both parameters needs to be sought in other mechanisms. Only the final experiment is able to show for which relations this problem occurs. The results show that a typical analysis of simulation data needs to be improved because wrong conclusions are easily drawn. The modeller needs to find the *mechanisms* underlying the change in a model and not simply the *relations*.

Further work on the dynamic path approach should be directed towards the conditions, required for the approach to function well. Amongst other things, the requirements for simulation data should be formulated. This would improve the usability of the tool for the dynamic path approach and would underpin the results it gives.

8 Playing with Transitions

> You have to learn the rules of the game.
> And then you have to play better than anyone else.
> *Albert Einstein*

8.1 Introduction

Energy infrastructures are complex socio-technical systems[1]. Decision-making in these systems is distributed: different actors have different roles, means and goals. Where competition has been introduced, such as in the European gas and electricity infrastructures, there is no room for 'central planning'. Policy makers need to achieve their goals by changing the rules of the system, rather than through direct control. When we adopt a transitions perspective, we have to acknowledge that looking at the pathway is as important as the end goal. Transitions focus on long-term, structural changes in socio-technical systems. Using the idea of transition management, which necessarily implies shaping infrastructures, we need to come up with strategies for policy makers that is robust in providing a transition to some desired future state of the socio-technical infrastructure. As a policy maker, it is difficult, or maybe impossible, to see through all effects of possible strategies and actions. Therefore, many decision-support tools have been developed to aid this process. Simulation models and serious games are examples of these, which have their own pros and cons.

8.1.1 The use of simulation models for decision support

The use of simulation models is widespread throughout many research domains. Simulations are used for decision-support as well. The analysis and interpretation of simulation results should provide an answer to the question what strategy to pursue. However, the systems at hand are complex and simulation models can never predict future states of complex systems perfectly (Nikolic, 2009; Chappin and Dijkema, 2010a). Consequently, the results of a simulation model do not necessarily reveal the optimal strategy. Simulation models should rather be used to gain insight in the dynamics of a system: what types of strategies are possible and what kinds of results may be expected. In order to

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[1] This chapter is partly based on (Chappin, Dijkema and Vries, 2010; de Vries and Chappin, 2010)

make better decisions, policy makers in energy infrastructures need richer understanding of the underlying mechanisms in the systems they are part of.

Traditionally, the users of simulation models (have to) assume that the models provide the best answer, if not the truth. Models that governments use for planning are designed to *predict* the future. Examples are models from the IEA, IPCC and the models of the Netherlands Bureau for Economic Policy Analysis (CPB). These models are often very big, with underlying assumptions strongly connected to the class of the models to which they belong. They are multi-purpose models and are to provide a result that reduces the complexity for decision-making. These models are useful for systems that are relatively stable: a constant set of rules and a static system structure allow for the development of such models.

However, we focus on the long-term evolution of energy infrastructure systems: it implies that also the structure of the system changes. For such a perspective, the validity of the models used for planning is lower. We, therefore, need new simulation models that embrace the emergent character of evolving socio-technical systems. Since there are more degrees of freedom in these models, the predictive value will be lower. Even stronger, we postulate that users of simulation models should not strive for results that reduce complexity.

We propose that simulation models of complex systems generally, and of transitions specifically, should have a very different role. Simulation models should provide understanding of and insights in these systems and bring about discussion. Therefore, the consequences of both interpretations and limitations of the simulations are crucial. They are more important than a specific result in modelling terms, which is only applicable under very specific circumstances. When this new modelling objective is acknowledged at the beginning of the model development process, we can expect to develop models different in nature and usefulness. We postulate that simulation models can increase our understanding of these systems and derive potential strategies that are likely to be successful from the perspective of transitions and we have developed a framework for developing models of transitions in energy infrastructures (chapter 3), with which we have identified new and useful insights for different cases using that framework (chapters 4, 5, and 6).

8.1.2 The use of serious games

The problem we face now is how to convey the main results of the model to policy makers. The insights we formulate stem from the development process, which, amongst others, consist of a lot of discussion and is very iterative. Policy makers are only partially involved in this process and are not trained in the use of simulation models. This is a reason why policy makers find it difficult to gain deep understanding of simulation models. Because we believe the role of simulation models should change, we also need a new way of explaining the outcomes. The type of insights are often too subtle to convey through regular scientific and regular channels, such as journal articles, newspaper articles, reports, etc. They aim not at *reducing* complexity, but at making complexity *manageable*. Therefore, we posed the following research question. *How can the understanding of evolving energy infrastructure systems be increased?*

A number of solutions could be formulated to improve the level of understanding that policy makers gain from a simulation model. The first option is to use participative policy analysis (Geurts and Joldersma, 2001; Lasswell, 1971; Mason and Mitroff, 1981; Enk and Hart, 1985), in which the target group is part of the model development process, where most of the learning takes place. Practically, there are two difficulties with this approach. First, the target group is not able to spend the time and effort needed in such a lengthy and intensive process (Meadows, 2001). Second, the model may already have been developed, so the process is already finished.

Another option – as we will adopt – is to use serious games in addition to simulation models. Games have a special power to motivate and instruct (Meadows, 1999). Other advantages are that they can present complex environments, are repeatable, produce high levels of immersion, and are fun (Garris et al., 2002). Serious games provide a basis for organized communication about a complex topic (Duke, 1980, 1974; Kelly et al., 2007), often developed for learning within organizations (Senge and Sterman, 1992). Serious gaming has a long history of military purposes (Smith, 2009; Zyda, 2005) and has broadened to a variety of applications, such as business and management science, economics, and intercultural communication (Mayer, 2009; Raybourn, 2007). Games are used for education and for the exploration of strategies and policies (Gosen and Washbush, 2004) and, compared to other simulation techniques, games result in a high involvement of the users (Jahangirian et al., 2010).

However, the use of serious games on itself is not sufficient to provide a comprehensive set of insights (Bekebrede et al., 2005; Bekebrede, 2010), therefore, it should not be adopted in isolation. So far, in the literature the combination of serious games and simulation is only adopted as what is now referred to as *simulation games*: serious games with embedded aspects of simulation models. The main disadvantage of games is that there are strong limitations to the complicatedness and length of a game. Even stronger, a conceptually complex game needs to be relatively simple in mechanical terms in order to be effective (Meadows, 1999). Meadows refers to game design, which involves the art and craft of constructing games (Rollings and Adams, 2003). Although there is an elaborate literature on game design for non-educational purposes (cf. Fullerton et al., 2008; Rollings and Morris, 2004; Salen and Zimmerman, 2004; Schell, 2008), there is less literature on serious game design. Several approaches exist, though (cf. Aldrich, 2004; De Freitas and Oliver, 2006; Frank, 2007; Hall, 2009; Winn, 2009). Essentially, the challenge is to design a game with a good game-*play*, an interesting model of *reality*, and the correct underlying *meaning* (Harteveld, 2011).

We conjecture that a strength lies in a new combination of serious games and simulation models: play a simplified but attractive game to get some understanding of how subtle and complex systems under transition are. Afterwards, present and discuss the results you achieve with a more advanced and elaborate simulation model. The objective is that policy makers get a deeper understanding, with a more dynamic nature and make better decisions.

We have developed an approach that augments simulation models with serious games. We elaborate on this approach by showing a first application. We have developed a simulation model and a serious game of carbon policies and the power sector. We will describe both of them, respectively in the next two sections. Afterwards, we will address the combination of both approaches. We conclude with an outlook.

8.2 Approach

Understanding the dynamics of complex systems is not straightforward. The people studying such systems and making statements or arguments on which decisions are to be taken have to be aware of the complexity of the issues involved. We have argued that it is often not enough to have key stakeholders – the decision makers in these systems – on board when developing simulation models. Two possible reasons are that they are not able or willing to spend the time needed or that the model already has been developed. One crucial element is extracting their knowledge and using it for the development of simulation models. Another is how the results from such models are brought back to the same stakeholders, affecting their decisions. The approach we describe in this section is targeted at the second part. Herewith, we aim to aid the decision maker in making better decisions by improved understanding of the complex dynamics of energy systems, and not only by making the right decision given one single set of circumstances.

The approach builds on using serious games or simulation games as well as simulation models. A simulation game "combines the features of a game (competition, co-operation, rules, players) with those of a simulation (incorporation of features of the real world)" (Jones, 1995). A simulation game is to be played with the stakeholders. The notion of simulation also refers to a time aspect: while the game is played, time is passing by.

A simulation model to this respect is a representation of (a part of) a complex system in a computer program, which intends to lead to understanding of this system in the real world. Also here, the term simulation refers to modelling in which time plays a role. The main distinguishing characteristics of complex systems relate to time: chaos, intractability, emergence, etc. Therefore, simulating such a system, whether as a game or as a computerized model, implies incorporating time.

We have developed a framework for developing simulation models of energy infrastructures in transition (chapter 3). This framework enforces to take all the components that are needed to develop models that are able to grasp transitions in energy infrastructures. We expand on this framework to analyse the relationships between serious games and simulation models. In Figure 8.1, the approach is shown. Our approach contains a process in which the decision maker (the target group) will increase in a new way his understanding of the dynamics of a complex energy infrastructure. This serves as a new perspective for analysis and decision-making. The approach consists of three levels of activities. First, the user level, containing interaction with the users, the target group. Second, the gaming level, in which a simulation game is used. Third, the modelling level, in which the simulation model is developed. Parts of the existing framework for developing simulations of energy transitions are to be found at this level, so this is how these two works connect. The activities at the three levels are discussed separately below. In the process, the idea is that first a model is developed at level three. Next, crucial aspects are simplified and translated into a game on the gaming level. Finally, on the top level, interaction with the user takes place by playing the game and analysing the experience, incorporating the results from the simulation model.

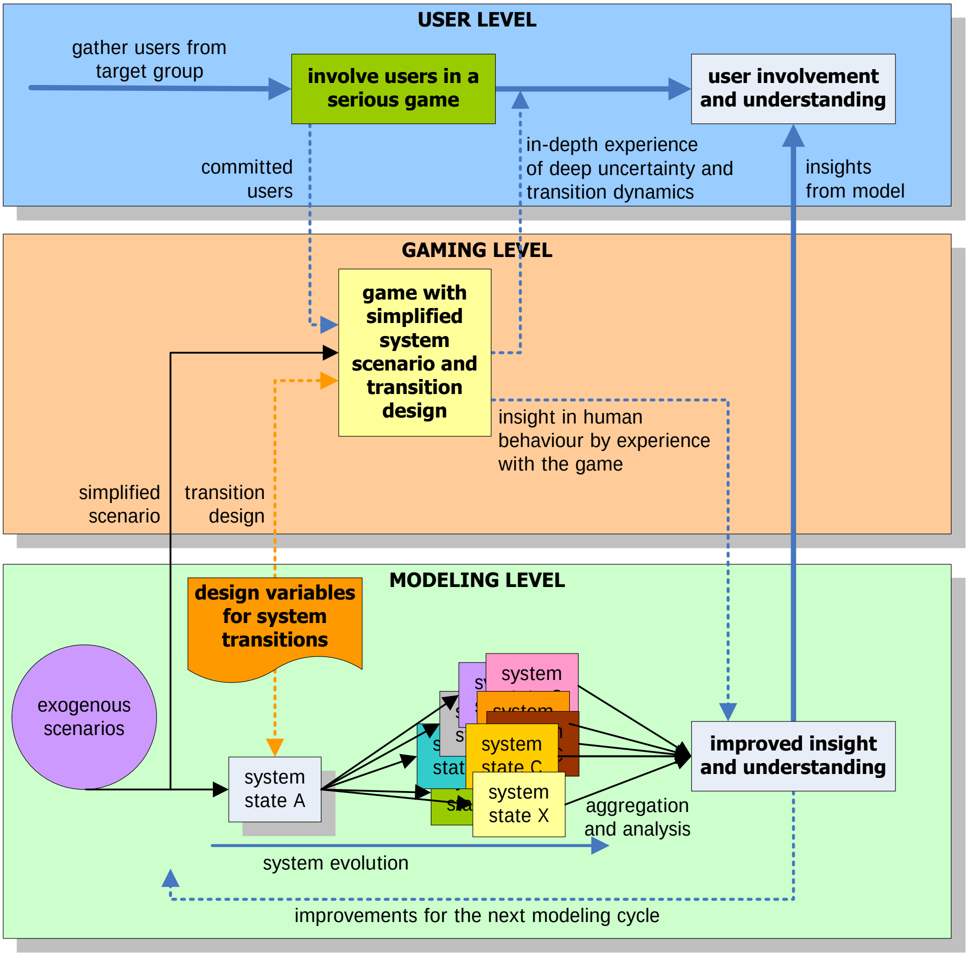

Figure 8.1 – Approach for augmenting insight from simulation models with serious games

8.2.1 User level

At the top level, the interaction with the user takes place. As said before, the role of users in the model development phase is relevant, but not explicitly discussed in this chapter. We rather focus on how users can learn to understand the dynamics of complex systems better. The user is brought to the scene by involving him in appealing issues in his field of study. He will be involved in a serious game and does not need to know that there is also a simulation model involved. The game needs to have everything to draw the attention of important stakeholders in the field of study, i.e. people from businesses, government, consultants, etc.

By playing the game, the user will experience the deep uncertainty involved in decision-making in complex systems. Still the game is limited: many real-life aspects are not incorporated. In this way, the limitations of a game help to understand the greater complexity of reality. Facing a complex system in a different role than in daily life, or a different complex system whatsoever, one can show the user what contributes to the evolution of the system as a whole.

After playing the game, one can confront the user with other research results. If the gaming sessions were successful, by now, the user is aware of the deep uncertainty involved and will be able to interpret the research results themselves. Knowing this in advance, one can optimize this aspect by a proper design of the game, the model, and the process and interaction with the users.

8.2.2 Gaming level

The game is played at the middle level. Once users are involved, they form teams and play a game, representing part of the system under study, which needs to be properly designed (cf. Duke and Geurts, 2004). Harteveld (2011) captured the design space for serious games in his 'Triadic Game Design', which span the three important dimensions – or worlds – for which the ultimate goal is to harmonize them in the design of a game. The first is *reality*: a game needs to have a model of reality, the way in which elements from reality are represented. The second is *meaning*: the underlying message and how this related to the perception of the game player. The final is *play*: the game concept, an idea of what the game is like, how the elements of the game create the game experience. The game must be appealing to play and promote a pro-active attitude of the players. When playing, users should really get involved and get excited. When they compete and collaborate, users are forced to discuss and make concrete decisions within limited time. The game has to be designed in such a way that interaction of the different players in the game will lead to the interesting emergent macro dynamics: rephrased in the game design methodology of Harteveld (2011), the game needs to have a good game-play and a useful model of reality, while at least part of underlying meaning of the simulation model will be understood when the game is played. Steering from the outside by game operators may be helpful. The players learn to understand the way their individual decisions lead to the dynamics they observe on the system level.

8.2.3 Modelling level

Playing the game does not lead to a holistic understanding of the system dynamics. Just because of the properties of complex systems, this would be impossible, since only a single instance or a couple of instances can be played. Herewith, it provides the insight of how your decisions lead to the emergent market dynamics. And this opens up the users' minds to allow for understanding what could happen under other circumstances, given other sets of assumptions etc. On this third level, the players could be modelled as computer representations. Using the capability of modern computers, it could be explained to the game players that they could play the same game over and over again, using several scenarios, as they have played a single instance of it. Also the decision-making rules and the structure of the model can be explained in comparison to the game instance.

Now the results shed a different light on the problem, since the players can relate every aspect of the game they played, and a new method for reflection appears. Therefore, the modelling level feeds back its results to the users through the gaming level. This effect is enabled if the system in the game resembles the system in the simulation model and if users are facilitated to map what happened in the game with simulation results.

8.2.4 Linking the game and the model

The approach encompasses more than using a model and a game. Both how the two are set up and linked to each other are crucial. This includes the types of simulation model and games that are used. The characteristics, displayed in Table 8.1, play a role in this set-up. Although they are related, the game and the model cannot be similar, since both methods have their strengths and weaknesses and are developed with a different purpose.

Both the model and the game need to entail decision-making. In a game, players need to make decisions of some kind in order to achieve their objectives. Similar decisions can be made in models, by using agents in agent-based models (ABMs). If such models are used, the users will be able to understand the result in the end, just because they were involved in similar decision making. This still leaves room for how these decisions are taken: how information is processed, what information is used and what kind of analysis is performed. Players of a game are able to use soft information. They can make decisions based on vague expectations, based on informal contacts, and based on experience and knowledge which already exist. This is very difficult with a simulation model, although agents can be programmed to deal with softer information. At least the agents' decision-making is logical. Specific irrationalities can of course be incorporated.

Players need to be involved in an exciting game, and it is, therefore, important to include features that are exaggerated compared with reality. Where in a simulation model, you do not want such effects to occur, reality needs to be simulated as far as is achievable. In a game, unrealistic effects can be very fruitful.

The aspect of time in a game can be modelled in rounds or blocks of activities. Such rounds or blocks span a rather long amount of real time because users are limited in the total amount of time they spend playing. For a simulation, time is far less restricted, and a larger horizon and a higher resolution are possible. This also allows for the simulation of different scenarios, where the conditions between simulations are varied. Since players are only able to play the game once, they need the model for understanding what would happen in other cases, under different or even the same circumstances.

8.3 Introduction to the case: power generation and carbon policy

A case was developed in which this approach was adopted. This case deals with CO_2 policy that is implemented in the power generation sector (please recall Figure 4.2 on page 85). Research results from the agent-based model (chapter 4, experiment 2) show how different policies work out in this particular sector, given a set of assumptions. In the simulation model, three policies for CO_2 reduction were evaluated and compared: a no intervention policy which was the base case, an emissions trading scheme, such as implemented in the EU, and a carbon taxation scheme, in which tax for emitting CO_2 has to be paid to the government. In the game, only the CO_2 emissions trading scheme

Table 8.1 – Design characteristics of serious games and simulation models

Characteristic	Serious Game	Simulation Model
Decisions	Players make decisions in the game.	Decisions are captured in decision rules for agents. They are by definition logical, but do not have to be rational.
Information asymmetry	Lack of information prevents forecasting or projecting.	Decisions have to be made under deep uncertainty. All available information can be processed, but decisions are still made under deep uncertainty.
Soft information	Soft information can be fed to the players who need to deal with this somehow.	It is not possible to use soft information, since it would be difficult to process this in a simulation model.
Competition	Players need to be involved in order to start the learning process.	Agents have to perform in a competitive setting, under assumptions this may be unrealistic.
Scenarios	A single gaming instance is played with one scenario.	Many simulation runs can be executed, given a set of scenarios, of which one corresponds to a certain extent to the scenario of the game that is played.
Analysis	Analysis is done in debriefing sessions, and can be combined with result from simulation model.	Analysis contains the process in which the modeller analyses the data from simulations through discussions in the modelling group.
Time	Time passes by in timed rounds, or in blocks in which players can take actions. Rounds or blocks represent rather long real time in order to grasp a part of the future.	Time passes by in simulated steps with the length needed for adequate simulation results.
Time pressure	Only a limited computational capability is present during a gaming session.	There is no very strict time pressure, although computational capabilities are limited.

is implemented, which is usually turned on halfway the game. The players have to cope with the transition of no policy to the emissions trading scheme.

The main actors in the power generation sector are the power generation companies (see Figure 4.2). They own, operate, and invest in their power plants. Some power generation technologies, notably the ones using coal and gas, result in CO_2 emissions. Others, such as wind, biomass, and nuclear have no CO_2 emissions. Since the demand for electricity is growing steadily and it is not sensitive to the electricity price, power producing companies aim to meet a rising demand that entails a growth in emissions. Governments, however, aim at CO_2-emission reductions.

Emissions of currently installed power plants cannot go down, because they are bound by fuel consumption. Affordable upgrades have only marginal effects and fuel switching is typically limited to 15% co-firing a CO_2 extensive fuel, such as natural gas or biomass. Therefore, significant reductions need to come from investment in new power generation capacity. As a consequence, the investments play a crucial role in both the simulation model and the game. In the short-term, electricity needs to be sold, fuels need to be acquired and power plants need to be operated.

For many reasons, the evolving electricity market dynamics are complex and difficult to understand. In the short-term, due to the paucity of storage options, electricity markets are highly volatile. In the long-term, investment decisions have long lead times and result in structural change of the power generation sector. In addition, the complexities of imperfect competition and uncertainty, due to unpredictable fuel prices and policy changes pose significant challenges to the analysis of the long-term behaviour of electricity markets.

Therefore, teaching about this dynamic behaviour – whether teaching students the basics or communicating to policy makers and strategists the possible consequences of new policy measures – is difficult. An alternative would be to use qualitative or static analyses, but conveying the message fully turned out to be problematic. In addition, it proved to be difficult to convey the results of dynamic models to people who were not involved with creating such models themselves. Teaching the potential effects of different carbon policies on such a complex infrastructure system to students or telling the policy makers proved to be difficult.

8.4 Experience with the power generation model

The agent-based modelling approach consists of four components: agents, physical installations, the carbon policy, and scenarios of exogenous parameters (please recall Figure 3.3 on page 64).

The main *conceptualization* of the model is one of nodes and links. Two types of node exist, namely agents and (technological) installations. The main component is the agent, who interacts with other agents. All social interaction is modelled as negotiating, bidding, and contracting between different *agents*. Therefore, markets are also modelled as agents who facilitate trade between market players, similar to power pools in reality. Agents interact and establish links through negotiation and contracts. Agents display three types of behaviour: strategic management, operational management, and control of installations. Strategic management includes investment in and dismantling of installations. Operational management includes negotiation and contracting with other agents. Control of installations refers to enabling and disabling each technological installation. Agents base their behaviour on a set of rules that are unique per agent. The physical world is owned and controlled by agents. The physical world includes nodes: the individual *technological installations* such as power plants. Technological installations are conceptualized as boxes with inputs and outputs that are streams of physical goods. The links between the technological installations are, therefore, flows of goods that exist at a certain moment in time. Technological installations are created when agents decide to invest in them and disappear when they are dismantled. Technological capabilities are based on a set of technology characteristics subject to learning curves.

The *policy options* are different choices at the start of the simulation. When choosing carbon taxation, the carbon tax level needs to be defined for the simulated period. In the case of emissions trading, the total amount of rights that are made available (the cap) and method for the allocation of rights (grandfathering or auctioning) need to be defined.

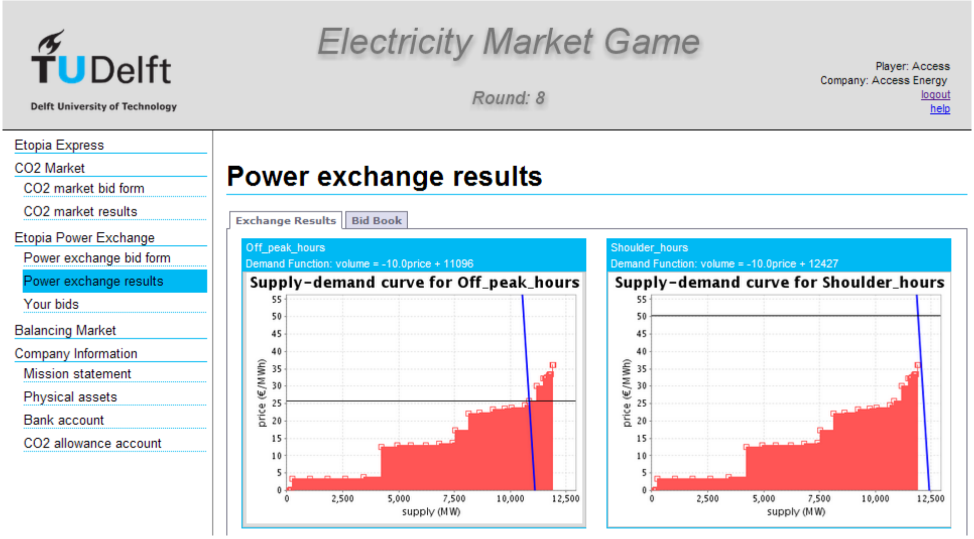

Figure 8.2 – The player interface of the Electricity Market Game with an example of a load-duration curve of the power exchange

The *scenarios* in the simulations are based on a set of exogenous parameter settings to resemble a typical European electricity market. The parameters include price levels and trends for fuels (natural gas, coal, uranium, and biomass), the availability of import and export capacity, the available set of power plants, and electricity demand trends.

The *simulation results* indicate that both carbon taxation and emissions trading do deliver in the long run. Characteristics of the system development under taxation differ substantially from the power production system developing under emissions trading.

8.5 Design of the Electricity Market Game (EMG)

In this section, we highlight the main features of the game: the game-play, the players, the power stations, the power exchange, and the CO_2 market[2]. In the design, we have used the game design approach of Duke and Geurts (2004) and Harteveld (2011), being aware that we use and develop it concurrently with the related simulation model.

8.5.1 The game is played in rounds over the internet

In the Electricity Market Game (EMG), the power market is simulated in an imaginary country called 'Etopia'. It is played in rounds, each of which represents a year. A long period, e.g. two decades, is simulated in order to give the players insight in the long-term consequences of their actions. The game is played and operated through the internet: players log in on a dedicated server[3]. Figure 8.2 shows the players' interface. All inform-

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[2] More details regarding the game have been published elsewhere (de Vries, Subramahnian and Chappin, 2009; de Vries and Chappin, 2010)

[3] The server on which the game can be played is accessible at http://emg.tudelft.nl.

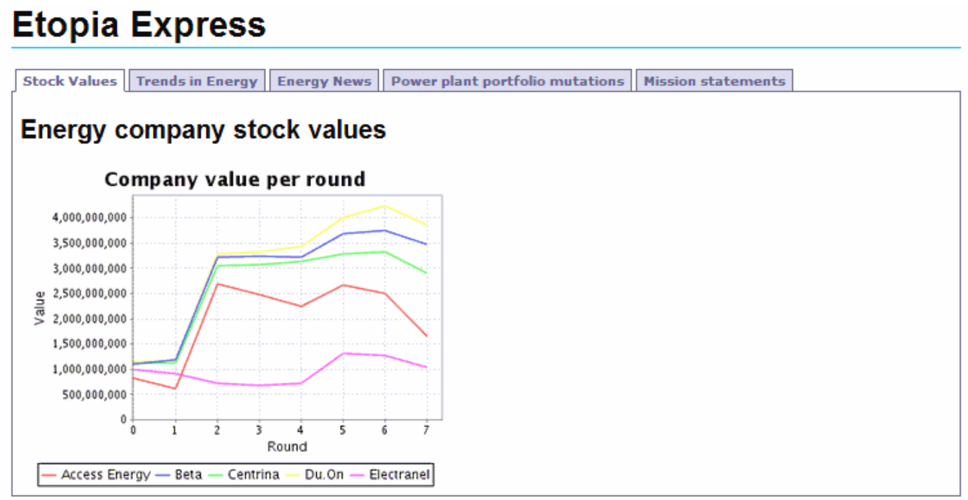


Figure 8.3 – The 'Etopia express' provides the player with information on stock values (shown) and an overview of public energy news and trends

ation is available at all times and the players do not have to be physically together. As a result, only a limited amount of contact time needs to be spent on the introduction and, at the end, the evaluation of the game.

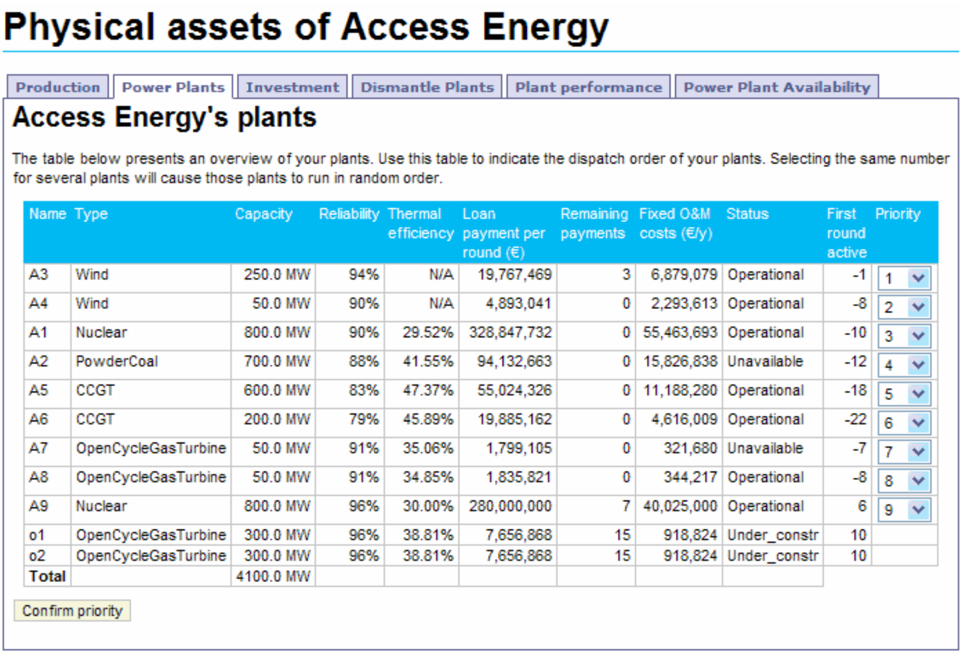
The operator can start the next round through a part of the website that is available to him only. In the process of starting a new round, the power market is cleared and information is processed, calculating which plants ran, how much power they sold, and accounting all revenues and costs. Therefore, the online simulation package performs all administrative tasks for the game operator. As a consequence, he can concentrate on analysing the game while it is played and on coaching the participants, where necessary. The player with the highest bank balance at the end of the game wins the game, because he achieved the highest return on investment.

8.5.2 Competing power companies

The players participate in one of the five power generation companies that compete by means of generating and selling electricity through the power exchange. A power company is run by two to three participants, to share work-load and stimulate discussion. Each company has its own website, part of which provides public information, such as news and market prices and part of which contains private information such as the company's assets and its bank account (see Figure 8.3 for an example).

Each round, companies have to perform a set of tasks. First, they have to offer electricity to the power exchange. Second, they decide whether to build new power plants and/or to dismantle old ones. Third, they have to acquire CO_2 credits, after the CO_2 market has been turned on, which is usually around round 6 or 7.

To be able to perform these tasks, data and information are available throughout the web pages. The main information sources include a history of prices of fuels; CO_2 prices



Physical assets of Access Energy

Access Energy's plants

The table below presents an overview of your plants. Use this table to indicate the dispatch order of your plants. Selecting the same number for several plants will cause those plants to run in random order.

Name	Type	Capacity	Reliability	Thermal efficiency	Loan payment per round (€)	Remaining payments	Fixed O&M costs (€/y)	Status	First round active	Priority
A3	Wind	250.0 MW	94%	N/A	19,767,469	3	6,879,079	Operational	-1	1
A4	Wind	50.0 MW	90%	N/A	4,893,041	0	2,293,613	Operational	-8	2
A1	Nuclear	800.0 MW	90%	29.52%	328,847,732	0	55,463,693	Operational	-10	3
A2	PowderCoal	700.0 MW	88%	41.55%	94,132,663	0	15,826,838	Unavailable	-12	4
A5	CCGT	600.0 MW	83%	47.37%	55,024,326	0	11,188,280	Operational	-18	5
A6	CCGT	200.0 MW	79%	45.89%	19,885,162	0	4,616,009	Operational	-22	6
A7	OpenCycleGasTurbine	50.0 MW	91%	35.06%	1,799,105	0	321,680	Unavailable	-7	7
A8	OpenCycleGasTurbine	50.0 MW	91%	34.85%	1,835,821	0	344,217	Operational	-8	8
A9	Nuclear	800.0 MW	96%	30.00%	280,000,000	7	40,025,000	Operational	6	9
o1	OpenCycleGasTurbine	300.0 MW	96%	38.81%	7,656,868	15	918,824	Under_constr	10	
o2	OpenCycleGasTurbine	300.0 MW	96%	38.81%	7,656,868	15	918,824	Under_constr	10	
Total		4100.0 MW								

Confirm priority

Figure 8.4 – An overview of the power plants for one of the players

and power prices grow during the game. News items, written by the game operator, also become available, providing some degree of insight into future energy price developments and a partial analysis (based on 'public' data only available to all participants) of what is happening in the market in the game. In addition, detailed characteristics are available on the power plants in their power production portfolio and the available new generators. All revenues and expenses of the companies appear in their bank account: revenues from selling electricity and the costs of each power plant, including fuel costs. The 'stock values' of the companies are plotted in the game's news bulletin, so the players can see how well they are doing.

8.5.3 Power plants

The power companies all start with a comparable set of generators, including coal, gas, wind, and nuclear generators (see Figure 8.4 for an example). Power plants differ with respect to load cost, age, size, capacity, fuel efficiency, and reliability. Existing plants deteriorate with respect to reliability: the chance it fails during a particular round increases. New plants become more fuel-efficient and cheaper over time.

Players automatically pay for capital cost for power plants, in the form of loan payments. Additionally, players pay for fuel cost for actual production, and for operation and maintenance. It takes time to build new plants, from two rounds for a cheap and inefficient open-cycle gas turbine to eight rounds for a nuclear power station.

Loan payments end after a number of rounds, but the fixed operating and maintenance costs and declining reliability of power stations provide an incentive to the decommission of old plants. Decommissioning is free, but keeping old plants can be attractive in order to cover demand growth.

8.5.4 Power exchange

All the produced electricity is sold on the power exchange, modelled after European power exchanges. There are two main differences with reality. First, there are no contracts outside the exchange, so the price on the market is uniform for all players. Second, within one round, representing one year, the market is split up in three segments, one containing 5000 hours with base demand, one containing 3600 hours with shoulder demand and one containing 160 hours with peak demand. This means that there are three electricity prices each year: a base, a shoulder, and a peak price.

Power producers place bids for all their available power plants in each of the market segments. To calculate their bids, players use information on the cost structure of the power plants, the fuel prices, and the wind factor. Bids can be different in the three segments, so they can try to manipulate the market. Sources for uncertainty are the availability of competitors' generators and the exact levels of demand, while historical data, given to the players, provide an indication only.

8.5.5 CO_2 market

Halfway through the game, the operator enables the CO_2 market. Already announced by new items, the players now need to be in possession of credits for their CO_2 emissions. Every round, CO_2 emissions can be bought at an auction. There is a cap on the total number of rights that are sold and, as with the power exchange, there is a uniform price to be paid to the auction for all accepted bids, determined by the lowest accepted bid. If players have an abundance of credits, they are banked to future rounds. A shortage is punished with a penalty and need to be bought in the next round to prevent future penalties. The game operator sets the cap on the total number of rights available and the penalty level. Players have information on their CO_2- emission intensities of their generators and they have to estimate the number of credits they have to buy at the auction. Players can avoid emissions by investing in CO_2-extensive generators, such as coal with carbon captures and storage, wind or nuclear.

8.6 Comparison of the implementation of the game and the simulation model

The game and simulation model essentially deal with the same topic, but differ in many aspects (see Table 8.2). These differences are mainly needed, because in the game there is interaction with humans, the players, and in a simulation model there is not. The simulation model is developed using a software stack for developing agent-based models of socio-technical systems (Nikolic, 2009; van Dam, 2009; Nikolic et al., 2009), essentially using the Java programming language. On top of this, a framework for energy transition models has been developed, in which both the simulation model and the game fit (Chappin and Dijkema, 2010a). The technology used for developing the game is different. It is played on the internet, on a server, and is written in Java for Server Pages (JSP files) and Java files. Because both are built on top of the Java programming language, parts of the software stack and Java code are shared.

On the content, there is even more overlap. Logically, many algorithms apparent in the simulation model have a representation in the game. The players or agents both start with a set of generators. In the game they are comparable, and each player owns generators using all available energy sources (natural gas, coal, uranium, and wind). In contrast, at the start of the simulation model, the agents start with a random portfolio each run. The only limitation is that, at the start, the portfolio of all agents together is set to reflect the Dutch portfolio in 2004.

There are two main differences in the power market. First, in the simulation model, the market is split up in more segments, since the effort for software agents to bid in many segments is negligible compared with human players. Second, in the simulation model, the demand is perfectly inelastic within a year. This choice is made for easy price calculation in the model, in which agents bid according to the rules for a perfect market. In the game, such a setup could lead to extremely high prices and, consequently, unrealistic possibilities to manipulate the market.

In the modelling of carbon policies there are two differences. First, in the model, the emissions trading market and the power exchange come to a price in a recursive algorithm. In the game this is not needed, since the CO_2 auction is cleared one round earlier. The second difference is that there is no CO_2 tax in the game, since playing under a taxation scheme is less exciting. In the model we can make the comparison, since it only requires more computational power. It is not difficult to write the code for a taxation scheme, therefore, it would be a relatively simple add-on. In addition, we reasoned that it is easier to understand a taxation scheme after having played an emissions trading scheme than the other way around.

To make the game more interesting and increase the level of uncertainty, the scenario of fuel prices is volatile. In the model this is not needed, since it only clutters analysis and the agents are not aware of the lack of volatility. Data about innovation and power plants are somewhat exaggerated in the game, to enhance the game play and speed up the change in the game. In this way, it decreases the number of rounds that need to be played.

Purely to deal with human attempts for manipulation and errors, many pieces of code for the game need to be different from the simulation. In a way, many more checks and balances are needed, since more things can go wrong. Stability is much more important in a game, because the simulation can be improved or adapted when it appears to be not error-prone. A key example is the balancing market. In the game, players can offer selling electricity they cannot produce. Therefore, a second market was implemented, punishing such behaviour and making sure that the 'physical reality' is correct. A balancing market in the simulation model is superfluous, because the agents can easily be programmed to offer exactly as much as they can produce.

Both model and game are implemented to allow for comparison on a conceptual level, not to be exactly similar.

Table 8.2 – Differences in main aspects between the game and the simulation model

Aspect	Serious Game	Simulation Model
Unit	Player is a part of a power generation company.	Agents with individual preferences are power generation companies.
Technology	Internet-based, using Java server pages and parts of the ABM software stack.	Java-based, using the software stack designed for ABMs.
Generators at the start	The players all start with a comparable but not equal portfolio of power generators using gas, coal, nuclear, and wind.	The agents start with a random set of generators, but the aggregate portfolio is similar at all simulation runs, reflecting the portfolio of the Netherlands.
Time	Time is represented in rounds for years. The game starts slow, to allow the players to learn playing the game. Pace is increased over time. The duration of the first rounds with new policy is longer again.	Time passes by in simulated steps with the length needed for adequate simulation results. The simulation is executed as fast as possible, on a high performance cluster.
Power exchange	Runs as an algorithm when going to the next round. Demand levels are slightly elastic so prices always form, also when players bid strategically. The market is split up in three segments with different levels of demand.	Modelled as an agent in the sector connecting supply and demand in 10 segments per year. Demand within a year is inelastic to price. Agents are asked to place bids.
CO_2 policy	An emissions trading market can be enabled. Players have to acquire their rights for the next year at an auction, where the total amount is capped by the operator. A penalty is given to players who do not have enough credits. A carbon tax is not (yet) available in the game, since the game is more fun to play with an emissions trading market.	Both an emissions trading market and a carbon tax are modelled. The emissions trading market is modelled as an agent performing an auction. Clearing this market is in an iterative algorithm, connected to the power exchange agent, who clears this market. The carbon tax is modelled as a government agent, collecting the tax. The tax level matches on average the prices on the emissions trading market, but with an increasing trend.
Scenario	A scenario of fuel prices, wind availability, and demand growth rates is modelled after compressed historical data with ups and downs.	Fuel prices and demand are modelled as gradually rising trends.
Technology	The data of power generators are adapted to make playing the game as interesting as possible, i.e. innovation, modelled in increasing efficiency and decreasing investment cost of new plants is rather high.	Many options are available, based on power plant literature. The data are as realistic as possible. Innovation is reflected in the gradually increasing efficiency and decreasing investment cost of new plants.
Balancing market	There is a balancing market for power to account for errors of players and for punishing players who sell more than they can produce.	There is no need for a balancing market, since agents bid perfectly.

8.7 Observations and analysis

In this section, we describe and analyse the experience in this case with the framework of combining a simulation model with a game in order to increase the level of understanding amongst participants. First, we describe the setting in which the framework is tested. Afterwards, the main lessons are explained, first on the content and then on the framework.

8.7.1 Settings in which the game was played and model results were presented

The serious game was primarily developed for education: to teach students the working of various aspects of the electricity sector. The design of the game was published (de Vries, Subramahnian and Chappin, 2009; de Vries and Chappin, 2010) and it has been used and improved over the last four years, during which it played a central role in a Master level course on electricity and gas market design. Herewith, the interest to use the game for trainings grew. Amongst others, the game was part of the energy markets track of the NGInfra Academy[4], a one-week course for young professionals in the energy domain in 2009 and 2010. Participants form groups of 3-4 people. When there are more than 20 participants in the game, multiple groups play in parallel games. This offers the interesting opportunity of applying different policy instruments to otherwise similar game scenarios.

The game itself proved useful: Chernenko (2010, p. 10): "The students admitted that the game was quite useful for teaching them the mechanics of the electricity market and understanding the idea of energy efficiency and marginal cost (even for students with an economic/engineering background). Investment opportunities and carbon trading make the game quite unpredictable. The dynamic character of the game helps develop strategic thinking about the company's position on the market and vis-à-vis its competitors."

The simulation model has been used to evaluate the merits of emissions trading and carbon taxation and has been published (Chappin, Dijkema and Vries, 2010; Chappin et al., 2009). The ideas behind it and the simulation results have been used for various Master level courses. In recent instances, a combination of the two has been done, developing and testing the framework presented in this chapter. The analysis below stems from observations done during the game, during the evaluation sessions, and in some occasions also through the use of an evaluation form.

8.7.2 Participants understand how electricity markets work

Understanding the effects of competition Participants learn the rationale of marginal cost bidding on a (relatively) competitive power market. Through trial-and-error they also learn the possibilities and limits of influencing the electricity price through bidding higher or withholding generation capacity. Because the price-elasticity of demand is relatively high, efforts to raise the price lead to such a loss of sales that competitors usually benefit more. Nevertheless some players continued to bid high, while they were not

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[4] http://www.nextgenerationinfrastructures.eu/academy

aware of this effect. In reality, this could be measured, and because abusing market power is illegal, the Competition Authority would intervene. In the game this can be observed even more easily, since the game operator has full information. Therefore, the game operator can intervene in the form of a warning, a pending investigation or a fine by the Competition Authority.

The participants, understanding marginal cost bidding, can understand what happens when all players would use this strategy and there would be no market power. That would be unrealistic, but still it becomes imaginable. In other words, by playing the game players learn to understand how certain patterns of electricity prices in the simulation model emerge from bidding strategies of agents. Having such understanding allows participants to take the next step and connect electricity price patterns to other information. An example could be to gain an understanding of how CO_2 prices co-evolve with electricity prices.

Understanding investments in an uncertain environment Investment decisions appear to be more difficult to participants when they have to make them themselves, not knowing competitors' plans, future electricity demand or future fuel prices. The simulation game lets participants experience the dilemmas of investing in an uncertain environment. Its positive effects were immediately clear from the substantial improvement in students' answers to test questions regarding how electricity market prices were formed and how investment decisions were made.

One of the lessons learned is that it is worth waiting with an investment until the need for new plants is more certain, which is a lesson of Real Options Theory (Dixit and Pindyck, 1994). A consequence may be that if everybody waits with investment, a power shortage will develop. The lead times of the most cost-efficient power plants are long; only inefficient open-cycle gas turbines can be installed in the short-term. The high prices of a power shortage may also cause players to overreact, leading to excess supply and low prices a number of years later. Thus players learn about the difficulty of planning in a liberalized market, in which there is no central coordination.

With respect to investment, the participants in the game learn the dilemmas of having to choose when to build which kind of power plant – existing plants are ageing, demand is growing – when the relative costs of fuels are highly uncertain.

They also learn that, contrary to neo-classical economic theory, the interests of the producers and consumers do not converge. In a dynamic and uncertain environment, producers' interest in delaying investment projects until they are more certain to pay off runs is contrary to the consumers' interest in sufficient generation capacity. As soon as there is a shortage, electricity prices rise quickly, often to many times the cost of generation. These dynamics have been observed in practice, (cf. Dixit and Pindyck, 1994).

Having made these decisions, participants can better understand how agents in the agent-based model make similar decisions. They also understand that different agents can make different decisions, because every agent has different information, different preferences, and different priorities. Many characteristics of investment in the agent-based model become far more intuitive than they were before playing the game.

Understanding the need for policies and evaluating policy designs Participants also gain insight in when private decisions do and do not coincide with the public interest.

The game can be used together with simulation models for understanding existing power markets, including the development of related policies. The example that we discuss in this chapter is the introduction of CO_2 policy, and it will be discussed below. Other possibilities are policies related to generation adequacy and demand response. Related questions are about the conditions for the effectiveness of specific policies, about the costs and about who pays for them. We are working on simulation models and games focusing on such policies at the moment.

8.7.3 Participants understand how CO_2 markets work in combination with electricity markets

Understanding how CO_2 markets work and how they impact the power market The game design provides a basis for adding different scenarios and policy instruments. The first such policy instrument is a CO_2 market. Also in the simulation model, a CO_2 market is modelled and it is compared to the main other option: a carbon taxation scheme.

The newspaper of the game is used to introduce the plans to implement a CO_2 market. The participants learn to understand that the uncertainty regarding the CO_2 market is multidimensional: Will an emissions trading scheme be actually implemented at all, when will emissions trading start, how high will the emissions cap be, and what will be the effects on the costs of electricity production and on electricity prices? It proved to be very difficult for players to determine their willingness to pay for CO_2 credits, as this depends on the electricity prices in the next round. Another important goal that will be achieved in this way is understanding of the relations between these two markets.

In the simulation model, the solution for determining the willingness to pay for CO_2 emission credits is to optimize the CO_2 and power prices by an iterative procedure. This represents auctioning, similar to the game, and a secondary market, which is not in the game for reason of simplicity. Players were able to understand why this was necessary and under what conditions this is an adequate solution. As a consequence, players understand better what it means when they see CO_2 and power prices evolving.

Understanding the increased investment risk caused by volatility in CO_2 prices The CO_2 market introduces extra complexity in the decision to build new plants, because of the volatility and uncertainty of future CO_2 prices. They will be influenced by the growth rate of electricity demand, investments in CO_2 abatement by competitors and, of course, by changes to the emissions cap and penalty.

Participants, having made these investment decisions under the CO_2 market, and being punished by their past decisions, appreciate they can repeat the analysis by investing agents. It is very difficult to compare how different CO_2 policies affect the way investment decisions are made, since the systems are so different and since so many factors need to be taken into account. Playing the game makes it far easier to analyse and interpret that the impact of CO_2 emissions trading can be counter-intuitive and counter-productive, as we have concluded from an in-depth analysis of the simulation model.

Expectations stemming from irrational behaviour can shift the whole market In the game, expectations of CO_2 prices can be very important for the formation of future

CO_2 prices. The level of understanding of the CO_2 market is limited in the initial rounds, but it is important. The CO_2 prices emerging in the first few rounds with the emission-trading scheme turned on, determine to a large extent the expectations of future prices. As a consequence, these initial rounds have a big impact on the strategies that players deploy. Since this may well be irrational, the game can be in a very suboptimal state, from the perspective of the individual players and the market as a whole. This is an interesting observation that we cannot easily model, but is observed in reality as well.

Since we model agents to behave as rational as they can, given their individual preferences and the limited set of information, the observations in the game make our understanding of the relation between the CO_2 market and the power exchange richer.

There is not a single optimal strategy Game players learn to understand that it is not possible to formulate a single strategy that is optimal: it always depends on what the other players do. This fact, which is also true for reality, is important in relation to policy makers for two reasons. First, also the best policy is not optimal by definition. It depends on how people react. Second, it is very difficult to determine what are robust strategies.

Excitement leads to strong involvement The classroom's bidding exercise effectively demonstrated why competition tends to force prices down, but left the question open how they wanted to recover their investments. Playing the game stimulates participants to voluntarily spend significantly more time thinking about short and long-term market dynamics than when they only received a lecture – whether or not with discussion – or when they were asked to perform exercises on these topics. To have a chance of winning, players need to 'reverse engineer' the game, at least in part, by developing a spreadsheet for determining their bids in the electricity market. In some cases, they also use a spreadsheet for estimating the future profitability of new power plants. From active thinking about a strategy and developing these spreadsheets, trying their strategy and adjusting it in response to how well they do, players learn substantially more than through conventional teaching methods. The reason is clear: the game, with its competitive peer pressure, stimulates participants to be more actively involved, which means that they will retain more of what they learned. This corresponds to earlier experience with simulation games (Randel et al., 1992).

This excitement is also apparent when presenting, explaining and discussing simulation model results. It proved to be an important effect. Participants of the game opened up and were more willing to engage in further discussion of modelling implications.

8.7.4 How participants react to soft information and guidance

As mentioned above, the game operator provides a variety of soft information. A Competition Authority can warn for and punish market power abuse. Herewith, the principles of competition policy can be communicated to the players and the game remains within control, which is crucial for other lessons that have to be learnt. Etopia's government can make policy-related announcements, such as urging the power companies to invest in CO_2 extensive technology or in the implementation of a CO_2 emissions trading scheme. Analysts can reflect and provide predictions of all relevant information in the game, such as fuel price predictions, reasons for lack of investments, etcetera.

We can, therefore, see how participants react to soft information. The main events are revisited during the evaluation. One participant got a warning for market power abuse and reflected during the evaluation that he regretted that the Competition Authority only gave a warning and that he had remained unpunished. Many participants claim to be confused by the often conflicting news items.

Soft information makes the game richer than the simulation model in which no soft information is available. This leads to two insights: The first insight concerns the content. Expectations have been crucial for the emergence of CO_2 prices. We dwell on this later, when the CO_2 emissions trading scheme is discussed. The second insight is for the participants. Soft information increases the realism and the fun for the participants to play the game. Players feel they blindly make decisions, which is an important lesson.

An important translation step of simulation results to the real world is including all kinds of relevant, but unclear aspects. We have tried to capture the most relevant aspects in the news and participants can use that experience to reflect on results and analyses of the simulation model.

8.7.5 Participants deal with conflicting assumptions

Participants usually think within a certain paradigm, stemming from their experience in the field, whether a policy maker, a manager or a student. The fact that the game and the simulation model are based on different assumptions helps to break open the paradigm. Participants have to deal with conflicting assumptions, since two sets are presented to them. And since they are involved, they often want to deal with that. This is another reason why especially the combination of gaming and simulation models can lead to eye-openers. Examples for this case are the assumption of a competitive market in the simulation model, assumptions related to technological innovation, and assumptions about price formation in both the power and the CO_2 markets.

8.7.6 Experience leads to deep understanding

In many ways, experience leads to deeper understanding then lectures or classroom exercises. We observed the effects of time pressure and repeated decision making.

Time pressure enables focused and passionate discussion We observed earlier that participants feel involved and committed to the game. Since we also impose time pressure – there is a strict deadline for taking actions – participants are forced to communicate fast and intensive and engage in passionate discussions. We found that when time-pressure is very high, which is the case when we play multiple rounds per day and complete the game within a week, playing the game can even be stressful. Some participants were even found spending their time off on the game, either in strategy discussions or in supporting spreadsheet analyses.

When time pressure is lower, when it is played with two to three rounds per week, this also has impact on the priority of the participants to play the game. Although it allows for more discussion, thinking, preparation, and analyses we postulate that lack of time pressure and intensiveness result in a decreased level of understanding. Some settings do not allow for intensive game playing, though; we did find that the participants appreciated the game in relation to the simulation model so, even in that situation the combination was useful.

Repeated decision making enables deeper understanding In the game, the decisions to be made and the actions to be taken are recurrent. In the beginning it is difficult to come up with a strategy, because of the low experience with all the peculiarities in the game. The only change occurs when the circumstances change: the implementation of a CO_2 market introduces new tasks. Since decisions are made regularly, the analysis players have to make in order to come to a decision is done multiple times and sinks in better. Also, it allows players to think on a longer time-scale: participants perform the immediately necessary tasks but they also learn to think of their strategy for the coming 10 rounds or so.

The effect of forced repeated decision-making is important for the understanding of results from a simulation model. The insights and understanding that stem from simulation results get the time to sink in, since the game is played up front. Much of the material is already dealt with, although in a different way, so the barrier towards the complexity of simulation results is lower. It allows for a deeper understanding of the complexity of energy systems.

8.7.7 Participants start asking ‘modelling’ questions during the game

On some occasions we observed that participants started to ask what would happen if the game was played many times, under different circumstances. In a way, they asked for a more systematic view on what this game meant, in the sense that they feel that the results from a single instance are not representative. The game enabled an open mind for at least some of the participants.

8.7.8 Evaluation sessions are crucial

The model is combined with the game during the evaluation session, which is the end of the game. The game is reflected with the results of the simulation model, by confronting the participants with a number of ‘what-if questions’: what if the game was played with another policy? What if you could play the game hundreds of times? What happens under different scenarios (in this case fuel prices, demand growth rates or innovations)? Participants demand answers to such questions, and they get some in the evaluation session.

8.8 Conclusions

The traditional role of simulation models is to provide predictions that reduce the complexity of decision making for policy. However, when looking at transitions, this is impossible: since the structure of systems change no perfect predictions can be made. We believe that the role of simulation models is to provide understanding of the dynamics of complex energy systems. Ideally, this leads to better decisions of policy makers. An approach has been presented to improve the process in which policy makers learn from simulation models. In the approach, serious gaming is used to enable getting experience in the embracing of the features of complex systems.

We have presented a case on CO_2 policy and the electricity sector, for which both a serious game and a simulation model have been developed previously. Both have already proved their value. We hav8e observed that participants of the game learn demonstrably more about the short and long-term dynamics of electricity markets than they would have learnt through lectures or other traditional means of teaching.

Subjects that appear simple on the blackboard, such as a price equilibrium caused by the different supply and demand functions of sellers and buyers of electricity, are much better understood when players need to perform the actions themselves. Moreover, only then do they realize the difference between a static equilibrium and a dynamically changing situation. When the simulation game is combined with a modelling effort, the game can successfully be used to get participants, such as policy makers, students or professionals, involved who get a far deeper understanding of the implications of results from simulation models of energy infrastructures. We believe that the role of simulation models in politics should go from the scientific argument to a tool embracing complexity and debate.

9 Conclusions and Discussion

Somewhere we'll find a new way of living.
Stephen Sondheim – West Side Story, 1961

9.1 Conclusions

In this thesis, we explored ways to aid strategic decision makers in energy infrastructures. We argued that strategic decisions are hard to make, because of the complexity of energy systems. Since it is an important but relatively new approach to energy policy, the topic of *transitions* is especially interesting. We started out with the following central research question:

> *How can we assess the long term consequences of policy interventions in evolving energy infrastructure systems?*

We can conclude that we *can* assess what the long term consequences of policy interventions may be in evolving energy infrastructure systems. It can be done by way of systematically developing and analysing agent-based models using the modelling framework developed in this thesis. We have shown this by presenting that modelling framework, a number of agent-based models, a serious game, and analyses of the simulation results, which together lead to insights in how interventions can be traced in our energy infrastructure systems. The main findings are presented in the following subsections. After reflecting on these results in section 9.2, recommendations for future research are given in section 9.3.

9.1.1 Interventions in energy infrastructures

In chapter 2, we discussed how to trace the effects of specific interventions in the evolution of energy infrastructure systems.

> *Conclusion 1 – The literature on transitions and transition management is inconclusive with respect to whether and how the effects of specific interventions can be traced. Suitable tests and indicators are required to trace those effects. Such tests and indicators are necessary ingredients for an assessment of the viability of transition management.*

Energy infrastructures are true socio-technical systems. From a socio-technical system's perspective, transitions emerge out of the distributed decisions of a myriad of actors that are made in interaction with each other and with their physical assets. The literature focuses on transitions towards sustainability, but a system's perspective implies that the notion energy transition is more generally applicable. Therefore, we have defined transition as "substantial change in the state of a socio-technical system" (chapter 2).

Transition case-studies regarding *unplanned* transitions have led to the recognition of phases in transitions, similar to innovation-diffusion patterns. Furthermore, a transition is depicted as a shift from one regime to another. Unplanned transitions need to be distinguished from *managed* transitions, which imply that we can at least partly engineer a socio-technical system.

Transition studies investigate the change-over processes in socio-technical systems. Therefore, one could use *transition thinking*: think of transitions in socio-technical systems. Transition thinking can then be seen as a different perspective to already existing topics. Consequently, transition research does not imply thinking about different things, but thinking in a different way. In those terms, transition management implies looking for the way to make most of the journey. Therefore, we defined transition management as "the art of shaping the evolution of socio-technical systems" (chapter 2). We have argued that any policy interventions affecting energy infrastructures is an attempt towards transition management.

By managing an energy transition, we should be able to substantially improve the performance of our future energy infrastructures. However, the literature on transition management gives no conclusive answers how it can be done. The main reasons are that 'success' and 'performance' of transition management are ill-defined. Furthermore, there is a myriad of prescriptive and partially conflicting transition management elements. Moreover, there is a strong focus on environmental sustainability, which excludes other performance aspects. Finally, the role of government is highly debated. By rephrasing transition management into a *design* problem, we have translated these issues in three knowledge gaps that may prevent us from successfully managing a transition: transition *instruments*, *indicators*, and *tests*. These knowledge gaps can be filled by developing domain-specific literature on transition instruments, on indicators, and on tests. By doing so, we *can* test transition management and validate it bit by bit. This thesis represents a step towards this goal.

9.1.2 Building simulation models

Underpinning the long-term effects of interventions in energy infrastructures requires us to develop *simulations* that function as tests of (assemblages of) interventions. In chapter 3, we set out to find out how *simulation models* of transitions in energy infrastructure systems (which are complex and socio-technical) can be developed, run, and interpreted.

We have developed a *framework* – a set of guidelines – to develop such models, which is summarized in Figure 9.1. Based on the concept of energy infrastructure systems as complex evolving socio-technical systems, we have selected *agent-based modelling* to simulate specific interventions. Along the way, this led to a (conceptual) framework that structures the discourse on transitions in energy infrastructures. Using this framework

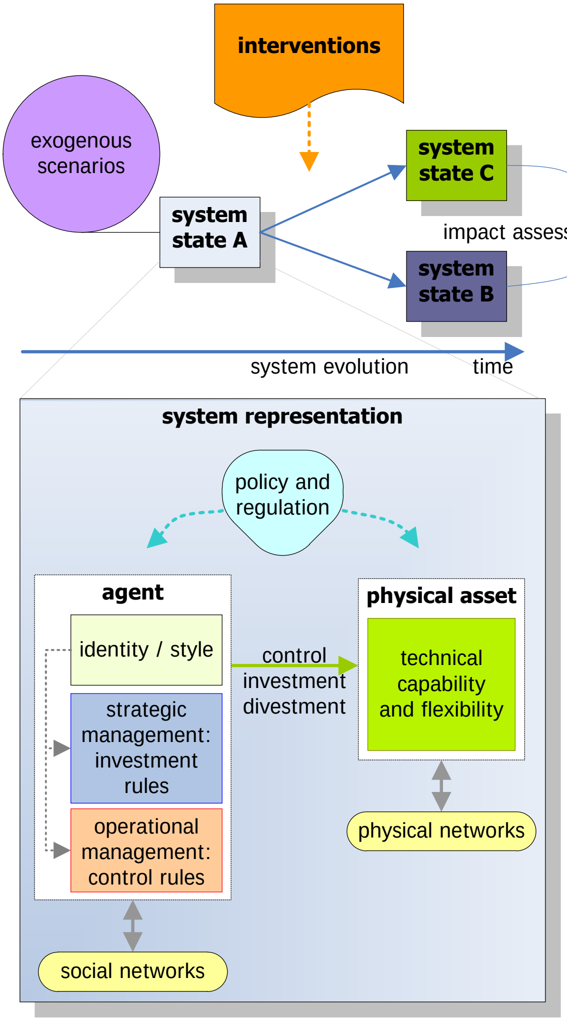

Figure 9.1 – Modelling framework for simulating energy transitions. Although the framework is not specific to a modelling paradigm, the system representation is made operational for the use with Agent-Based Modelling (ABM).

we are able to define the problem scope, system studied, relevant characteristics, and the resolution of the required results. Once these have been identified and described, the resulting narrative or specification can be translated to a simulation model. The modelling paradigm selected may be – but is not necessarily limited to – agent-based modelling.

As a necessary ingredient for determining the viability of energy transition management, we need some form of *impact assessment* that shows the effects of specific policy interventions. This need has several implications as for the properties the simulation models should have. The system under study is represented in such a way that the effects of various transition designs can be explored. The framework consists of the following five parts:

System representation The system is represented using a socio-technical system's perspective. The modeller needs to choose which actors are part of the system and with what granularity to represent their state and behaviour. In addition, relevant physical elements and their properties need to be selected.

Exogenous scenarios The changing environment of the system to be modelled is captured in scenarios that describe the possible development of the world exogenous to the system. A modeller must identify, characterize and select the relevant aspects of this external world and decide how the dynamics, the spread, and the uncertainty are represented. Scenarios may comprise static values that can be changed between runs (e.g. oil prices), trends, or models that specifically relate a variety of parameters exogenous to the modelled system. To be relevant, the infrastructure system model must be able to respond to scenario parameter changes.

Interventions A key element is to identify policy interventions that may affect the evolution of the energy infrastructure system. Individual interventions, or an assemblage of interventions, can be selected to form *transition designs*. These should be explicitly distinguished from the exogenous scenarios. *How* the transition designs are represented strongly affects both the level of complexity of the modelling effort and the ability of the model to simulate the effects of the modelled interventions.

System evolution Running simulations lets the socio-technical system modelled evolve over time in-silico. The actors' decisions affect the system structure and system performance, at each simulated point in time. Multiple runs are completed to collect an adequate sample across the scenario and intervention space. The evolution of each and every parameter in each run is recorded for monitoring and analysis. The indicator variables of the structure and performance of the system need to be selected, as well as the interactions they are based upon.

Impact assessment The effects of interventions can be traced and assessed through analysis of the simulation output. By developing graphical representations of key system indicators patterns can be identified, effectively resulting in an assessment of the system *performance*. Additionally, the system's *structural* change and the underlying causalities must be assessed.

The modeller has to make choices for each of these parts: by operationalizing and implementing these five parts in a case study, simulation models of transitions in energy infrastructures can be developed that are able to trace the effects of specific interventions.

> *Conclusion 2 – Agent-based models are suitable to simulate energy transitions, because they can capture change in the system structure and dynamics.*

From the modelling paradigms available – *Agent-Based Modelling* (ABM) is the preferred paradigm for gaining insights specific to transition studies, because only ABMs allow the system structure – which, by definition, changes during a transition – to be dynamic and emergent. Within the literature on agent-based modelling, there is no method or approach by which ABMs can be systematically developed, because of the range of applications and domains that are covered. Therefore, the agent-based modelling approach is

Table 9.1 – Typology of transition models. The typology is cumulative in the sense that higher levels have additional requirements and provide additional abilities to the model. Only level 3 models are able to trace the effects of specific interventions in energy infrastructure systems.

Level	Representation of intervention	Additional modelling requirement	Additional capability of the model
1	Implicitly modelled	System representation	Captures system evolution
2	Fixed as system parameter	Responsiveness	Observes transition impact
3	Exogenous in scenario	Flexibility	Assesses and compares transition designs

substantiated, specifically targeting at tracing the effects of specific interventions in energy infrastructure systems, with the developed framework. Agent-based models allow socio-technical systems to be represented as a collection of social and technical elements (recall the system representation in Figure 9.1). Actors are represented as computer-coded *agents*, having properties constituting an individual identity or management style. In addition, agents have coded decision rules allowing for their strategic and operational decisions. The term agents is reserved for pro-active, autonomous components in the system. Markets are represented as agents if they are institutionalized with their own rules according to which, for instance, prices are determined. Physical components do not make autonomous decisions. They are represented as computer-coded physical nodes/elements with properties regarding technical capabilities and flexibilities. Both social and physical components can interact. Any intervention may affect the agents in the decisions they make.

> *Conclusion 3 – Simulations can be suitable tests for tracing the effects of specific interventions, if the system is modelled in a way that it captures its evolution, and is responsive and flexible to the interventions modelled.*

Crucial to the ability of a simulation model to trace specific interventions is *the way in which individual interventions are modelled*. We have defined three ways to do so in a *typology of transition models* (see Table 9.1). This typology allows for a classification of existing and new transition models, based on a conceptual description of the model. Therefore, the typology can be used to ex ante show the potential ability of the model in tracing and assessing the effect of interventions.

The three levels differ in *how* interventions are represented in the model. On the lowest level, the model is implicitly specific to a single set of one or more interventions. Models on level 1 require the system to be adequately represented so that the evolution of the system can be captured. Because the interventions are not explicit, the impact cannot be assessed. Therefore, models on level 1 cannot be used to trace the effects of specific interventions.

In models on level 2, the intervention is mentioned explicitly, but it is a fixed system parameter. The system represented in the model has to be able to respond to this parameter: the actors represented in the model need to factor the parameter in somehow. This is an improvement compared to level 1, because it requires the modeller to make choices regarding the *response* of actors to this specific system parameter. As a consequence, on level 2, the effect of a single intervention can be *observed*. However, it cannot be compared to other interventions, nor to a no-intervention alternative. Although the effects of the intervention are visible, it may prove very difficult to attribute specific consequences to the intervention itself, because no comparison is possible.

In models on level 3, a variety of interventions are modelled as exogenous scenario parameters. In addition to the fact that the modelled system needs to capture system evolution and respond to the intervention, it also needs to be *flexible*: actors represented in the model need to deal with a variety of possible interventions. At this level, the effects of various interventions, or a lack thereof, can be compared. Comparing interventions may point out effects and patterns that only occur as the consequence of some of the modelled interventions. And that is an important mechanism of how insights are developed. Furthermore, comparing a single intervention to a no-intervention alternative allows to trace the effects of a single intervention on the long-term evolution of the modelled energy infrastructure.

> *Conclusion 4 – Transition models existing in the literature generally do not meet the criteria to trace the effects of specific interventions.*

We have shown that the lowest two levels are incapable of tracing the long-term effects of specific interventions. Existing models specifically dealing with transitions and transition management can be classified as level 1 or 2. As a consequence, their potential for assessing the viability of transition management is poor. The agent-based models in the three case studies in this thesis are on level 3, which allows for tracing the effects of individual interventions.

9.1.3 Case-specific insights in energy transitions

In chapters 4, 5 and 6, we explored what insights can be gained from simulation models of interventions in energy infrastructure systems. Three cases were executed to develop the framework discussed above and trace the effects of interventions in subsystems of our energy infrastructure. For each of the cases, an overview of the main insights is given below.

> *Conclusion 5 – Insights gained from simulations of agent-based models (ABMs) show advantages and disadvantages of specific policy interventions in energy infrastructures, by showing the variability in the long-term effects on the affected energy systems.*

The largest case which was developed was on *decarbonizing the electricity infrastructure* (chapter 4). Significant reduction of CO_2 requires investment in ‘clean’ technologies. The electricity industry is capital-intensive and as a consequence, power generation plants have a long technical lifespan. Public policy choices for emission reduction have led to the implementation of the EU emissions trading system (ETS). We asked the following question: *will the transition to a CO_2-extensive power generation portfolio be successful?* We found that the transition to low-carbon electricity generation can indeed be influenced and that an efficient transition requires significant change of the current policy.

The current implementation of the ETS may have a poor performance, because market players can get around the cap by importing credits from JI/CDM. Even if the cap is made more strict, there is an inherent flaw in the ETS. The fact that the CO_2 price on the market is *volatile* introduces a fundamental *investment risk*. As the CO_2 price is highly unpredictable, investors become risk averse. Because of the long lead times and high capital cost of power plants, this effect is strong. As a consequence, investment in CO_2-extensive installations is lower than expected, given the average CO_2 price. The transition under an emissions trading scheme is, therefore, partially held back by this volatility. We found that a carbon taxation scheme does not have this drawback and, accordingly can be designed to achieve a smoother transition trajectory. One can argue that a progressive taxation scheme, using a relatively low tax level at the start and rising over time, can be implemented. Overall, a taxation scheme with an average level equal to the CO_2-market price leads to a far smoother transition. Emission reductions are faster and further and income transfer from consumers to producers is also lower.

However, although not impossible, replacing the EU ETS by a carbon taxation scheme is highly unlikely from a political point of view. Therefore, we experimented with assemblages including the current EU ETS. A first analysis showed that augmenting an emissions trading scheme with either a taxation scheme, a feed-in tariff or imposing a floor in the carbon price will improve the transition to low carbon electricity supply.

The second case regards *transition of the market for Liquefied Natural Gas* (LNG, chapter 5). The LNG market is traditionally governed by long-term high-volume bilateral contracts. Indications have been found that the LNG market may develop into a market where flexible spot trading is pursued. In this case study, we explore a potential transition towards spot trade. The question in this case is: *how can we simulate the LNG sector and let the transition to spot trade in the LNG market emerge?*

We identified four drivers for transition in the LNG market: growth of the market, uncommitted capacity, technological innovations, and the LNG market reinforcing itself. These drivers have been put to the test in an ABM of LNG agents representing companies active in the LNG market. These agents engage into contracts on LNG trade by optimizing their expectations regarding future options based on their experience.

We have observed the evolution of the LNG market under different circumstances: a variety in demand growth, the inclusion of endogenous innovation, different returns on investment for new technologies, different expected duration of partnerships, and different probabilities of meeting with other agents. A spot market is found to have significant potential. Spot-trade shares of 20% are common. The identified drivers growth, uncommitted capacity, and innovation are important for the development of spot trade. Contrary to many expectations, we have not observed that spot-trade reinforces itself.

The third case was on *transitions in consumer lighting* (chapter 6). In the EU, the incandescent bulbs are phased out since 2009. Therefore, a transition in consumer lighting can be expected. It is a prime example in which direct regulation forces the transition. We asked the following question: *what are the effects of government policies on the transition to low-electricity consumer lighting?* We modelled a network of consumer agents that have a demand for lighting. Given a set of luminaires the agents replace lamps that failed by purchasing the one of their preference in the lamp store. Consumer agents use a variety of lamp properties to make their choice. They also have perceptions and a memory and share these over the social network.

The simulation model confirms that, in the long run, the 'ban on bulbs' is the most *effective* way of achieving a lower electricity usage for lighting. Alternatively, a taxation of €2 per incandescent bulb is also effective in the long run. A subsidy on LEDs at acceptable levels is, however, not effective.

An important disadvantage of a ban is the burden on consumers: expenditure spikes during the phase in of the ban. This might be considered unacceptable. In contrast to the ban, a tax could be made income neutral. Whether it is a ban or a tax, it is crucial to attack all unwanted products. In this case halogen is *not* more electricity extensive than incandescents, but is not banned or taxed. If the penetration of halogen proceeds, it hampers the transition to lower electricity consumption in the sector.

We have shown that these conclusions are robust by performing experiments that replicate patterns from the 1980s and 1990s. The simulations show that – if politically feasible – a transition policy which *limits* the options for consumers can be a way to overcome the lock-in effect of, in this case, socket-specific luminaires.

9.1.4 Analysing and explaining simulation results

In chapter 7, we focused on how simulations can be interpreted when the system structure changes.

> *Conclusion 6 – The Dynamic Path Approach (DPA) analyses simulation results by showing how relevant causalities in the system develop over time. The network of causal relations is a representation of the relevant mechanisms in the system.*

Traditionally, simulations are analysed by observing the development in key indicator variables. However, these indicators may not clearly show the mechanisms causing the development of these indicators in this way. Therefore, we have explored a new approach to the analysis of simulations results. This approach assesses the validity of a conceptual causal model of how parameters affect each other, instantaneous or delayed in time. The development of this approach is coined as the *Dynamic Path Approach* (DPA). The software developed for this approach has been released as an open source module. Using the approach we have verified that impacts of autocorrelations and time-lagged relationships are significant. Furthermore, we found that the relations can change significantly over the simulated time. There is not a single causal model that is valid throughout the simulation. This is an indicator that crucial mechanisms are changing over time, which indicates a transition.

Using the DPA, we showed that it is vital to take into account all causalities at once and how causalities change over time. Neglecting either of these leads to overestimating causal relations between parameters that change together over time. The reason for wrongly estimated relations should be sought in other mechanisms. The dynamic path approach can show for which relations this issue occurs. Then the analyst can try to find the mechanisms underlying the observed change in a model and not simply the relationships that can be observed in the data.

In chapter 8, we studied how *serious gaming* can be used to enrich the decision makers' understanding of energy transitions.

> *Conclusion 7 – The use of a serious game facilitates the knowledge transfer from modellers to strategic decisions makers in energy infrastructure systems. It increases the ability to reflect on insights from simulation models regarding the long-term effects of interventions in energy infrastructure systems.*

Insights from simulation models of energy transitions prove difficult to grasp by non-modellers. We have used a serious game to facilitate the knowledge transfer from the modellers to the target audience: strategic decision makers in energy infrastructures, researchers, etc. The game was developed to capture important features that make energy infrastructure systems complex: the game allows for experiencing this complexity. Facing the complexity in decisions made in a competitive environment, increases the understanding of simulation results on energy transitions.

We applied our approach to the case on CO_2 policy and the electricity sector for which both a simulation model and a serious game were developed. We have observed that participants of the game learn demonstrably more about the short and long-term dynamics of electricity markets than they would learn through lectures. Moreover, only after having played the game participants realize the difference between a static and a dynamically equilibrium, which is fundamental for understanding how complex systems evolve. After playing the game, we noted that participants were able to understand the insights from related simulation models more thoroughly and faster and were better able to reflect upon the long term effects of policy interventions.

9.1.5 Transition management in complex socio-technical systems

Energy infrastructures are merely examples of complex socio-technical systems. What have we learned regarding the long-term evolution of socio-technical systems when we intervene now? Is transition management viable? How can it be done?

> *Conclusion 8 – Necessary for transition management is to be able to intervene in such a way that the many distributed decisions taken by relevant actors are likely to alter the dynamics and the structure of the socio-technical system along a desired trajectory. ABMs can determine likely effects of interventions without claiming to perfectly predict future states of socio-technical systems.*

We have shown that a necessary ingredient for transition management is to select and implement specific interventions that affect the many distributed decisions taken by relevant actors in a way that it is likely to alter the dynamics and the structure of the socio-technical system along a desired trajectory. Translating transition management into specific interventions – which is different from how transition management is perceived in the traditional transition management literature (cf. Rotmans, 2003; Loorbach, 2007) – made it possible to use ABMs to show advantages and disadvantages of specific interventions in complex socio-technical systems. The viability of transition management may be proven when the core aspects of management – intervening, monitoring, and adapting – can be simulated.

At some times the simulation results have surprised us. Although ABMs are quantitative, crucial results and insights from ABMs are not necessarily quantitative. There is a strong qualitative part, especially regarding the analysis and interpretation of results. The value of the models is partly based on the attention given to the analysis and interpretation of simulation results. Based on that, several recommendations on intervention policies for energy policy makers originate from the models described in this thesis.

Although, at this point in time we cannot show with real-world data that they are true – some of the systems do not exist, nor are they likely to exist any time soon – we were able to argue clearly and openly under which conditions the derived advantages and disadvantages hold. The product of this thesis is a set of tools and an approach to develop more of these tools that enable us to explore how the evolution of these socio-technical systems can be affected.

We are now able to discern the 'logical' consequences of specific interventions in a systematic way, by analysing the range of possible futures in a delineated system with a set of rules regarding the behaviour of its elements. Its value is not purely the fact that the system structure emerges out of the interaction – there is no 'magic' involved. The system structure is 'simply' the result of the modelled interactions – which constitute a large part of the modelling choices. Its value is that these emergent dynamics can be counter-intuitive and that these results are practically impossible to derive 'on paper'. The value of the model, and any other model, therefore, depends on the validity of what is modelled and how it is modelled. In this thesis, we strived to find a balance in what specific issue is looked at (the *'why?'*), how the systems in our models are delineated (the *'what?'*), how real-world decisions are simulated (the *'how?'*), and how the results are analysed and interpreted (the *'so what?'*). This balance allowed for the generation of concrete and specific insights regarding – and recommendations for – interventions in energy infrastructures.

9.2 Reflection

In this section, we reflect on the findings in this thesis with respect to our perspective on transitions and the limitations of agent-based models.

9.2.1 Interdisciplinary transition perspective

Tackling questions regarding transition management in energy infrastructures required us to bring together a wide range of knowledge. Reflecting on the approach we used, the notion of transition and transition management can be overhauled by sketching a new perspective. Societal or socio-technical transitions are about the evolution of complex socio-technical systems. Therefore, transition management deals with the long term effects of interventions in such systems. From that angle, the transition story changes fundamentally: our perspective requires us to look at *how* complex systems actually adapt. This is a challenge, because the language in transition theory and transition management – such as desired goals, regimes, niches, and management, is far away from the terminology used in complex adaptive systems – such as intractability, lock-in, variation and selection, and emergence.

This thesis may lay some of the foundations for the long bridge that is necessary to provide the content of a renewed transition perspective. In between are many fields that we have used. Notions from engineering depict the working of technology and technological systems. A variety of economics fields are relevant, notably neoclassical and institutional economics, which – in a practical sense – provide handles to model the rules of the game in many real-world systems. Many insights from the social sciences – sociology, decision making under deep uncertainty, etc. – may be put into a perspective on how specific decisions are made.

Connecting all these bodies of knowledge into a simulation model is challenging, if not impossible. The notions from various fields are so different that they are often hard to link conceptually, let alone to formalize them into a computerized simulation model. There are three dimensions to this issue. First, we need to select the correct notions. This is challenging, because the interdisciplinary character implies that there is probably no agreement on what the relevant notions are. Second, there is the matter of modelling the notions themselves: translating the conceptual notions into code. The mere fact that we use ABM requires us to translate a notion into model parameters, agent properties, and agent decision rules. This forces us to make a representation of how these conceptual aspects affect decisions of agents. This may be very challenging, particularly for 'soft' notions. Some level of logic and rationality must be introduced, although this may be in conflict with the notion itself, such as programming agents with illogic behaviour and bounded rationality. Third, we need to deal with the interactions between notions from different fields for which there is no shared language (e.g. coupling 'trust' to 'risk' and 'uncertainty', which may be needed in the same set of decision rules).

Many ABMs in the literature are mono-disciplinary, i.e. they are either ABMs strongly rooted in the social sciences, or they are multi-agent systems, performing specified distributed tasks. Therefore, one could argue that we have been 'creative' at points, in order to come up with strategies to develop our models, which, by necessity, are multi-disciplinary. The field of ABMs is yet young and lacks approaches that sufficiently address how the translation of all the relevant research fields can be done in a more systematic and profound way. Despite this fact, the approach used in models may result in a reflection on how such maturity may be developed. Naturally, when we are able to put all the necessary ingredients into a quantitative simulation model, it may well be possible (or at least easier) to communicate between research fields about the wide variety of notions involved in the evolution of complex socio-technical systems and the effects of specific interventions.

We believe that the literature on transitions would strongly benefit from work that is targeted at finding common ground in various bodies of knowledge. Such work can also be expected to provide valuable input to complex systems theory. Despite the fact that there is some literature on bridging work on a conceptual level (cf. Hekkert et al., 2007), we conjecture it is valuable to use simulation models as vehicles, as they will require formalization and coding/computerization. Such work should focus on bringing selected theory into a perspective in which they can be used as tools for exploration – and some of the conceptual argumentation may be put to the test. However, it stands out that simulation of many of 'the social' may be extremely challenging: there is a limit to how agents can simulate human that are irrational, creative, capable of trusting, lying, etcetera. Serious games are in many ways complementary to ABM: they are a simulation of interaction between humans. Results from serious games may be valuable input into agents in models of systems similar to those of these games. Although no universal agent-based model can ever be developed to grasp the complex behaviour of our infrastructures, enriched 'social' agents may provide valuable insights.

This thesis provides examples of what can be done, and the types of insights that can be gained, the types of studies that are relevant and useful. Therefore, the nature of this thesis is both exploratory and explanatory. It is exploratory with respect to how simulation models can and cannot be used. It is explanatory with respect to the design and implementation of policies. This thesis has not aimed to reduce the complexity of energy infrastructure systems, but to embrace it and learn how to deal with it. And that is at the core of our interdisciplinary transition perspective.

9.2.2 Limitations of agent-based models

Based on the experience in this thesis, we can reflect on the applicability and limitations of agent-based models (ABMs). What can simulation models do and what can they not do? How can they be most useful? We believe that the strengths of agent-based models – and the way we have developed them – is that they help us to gain insight in the *mechanisms* that govern the behaviour of complex systems. These mechanisms show the potential for intervention. Although the experience in this thesis may indicate the utility of our approach specifically and ABM generally, there are strict limitations regarding how we can use ABM to represent social and technical aspects, observe patterns, and design experiments. Below we will discuss these limitations in detail.

Applicability and utility Central for the validation of models is whether they are *fit for purpose* (Chappin, 2006, p. 50). Therefore, the usefulness of the models is crucial with respect to the validity of the conclusions presented above. The general lack of accepted agent-based modelling conventions and validation techniques makes it difficult to objectively judge the applicability and utility of our approach. A first step in assessing such usefulness has been done by gathering feedback from scientists and strategic decision makers in energy infrastructures throughout the period 2007–2010. The models were presented in the scientific community on a variety of conferences, and on a number of occasions outside the scientific community. These presentations did not only provide feedback for future improvements, but also on the usefulness of the approach itself.

Without systematically analysing the feedback received, we can make a number of observations. Generally, the presentations and workshops inspired lively discussions regarding the notion of energy transition, the specific case discussed, assumptions, implications, and the abilities of agent-based models. We generally received positive feedback regarding the simulation results that we presented. This may be caused by the fact that the models 1) are different/unconventional, 2) bring new arguments to the existing debate on energy transition, or 3) bring a different perspective on issues in energy infrastructures. Either one can be considered a useful contribution to complexity science, transition management, and policy studies. Another observation is that strategic energy decision makers appear to have no simulations available that are able to generate similar insights. Therefore, the models of this thesis, and similar models, may actually help them and fill one of their needs. Nonetheless, our audience will only use them if and when they actually lead to an increased understanding of the complexity of the infrastructure systems they are part of. Exactly this is not trivial, since we experienced that quite some of our problem owners are not eager to hear about agent-based models, either because they have not heard of them or earlier experiences were not appreciated. Such an attitude may be rooted simply in the way in which information is used for decisions by strategic management (cf. in decision-support systems) that typically aims to *reduce* the complexity of their decisions. Perceived incompatibility may severely hamper the potential for agent-based models. Fortunately, during and after presentations, we observed a more positive attitude towards modelling in general and simulations of energy transitions in particular. Participants of the game were especially perceptive of the potential usefulness of agent-based modelling, because they liked the idea of 'repeating' the game inside a computer by representing the human players as software agents.

Representing the social A worrisome aspect of our models is the conceptualizations and simplifications that are hard to back up with objective arguments. In our models, we aimed to grasp large infrastructure systems, but they are still strictly delineated. Of course there are limitations to which (social and technical) elements in the system can be represented. Furthermore, we have not modelled the *social process*, i.e. the process in which the policy interventions are prepared, chosen, and implemented. Such a social process is extremely difficult to capture in an agent-based simulation model. How could the behaviour of all relevant actors in the social process be captured and successfully simulated? Despite no simulation models in the transition literature were developed yet to capture such processes, such an effort would be at the core of the transition management literature. The use of serious games may be complementary to ABM in this respect: the social process may be captured in a serious game and, after playing such a game, the long-term effects of the outcome of the social process may be evaluated in an ABM. Part of the social process may be to decide on an acceptable model of the complicated technical system, to which the intervention in applied. Outcomes of that this process may be valuable input into the technical system of the ABM and, consequently, its validity: if the game is played by experts and strategic decision-makers, they may – through the game – test the validity of the technical representation. In this way, the social process captured in a serious game can also be used for validation of an ABM.

Even without modelling the social process in which policy interventions are developed and selected and 'simply' selecting a couple (e.g. on the basis of political feasibility or their theoretical potential), or combinations of interventions, there is a fundamental problem in representing the social. It is not trivial to come up with a structure, a conceptualization, and a simplification for at least 1) the *types of decisions* that can be made, 2) the *types of interactions* that are allowed, 3) *parameters/notions* that are taken into account when decisions are made, 4) *how* actual decisions are made, 5) what the *consequence* of any decision is, and 6) how actors learn. The complexity of the real-world system is grasped in the choices regarding these six items: the *decision-making structure*.

For some systems, for some of these simplifications and conceptualizations, literature is available. Despite the available literature, for instance on how consumers make decisions, most theory regarding the decisions we want to model is not really about *how* decisions are made, but about the *consequences* of those decisions. Consequently, for the larger part, we have used real-world observations, intuition, and existing or new conventions in order to deduce how individual decisions are made. An example is the notion of price elasticity, a common concept in economics that portrays how a set of consumers switches as a consequence of a change in price. The price elasticity of electricity demand is known to vary greatly between short and long term, between countries, and between groups of users. Translating the notion of price elasticity to a model of individual consumers making choices, is not trivial: it requires many additional behavioural choices ('who reacts to changes in price?', 'who does not?', 'how do they react?', 'how will past actions and their consequences affect future reactions to changes in price?', etc.). And only within the behavioural model we come up with – the model of complexity – we are able to capture structural change, and changing dynamics.

Any choices for the structure in decision making essentially causes that the decision making entities – the agents – to be rational in the sense that they follow some logic. It may be the only feasible interface between the modelled human actions/interactions and the modelled physical world. But whatever choices are made, the social representation may be weak or even invalid. In terms of the example of electricity price elasticity: even if the consumer agents purchase in the model electricity and the results show that the elasticity numbers are consistent with measured data, this is not a conclusive argument that the way consumers make their decisions is simulated correctly (nor the other way around, when the data are different). Any altered condition, even one that is generally considered unimportant, could have caused a deviation, or a lack thereof. By definition, models are simplifications and "they are wrong" (Box, 1979) – so how can we confirm their validity?

In the literature, the validity of ABM is challenged, because it is rather new and there are not yet accepted/proven representations/conventions (e.g. Klügl, 2008; Ormerod and Rosewell, 2009; Heath et al., 2009). But also other paradigms face similar (but other!) limitations, although the *conventions*, ways of representing real-world phenomena, are far more accepted. The fact that they are more accepted must be mainly sought in the fact that they have been practised longer and that they have been 'useful', not necessarily that they are 'better'. Essentially, all modelling paradigms face similar fundamental problems regarding the validity of their representation. This does not make such models faulty, nor useless. For each modelling paradigm, there are other conventions, and this makes it important to use a portfolio of models/model types, so they can complement each other. Valuable insights may be achieved by comparing the various representations, and the emerging patterns. This is similar to the fact that we have argued that a variety of experiments per model help us to increase our understanding of the complexity of energy infrastructure systems – although neither can perfectly predict the future, they can be combined in a single storyline on the viability of energy transition management. Future work in the ABM domain would expect to benefit largely from accepted conventions regarding representation of the decision making structure.

Interpreting patterns Focusing on the mechanisms of complex systems requires to look at *patterns* emerging in simulations. We have, therefore, aimed to recognize patterns from the data of various simulation runs. We expect that these patterns tell us a story: bring us the insight in how to steer the development of our energy infrastructures, what are advantages and disadvantages and, possibly, how should we *monitor* the system in the real-world. What are these patterns really? When can we consider something we observe a pattern? Can we improve the process in which we derive patterns? Or automate it?

Humans are excellent at recognizing patterns. For instance, the part of our brains called *fusiform gyrus* is (mainly) there to visually recognize faces. One aspect is processing the stream of visual information by searching for face-like patterns. But both the questions ‘do we see a face?’ and ‘who is it?’ need to be answered. Comparing patterns we observe with what we already know makes it useful. It has always been challenging to make a computer do the trick, because of the processing power needed, and because it is extremely difficult to properly define what patterns really are. There are functional examples though (e.g. fingerprint recognition). The use of pattern recognition has increased considerably in the last decade. Today, with the computational power available to us, personal computers automatically recognize faces on photos. Some photo cameras even recognize where the faces are while taking the picture, to assure they are in focus. There are smart phone applications that allow for speech recognition, and recognize what music is playing. The computational power available is crucial, but not the whole story. Intuitively, when we know what to look for, it is much easier to recognize a pattern. Google’s speech recognition is efficient because they are so good at making a (long) list of the keywords I may be asking for.

What are the things that constitute a pattern? For recognizing a piece of music that is playing in the environment, three dimensions of data are available after the recording of a fraction of music in a noisy environment: frequency, amplitude and time. A smart and efficient pattern recognition algorithm is needed to analyse the data on these dimensions and to match the resulting pattern with a complete database to check whether a pattern has been recognized. *Shazam*[1] recognizes music by finding such a pattern – a representation of (a piece of) a song – through an elegant way of processing the peaks in a so-called *spectrogram* (a visualization of the density, the loudness of frequencies over time). Shazam’s algorithm shows that the pattern in music can be captured in a time-related set of *hashes*, each reflecting the frequency of and relative moment in time of exactly two sound peaks. By matching a sequence of hashes to the files in the database, the algorithm is even able to recognize multiple pieces of music played simultaneously, and distinguish between different recordings of the same song.

The example above shows that patterns can only be observed by looking at a (limited) set of clearly defined and measured parameters or dimensions. These parameters are measured on the *system level*, i.e. they should allow for a qualification of the evolution of the system’s state. Therefore, the selection of parameters is very important. In order to find patterns in a simulation on the long-term effects of a specific policy intervention, a combination of macro-economic figures such as ‘gross domestic product’ and ‘number of jobs’, may give insights into the intervention’s effects that are very different to a combination of aggregated (micro-economic) parameters such as ‘yearly money invested’, ‘average price’, and ‘total consumer sales’. In his choice which parameters to use when he searches for patterns, the analyst may take into account which *mechanisms* – which causal effects – he expects to be important. He may prefer parameters or dimensions that are likely to reflect those mechanisms.

Some sort of algorithm is needed to translate the data of selected parameters into a pattern: a simplified and systematized characterization, a qualification or one or more

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[1] Shazam is an application for smart phones, available at http://www.shazam.com. Information on its pattern recognition algorithm can be found in a paper by the developers (Wang, 2003).

'snapshots' of the data. It may be possible to do this by means of a computer, for instance by plotting slices of the data that may be insightful. This process of pattern creation must be repeatable, so a database of existing, or plausible patterns can be used to compare the findings with – finding out whose fingerprint it is, what the song's identification is, etcetera. In our models, patterns are represented in the shape of the graphics that show aggregated data from the simulations. Similar pictures can be drawn from various sets of simulation runs in order to compare the shapes for different scenarios or specific interventions. In chapter 7, we showed a very different approach of finding patterns, by looking how specific causalities develop over time[2].

Only *interpreting* patterns makes them useful. However, what a found pattern *actually implies*, cannot be captured by the pattern recognition algorithm. The fact that the identification of a song is coupled to the name of the song, the composer, the artist, the album that features the song, and its rating, is through the implications of the pattern found. The interpretation is the most valuable part of the pattern. Essentially, patterns observed in simulations are an interpretation of an analyst or an expert. The song's rating is not a fact, it is a collection of interpretations, judgements of the piece of music the pattern is about. From simulation models, there are many relevant parameters/dimensions – there are a lot of data available – the interpretation aspect is even more important and challenging. We do *not* always know what to look for, what constitutes a pattern in the case of tracing the effects of specific interventions in socio-technical infrastructure systems. It is much more than only the spectrogram of a piece of music: it is more than using the *tools* to display the results. Hidden in the idea of patterns is the fact that we assign properties to patterns we find when we recognize them: we generate meaningful ways to look at 'things', meaningful interpretations of trajectories in the system's state. Discerning patterns, at least requires us to study the trajectories of a set of indicators of many simulations and translating this into a consistent story. Such study may by about leverage points (when and how the system can be manipulated to significantly go into another direction), or about classification of the types of patterns found in different runs. Expertise or in-depth knowledge of the system under study and the way it is modelled is necessary to be able to interpret these patterns. An inherent limitation to ABM in particular, and modelling and simulation in general is, therefore, the ability of the analyst to properly choose indicators, recognize patterns, and draw up a story of implications. For simulations, there are no general guidelines on how to do so, and there is no objective way to show how well it was done.

Smart design of experiments In order to be able to discern the patterns we are after, we need to be smart in how we design our experiments. They need to allow us to see a specific big picture while the details can still be understood. This calls for tailored experiments. However, we observed in this thesis, that such experiments are necessarily quite elaborate. When models get larger, they can easily grow beyond the comprehension of the analyst. This is the classic argument for keeping models simple, also known as the KISS principle[3], which fits in the reductionistic tradition of splitting up problems and

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[2] The dynamic path approach, as described in chapter 7, appears to be promising with respect to pattern recognition. The approach has similarities to computerized pattern recognition algorithms in some medical sciences, particularly in the analysis of sets of photos of brain activity.

[3] Keeping models as simple as possible is known as the KISS (Keep It Simple Stupid) principle.

looking in much detail at specific aspects of a system. Reductionism typically leads to static models with a fixed structure and a narrow scope that explicate a clear, well-known line of thought, under strict assumptions. Unfortunately, when we focus on the long-term effects of interventions in energy infrastructures, models with a narrow scope or a fixed structure are simply not viable. A strongly delineated model can never contain all crucial mechanisms and will, therefore, lead to faulty conclusions. We are in need of approaches with more exploratory power.

In holistic approaches, (quantitative) modelling and simulation is less common. Where it has been done, *abstract* models are popular. The insight that one could gain from an abstract model is not about *specific* interventions in specific infrastructure systems. Making specific observations and developing insights regarding the long-term effects of specific interventions using abstract models is, therefore, extremely difficult.

When the KISS principle is applied in our case, and models are developed as simple as possible, they are still rather large and complex. The design of the experiments need to be smart: both purely reductionistic and purely holistic approaches are insufficient. ABM may be a sensible way to combine both in one approach and handle the complexity we face in making our decisions. We deal with this paradox by developing very specific, tailored models. The fact that the models presented in this thesis are rather large and, possibly, difficult to understand and validate, does not make them useless. We focused a significant part of the modelling effort on how they can be interpreted, understood, and explained. Despite these efforts we appear to approach a limit in what we can do with simulation models; they are at the frontier of our knowledge – in between the traditional scientific approaches.

Utilizing opportunities of simulations for policy support In this thesis we have focused on *scientific* modelling questions with a relevant societal need for understanding or improvement. An issue for simulation modelling are the windows of opportunity for the use of modelling for *supporting policy decisions*. Strategic decision makers may have a demand (and financial means) for development of simulation models that answer urgent questions. Such questions may, for instance, be related to new political winds, detailed policy design, strategic business decisions, and lobbying efforts of new players or incumbents. Utilizing such opportunities by means of ABMs is difficult, because the effort of developing simulation models with the level of detail, such as the ones in this thesis, is too time consuming and too costly.

We need to lower the burden for modellers, come up with simpler set-ups that allow for faster experimentation. Steps have been taken, such as the use of high performance computing, automated scripts to perform and analyse experiments, partial generic code that can be shared, and repositories in which the code and scripts reside. A possible next step is to develop a (more) generic energy model that allows for more modular and quicker adaptation, so some questions specific to that infrastructure can be answered faster. Some details regarding such a model are discussed in section 9.3.

9.3 Directions for future research

In this final section, a number of possible angles for future research are outlined.

9.3.1 Transition research

Studies regarding transitions focus on processes of long term change in large systems. The other way around, many studies regarding large systems are about *change* in these systems. Therefore, the scope of transition research is large and only some parts have been explored. This thesis has attempted to broaden the field in directions regarding *energy infrastructures* and *simulation*. We showed that transition research is strongly connected to policy studies. In addition, we envision other useful directions for transition research.

First, many elements in the transition management literature focus on *cooperation* between actors, for example the idea of a transition arena. Research that focuses specifically on cooperation (cf. Ligtvoet et al., 2010) in the context of transition may lead to different approaches for transition management.

Second, *sets of transition management instruments* may be operationalized and tested in case studies, whether it is in the real world or with simulation. Typically, the interaction between multiple instruments lies beyond the scope of individual studies. Understanding the outcome of pancaking of instruments (cf. Yücel, 2010), whether they stem from the transition management literature or from policy studies, may well lead to surprising insights.

A third new direction for transition research is related to the *interdependencies of infrastructure*. Although practically all infrastructures depend on energy infrastructures, each infrastructure has different elements, interactions, and characteristics. Cross-infrastructure research may be targeted at transition. Important examples are the mutual dependence of infrastructures within the energy sector, such as electricity, gas, and heat networks, between energy and ICT infrastructures in applications such as smart meters and smart grids, and between energy and transport infrastructures in the applications related to electric vehicles.

9.3.2 Simulation models of energy infrastructures

Extending cases We have developed agent-based models on level 3 of our typology (see Table 9.1): for each case a variety of interventions are modelled as exogenous scenario parameters. We could envision a 4^{th} level, in which policy interventions are *endogenous* to the system. The intervention is not static, but it is adapted based on actual or expected system performance. This allows to explore the interaction between how a system changes as the consequence of an intervention and how interventions are adapted based on change in the system. The effects of the intervention can be traced, including relevant feedback effects on the intervention itself.

At this level, policy development is endogenous. This implies the government is an actor included in the system representation who decides during a simulation run on their policy and regulation. Governments' actions are the outcome of its decision-rules and the state of the system, i.e. past, current and expected values on system parameters. Since the systems state depends on agents' reaction to government policy, the government behaviour would be a result of its own behaviour in the past in relation to the behaviour of other agents. As a consequence, the policy setting is an emerging property of the system and models of *adaptive policy making* can be developed. Modelling policy and regulation as an endogenous system parameter leads to tough requirements for the other model components. One needs all relevant interdependencies with other parameters in the model. It may prove to be difficult to validate how governments respond to the performance over time. For each of the three cases, this provides room for additional experimentation and developments.

With the power generation model, many policy related experiments can be done: the investment algorithm using levelized cost of electricity can be altered to include softer criteria. The model could be run using a range of data sets regarding power plant properties, possibly the complete set of existing power plants in the EU, and with a variety of existing scenarios that have been developed by institutes, such as KEMA, the IEA and Shell. Agent strategies could be made more specific by performing empirical research, possibly in collaboration with energy companies, research institutes and/or government. Furthermore, the model could be calibrated to find the carbon tax trajectory at which the CO_2 target is reached most efficiently.

The electricity market game could be extended in parallel to the power generation model. Many policy measures, developed for the power generation model, can be implemented and evaluated as well. In this way, even if players have heard from the game, they will never know what is ahead. It also allows for shifting policy and combining a variety of policies. The game also allows for including other soft mechanisms, such as a possible delay in permitting or construction of nuclear power plants, limited sites for specific power stations, and the possibility of bilateral trade.

The LNG case could be further developed by exploring agents that switch from the long-term market back to the spot market by breaching an existing long-term contract. Furthermore, it could be interesting to look at various portfolio management strategies. For instance, to cover only part of the capacity of a project in a long-term partnership and allow for spot market trading with the remainder. Finally, innovative technologies, such as floating regasification and liquefaction, can be included.

For the consumer lighting model, additional experiments could be designed from a marketing perspective. Those experiments could be very insightful for companies such as Philips: which marketing strategies are likely to be successful? One could think, for instance, whether a company should wait with the introduction of LEDs until they perform well or start the introduction as soon as possible. Such experiments could be performed with the model with minor adaptations in the way new lamps are introduced. From a policy perspective, also the incandescent taxation scheme could be calibrated in order to find out a good taxation level.

Further work on the dynamic path approach should be related to a systematic analysis of conditions that underlie finding proper solutions, regarding simulation data, type of relations, number of relations, and approaches for time-lagged parameters. This would improve the usability of the tool for the dynamic path approach and would further underpin the method as well as the tool. The tool could also be used for causal models of (empirical) survey data.

An agent-based energy markets model Another interesting development could be that of a modular and generic agent-based energy markets model. An advantage of such a model over current models is the ability to add modules to the generic core that would speed up the experimentation process. Another advantage could be found in the fact that the development can be done by a team of modellers, in other words, form an ‘energy complexity lab'. This would have positive consequences, with respect to modelling conventions, the robustness of the code, and documentation. Additionally, the modelling school would be less dependent on individual researchers. It may be possible to hire qualified programmers to support the modelling team and increase the quality of the code produced. When successful, such a lab could provoke serious attention and gain momentum.

However, there are risks in such an effort. There will always be a demarcation problem: it could be uncertainty – or disagreement – about the abilities of such a model (and its parts) and how these can be translated into a specification of boundaries. Part of this problem is the trade-off between resolution and scope. A high resolution is required to model questions that are related to the integration of wind, hydro, electric vehicles, and the development of smart grids. A low resolution is necessary to model policies that affect investments. A choice needs to be made for the range of resolutions that are applicable. This has severe consequences for the implementation of market algorithms and agent behaviours.

Furthermore, there might be a conflict in the choice of modelling technology and platform, as a group of modellers will have their own backgrounds, uses, and styles. A choice can be made for an internet-based, server-run application, a Java standalone application, a model in Matlab, etc. Access to, use of, and storage of code, applications, documentation, and simulation results need to be arranged and standardized.

In addition, it would require significant time and money to develop an initial core that performs results similar to what already has been done. Therefore, there would be only small scientific and societal incentive to do so. Consequently, finding the people and the money to develop the initial core may well prove difficult.

At least, an agent-based energy markets model should be modular. In the model, a variety of infrastructures should be distinguished: not only electricity, but also natural gas, LNG, and oil. Agents should be modules that represent relevant actors, such as producers, network operators, large and small consumers, policy makers, and authorities. Institutionalized markets should be modules that have algorithms specific to their market design at resolutions matching that of agents operating on these markets. Various types of markets are relevant, i.e. power exchanges, bilateral markets, balancing markets, green-certificate markets, and CO_2 markets. The physical system should contain modules with physical assets, such as power stations, power grids, natural gas pipeline systems, and large and small consumer appliances. Finally, there should be policy modules, regarding emissions trading schemes, carbon taxation, green certificates, feed-in tariffs, other regulations, and obligations.

A balance needs to be found between the identified advantages and risks, and choices should be made. The main focus should be to be pragmatic and keep the threshold for modellers as low as possible. Through slowly involving more people, the development and use of the energy markets model could gain momentum.

For the time being, we only gain small improvements in parts of the society we cherish. Through starting at the backbone of it all – the infrastructures that bring us our energy – we can only be optimistic about improving the way we live our lives.

Appendices

A Transition Literature

This appendix contains an overview and analysis of the literature on transitions.

The literature review scope is limited to scientific publications. The literature search was done in Scopus (2009), using the following literal phrases in abstract, title and keywords:

- “sociotechnical transition” (3 results)
- “socio-technical transition” (8 results)
- “societal transition” (37 results)
- “technological transition” (78 results)
- “transition management” (153 results)

Within these results, a significant number of papers was excluded because they referred to transitions in other contexts, for instance transition economies. Some papers were found in the results of more than one of the searches.

For key articles, the references in the results are analysed, too, in order to reach underlying publications. For both publications not listed in Scopus and publications on Scopus without access to the full paper we augmented the search with results from websites of individual authors, relevant publications from the KSI network[1] and papers present in Google Scholar. The search was performed at the beginning of this study, in 2007 and again mid-2009. The total number of papers is 142.

A.1 Scientific publications related to transitions

In Table A.3 we present an overview of all scientific publications on the topic of transitions. In chapter 2 we review this literature, including the development process. More than half of the publications stem from 2007 or later, which indicates that the body-of-knowledge on transitions is growing fast.

We analysed the articles for which the full text can be accessed. Abbreviations for theory can be found in the list of abbreviations, abbreviations for countries were adopted from http://www.greenbuilder.com/general/countries.html.

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[1] the Knowledge network for System Innovation and Transitions, http://www.ksinetwork.nl/?content=publications

Table A.1 – Cross-table of transition literature papers

	Developing theory	Adopting theory	Transition management	Simulation	Case
Developing theory	*51*				
Adopting theory	23	*73*			
Transition management	32	42	*79*		
Simulation	5	10	6	*19*	
Case study	19	49	51	13	*94*

All papers were analysed in terms of the development or refinement of theoretical constructs, what theoretical concepts were used, was transition management discussed in addition to the emergence of transitions, did the paper involve any application of simulation models, and did the paper contain a case study (and its topic if present). Also the country and city of publication are noted. A cross table of the results can be found in Table A.1.

A.2 Elements in transition management

In addition to an overview of scientific publications on transitions, we focused on how transition management has come about. For such an analysis, the papers were reviewed for their references to elements of transition management. They were referred to in different ways: transition characteristics, instruments, principles, etc. In Table A.2 an overview of these elements is presented.

A.3 Publications with simulation models of transitions

In Table A.4, an overview is given of the papers with simulation models regarding transition. Of each model, the *methodology* and *development status* are listed. In addition, the simulation models in which transition can *emerge* during simulations, the ones that deal with transition *management* are marked and the models in terms of the *typology* presented in chapter 3 are classified.

Table A.2 – Transition Management Elements

Element	References	Denoted as
long-term thinking for framing short-term policy	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); Rotmans, Loorbach and van der Brugge (2005); Drift (2006); Loorbach and Rotmans (2006)	characteristic, principle, rule of thumb, key element
multi-domain; integrated policy	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); Rotmans, Loorbach and van der Brugge (2005); Drift (2006); Loorbach and Rotmans (2006); Rotmans and Loorbach (2009)	characteristic, principle, rule of thumb, key element
multi-actor	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); Rotmans, Loorbach and van der Brugge (2005); Drift (2006); Loorbach and Rotmans (2006)	characteristic, principle, rule of thumb, key element
multi-level governance	van der Brugge and Rotmans (2007)	management principle
multi-level	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); Rotmans, Loorbach and van der Brugge (2005); Drift (2006); Loorbach and Rotmans (2006); van der Brugge and Rotmans (2007); Rotmans and Loorbach (2009)	characteristic, principle, rule of thumb, key element
learning-by-doing and doing-by-learning; learning processes should be organized; use process management	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); van de Kerkhof and Wieczorek (2005); Drift (2006); Wiek, Binder and Scholz (2006); Rotmans and Loorbach (2009)	characteristic, principle, rule of thumb, key element
trying to bring about system innovation alongside system improvement; combine improvement with system change	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002)	characteristic, principle
keeping a large number of options open	Rotmans, Kemp and Van Asselt (2001); Vollenbroek (2002); Drift (2006)	characteristic, principle, rule of thumb
transition objective	Rotmans, Kemp and Van Asselt (2001)	stage
transition visions; the creation of challenging visions for a sustainable future as a road map towards system innovation	Rotmans, Kemp and Van Asselt (2001); Bruggink (2005)	stage
interim objectives	Rotmans, Kemp and Van Asselt (2001)	stage
evaluating and learning	Rotmans, Kemp and Van Asselt (2001)	stage
creating public support	Rotmans, Kemp and Van Asselt (2001)	stage
The state of the system determines how to steer it	Rotmans, Loorbach and van der Brugge (2005)	assumption
It is essential to steer on system level	Rotmans, Loorbach and van der Brugge (2005)	assumption
Objectives on system level need to be flexible and adjustable	Rotmans, Loorbach and van der Brugge (2005)	assumption
Timing and type of intervention is crucial	Rotmans, Loorbach and van der Brugge (2005); van der Brugge and Rotmans (2007)	assumption, management principle
Newcomers in a protected environment can effectively create a new regime	Rotmans, Loorbach and van der Brugge (2005)	assumption
Managing complex adaptive systems means using non-equilibria	Rotmans, Loorbach and van der Brugge (2005); van der Brugge and Rotmans (2007)	assumption, management principle
Societal change is whimsical and non-linear, containing surprises and discontinuities	Rotmans, Loorbach and van der Brugge (2005)	assumption
Complexity and uncertainty are no problems, but handles for steering societal change	Rotmans, Loorbach and van der Brugge (2005)	assumption
Everyone steers, realizing their potential and their limitations	Rotmans, Loorbach and van der Brugge (2005)	assumption
Society is not fully engineered, but partially engineerd	Rotmans, Loorbach and van der Brugge (2005)	assumption
Control over processes of societal change is an illusion, only coordination and influence is possible	Rotmans, Loorbach and van der Brugge (2005)	assumption
Transition arenas	Loorbach and Rotmans (2004); van de Kerkhof and Wieczorek (2005); Rotmans, Loorbach and van der Brugge (2005)	step, instrument
Integrated system analysis	Rotmans, Loorbach and van der Brugge (2005)	instrument
Transition agendas, agenda-building	Rotmans, Loorbach and van der Brugge (2005), Loorbach (2007)	instrument, element
Scenario development	Rotmans, Loorbach and van der Brugge (2005)	instrument
Transition visions	Loorbach and Rotmans (2004); van de Kerkhof and Wieczorek (2005); Rotmans, Loorbach and van der Brugge (2005); Loorbach and Rotmans (2006)	step, instrument,key element
Transition paths	Loorbach and Rotmans (2004); van de Kerkhof and Wieczorek (2005); Rotmans, Loorbach and van der Brugge (2005)	step, instrument
Transition monitoring	Rotmans, Loorbach and van der Brugge (2005)	instrument
Transition evaluation	Loorbach and Rotmans (2004); van de Kerkhof and Wieczorek (2005); Rotmans, Loorbach and van der Brugge (2005)	step, instrument
Innovation networks	Rotmans, Loorbach and van der Brugge (2005)	instrument
Arenas of arenas	Rotmans, Loorbach and van der Brugge (2005)	instrument
Space for experiments, Participative involvement of companies, research institutes and civil society	Rotmans, Loorbach and van der Brugge (2005); Bruggink (2005); Loorbach (2007)	instrument, element
Experiment gardens	Rotmans, Loorbach and van der Brugge (2005)	instrument
Practical experiments	Rotmans, Loorbach and van der Brugge (2005); Loorbach and Rotmans (2006)	instrument, key element
Focus on innovation and optimization	Drift (2006); Loorbach and Rotmans (2006)	rule of thumb, key element
Backcasting and forecasting (by using long-term sustainability visions, scenario-studies, trend-analyses and short-term possibilities)	Loorbach and Rotmans (2006)	key element

— *Table continued on next page* —

Element	References	Denoted as
Backcasting (by analysing needs, identifying options for improvement, creating a common future vision with stakeholders, developing pathways that could lead to this vision and developing consensus on these pathways	Mulder (2007)	method
Learning about a variety of options	Loorbach and Rotmans (2006)	key element
Trying to change the strategic orientation of regime actors	Loorbach and Rotmans (2006)	key element
Participation of and interaction between stakeholders	Loorbach and Rotmans (2006); van der Brugge and Rotmans (2007)	key element, management principle
Stakeholders have to be aligned	van der Brugge and Rotmans (2007)	management principle
Long-term goals must be adaptive to emergent innovations and macro-developments	van der Brugge and Rotmans (2007)	management principle
The phase of the transition is guiding for the employing management strategies and instruments	van der Brugge and Rotmans (2007)	management principle
A mix of top-down steering, network steering and self-steering instruments should be used, depending on the transition dynamics at hand	van der Brugge and Rotmans (2007)	management principle
Multi-actor policy making	Loorbach (2007)	element
Long-term, collective goal setting and anticipation	Loorbach (2007)	element
Evaluation, adaptation and reflexivity	Loorbach (2007)	element
Knowledge diffusion and learning	Loorbach (2007)	element
Creating space for niches	Rotmans and Loorbach (2009)	principle
Focus on frontrunners	Rotmans and Loorbach (2009)	principle
Guided variation and selection	Rotmans and Loorbach (2009)	principle
Radical change in incremental steps	Rotmans and Loorbach (2009)	principle
Empowering niches	Rotmans and Loorbach (2009)	principle
Anticipation and adaptation	Rotmans and Loorbach (2009)	principle
Knowledge generation	Wiek, Binder and Scholz (2006)	requirement
Knowledge Integration	Wiek, Binder and Scholz (2006)	requirement
Adaptation	Wiek, Binder and Scholz (2006)	requirement
Transdisciplinarity	Wiek, Binder and Scholz (2006)	requirement
Change management	Wiek, Binder and Scholz (2006)	activity
Entrepreneurial activities	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Knowledge development (which as indicators: R&D projects, patents, investment in R&D)	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Knowledge diffusion through networks	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Guidance of the search (limit the number of options to allow for enough resources for individual options)	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Market formation	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Resource mobilization	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
Creation of legitimacy/counteract resistance to change	Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	function
R&D funding	Jacobsson and Bergek (2004)	inducement mechanism
Investment subsidies	Jacobsson and Bergek (2004)	inducement mechanism
Demonstration programmes	Jacobsson and Bergek (2004)	inducement mechanism
Legislative changes	Jacobsson and Bergek (2004)	inducement mechanism
Firm entry/activity	Jacobsson and Bergek (2004)	inducement mechanism
Feedback from market formation	Jacobsson and Bergek (2004)	inducement mechanism
High uncertainty in technological, economic and market terms	Jacobsson and Bergek (2004)	blocking mechanism
Lack of legitimacy of the new technology in the eyes of different actors	Jacobsson and Bergek (2004)	blocking mechanism
Weak connectivity (weak learning and political networks)	Jacobsson and Bergek (2004)	blocking mechanism
Ambiguous and/or opposing behaviour of established firms	Jacobsson and Bergek (2004)	blocking mechanism
Government policy	Jacobsson and Bergek (2004)	blocking mechanism
Top-down: formal rules, regulations and laws	Elzen and Wieczorek (2005)	government instrument
Bottom-up: financial incentives (subsidies, taxes)	Elzen and Wieczorek (2005)	government instrument
Process: learning processes, network management: experiments, demonstration projects, vision building at scenario workshops and foresight, network building through seminars and strategic conferences, public debates	Elzen and Wieczorek (2005)	government instrument

Table A.3 – Transition Literature, sorted on last name of first author

Reference	Developed transition theory	Adopted transition theory	TM	Simulation	Case study	Institute
Agnolucci and Ekins (2007)	–	SNM, MLP	+	–	Hydrogen economy	Policy Studies Institute, London, UK
Agnolucci and McDowall (2007)	Technology change in niches	–	–	–	Cell auxiliary power units	Policy Studies Institute, London, UK
Ackerman (1982)	TM in organization	–	+	–	–	Bryn Mawr, US
Ahlqvist (2005)	–	Societal Change	–	–	From information society toward biosociety	Turku, FI
Alas and Rees (2005)	–	–	+	–	Estonia	Tallinn, ES
Alkemade, Frenken, Hekkert and Schwoon (2009)	Technology assessment methodology	–	+	+	Future car systems	Utrecht, NL
Ansari and Garud (2009)	–	–	–	–	Mobile communications	Rotterdam, NL
Bach and Matthews (1979)	–	–	–	–	Strategies for transitions in energy	Münster, DE
Backhaus (2003)	–	–	–	–	Privatization in Central and East Europe	Thuringia, DE
Ball (2005)	–	–	–	–	Environmental accounting in the UK	London, UK
Bathgate, Omar, Nwankwo and Zhang (2006)	–	–	+	–	Transition to a market orientation in China	London, UK
Bolesta, Andersen and Zeni (1988)	System implementation	–	+	–	–	Hazelwood, US
Beaudry, Collard and Green (2005)	–	–	–	+	Technological transition	British Columbia, US
Bergman et al. (2008)	MATISSE	MLP, MPP, Transition pathways	–	+	–	Oxford, UK
Berkhout, Smith and Stirling (2003)	Transition trajectories	Regime, Niche	+	–	–	Sussex, UK
Bhattacharyya (2007)	–	–	–	–	Power sector reform in China	Dundee, UK
van den Bosch, Brezet and Vergragt (2005)	–	MPP	+	–	To a fuel cell transport system in Rotterdam	Delft, NL
Brah and Hunsucker (2000)	Transition life cycle model	–	+	–	–	Singapore, SG
Brown, Vergragt, Green and Berchicci (2003)	–	Metal ecology	–	–	From conventional to lead-free solders	Clark, Worcester, US
van der Brugge, Rotmans and Loorbach (2005)	–	MLP, MPP, TMA, TMC	+	–	Dutch water management	Rotterdam, NL
van der Brugge and Rotmans (2007)	–	MLP, MPP, TMA, TMC, CAS	+	–	European water management	Rotterdam, NL
van der Brugge and van Raak (2007)	–	MLP, SNM, TMA	+	–	Water management, Rotterdam, NL	
Bruggink (2005)	–	–	+	–	Future energy transition scenarios	ECN, Utrecht, NL
Caniëls and Romijn (2008)	SNM	–	+	–	–	Eindhoven, NL
Caron-Flinterman, Broerse and Bunders (2007)	–	MLP, MPP, TM	+	–	Patient participation in Biomedical Research	Amsterdam, NL
Chakravorty, Magné and Moreaux (2006)	–	–	+	+	Limiting allowed emissions from energy	Central Florida, US
Davison, Wagner and Louis (2005)	–	–	+	–	To e-government	Hong Kong, HK
Dolata (2009)	Patterns of technological change	–	–	–	–	Max Planck, Köln, DE
Duckney (1996)	Visions	–	+	–	–	4C's Associates, London, UK
Elzen and Wieczorek (2005)	–	overview of Elzen, Geels and Green (2004)	+	–	–	Twente, NL
Faber and Frenken (2009)	Evolutionary economics models	SNM	–	–	–	MNP, Bilthoven, NL
Faden (1999)	–	–	–	–	Cinema technology	
Foxon (2006)	–	MLP, IS	–	–	–	Cambridge, UK
Foxon, Reed and Stringer (2009)	Combining TM and AM	TM	+	–	UK Upland	Leeds, UK
Frantzeskaki and de Haan (2009)	Clover model	MLP, MPP	+	–	–	Delft, NL
Gan and Yu (2008)	–	–	–	–	Bioenergy transition in rural China	Oslo, NO
Gebauer and Friedli (2005)	–	–	–	–	From products to services	Gallen, CH
Geels and Kemp (2000)	–	MLP	+	–	Low-emission energy supply in the Netherlands	Twente, NL
Geels (2002a)	–	MLP	–	–	Sailing ships to steamships	Twente, NL
Geels (2004)	MLP	–	–	–	–	Eindhoven, NL
Geels (2005c)	MLP	–	–	–	–	Eindhoven, NL
Geels (2005a)	–	MLP	–	–	Water supply and personal hygiene in the Netherlands	Eindhoven, NL
Geels (2005b)	–	MLP	–	–	Horse-drawn carriages to automobiles	Eindhoven, NL
Geels and Raven (2006)	–	Niche development	–	–	Biogas in the Netherlands	Eindhoven, NL
Geels (2006a)	–	MLP, System innovation typology	–	–	From propeller to turbojet aviation	Eindhoven, NL
Geels (2006b)	–	Regime transformation	–	–	From cesspools to sewer systems	Eindhoven, NL
Geels (2006c)	–	MLP	–	–	American factory production	Eindhoven, NL
Geels and Schot (2007)	MLP, transition pathways	–	–	–	–	Eindhoven, NL
Geels (2007c)	–	MLP, LTS	–	–	Dutch Highway System	Eindhoven, NL
Geels (2007a)	–	MLP	–	–	Rock 'n Roll	Eindhoven, NL
Geels and Kemp (2007)	Typology of change	MLP	–	–	Variety of past cases	Eindhoven, NL
Geels (2007b)	Middle Range Theory	MLP	–	–	–	Eindhoven, NL
Genus and Coles (2008)	MLP	–	–	–	–	Newcastle upon Tyne, UK
de Haan (2008)	–	Regime, Niche	–	+	–	Rotterdam, NL

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Reference	Developed transition theory	Adopted transition theory	TM	Simulation	Case study	Institute
Heiskanen, Kivisaari, Lovio and Mickwitz (2009)	–	TM, MLP	+	–	Transition Management applied to policy in Finland	Helsinki, FI
Hekkert, Suurs, Negro, Kuhlmann and Smits (2007)	Functions of IS	–	+	–	–	Utrecht, NL
Hekkert and Negro (2009)	Functions of IS	–	+	–	Biomass	Utrecht, NL
Hendriks (2009)	–	TM	+	–	Democracy and TM in the Netherlands	Canberry, AU
Hetland and Mulder (2007)	–	–	–	+/–	Future transition to hydrogen	Trondheim, NO
Hirsch (2009)	–	–	–	–	Frontiers in Thailand	Sydney, AU
Hofman, Elzen and Geels (2004)	–	MLP			Scenarios for electricity in the Netherlands	Twente, NL
Holtz, Brugnach and Pahl-Wostl (2008)	Regime	–	–	–	–	Osnabrück, DE
Hunsucker, Law and Sitton (1988)	TM in organization	–	+	–	–	Houston, US
Hunsucker (1990)	TM in organization	–	+	–	–	Housten, US
Jänicke (2008)	Ecological modernization	–	+	–	–	Berlin, DE
Jong and Stout (2007)	–	GT	–	–	Telegraphy to telephony in The Netherlands	Delft, NL
Kemp (1994)	Regime	–	–	–	–	Maastricht, NL
Kemp, Parto and Gibson (2005)	–	Governance, Sustainable Development, TM	+	–	–	Maastrict, NL
Kemp, Loorbach and Rotmans (2007)	–	MLA	+	–	Dutch waste management	Maastricht, NL
Keppo and Rao (2007)	–	–	+	+	Climate change mitigation	Laxenburg, AT
van de Kerkhof and Wieczorek (2005)	Learning	TMA, TMC	+	–	–	Amsterdam, NL
Kern and Smith (2008)	–	MLP	+	–	Energy transition management in the Netherlands	Sussex, UK
Köhler (2006)	–	Regime, Niche	+	–	Transport systems	Cambridge, UK
Langowitz (1992)	TM in organization	–	+	–	UPS	Boston, US
Lefebvre, Cassivi and Lefebvre (2001)	–	–	+	–	Business-to-Business E-commerce	Montreal, CA
Lenaghan and Seirup (2007)	–	–	–	–	Transition in employment contracts	Hempstead, US
Liping (2008)	–	Modernization, development	–	–	China	Beijing, CN
Lin, Pervan and McDermid (2007)	–	–	+	–	Transition of Public sector outsourcing	Joondalup, AU
Lindig-Cisneros, Desmond, Boyer and Zedler (2003)	–	Irreversible Transition	+	–	Reversing degradation transition in Wetland	Morelia, ME
Loorbach (2007)	TMA	MLP, MPP, CST	+	–	Several cases	Rotterdam, NL
Loorbach, van der Brugge and Taanman (2008)	–	MLP, MPP, CAS	+	–	Energy transition in the Netherlands	Rotterdam, NL
Low (2007)	–	TM in organization	+	–	Huawei Technologies	Sydney, AU
MacCormack and Iansiti (2009)	–	–	+	–	Response of Microsoft to Technological Transitions	Cambridge, UK
Manderscheid and Ardichvili (2008)	–	Leadership transition	–	–	–	Minnesota, US
Marangos (2005)	Transition paths	–	+	–	–	Fort Collins, US
Marks and Mirvis (2000)	TM in organization	–	+	–	Mergers	San Fransisco, US
Martens and Rotmans (2005)	–	MPP	–	–	Sustainable development scenarios	Maastricht, NL
Matthews, Rotmans, an d J. Waller-Hunter and Zhu (1997)	Transition definition, transition policy	–	+	–	–	
Metcalfe and Afanassieva (2005a)	–	–	+	–	Communist economic system to a market economy	Hull, UK
Metcalfe and Afanassieva (2005b)	–	–	+	–	Women in Russia	Hull, UK
Mirzoev, Green and Newell (2007)	–	–	+	–	Health reform in Tajikistan	Leeds, UK
Modis (1993)	–	–	–	+	Fischer-Pry model for technological transition	Geneva, CH
Mulder (2007)	Backcasting for Transitions	Taxonomy of innovation	+	–	Plastics	Delft, NL
Murray, Seymour and Pimenta (2007)	–	–	–	–	Future transition to hydrogen in Portugal	Lisbon, PT
Nadler (1982)	TM in organization	–	+	–	–	
Nill and Kemp (2009)	–	SNM, TM, TS	+	–	–	Sevilla, ES
Nooteboom (2007)	Impact assessment procedures	CST	+	–	–	Rotterdam, NL
Nykvist and Whitmarsh (2008)	–	MLP	–	–	Mobility in the UK and Sweden	Stockholm, SE
Park, Chunag and Gelegdorj (2008)	–	–	–	–	Iron artefacts in Mongolia	Chochiwon, KR
Perrels (2008)	Radical change	TM	+	+	Sustainable consumption	Helsinki, FI
van de Poel (2003)	Regime transformation	Regime, Niche	–	–	Variety of past cases	Delft, NL
Raven and Verbong (2007)	Multi-regime interaction	Regime	–	–	CHP in the Netherlands	Eindhoven, NL
Reinstaller (2008)	transition vs diffusion	technology diffusion	–	–	to chlorine free pulp bleaching	Vienna, AT
Ribeiro and Rodrigues (1997)	–	–	–	–	Sustainable development strategies in Portugal	Lisbon, PT
Riccaboni and Moliterni (2009)	–	–	+	–	R&D alliances	Trento, IT
Rice, Leifer and O'Connor (2000)	–	–	+	–	From R&D to Operation	New York, US
Rice and Leifer (2002)	–	–	+	–	From R&D to Operation	Babson Park, US
Rohracher (2001)	–	–	+	–	To sustainable construction of buildings	Graz, AT
Rohracher (2008)	–	MLP, SNM	+	–	Social sciences and energy transition	Graz, AT
Ros, Nagelhout and Montfoort (2009)	Evaluation method	MPP	+	–	Mobility	MNP, Bilthoven, NL
Rotmans, Kemp, Asselt, Geels, Verbong and Molendijk (2000)	–	MLP, MPP	+	–	Low-emission energy supply in the Netherlands	Maastricht, NL

— *Table continued on next page* —

Reference	Developed transition theory	Adopted transition theory	TM	Simulation	Case study	Institute
Rotmans, Kemp and Van Asselt (2001)	MLP, MPP, TM	–	+	–	Low-emission energy supply in the Netherlands	Maastricht, NL
Rotmans, Loorbach and van der Brugge (2005)	–	MLP, MPP, CAS, TMC	+	–	–	Rotterdam, NL
Rotmans and Kemp (2008)	–	–	+	–	–	Rotterdam, NL
Rotmans and Loorbach (2009)	TMC	CST, CAS	+	–	–	Rotterdam, NL
Schilperoord, Rotmans and Bergman (2008)	MATISSE	MPP, MLP	–	+	–	Rotterdam, NL
Scholz, Lang, Wiek, Walter and Stauffacher (2006)	TCS	–	–	–	–	Zurich, CH
Scholz and Stauffacher (2007)	–	TCS	–	–	Traditional industries in Switzerland	Zurich, CH
Schot and Geels (2007)	Niche development	–	–	–	–	Eindhoven, NL
Scott and Häfele (1990)	–	–	–	–	Transition to hydrogen age	Victoria, CA
Shove and Walker (2007)	–	–	+	–	–	Lancaster, UK
Shove and Walker (2008)	–	–	+	–	–	Lancaster, UK
Smith, Stirling and Berkhout (2005)	Typology for TM	Regime transformation	+	–	–	Sussex, UK
Sondeijker, Geurts, Rotmans and Tukker (2006)	–	TM, Scenario	+	–	–	Rotterdam, NL
Squazzoni (2008)	–	MPP, MLP	–	–	–	Brescia, IT
Stephens et al. (2008)	–	TM	+	–	Higher education as transition agent	Clark, Worcester, US
Suarez and Oliva (2005)	Typology of environmental change	–	–	–	–	Boston, US
Suurs and Hekkert (2005)	TM Evaluation	IS	+	–	–	Utrecht, NL
Tatoglu and Demirbag (2008)	–	–	+	–	Transition in Turkey	Istanbul, TR
Timmermans (2006)	–	MPP, Regime, LSoA	–	+	–	Rotterdam, NL
Timmermans (2008)	–	MPP, Regime	–	+	–	Rotterdam, NL
Timmermans, de Haan and Squazzoni (2008)	–	MPP, MLP, TM	–	–	–	Rotterdam, NL
Tripsas (2008)	Customer Preference Trajectories	–	–	–	Typesetter industry	Boston, US
Tukker and Butter (2007)	Four approaches to TM	Cultural Theory	+	–	–	TNO, Delft, NL
Verbong (2000)	–	–	–	–	History of energy supply in the Netherlands	Eindhoven, NL
Verbong and Geels (2007)	–	MLP	+	–	Dutch electricity system	Eindhoven, NL
Vergragt (2004)	Sustainable mobility transitions	TM	+	–	Personal aeromobility	Newark, US
Verhoef, Dijkema and Reuter (2004)	–	–	–	+	Lead free solder	Delft, NL
Vollenbroek (2002)	–	System innovation, TM Principles	+	–	Dutch Poldermodel	Min. Environment, The Hague, NL
de Vries and Riele (2006)	–	MLP	+	–	Environmental Product Policy in the Netherlands	2eco, Deventer, NL
Wang and Chen (2008)	–	MLP	+	–	Low-carbon economy in China	Hangzhou, CN
Weisbuch (2000)	–	–	–	+	Environmental systems	Paris, FR
Wiek, Binder and Scholz (2006)	MPP, Requirements for TM, Scenarios	MPP	+	–	Small cases in Switzerland	Zurich, CH
Yücel and Chiong Meza (2008)	–	–	–	+	Dutch waste management	Delft, NL

Table A.4 – Publications with simulations models of transitions

Source	Methodology	Emergent	TM	Level	Status
One offs					
Alkemade, Frenken, Hekkert and Schwoon (2009)	Fitness landscapes	–	+	1	Implemented
Beaudry, Collard and Green (2005)	Equilibrium	–	–	1	Implemented
Chakravorty, Magné and Moreaux (2006)	Equilibrium	–	+	1	Implemented
de Haan (2008)	Differential equations	–	–	1	Implemented
Hetland and Mulder (2007)	Scenarios	–	–	0	Implemented
Keppo and Rao (2007)	Systems-engineering optimization	–	+	1/2	Implemented
Modis (1993)	Differential equations	–	–	1	Implemented
Perrels (2008)	Economic & econometric	–	+	1	Implemented
Verhoef, Dijkema and Reuter (2004)	System dynamics	–	–	1	Implemented
Weisbuch (2000)	Automata	+	–	1	Implemented
Yücel and Chiong Meza (2008)	SD	+/–	–	1	Implemented
MATISSE project					
Bergman et al. (2008)	ABM & SD	+/–	–	1	Prototype
Schilperoord, Rotmans and Bergman (2008)	ABM & SD	+/–	–	1	Prototype
Timmermans' Non-linear system of action					
Timmermans (2006)	Transactions	+	–	1	Implemented
Timmermans (2008)	Punctuated equilibrium	+	–	1	Implemented

B Power Generation Model

B.1 Experiments 1, 2 & 3: Fuel and power plant definitions

B.1.1 Energy densities of fuels

We have used the following conversion throughout the experiments with the power generation model (see Table B.1).

Table B.1 – Conversion factors for power plants

Fuel	Energy density
Biomass	15 GJ/ton
Coal	25 GJ/ton
Natural gas	0.0383 GJ/m^3
Uranium	1,865,150 GJ/ton

B.1.2 Power plant definitions

For experiment 1, we gathered data on power plants using nuclear technology, natural gas, coal, wind, coal with CCS and biomass. An overview of the data used in the model can be found in Table B.2.

When developing experiment 2, we adopted new publicly accessible data about natural gas and coal power plants. An overview of the data used in the model can be found in Table B.3. A variety of coal and gas plants replaced the original data. Both for coal and gas plants, various CCS technologies are added as well. Also coal gasification with CCS is included. The data on biomass, nuclear and wind remained the same.

For experiment 3, data from IEA (2010) was adopted for all plants. An overview of the data used in the model can be found in Table B.4. Additionally, data on expected maximum loads, technical lifetimes, and construction times were introduced.

Table B.2 – Power plants in power generation model, experiment 1 (from Chappin, 2006)

Power plant	Lifetime (year)	Capacity (MW$_e$)	Investment (€/MW$_e$)	Variable costs (€/MWh$_e$)	Fuel usage (kWh$_e^{-1}$)
Coal	30	1000–2000	1,250,000	3	0.276 ton
Coal CCS	30	1000–2000	2,000,000	10	0.276 ton
CCGT	30	1000–2250	500,000	2	222 m^3
Biomass	30	100–225	1,250,000	4	0.276 ton
Wind	25	100–2250	1,150,000	3	n/a
Nuclear	40	550–2000	2,000,000	5	2.00 × 10^{-5} ton

Table B.3 – Power plants in power generation model, experiment 2 (from Chappin, Dijkema and Vries, 2010)

Power plant	Efficiency (%)	Mod. (%)	Investment (€/MW$_e$)	Mod. (%)	O&M (€/MWh$_e$)
Coal Pulv.	44	0.4	1,144,715	1.0	7
Coal Pulv. CSS Fluor	35	0.5	1,608,943	1.0	7
Coal Pulv. CSS MHI	35	0.5	1,660,976	1.0	7
Coal Pulv. CSS Oxy	35	0.5	1,792,683	1.0	12
Coal Shell Gasif.	43	0.4	1,311,382	1.0	12
Coal Shell CSS	35	0.5	1,791,870	1.0	12
Coal GE Conv.	38	0.4	1,169,919	1.0	9
Coal GE CSS	32	0.5	1,475,610	1.0	13
Gas Conv.	56	0.4	405,691	0.5	2
Gas CSS Fluor	47	0.5	706,504	0.5	4
Gas CSS MHI	50	0.5	721,138	0.5	4
Gas CSS Oxy	45	0.5	1,245,528	0.5	6
Biomass	35	0.4	1,250,000	1.0	4
Wind	35	–	1,150,000	2.0	3
Nuclear	–	–	2,000,000	0.0	5

Table B.4 – Power plants in power generation model, experiment 3 (from IEA, 2010)

Power plant	Efficiency (%)	Mod. (%)	Investment (€/MW$_e$)	Mod. (%)	O&M (€/MWh$_e$)	Load	Lifetime (year)	Construction (year)
Coal pulv.	41	0.40	1,570,937	1.0	4.43	0.85	40	4
Coal CCS	35	0.50	2,457,080	1.0	10.02	0.85	40	4
CCGT	57	0.40	787,107	0.5	3.30	0.85	30	2
CCGT CCS	40	0.50	1,419,630	0.5	4.19	0.85	30	3
Biomass	35	0.40	2,181,724	1.0	8.90	0.85	30	3
Wind	–	–	1,729,357	2.0	16.14	0.25	25	1
Nuclear	–	–	3,020,035	0.0	10.85	0.90	60	7

Table B.5 – Parameters of the investment algorithm using MCA, NPV, and LCOE

Parameter	Definition
$\mathbf{t}$	Set of weight factors
$\mathbf{a}$	Set of alternatives
$\mathbf{S}$	Score matrix
$\mathbf{S}^*$	Normalized score matrix
$\mathbf{E}$	All the absolute expected costs/revenues
$\mathbf{N}$	Set of NPVs $\mathbf{n}$
m	Number of alternatives
$s_{i,j}$	Score for alternative i on criterion j
$s^*_{i,j}$	Normalized score for alternative i on criterion j
r_i	Final weighted score for alternative i
a_j	Selected alternative from $\mathbf{a}$
q	Number of repetitions of the method
r	Interest rate
n	An NPV per MWh$_e$ generated
l	Number of cost/revenue types
t_{life}	Lifetime
$e_{k,t}$	Expected absolute revenue/cost at time t for cost/revenue type k

B.2 Experiments 1 & 2: Investment decisions using multi-criteria analysis

For two of the models, a generic method for Multi-Criteria Analysis (MCA) has been developed. For both it is assumed that more than one criterion is used to select the best alternative from a list of options. First, we used MCA for the decision on *power plant type* of the electricity producers in the power generation model (see chapter 4). Second, we adopted MCA in the lamp purchase decision by the household agent in the consumer lighting model (see chapter 6). Therefore, the method is developed in a generic way, which is discussed below. A definition and an overview of the parameters in the method can be found in Table B.5.

In a multi-criteria analysis a number of alternatives are evaluated to more than one criterion. By weighing the different criteria, the best scoring alternative is chosen.

The set $\mathbf{t}$ contains k weight factors – actual values – that rank the importance of criteria of the multi-criteria analysis. The ranking in t can be different for every agent, making the agents unique in their decisions: they have a unique management style or personal preference. It is important to note that *only* $\mathbf{t}$ is agent-dependent. The other parts of the decision process are the same for all agents. The set of factors for the multi-criteria analysis is represented in:

$$\mathbf{t} = \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_k \end{bmatrix} \tag{B.1}$$

In the first experiment of the power generation model, for instance, five criteria are used, namely the yearly expected profitability, nuclear acceptability, market adoption, nuclear fear and the availability of locations. The agent-based approach makes it possible to include the softer criteria, such as nuclear fear. Electricity producing agents all evaluate those five criteria. Therefore, k equals five. The consumer lighting model contains more criteria, also regarding perceptions and memory. As described above, they do assign different levels of importance to these criteria, grasped in $\mathbf{t}$.

Let $\mathbf{a}$ be the alternatives that are evaluated in the analysis (the technologies that represent possible alternatives with their economic, physical and design properties, and possible operational configurations) and assume that m alternatives are evaluated then $\mathbf{a}$ can be represented as:

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \tag{B.2}$$

A number of alternatives are evaluated (m). Again, the first experiment of the power generation model contains five alternatives: a coal fired power plant, a natural gas power plant, a wind farm, a biomass power plant, and a nuclear power plant. In this case, all electricity producers evaluate the same set of alternatives. In the consumer lighting model, 70 different lamps are evaluated, but first they are filtered to be able to fit in the required socket.

Next, a score matrix $\mathbf{S}$ is built in which the score of each alternative on all criteria is listed:

$$\mathbf{S} = \begin{bmatrix} s_{1,1} & s_{1,2} & \cdots & s_{1,k} \\ s_{2,1} & s_{2,2} & \cdots & s_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m,1} & s_{m,2} & \cdots & s_{m,k} \end{bmatrix} \tag{B.3}$$

Agents have the ability to calculate the score of all evaluated alternatives on the criteria. In other words: agents are able to calculate $\mathbf{S}$. The data needed of the alternatives are represented in technology objects with physical, economic, and design properties. For instance, the expected yearly profitability is calculated on the basis of the economic properties of the different power plants, fuel consumption, fuel prices, etc. All data necessary are expressed in concepts defined in the ontology (van Dam, 2009; Nikolic, 2009).

After filling $\mathbf{S}$ with scores, a normalization procedure is executed in order to make the criteria comparable. Now the scores are not related to chosen units; the scores on different criteria are comparable. Matrix $\mathbf{S}^*$ contains the normalized values of matrix $\mathbf{S}$, represented in:

$$\mathbf{S}^* = \begin{bmatrix} s^*_{1,1} & s^*_{1,2} & \cdots & s^*_{1,k} \\ s^*_{2,1} & s^*_{2,2} & \cdots & s^*_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s^*_{m,1} & s^*_{m,2} & \cdots & s^*_{m,k} \end{bmatrix} \tag{B.4}$$

Several normalization methods are possible. The most popular method is *range-normalization*, in which values are normalized between 0 and 1, where 0 refers to the lowest, and 1 to the highest score on a criterion. The normalization procedure for range-normalization is as follows. Let C be the subset of elements $1,2,\ldots,k$ for which holds that the criteria t_C for all elements in C is positively oriented: a higher score s means a better score. For the elements $\{1,2,\ldots,k\}$ not in C this is not the case: in other words, those criteria are negatively oriented. The normalized scores fill $\mathbf{S}^*$. Given this subset c, normalization is executed as follows:

$$s^*_{i,j} = \begin{cases} \dfrac{s_{i,j} - \min\limits_{l\in\{1,2,\ldots,m\}} s_{l,j}}{\max\limits_{l\in\{1,2,\ldots,m\}} s_{l,j} - \min\limits_{l\in\{1,2,\ldots,m\}} s_{l,j}} & j \in C \\ \\ \dfrac{\max\limits_{l\in\{1,2,\ldots,m\}} s_{l,j} - s_{i,j}}{\max\limits_{l\in\{1,2,\ldots,m\}} s_{l,j} - \min\limits_{l\in\{1,2,\ldots,m\}} s_{l,j}} & \text{else} \end{cases} \quad \text{with} j \in 1,2,\ldots,k \tag{B.5}$$

A disadvantage of the range-normalization is that individual normalized scores are affected by scores of other alternatives. Therefore, a bad alternative that should not be in the analysis can have an impact on normalized scores of good alternatives, possibly affecting the outcomes. In this way, to a certain extent weighing is mixed up with scoring. An alternative, solving this issue, is *good-neutral* normalization. In this method, two hypothetical alternatives are included in the analysis, one referring to a *good* score on each criterion, and one referring to a *neutral* score on each criterion. Values referring to good and neutral are of course subjective, but it makes the method as a whole more transparent. One could even think of agents having individual good and neutral values. Normalization in this respect translates neutral to 0 and good to 1. All other alternatives are scaled with respect to good and neutral:

$$s^*_{i,j} = \begin{cases} \dfrac{s_{i,j} - s_{\text{neutral},j}}{s_{\text{good},j} - s_{\text{neutral},j}} & j \in C \\ \\ \dfrac{s_{\text{good},j} - s_{i,j}}{s_{\text{neutral},j} - s_{\text{good},j}} & \text{else} \end{cases} \quad \text{with} j \in 1,2,\ldots,k \tag{B.6}$$

After normalization the scores are comparable: either the 'best' scoring alternative has value 1, the 'worst' scoring alternative has value 0 (range-normalization), or they reflect how well they score with respect to a 'good' and 'neutral' alternative. Note that $\mathbf{S}^*$ is the same for all agents, since they evaluate the same alternatives using the same criteria. However, the scores can now be weight by multiplication with $\mathbf{t}$, the vector containing agent-specific preference values.

$$\mathbf{r} = \mathbf{S}^*\mathbf{t} = \begin{bmatrix} s^*_{1,1} & s^*_{1,2} & \cdots & s^*_{1,k} \\ s^*_{2,1} & s^*_{2,2} & \cdots & s^*_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s^*_{m,1} & s^*_{m,2} & \cdots & s^*_{m,k} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_k \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_m \end{bmatrix} \tag{B.7}$$

After weighing, the alternative a_j corresponding to the highest score r_j is selected:

$$r_j = \max_{i\in\{1,2,\ldots,m\}} r_i \tag{B.8}$$

Since r_j has the highest weight score, the chosen alternative is the j^{th} element of a (element a_j). Although $\mathbf{S}^*$ not static over time, $\mathbf{S}^*$ is equal for all agents at a certain point in time. Only the weight factors **t** differ, possibly leading to different selections for the preferred alternative power plant type, a_j. If for some weight factors, 0 is chosen, the criterion does not play any role in the decision. In this case, the used criteria are agent-specific as well. One could, therefore, also opt for an agent-specific set of criteria with the same structure.

B.3 Experiment 3: Investment decisions using levelized cost of electricity

In the third experiment of the power generation model, we introduce a new method for evaluating investments, which is levelized cost of electricity (LCOE). Levelized cost of electricity is widely used and adopted by the IEA, US Department of Energy and the UK government (Gross et al., 2007). LCOE takes different usage profiles into account as well as all relevant costs and revenues throughout the lifetime of a plant to allow for choosing a technology type. LCOE is closely related to the more generic notion of net present value (NPV), also used in the analysis.

B.3.1 Ingredients for the investment decision

Levelized cost of electricity Typically, an LCOE (in €/MWh$_e$) is calculated as follows:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + (F_t \times G_t) + (C_t \times c \times G_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} \tag{B.9}$$

In this formula, t refers to a year, n is the lifetime of the power plant (including construction and dismantling), and r is the interest rate. c is the carbon intensity of the plant (in ton/MWh$_e$). G_t is the generation of electricity (in MWh$_e$/year), in which a capacity factor can be taken into account. The other variables refer to the various types of cost: I_t investment cost, M_t operating and maintaining cost, F_t fuel cost and C_t carbon cost, all in year t. Subsequently, the levelized cost for electricity is the net present value of all these costs over the lifetime of a power plant, phrased in terms of €/MWh$_e$.

Electricity revenues and the NPV For reasons of comparison, this would be sufficient, but revenues are required to assess the profitability in absolute terms. This is needed to assess whether investing in any power plant is sound. Therefore, the profitability of the power plant can be determined by also taking the expected net present value of the revenues into account:

$$\text{NPV}_{\text{revenues}} = \frac{\sum_{t=1}^{n} \frac{R_t \times G_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} \tag{B.10}$$

R_t refers to the revenues of electricity in year t. Combining the above results in:

$$\mathrm{NPV} = \mathrm{NPV}_{\mathrm{revenues}} - \mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{R_t \times G_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} - \frac{\sum_{t=1}^{n} \frac{I_t + M_t + (F_t \times G_t) + (C_t \times c \times G_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} \tag{B.11}$$

This simplifies to:

$$\mathrm{NPV} = \frac{\sum_{t=1}^{n} \frac{G_t \times (R_t - F_t - C_t c) - I_t - M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} \tag{B.12}$$

Brownian motions as predictions of fuel prices The score of each power plant a_i, using among others LCOE methodology, is dependent on expected investment, fuel and carbon cost, electricity revenues, and a capacity factor. Although developments in those prices are very uncertain, Pindyck (1999) showed that geometric Brownian motions successfully replicate oil and coal prices. The yearly change in such a motion is defined as follows:

$$\partial s_t = \mu s_t \partial t + \sigma s_t \partial W_t \tag{B.13}$$

s_t is the price level at time t, μ the mean expected growth rate, σ the annual volatility and W a Wiener process.

B.3.2 Algorithm for investment decision

The notions of LCOE, NPV, and Brownian motions come together in the method of investment. Although the method is applied to power generation technologies but similar to MCA above, we have modelled the method in a far more generic way to make it reusable and flexible. A definition and overview of the parameters in the method are in Table B.5.

Similar to MCA, we define **a** as the alternatives that are evaluated in the analysis (the technologies that represent possible alternatives with their economic, physical and design properties, and possible operational configurations) and assume that m alternatives are evaluated then **a** can be represented as:

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \tag{B.14}$$

We assume there are l number of costs and/or revenues. For each type of cost and revenue, different options are used for the types of cost and revenue. The method could handle any other type of cost or revenue in ways specific to that cost or revenue.

- For carbon and fuel cost a Brownian motion of length t_{life} (the life time of the plant).
- For investment cost a certain value at t_i (the time of investment) and 0 at $t \neq t_i$.
- For electricity revenues and O&M, a constant value when $t_i < t < t_{\text{life}}$.

For each alternative option a_i from $\mathbf{a}$, the results are put into a matrix $\mathbf{E}_i$:

$$\mathbf{E}_i = \begin{bmatrix} e_{1,1} & e_{1,2} & \cdots & e_{1,t_{\text{life}}} \\ e_{2,1} & e_{2,2} & \cdots & e_{2,t_{\text{life}}} \\ \vdots & \vdots & \ddots & \vdots \\ e_{l,1} & e_{l,2} & \cdots & e_{l,t_{\text{life}}} \end{bmatrix} \tag{B.15}$$

As we use Brownian motions for fuel and CO_2 prices, the matrix $\mathbf{S}_i$ is different every time it is calculated. And each $\mathbf{S}_i$ is used to calculate exactly *one* NPV of a power plant. Each NPV n per produced MWh_e is calculated using all the costs and revenues using the following generic formula, derived from the LCOE and revenues descriptions above. All the values are made present by the following formula:

$$n = \sum_{k=1}^{l} \left(\frac{\sum_{t=1}^{t_{\text{life}}} \frac{e_{k,t}}{(1+r)^t}}{\sum_{t=1}^{t_{\text{life}}} \frac{G_t}{(1+r)^t}} \right) \tag{B.16}$$

For m alternatives in $\mathbf{a}$, the calculations are done q (= 500) times and put in $\mathbf{N}$:

$$\mathbf{N} = \begin{bmatrix} n_{1,1} & n_{2,1} & \cdots & n_{m,1} \\ n_{1,2} & n_{2,2} & \cdots & n_{m,2} \\ \vdots & \vdots & \ddots & \vdots \\ n_{1,q} & n_{2,q} & \cdots & n_{m,q} \end{bmatrix} \tag{B.17}$$

Four algorithms have been determined to select the preferred option from $\mathbf{N}$:

1. Maximize expected profit: $r_j = \max_{i \in \{1,2,\ldots,m\}} \bar{n}_i$
2. Maximize most likely value: $r_j = \max_{i \in \{1,2,\ldots,m\}} \text{mode}_i$
3. Maximize expected profit, being risk averse: $r_j = \max_{i \in \{1,2,\ldots,m\}} \frac{\bar{n}_i}{\sigma_i}$
4. Maximize return on investment: $r_j = \max_{i \in \{1,2,\ldots,m\}} \frac{R_{t,i} E_{t,i}}{I_{t,i}}$

Investments are only done when the expected profit is positive. Technology j refers to the selection option, $\bar{n}_i$ is the mean of the NPVs of technology i (column i in $\mathbf{N}$), σ_i is the standard deviation of the NPVs of technology i (column i in $\mathbf{n}$). In the model, the different agents will choose one of the algorithms to make their investments.

C LNG Market Model

C.1 Experiment 1: Linking LNG equations to the world of agents.

The belief-system of the LNG agents, i.e. their expectations about future market developments and the resulting decision making is coded as an adapted equilibrium model from the literature. Brito and Hartley (2007) developed the *Diamond model* of contracting and trading in the LNG market with multiple equilibria in which expectations influence which equilibrium eventuates, based on the ideas developed by Diamond and Maskin (1979, 1980); Diamond (1984). To our purposes – i.e. a belief-system of a single-agent's world – we adapted it to incorporate decision-support for the agents.

C.1.1 Fundamental differences between the original Diamond model and the adopted version

Table C.1 lists the fundamental differences between the original and our version. The fact that the social building block is an agent now, is a conceptual change in the model, but does not require any adaptation to the mathematical representation. The technical building block is adapted from a single project that encompasses the entire LNG value-chain to separate projects for liquefaction, shipping, and regasification technologies. Since a value chain contains three components now, it can also be constructed by two contracts, a feature that results in a multiplication of the strategic options of the LNG agent. The probability of success for a long-term partnership, search time before forming a partnership, and the ROI on the spot market become emergent properties (as opposed to predetermined in the original model). Finally, each agent is unique and optimizes according to its own portfolio and past strategies. This makes the adopted strategies emergent as well and allows for the co-existence of multiple strategies.

The above-mentioned changes of the Diamond model resulted in a dramatic increase of its size and capabilities. We present an overview of the most relevant model parameters and mathematical equations: an EB optimization problem that involves 109 equations. The logic and mathematical fundamentals of the different strategies agents can select, Table C.2) are discussed here.

Table C.1 – Assumptions of the original Diamond model and the new model, adapted from Praet (2009)

Characteristic	Original model	Adapted model
Social building block	Firm	Agent
Technical building block	Value-chain	Project and Technology
Contract	Zero or one contract per value-chain	Zero, one or two contracts per value-chain
Possible firm/agent strategies	Six per value chain	Seven × three per project
Probability of success for long-term partnership	Predetermined	Emergent
Search time for partnership	Fixed	Emergent
ROI of the LNG spot market	Fixed	Emergent (experiment 2)
Identity	Equal firms	Unique agents
Strategy	Predetermined	Emergent

C.1.2 LNG-Model (Adapted) Equation-Based Principles

Agents own LNG Projects X of type i which they operate in strategy s and partner with projects of type j. The existing number of projects is denoted by x while $v_s(X_i)$ refers to the expected value of each project and $t_s(X_i)$ to the expected time that the agent must search before he can form a partnership for his project. Once a partnership is formed, the probability of it being a good match is $p(X_i)$ while the probability of a poor match is $(1 - p(X_i))$. Whilst searching for a partner, the agent incurs an explicit cost c per unit of time and since no revenues are incurred during this search process the costs of postponing a partnership are dependent on the interest rate r and the required initial capital investment $k(X_i)$. Brito and Hartley (2007) note that despite the fact that the quality of matches is most accurately represented by a continuum, they allow, for simplicity, just two types of matches – good ones and poor ones. We adhere to this principle. A good match obviously returns a higher surplus, $2u_{\text{good}}$, to the partnering agents per unit of time than a poor match, $2u_{\text{bad}}$. Trading in the spot market returns a surplus u_{spot} that is lower than a poor match. This is expressed by the fact that $u_{\text{good}} > u_{\text{bad}} > u_{\text{spot}}$. The surplus of such a partnership is evenly divided by both partners and is allowed to accrue over time. Our model assumes that the probability of meeting per time unit a, or potentially matching, a specifically designated partner is independent of the number of other potential partners. Finally, there is the possibility that a partnership is dissolved for exogenous reasons (force majeure) per unit of time $\delta(X_i)$ which causes both partners to exit the market. For ease of later reference, Table C.2 lists the variables, strategies and their definitions.

C.1.3 Investment and Managerial Decision Making Input

Agents take their investment and managerial decisions based on the expected ROI. In the LNG model this equated with the expected value $v(X_i)$ of a decision which in turn is dependent on the variables of Table C.2. Before we proceed with the equations of the expected value $v(X_i)$ we need to derive the expected search time $t(X_i)$. Expected

Table C.2 – Parameters of the equation-based model used by the LNG Agents

Parameter	Definition
Project-specific	
$x(X_i)$	Number of existing instances of project X_i in the market with technology type $i \in 1-3$ i, $i=1$ for liquefaction, $i=2$ for shipping and $i=3$ for regasification
$x(X_j)$	Number of existing instances of project X_j in the market with technology type $j \in 1-3$ where $j \neq i$
X_{s_1,s_2,s_3}	Agents formulated strategies are $s_1, s_2, s_3 \in 0-6$ respectively for liquefaction, shipping and regasification
$v_s(X_i)$	Expected value of a project X_i in the market, for strategy $s \in 0-6$ s_0: Initial investment decision; s_1: Searching without investing; s_2: Searching without a partner after investing; s_3: Continue to search in a poor match; s_4: Stop searching in a poor match; s_5: In a good match; s_6: Indirect partnership, no search required.
$t_s(X_i)$	Expected search time for a strategy of project X_i, for strategy $s \in 0-6$
$k(X_i)$	Expected investment cost for project X_i
$p(X_i)$	Probability that a new match of project X_i will be successful
$\delta(X_i)$	Expected rate of partnership dissolution for exogenous reasons
Set of projects	
Y	A (partial) value chain, as set X_i's that are in a partnership. Y is a set of 1, 2 or 3 projects of types i each with strategies $s_1, s_2, s_3 \in 0-6$
Constants	
c	Searching cost for a partnership
a	Probability of meeting
r	Interest rate
u_{bad}	Expected surplus rate of an unsuccessful match
u_{good}	Expected surplus rate of a successful match
u_{spot}	Expected surplus rate from trading in the spot market

search times $t_s(X_i) s \in 1-3$ denote the expected time the owner of a project needs to search before being able to establish a suitable partnership. $t_1(X_i)$ for example refers to the expected search time for a suitable partnership between two projects whose investment is delayed until a partnership is formed (s_1 in Table C.2). $t(X_i)$ is based on both the possible number of matches that can be made and the probability that a partnership is indeed established when a suitable partner is found. In accordance with Brito and Hartley (2007), agents that delay their investment until after the partnership formation (s_1) can only search for partners with identical strategies and different technologies (Equation C.1). Owners of projects that delay the search for a suitable partnership until after the investment (s_2 in Table C.2) can form partnerships with partners that pursue the same strategy with different technologies and projects, and continue their search in a poor match (s_3 in Table C.2). The probability that a match between two s_2 projects is a good match equals $p(x_2(X_j) + x_3(X_j) - 1)$ and the probability for a poor match

$(1 - p)(x_2(X_j) - 1)/(x_2(X_j) + x_3(X_j) - 1)$. Note that the match between s_2 and s_3 projects equals $p(x_3(X_j))/(x_2(X_j) + x_3(X_j) - 1)$ as the match is only acceptable if this results in a good match (Equation C.2). Finally, for the search time t_3 for projects s_3, the probability of meeting a partner equals $a(x_2 + x_3 - 1)$. This implies that the probability of making a good match per unit of time equals $pa(x_2(X_j) + x_3(X_j) - 1)$ and that $t_3(X_i)$ equals Equation C.3

$$t_1(X_i) = \frac{1}{a(x_1(X_j) - 1)} \tag{C.1}$$

$$t_2(X_i) = \frac{1}{a(x_2(X_j) + p(X_i)x_3(X_j) - 1)} \tag{C.2}$$

$$t_3(X_i) = \frac{1}{p(X_i)a(x_2(X_j) + p(X_i)x_3(X_j) - 1)} \tag{C.3}$$

Projects that are content with a poor match and projects in a good match (s_4 and s_5 in Table C.2) can only be dissolved for exogenous reasons. As such their expected values $v_s(X_i)$ are equal to the present value of the surplus t periods in the future ($e^{-rt}u_{\text{good}}$ or $e^{-rt}u_{\text{bad}}$) multiplied by the probability $e^{-\delta(t)}$) of the partnership surviving t periods, integrated over all possible survival intervals. $v_s(X_i)$ is thus determined by u_{bad} or u_{good}, r and $\delta(X_i)$. Accordingly, the ROI of these strategies is:

$$v_5(X_i) = \frac{u_{\text{good}}}{r + \delta(X_i)} \tag{C.4}$$

$$v_4(X_i) = \frac{u_{\text{bad}}}{r + \delta(X_i)} \tag{C.5}$$

It becomes more complicated for projects that continue their search in a poor match (s_3 in Table C.2) as the distinction between liquefaction, shipping and regasification increases the number of potential partner projects. The expected value $v_3(X_i)$ depends on $t_3(X_i)$, $v_2(X_i)$ and $v_5(X_i)$:

$$v_3(X_i) = \frac{v_2(X_i)}{e^{(r+\delta(X_i))t(X_i)}} + \frac{(u_{\text{bad}} - c)e^{(r+\delta(X_i))t(X_i)} + u_{\text{good}} - u_{\text{bad}} + c}{e^{(r+\delta(X_i))t(X_i)} + \frac{x_3(X_j)-1}{x_2(X_j)+x_3(X_j)-1}} \tag{C.6}$$

Where:

- Expected value $v_2(X_i)$ equals Equation C.7 when it is optimal to continue the search in a poor match ($v_3(X_i) > v_4(X_i)$) or Equation C.8 when this is suboptimal ($v_3(X_i) < v_4(X_i)$).
- Expected value $v_5(X_i)$ equals Equation C.4.
- Expected search time $t(X_i)$ equals Equation C.3
- Net benefits rate per unit of time $= u_{\text{bad}} - c$

- $x_2(X_j)$ refers to the number of projects in the market where either strategy s_1, s_2 or s_3 equals 6 while the other strategies of the project equal 0.
- $x_3(X_j)$ refers to the number of projects in the market where either strategy s_1, s_2 or s_3 equals 6 while one of the following conditions hold:

  I the other two strategies equal 3
  II one of remaining strategies equals 3 and the other equals 4
  III one of remaining strategies equals 3 and the other equals 5

Because the agents are free to pursue the strategy that is most beneficial to them the EB-component of the LNG-model calculates two sets of equations simultaneously: one for a market in which search is optimal after a poor match and one where this is suboptimal. Because the agents of the LNG-model are rational they will select the strategy with the highest expected surplus. If $(v_3(X_i) > v_4(X_i))$ the expected value for projects that invest prior to the formation of a suitable partnership (s_2 in Table C.2) depends on $t_2(X_i)$, $v_3(X_i)$ and $v_5(X_i)$:

$$v_2(X_i) = \frac{\frac{c - u_{\text{spot}}(1 - e^{rt(X_i)})}{r} + \frac{p u_{\text{good}}}{r + \delta(X_i)} - [p(X_i) - \frac{x_2(X_j) - 1}{x_2(X_j) + x_3(X_j) - 1}] v_3(X_i)}{e^{rt(X_i)} - \frac{p x_3(X_j)}{x_2(X_j) + x_3(X_j) - 1}} \tag{C.7}$$

If $(v_3(X_i) < v_4(X_i))$ the expected value for projects that invest prior to the formation of a suitable partnership (s_2 in Table C.2) depends on $t_2(X_i)$ (Equation C.2), $v_4(X_i)$ (Equation C.5) and $v_5(X_i)$ (Equation C.4):

$$v_2(X_i) = e^{-rt_i}[\frac{p u_{\text{good}} + (1 - p) u_{\text{bad}}}{r + \delta(X_i)}] - \frac{c - u_{\text{spot}}(1 - e^{-rt(X_i)})}{r} \tag{C.8}$$

Where:

- Expected value $v_3(X_i)$ equals Equation C.6 when search is optimal after a poor match.
- Expected value $v_4(X_i)$ equals Equation C.5 when search is not optimal after a poor match.
- Expected value $v_5(X_i)$ equals Equation C.4.
- Expected search time $t(X_i)$ equals Equation C.2
- $x_2(X_j)$ refers to the number of projects in the market where either strategy s_1, s_2 or s_3 equals 6 while the other strategies of the project equal 0.
- $x_3(X_j)$ refers to the number of projects in the market where either strategy s_1, s_2 or s_3 equals 6 while one of the following conditions hold:

  I the other two strategies equal 3
  II s_1 equals 6, while the remaining strategies consist of 3 and 4 or 5

III s_1 equals 4 or 5, while the remaining strategies consist of 3 and 6

When agents decide to delay their investment until after a partnership has been formed (s_1), the surplus of a good match equals $2v5(X_i) - k(X_i)$. For a poor partnership, the surplus is either $2v3(X_i) - k(X_i)$ or $2v4(X_i) - k(X_i)$ depending on whether it is optimal or suboptimal to continue the search. Accordingly $v_1(X_i)$ is given by:

$$v_1(X_i) = e^{-rt(X_i)}[p(X_i)v_5(X_i) + (1 - p(X_i))\max(v_3(X_i), v_4(X_i)) - k(X_i)] - \frac{c(1 - e^{-rt(X_i)})}{r} \tag{C.9}$$

For the initial investment decision (s_0), agents compare the surplus of initiating their projects in strategy (s_1) or (s_2) and select the highest ROI (with ROI > 0). $v_0(X_i)$ is thus given by:

$$v_0(X_i) = \max(0, v_1(X_i), v_2(X_i) - k(X_i)) \tag{C.10}$$

C.2 Experiment 2: Adapting the emergent return on the spot market

The main difference between the two experiments in the LNG case is how the expected return on the spot market is modelled. In the second experiment, the surplus of trading on the spot market u_{spot} is made to emerge in the model. In this section, we describe how.

Although emergent, the return on the spot market is restricted by the fact that it is not allowed to make $v_2 > v_3$ as this would fundamentally change the set of equations[1]. u_{spot} is made emergent by calculating the value of $u_{\text{calculate}}$ using Equation C.11 (itself derived from Equation C.6) with a fixed starting value for u_{initial}. $u_{\text{calculate}}$ is subsequently used to determine the value of u_{newspot} (see Equation C.12). u_{spot} equals $u_{\text{transition}}$ when ($u_{\text{transition}} > u_{\text{initial}}$) and u_{initial} when ($u_{\text{transition}} < u_{\text{initial}}$).

$$u_{\text{calculate}} = \frac{(c(X_i) - u_{\text{initial}}) \times (1 - \exp(r(X_i) \times t_2(X_i)))}{r(X_i)} \tag{C.11}$$

$$u_{\text{transition}} = \frac{-u_{\text{calculate}} \times r(X_i)}{1 - \exp(r(X_i) \times t_2(X_i))} + c(X_i) \tag{C.12}$$

C.3 Experiments 1 & 2: Linking the Java and Maple platforms

In addition to the conceptual connection between two modelling paradigms, also a technical link is necessary. In this section, the developments of this link are described.

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[1] Brito and Hartley (2007) note "It also may be realistic to assume $u_{\text{transition}} < u_{\text{calculate}}$ [renamed parameters to match our descriptions]. In particular, it may be much more risky to rely upon the spot market for all of one's customers or suppliers. The certainty equivalent revenue associated with spot market purchases may, therefore, be less than the revenue associated with contracted cash flows even if the two revenue streams have the same expected value."

Table C.3 – Java methods the modeller uses in the connection to Maple

Java method	Usage
initKernel	Starts Maple and creates the coupling from Java to Maple and back. This will fail if the location of Maple is unknown to the Operating System.
stopKernel	Stops Maple safely at the end of a simulation
restart	Clears all the variables in Maple and reinitializes the memory. Restarting after each performed analysis prevents memory leaks and errors through old remaining data.
initInput	Reads a text file that contains Maple code. Although the file is read, the code is not yet executed. In our case, this file contains the generic equation-based model with basic inputs. As the code is not yet executed, each basic input can be overridden afterwards. The optimization can, therefore, be performed for a specific case.
assignDouble	Assigns a value to a parameter in Maple that is not integer. This method uses *evaluate*.
assignInteger	Assigns a value to a parameter in Maple that is integer. This method uses *evaluate*.
evaluateReadInput	Executes the Maple code that was earlier read by *initInput*. This method uses *evaluate*.
evaluate	Is used by evaluateReadInput, assignDouble and assignInteger to execute Maple code. Evaluating Maple code usually returns in values on a variety of new or existing parameters, which in this method remain inside Maple. If the silent mode is enabled, no text is returned. Otherwise, textual feedback from Maple is fed to Java text output. Disabling silent mode can be useful for purposes of debugging Maple code.
returnValue	Retrieves the numerical value on a parameter from Maple. This method is used to retrieve the results of the execution of a piece of Maple code.
returnNotNumeric	Retrieves any type of value on a parameter from Maple. If an optimization is unsuccessful, Maple cannot compute numerical values. This method is useful for debugging and improving code.

The technical link between Maple and Java is supported by a Java library that is part of Maple, called *jopenmaple*. Through using the library, a number of classes and methods become available. These classes can be used to make, maintain and close the interaction between Maple and Java.

The most important class used from the library is the *Engine* class. For reasons of usability and flexibility, we have developed an additional class called *Maple*, which is located under the shared code (*SimulationGenerics/src/Maple*). With this *Maple* class, a number of methods become available to the modeller, so that complicated, generic parts of the code dealing with the connection between Java and Maple are not within individual models. The methods and their usage is explained in Table C.3.

At the start of the software, Maple is initialized by calling *initKernel*. During the simulation, an agent needs Maple to perform some analysis. The typical use is as follows:

- Maple is restarted by using *restart*.

- The equation-based model is read from a text file, prepared earlier, by using *initInput*.
- Many specificities are overridden by using *assignDouble* and *assignInteger*. This can be a lengthy piece of code, as it concerns many parameters. This is the first place in which the conceptual difference between the agent- and equation-paradigms is shown: what can be an individual parameter in equations, can be a bunch in Java/agents. For instance, the number of contracts in the market is a single parameter in Maple. In Java it is the summed length of the list of contracts of the agents. This translation, therefore, takes place when assigning specific values in Maple.
- The analysis is performed through calling *evaluateReadInput*.
- When the analysis was successful and returned in a solution, we call *returnValue* to retrieve all parameters in the solution. This is the second place where translation between the agent- and equation-paradigms takes place. Therefore, this is a lengthy part of the code.
- The decision algorithm uses the results retrieved from Maple to make a decision.

D Consumer Lighting Model

In this appendix, some details are provided on the Consumer Lighting Model presented in chapter 6. The following elements are in this appendix:

- In section D.1, the main parameters for the household agent are presented.
- In section D.2, an overview is given of the modelled lamps.
- In section D.3, an overview is given of the modelled luminaires, used only in the second experiment.

D.1 Experiments 1 & 2: Parameters of the household agent

The main parameters of the household agent are shown in Table D.1. Parameters at the start of the simulation include the initial portfolio of lamps. The main parameters of the social network are shown. Additionally, the numbers of luminaries and levels of usage are shown. Finally, the perceptions adopted by the household agents are presented.

D.2 Experiments 1 & 2: Lamps

Table D.3, on page 251 contains an overview of the data gathered on lamps in the consumer lighting model. Most data are collected from a variety of stores in the Netherlands, i.e. Ikea, Hema and Albert Heijn. Lifetime uncertainties and the colour rendering indexes (CRI) are estimated. Uncertainties are estimated based on the status of the technology used on the image of the brand. The uncertainty of the lifetime of an Osram bulb (generally considered an A-brand) is, therefore, lower than one of Ikea (generally considered a B-brand). Furthermore, the uncertainty of the lifetime of a LED lamp (new technology) is higher than of an incandescent (proven technology).

D.3 Experiment 2: Luminaires

Table D.2 contains an overview of the data on luminaires in the consumer lighting model. Luminaires have a number of sockets of a certain type, and can, therefore, hold a number

Table D.1 – Consumer lighting model parameters for the household agent

Parameter	Value(s)	Source
Parameters at the start of the simulation (experiment 1 only)		
Adopters of CFL lamps	60%	Bertoldi and Atanasiu (2006)
CFL lamps for adopters	20%	based on Taskforce Verlichting (2009) and Bertoldi and Atanasiu (2006)
Halogen lamps	20%	assumption
Luminaires and usage		
Number of luminaires	5-65 (median of 20)	based on Bartlett (1993)
Usage	0-20 hours/week	assumption
Weight factors of criteria in purchase decision		
Price	1–3, 2-6, or 3–9	assumption
Efficiency	1–3	assumption
Lifetime	0.5–1.5	assumption
Friends have it	1–3, 2-6	assumption
CRI	1–3	assumption
Light output	0.5–1.5	assumption
Light color	1–3	assumption
Perception lamp type	1–3	assumption
Perception brand	0.5–1.5	assumption
Perception lamp model	0.5–1.5	assumption

of lamps. Other relevant properties – light demand and maximum power – are adopted to allow for more elaborate experiments at some point in the future.

Table D.2 – Luminaires in the consumer lighting model

Label	Socket	Shape	Adoption 1985	Adoption 2005
Pear large	E27	Pear	90%	70%
Pear small	E14	Pear	10%	7%
Spot 230V	GU10	Reflector	0%	15%
Spot 12V	G53	Reflector	0%	5%
Tube	R7S	Tube	0%	3 %
Indirect	G24d2	Reflector	0%	0 %

Table D.3 – Lamps in the consumer lighting model

Type	Label	Average lifetime (hours)	Uncertainty lifetime	Light output (lm)	Power consumption (W)	CRI	Colour Temperature (K)	Shape	Socket	Price (€)	Introduced (year)
Incandescent	Gamma Gloeilamp	1000	0.40	210	25	100	2700	Pear	E27	0.45	1980
	Gamma Gloeilamp	1000	0.40	359	40	100	2700	Pear	E27	0.45	1980
	Gamma Gloeilamp	1000	0.40	675	60	100	2700	Pear	E27	0.45	1980
	Gamma Gloeilamp	1000	0.40	880	75	100	2700	Pear	E27	0.45	1980
	Gamma Spot	1000	0.40	240	25	100	2600	Reflector	E27	1.50	1980
	Gamma Spot	1000	0.40	600	50	100	2700	Reflector	E27	1.50	1980
	Gamma Spot	1000	0.40	900	75	100	2800	Reflector	E27	1.50	1980
	Hema Standaard Helder	1000	0.40	415	40	100	2700	Pear	E27	0.50	1980
	Hema Standaard Mat	1000	0.40	935	75	100	2700	Pear	E27	0.50	1980
	Hema Standaard	1000	0.40	120	15	100	2700	Pear	E27	0.50	1980
	IKEA Gloda	1000	0.40	210	25	100	2700	Pear	E14	0.50	1980
	IKEA Gloda	1000	0.40	415	40	100	2700	Pear	E27	0.35	1980
	IKEA Gloda	1000	0.40	710	60	100	2700	Pear	E27	0.35	1980
	Osram Classic P	1000	0.35	400	40	100	2700	Pear	E14	1.45	1980
	Osram Classic P	1000	0.35	400	40	100	2700	Pear	E27	1.45	1980
	Osram Classic P	1000	0.35	660	60	100	2700	Pear	E27	1.95	1980
	Osram Classic P	1000	0.35	90	15	100	2700	Pear	E27	1.95	1980
	Philips Mat	1000	0.35	220	24	100	2600	Pear	E14	1.45	1980
	Philips Mat	1000	0.35	415	40	100	2700	Pear	E27	1.45	1980
	Philips Mat	1000	0.35	710	60	100	2700	Pear	E27	1.95	1980
	Philips Mat	1000	0.35	930	75	100	2800	Pear	E27	1.95	1980
	Philips Soft	1000	0.35	295	40	100	2700	Reflector	E14	2.50	1980
Halogen	IKEA	1000	0.40	100	20	100	3000	Reflector	GU10	1.60	1995
	IKEA	2000	0.40	138	35	100	3000	Reflector	GU10	1.25	1995
	IKEA	2000	0.40	343	50	100	3000	Reflector	GU10	1.25	1995
	IKEA	2000	0.40	525	35	100	2700	Reflector	G53	1.25	1995
	IKEA Eco	2000	0.40	392	28	100	2800	Pear	E27	1.49	2009
	Massive	2000	0.40	138	35	100	2700	Reflector	GU10	2.50	1995
	Massive	2000	0.40	343	50	100	2800	Reflector	GU10	2.10	1995
	Osram Halopar	2000	0.35	600	50	100	3000	Reflector	E27	13.00	2007
	Osram Halolux T	2000	0.35	790	60	100	3000	Tubular	E14	12.00	2010
	Osram Decostar	2000	0.35	200	20	100	3000	Reflector	G53	4.05	1995
	Osram Halopar16ALU	2000	0.35	400	50	100	3000	Reflector	GU10	5.55	1995
	Osram Haloline	2000	0.35	3400	150	100	3000	Tubular	R7S	6.75	1990
	Osram Haloline	2000	0.35	3400	200	100	3000	Tubular	R7S	6.75	1990
	Osram Haloline	2000	0.35	5300	300	100	3000	Tubular	R7S	6.75	1990
	Philips Twist Line	2000	0.35	165	35	100	2700	Reflector	GU10	3.50	1995
	Philips Twist Line	2000	0.40	349	50	100	2800	Reflector	GU10	3.50	1995
	Philips Accent Line	3000	0.35	300	20	100	3000	Reflector	G53	1.60	1995
	Philips Eco Halo	5000	0.35	240	20	100	3000	Reflector	G53	6.22	1995
	Philips Eco Classic	2000	0.35	630	42	100	280	Pear	E27	3.50	2009
CFL	Gamma Spaarlamp	5000	0.50	377	7	80	2800	Tubular	E27	1.99	1995
	Gamma Spaarlamp	5000	0.50	612	11	80	2800	Tubular	E27	1.99	1995
	Gamma Spaarlamp	5000	0.50	928	15	80	2800	Tubular	E27	1.99	1995
	Gamma Spaarlamp Bol	5000	0.50	358	9	80	2700	Pear	E27	5.49	1995
	Gamma Spaarlamp Bol	5000	0.50	450	11	80	2700	Pear	E27	5.49	1995
	Go Green	8000	0.50	726	11	81	2800	Tubular	E27	5.00	2009
	Hema Sfeer	8000	0.50	190	5	80	2700	Pear	E27	6.25	1995
	Hema Sfeer	8000	0.50	610	12	80	2700	Pear	E27	6.25	1995
	Hema Spaarlamp	10000	0.50	900	16	80	2800	Tubular	E27	9.25	1995
	Hema Super Spaarlamp	8000	0.50	500	8	80	2800	Tubular	E27	6.25	2005
	Hema Minispaarlamp	8000	0.50	230	5	80	2800	Tubular	E27	4.25	2005
	Hema Minispaarlamp	8000	0.50	1100	18	80	2800	Tubular	E27	4.25	2005
	Hyundai SEMI	8000	0.50	180	5	80	2800	Tubular	E14	2.95	2000
	Hyundai ECO	8000	0.50	310	7	80	2800	Tubular	E27	2.95	2000
	IKEA Sparsam Globe	10000	0.50	530	11	80	2700	Pear	E27	3.50	1995
	IKEA Sparsam Globe	10000	0.50	260	7	80	2700	Pear	E27	3.50	1995
	IKEA Sparsam Tubular	6000	0.50	600	11	80	2800	Pear	E27	1.00	1995
	IKEA	8000	0.50	260	7	80	2800	Reflector	E14	5.39	1995
	Megaman Liliput SLU	10000	0.40	600	11	80	2800	Tubular	E14	9.35	2005
	Megaman SLU	10000	0.40	400	8	80	2700	Tubular	E27	9.36	2005
	Megaman PingPong	15000	0.40	200	5	80	2700	Pear	E27	13.95	2005
	Megaman Dimmerable	10000	0.40	1008	18	80	2800	Tubular	E27	22.95	2009
	Osram DeluxELLonglife	15000	0.40	240	5	80	2700	Tubular	E14	13.95	1990
	Osram Deluxstar	6000	0.40	250	5	80	2700	Tubular	E14	4.95	1990
	Osram DeluxD	8000	0.40	1200	18	80	2700	Tubular	G24d2	10.00	1990
LED	AH Puur&Eerlijk	25000	0.65	200	5	85	3000	Pear	E27	16.49	2009
	AH Puur&Eerlijk Dimbaar	25000	0.65	300	6	85	3000	Pear	E27	24.99	2009
	Gamma highpower	25000	0.65	70	2	75	5000	Pear	E27	23.95	2007
	Gamma 42	25000	0.65	50	2	70	5000	Pear	E27	22.95	2007
	Gamma 15 halogen shape	10000	0.65	16	1	70	5000	Pear	GU10	6.49	2007
	Gamma	25000	0.65	20	1.2	70	5000	Pear	E27	9.99	2007
	Lemnis Pharox Dimbaar	25000	0.65	336	6	85	3000	Pear	E27	29.95	2009
	Osram Phantom classic A	25000	0.55	30	2	75	2700	Reflector	E27	13.95	2007
	Osram Phantom classic P	25000	0.55	40	1.6	75	2700	Reflector	E27	13.70	2007
	Osram Phantom Globe	25000	0.55	50	3	80	2700	Pear	E27	24.95	2007
	Philips Spot Perfect Fit	22000	0.50	105	3	80	3000	Reflector	GU10	39.95	2010
	Philips Milky Dimbaar	45000	0.50	186	7	87	2700	Pear	E27	39.95	2010
	Philips Spot Dimbaar	45000	0.50	180	7	85	2700	Reflector	GU10	39.95	2010
	Philips Novallure	15000	0.45	50	2	80	3000	Pear	E14	16.45	2009

E Dynamic Path Approach

Based on the analysis in chapter 7, we have developed software for a new approach for the analysis of data from simulations. In this appendix, details are provided on the development of this approach which we have named the *Dynamic Path Approach* (DPA). In addition, we describe how the indices of fit can be used to interpret the results of the approach. The following elements are in this appendix:

- In section E.1, details are given regarding the development and the use of the software for the DPA.
- In section E.2, definitions of the indices for goodness of fit of structural equation models are given, which are adopted in the DPA.

E.1 Development and use of software for the Dynamic Path Approach

Based on the analysis in chapter 7, we have developed software for a new approach for the analysis of data from simulations. In this appendix, we describe why we developed a module for the statistical software R. In addition, the module is described and we show how it can be used.

E.1.1 Existing software for Structural Equation Modelling

For the development of the new tool, we intended to use existing software that can be extended and already partially fulfils our needs. We focused on software that can estimate Structural Equation Models (SEMs). Implementing SEM from scratch would be very time consuming and error-prone. It would be an advantage if the existing software components are open source, in order to share our developments with a broader community. We needed to develop a tool that is flexible with respect to the manipulation of data and allows to make *scripts*. This would aid the user in automating and repeating the analyses he performs. This way, different sets of relations can be tested, saved and analysed easily. In addition, the tool must be able to work with a graphical user interface, in order to visualize the results. For instance, the parameters and their relations need to be showed in a path diagram. Relations between parameters are to be shown in tables and graphs (e.g. scatter plot, x-y-plot, histogram, time plot). Finally, the tool must be user friendly, so that it is presented in a nice way and the threshold for new users is limited.

The software available for SEM are Lisrel (Scientific Software International, Inc., 2009), EQS (Multivariate Software, Inc., 2009), Mx (Neale, 2009), Neusrel (NEUSREL Causal Analytics GbR, 2009), R (Gentleman and Ihaka, 2009) and its SEM module (Fox, 2006, 2009), and Amos (SPSS Inc., 2009). Each of those tools have their own strengths and limitations. The criteria for selection are related to GUI's and scripting abilities on the one hand, and the possibility for extension on the other hand.

GUI and scripting abilities All of these tools – except for Amos – work *exclusively* through a so-called command line: a box through which commands are supplied by the user. The advantage of such tools is that it allows for developing scripts that are able to execute a number of preselected tasks. An important disadvantage is, however, the burden to new users, who are unaware of the syntax of the command line and need to go through a steep learning curve. To be able to overcome this barrier, a graphical user interface (GUI) is needed.

As mentioned, only Amos works through a graphical user interface. However, the command line and scripting abilities of Amos are insufficient for our needs. And only for R, a specific graphical user interface can be created by using available modules.

Possibility for extensions Of the software packages we mentioned, only R is open source and free to use on all commonly used operating systems (Windows, Mac and Unix). This allows us to observe source code of existing parts of the software and find out what choices were made. Furthermore, R has a very large extension base, i.e. 2,500 user-contributed modules, available through the Comprehensive R Archive Network (CRAN)[1]. This means that a structure for extending the existing R code (including the SEM module) is in place. It is also an indicator of the large and active user community of R. It has its own scientific journal, a Wiki, the annual useR! conferences (the International R User Conference) and the biannual DSC conference (the Directions in Statistical Computing conference).

For these reasons, R is the most promising alternative to the statistical software which is commonly used in business and education, e.g. SPSS (SPSS, 2007) and spreadsheet software such as MS Excel (Microsoft, 2009) and it is the only software that can estimate SEMs that can be extended into the Dynamic Path Approach.

E.1.2 Development and use of the DPA module in R

Within R, we selected several necessary modules and connected, extended and used those in a new module, as is common in R. Our new package is called *dpa*. Functionality is written in methods within this module, but the user's interaction is mainly through the user interface that is developed with it.

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[1] As of 13 October 2010, http://cran.r-project.org/

Structure of the DPA module The DPA module contains three files coded in the R language. Each of those files provides part of the functionality. The DPA module is released as an open source R package on the Comprehensive R Archive Network (CRAN). It is publicly accessible under http://cran.r-project.org/web/packages/dpa. Documentation is available in the format that R requires for packages under http://cran.r-project.org/web/packages/dpa/dpa.pdf. The following R files form the core of the DPA module:

- *dpa.r* is the main file that containing the graphical user interface, performing administrative tasks and holding the data.
- *sem.r* translates the required analysis into the format that can be used with the *sem* package already existing in R.
- *plot.r* contains all code for generating the graphs.

Within the three files, the functionality is split in functions. Each of the functions can be called from the user interface, but also through a script that executes some or all steps needed in the analysis. An overview of the main functions can be found in Table E.1. A short description is provided as well. As can be seen, the functions are separated in groups related to data, relations, analysis, and results. Below, we will first explain the usage through the graphical interface and afterwards through the means of a script.

The code builds upon other packages, which are available on CRAN. After installing R, they are generally loaded automatically when the DPA module is started. The only exception is the *sem* module, which needs to be installed from one of the CRAN mirrors. This is possible through the user interface in R.

Using the DPA module with the graphical user interface R can be installed on Windows, Unix and MacOs platforms and is available free online at http://www.r-project.org. The module is released as an R package through CRAN, with the name *dpa*. Therefore, it can be loaded by installing it from a CRAN mirror and loading it. Both are done in the user interface of R. The main screen is started by issuing the following command at the command-line, which is started with R.

```
dpa.start()
```

An image of the main screen is displayed in Figure 7.4, on page 174. In the first column, the user manages the *dataset*. Data can be imported from different files (CSV, XLS, SPSS, and R data) or by connecting to databases (Postgres and MySQL). Since R and specific R packages support many data formats, it is easy to extend the possible data sources. After loading the data they can be edited and saved in R format. This is recommended, especially when data was imported from a database (or at a later stage, when lags are generated) because it can save time when loading the data in another instance.

Core to the tool is specifying the *relations* the user assumes. These relations can be lagged or instantaneous. In addition, the user specifies whether the relationship is unidirectional or bidirectional. When a new relationship is added, time lagged data are generated and added to the dataset when they are needed and are not present in the dataset. After the user has finished adding the relations, they can be saved to disk, to be

Table E.1 – Main functions and descriptions in the DPA module

Part	Function	Description
DPA	start	Starts the GUI and sets the basic options
DPA	exit	Closes the GUI
Data	setWorkingDirectory	Change the base directory
	loadDataFromDisk	Loads data into the memory from a CSV file or from the R data format (RDA)
	loadDataFromDatabase	Loads data into the memory
	viewOrEditData	Opens the data on screen, so it can be edited
	checkData	Checks the data for missing values and sorts it
	saveDataToDisk	Saves altered data to the disk so it can easily be reloaded
Relations	loadRelations	Loads a set of relations from an earlier saved text file
	editRelations	Opens the relations on screen, so they can be edited
	addRelations	Adds a new relation to the set of specified relations
	saveRelations	Saves the relations to the disk in text format
Analysis	options	Displays a screen in which the main options for analysis can be set
	performDPA	Executes the analysis using the loaded dataset, according to the relations and the options set. Some plots are automatically generated. Afterwards, the results remain in the memory.
	saveDPA	Saves the main results of the last performed DPA to disk in text format
Results	setGraphDir	Changes the directory in which all the graphs are stored
	generateCoefficientsPlots	Generates a plot of the values of (a selection of) coefficients over time and saves it to disk
	generatePathDiagramPlot	Generates a plot of the path diagram and saves it to disk
	generateFitPlots	Generates a plot of (a selection of) goodness of fit indices over time and saves it to disk

recalled in a different session. The saved relations can also be edited easily by any text editor.

Before the tool can execute the analysis, some *options* need to be selected. The column in the dataset that depicts *time* should be specified, because it is essential to the analysis that will eventually be executed for each time step in the data. Furthermore, a selection should be made how time is used in the analysis. Either time-dependence can be ignored (similar to experiment 1b), time can be grouped in similar intervals, or every point in time in the data can be used separately. This choice results in respectively 1, the number of intervals, or the number of time steps performed analyses.

The analysis can now be *performed*. The specified relations are translated to the model specification in the format the *sem* package requires. The data are selected and the analysis is performed for each time step or interval, as required. The user is informed whether the analyses were succeeded. For all successful analyses, a *plot* of the path diagram of the relevant variables and their relations is generated. Furthermore, other plots can be generated, such as the coefficients over time, and how well the model fits the data over time. Both graphs (PDF and PNG) and numerical results (CSV) are saved for later use.

Using the DPA module with a script Using scripts is often more efficient than using the graphical user interface. Therefore, all functions (and some more options) are available through directly using the functions. In addition, analyses can be repeated more easily. After R is started, the first command loads the DPA module, the second starts the main screen. The third sets the base folder in which, for instance, the data resides.

```
library(dpa)
dpa.start()
dpa.data.setWorkingDirectory("D:/example")
```

The screen can be set aside or closed if one uses only scripts. Using the *start()* command is important to initialize all parameters correctly. After starting up, the relevant parameters can be set. Below we set the directory in which all graphs will be stored, we preselect the name of the column representing time and we specify that we want to perform the analysis for every time step in the data.

```
dpa.results.setGraphDir("D:/example/results")
time_column<-"tick";
rbVal<-"every_timeStep";
```

We can load the data from any supported file with the following command, assuming the data is stored in the current working directory:

```
dpa.data.loadDataFromDisk("data.rda");
```

Adding a relation is done by issuing the following command:

```
dpa.relations.addRelations("a","b","From","0","2","UniDirectional");
```

In this line of code *a* is the independent variable, *b* the dependent, *From* implies that there is a lag in the independent variable, which is 0 at minimum and 2 at maximum. By specifying *UniDirectional* as final argument, the relation is from the independent to the dependent variable only. When needed, time lagged data are generated and added to the data set after issuing this command. This can take some time. After specifying all relations, the set of relations and the data set including the lags can be saved to disk:

```
dpa.relations.saveRelations("relations.txt");
dpa.data.saveDataToDisk("data_adapted.rda");
```

After loading the data, specifying the relations, and selecting the options, the analysis can be performed by calling:

```
dpa.analysis.performDPA()
```

The results are stored in the memory and path diagram plots are generated and stored as graphs in the selected graph directory. The following commands, generate some graphs of (a set of) coefficients of parameters over time, (some of) the fits indices over time, and the output of the analysis. The final command closes the DPA main screen.

```
dpa.results.generateCoefficientsPlots()
dpa.results.generateFitPlots()
dpa.analysis.saveDPA()
dpa.exit()
```

A final, optional step is to use a tool such as ImageMagick[2] to convert the set path diagrams for each analysed time step into an animated GIF format. That is an efficient animation format for these graphs that can be used in MS Powerpoint or any web browser. After installing ImageMagick, the command below can be issued at the command-line of any operating system to generate an animated GIF file with the name *anim.gif*:

```
convert -delay 50 -loop 1 graph_relation*.png anim.gif
```

Please be aware that many of the functions have optional arguments that can specify for instance the file name of the graphs saved, the colours used in graphs, the selection of the parameters to be plotted, etcetera. Thisallows the scripts to create graphs that can be used directly.

E.2 Goodness of fit indices

For structural equation models, a number of indicators is available to estimate the performance of the model, i.e. whether the dataset fits well on the set of relations and the estimated parameters. The three most common indices are adopted. First, the goodness of fit index (GFI) is the most common measure for fit. It is defined as follows:

$$\mathrm{GFI} = 1 - \frac{\hat{F}}{F_b} \tag{E.1}$$

The fraction $\hat{F}/F_b$ reflects the discrepancy between the estimated parameters and the data. Using GFI as an indicator, a model with more parameters is always performing better. Therefore, the adjusted goodness of fit index (AGFI) is also included in the analysis. It corrects for the degrees of freedom available for estimation and is defined as follows:

$$\mathrm{AGFI} = 1 - (1 - \mathrm{GFI})\frac{d_b}{d} \tag{E.2}$$

This adapted GFI introduces a measure for the number of degrees of freedom, captured by d_b and d. d refers to the degrees of freedom in the actual model and d_b refers to the degrees of freedom of a baseline zero model, which is the maximum number of degrees of freedom that could have been obtained.

Although they are different, for both indices a value of 1 implies a perfect fit. Furthermore, for each of the indices a lower value is worse; only the GFI is bounded below by zero. An overview of these and other indices can be found in (Arbuckle and Wothke, 1999, p. 412–413).

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[2] ImageMagick is available free for common operating systems, http://www.imagemagick.org/

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Glossary

ABM	Agent-Based Model. 9, 50, 54, 57, 58, 60, 61, 63, 70, 71, 87, 124, 232, 303, 309
ACE	Agent-Based Computational Economics. 58
AGFI	Adjusted Goodness of Fit Index. 172, 258
AM	Adaptive Management. 229
BDI	Beliefs-Desires-Intentions. 63
CAS	Complex Adaptive System. 13, 32, 230
CCS	Carbon Capture and Storage. 82, 95, 99
CDM	Clean Development Mechanism. 72, 93
CFL	Compact Fluorescent Lamp. 144
CGE	Computable General Equilibrium. 5, 54, 55, 60
CHP	Combined Heat and Power. 86, 230
CO_2	Carbon dioxide. 77
CPB	Centraal Planbureau. 57, 182
CRAN	Comprehensive R Archive Network. 174, 254, 255
CRI	Colour Rendering Index. 147, 249
CST	Complex Systems Theory. 230
CT	Carbon Taxation. 71, 72, 78, 101
DES	Discrete Event Simulation. 54, 59, 60
DPA	Dynamic Path Approach. 168, 180, 253
DS	Dynamic Systems. 54, 58, 60
EBM	Equation-Based Model. 129
EEG	Erneuerbare Energien Gesetz. 86
EMG	Electricity Market Game. 190
ETS	Emissions Trading Scheme. 71, 78, 101, 208
FiT	Feed-in Tariff. 78, 85, 86
GAMS	General Algebraic Modelling System. 57
GFI	Goodness of Fit Index. 172, 258
GT	Game theory. 230
GUI	Graphical User Interface. 59, 254

HPC	High Performance Cluster. 73
IPAT	Intensity = Population × Affluence × Technology. 81
IQR	Inter-Quartile Range. 97
IS	Innovation Systems. 33, 229
JI	Joint Implementation. 93
JSP	Java for Server Pages. 194
LCOE	Levelized Cost of Electricity. 115, 238
LED	Light-Emitting Diode. 144
LNG	Liquefied Natural Gas. 9, 123, 209
LSoA	Linear System of Action (Coleman). 231
LTS	Large Technical System. 229
MAS	Multi Agent System. 58
MASON	Multi-Agent Simulator Of Neighbourhoods. 58
MATISSE	Methods and Tools for Integrated Sustainability Assessment. 229
MCA	Multi-Criteria Analysis. 89, 235
MEP	Milieukwaliteit van de Elektriciteitsproductie. 86
MLA	Multi-Level Approach to Transition Management. 36, 230
MLP	Multi-Level Perspective. 17, 20, 21, 229
MMBTU	Million British Thermal Units (1.055 GJ). 131
MPP	Multi-Phase Perspective. 19, 229
MSA	Master Sales Agreement. 125
NPV	Net Present Value. 115, 238
PV	Photovoltaic. 86
REPAST	Recursive Porous Agent Simulation Toolkit. 58, 75, 76
SD	System Dynamics. 5, 6, 54, 58, 60, 66, 232
SDE	Simuleringsregeling Duurzame Energy. 86
SDM	System Decomposition Method. 65
SEM	Structural Equation Modelling. 167, 169, 170, 179, 253
SNM	Strategic Niche Management. 37, 229
SPA	Sales and Purchase Agreement. 124, 125
SSH	Secure Shell. 73
SVN	Subversion. 73, 75
TM	Transition Management. 27, 229
TMA	Transition Management Arena. 35, 36, 230
TMC	Transition Management Cycle. 35, 230
TS	Time Strategies. 230

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Summary

Simulating energy transitions

Evolving energy infrastructures

In the 21st century, our energy infrastructure systems must change in order to secure the accessibility, affordability, reliability, and quality of energy services. This is due to the depletion of traditional resources, the threat of climate change, and globally increasing demand. This thesis explores simulation models as a tool for ex-ante assessment of interventions proposed to bring about structural change in our energy infrastructure systems. Such systemic change of energy infrastructures towards a more sustainable energy system is widely known as energy transition.

Energy infrastructures are socio-technical systems that enable suppliers and consumers of energy products and services to connect in terms of physical connections and contractual agreements. Many autonomous and heterogeneous actors make, given their own objectives, strategic and operational decisions regarding the parts of the infrastructure they own, regulate or influence. Such decisions are made in a dynamic and unpredictable environment. Energy infrastructures are complex systems, characterized by many non-linear interactions between social and technical elements across multiple levels of the system. Over a longer time period our energy infrastructures evolve. Every strategic decision or policy intervention is taken under deep uncertainty – we simply cannot predict the exact consequences of specific interventions, because we are dealing with complex evolving systems. At best we may explore trajectories of long-term development infrastructure and attempt to discern patterns of evolution emerging as a function of interventions.

The objective of the work in this thesis is to simulate evolving energy infrastructure systems and to create the enabling modelling and simulation platform. The simulation results are meant to support public and private actors in their strategic decision-making. Eventually, this should allow public and private actors to better anticipate the effects of their decisions.

The central research question addressed is:

> *How can we assess the long term consequences of policy interventions in evolving energy infrastructure systems?*

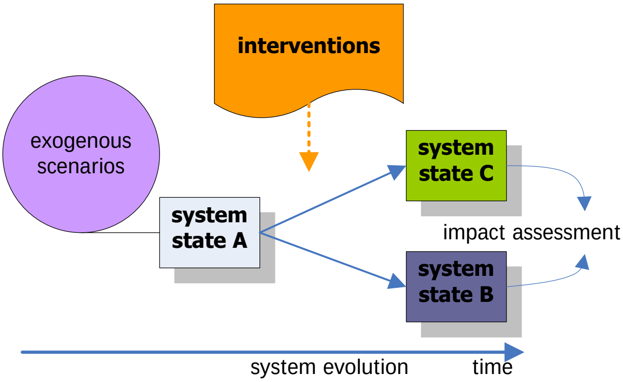


Figure 1 – Modelling framework for simulating energy transitions

In the literature, while definitions of transition vary, common aspects mentioned are the long time span, the involvement of structural and systemic change, and the many actors with their own preferences and means. Using a complex socio-technical system's perspective, we have defined transitions as "substantial change in the state of a socio-technical system" (chapter 2). Although many authors claim that energy transition can be 'managed', suitable tests and indicators to monitor the progress of energy transition as a result of specific interventions – and therewith verify the viability of energy transition management – are lacking.

Our hypothesis is that we can increase insight into the possibilities for steering transitions in energy infrastructures by simulating the evolution and behaviour of (subsystems of) these infrastructures. Such insight may contribute to an assessment of the viability of transition management, which we define as "the art of shaping the evolution of socio-technical systems" (chapter 2).

Building simulation models

It is not yet known how we can build simulation models which allow us to trace the consequences of interventions in energy infrastructures. Therefore, we need a framework – a set of guidelines – to develop and build such models. Based on the concept of energy infrastructure systems as complex evolving socio-technical systems, we have selected *agent-based modelling* to simulate specific interventions (or the lack thereof) in different subsystems of the energy infrastructure: 1) power generation and CO_2 policy, 2) the evolution of the global liquefied natural gas (LNG) market, and 3) the regulation of consumer lighting. Along the way, this led to a (conceptual) framework that structures the discourse on transitions in energy infrastructures (see Figure 1 and chapter 3). Using this framework we are able to define the problem scope, the system studied, the relevant characteristics, and the resolution of the required results. Once these have been identified and described, the resulting narrative or specification can be translated to a simulation model. The modelling paradigm selected may be – but is not necessarily limited to – agent-based modelling. The following elements are part of the framework:

- *System representation* – The system is represented using a socio-technical system's perspective. The modeller needs to choose which actors are part of the system and with what granularity to represent their state and behaviour. In addition, relevant physical elements and their properties need to be selected.

- *Exogenous scenarios* – The changing environment of the system to be modelled is captured in scenarios that describe the possible development of the world exogenous to the system. A modeller must identify, characterize and select the relevant aspects of this external world and decide how the dynamics, spread, and uncertainty are represented. Scenarios may comprise static values that can be changed between runs (e.g. oil prices), trends, or models that specifically relate a variety of parameters exogenous to the modelled system. To be relevant, the infrastructure system model must be able to respond to scenario parameter changes.
- *Interventions* – A key element is to identify policy interventions that may affect the evolution of the energy infrastructure system. Individual interventions, or an assemblage of interventions, can be selected to form *transition designs*. These should explicitly distinguished from the exogenous scenarios. *How* the transition designs are represented strongly affects both the level of complexity of the modelling effort and the ability of the model to simulate the effects of the modelled interventions.
- *System evolution* – Running simulations lets the socio-technical system modelled evolve over time in-silico. The actors' decisions affect the system structure and system performance, at each simulated point in time. Multiple runs are completed to collect an adequate sample across the scenario and intervention space. The evolution of each and every parameter in each run is recorded for monitoring and analysis. The indicator variables of the structure and performance of the system need to be selected, as well as the interactions they are based upon.
- *Impact assessment* – The effects of interventions can be traced and assessed through analysis of the simulation output. By developing graphical representations of key system indicators patterns can be identified, effectively resulting in an assessment of the system *performance*. Additionally, the system's *structural* change and the underlying causalities must be assessed.

By making the five parts operational, simulation models of evolving energy infrastructure (sub)systems can be developed that are able trace the effects of specific interventions.

Assessing transitions requires the investigation of structural change resulting from policy interventions. *Agent-based modelling* is the only modelling paradigm that allows for an emergent and changing system structure. In an agent-based model (ABM), actors are represented as computer-coded *agents*, having properties constituting an individual identity or management style. Agents are equipped with coded decision rules, some that determine their strategic decisions and some that determine their operational decisions. The term agents is, therefore, reserved for pro-active and autonomous components in the system. Markets are also represented as agents if they are institutionalized with their own rules according to which, for instance, prices are determined. Physical components are considered objects. They are represented as computer-coded physical nodes/elements with properties regarding technical capabilities and flexibilities. Both social and physical

Table 1 – Cases for simulation models of energy infrastructures

Case	Interventions
1 Power generation	CO_2 emissions trading, carbon taxation, secondary policies
2 LNG market	None, through the market
3 Consumer lighting	Ban on bulbs, incandescent bulbs taxation, LED subsidy

components interact. Any intervention may affect the agents in the decisions they make. The structure and dynamics of the system emerge from the physical causalities governing the system and from the decision making rules of agents, which make them respond to policy interventions.

Simulation results

Three subsystems of the energy infrastructure were selected as case studies. Each of them is a complex socio-technical system in itself. Each case covers a specific segment of the energy value chain (production, transport, consumption) and specific interventions (policy measure, governance/no intervention, regulation). An overview is given in Table 1.

The first case is the decarbonizing of the electricity infrastructure (chapter 4). Significant reduction of CO_2 emissions requires investment in clean(er) power generation technologies. The main question in this case is: *will the transition to a CO_2-extensive power generation portfolio be successful?* In the model, the agents represent power generation companies, operating their existing power generators and investing in new power plants, over the course of decades. The agents are subject to either a CO_2 emissions trading scheme, a carbon taxation scheme or no policy intervention and to uncertainty with respect to fuel prices and electricity demand. It was found that the emissions trading scheme implemented in the EU introduces an investment risk related to the price volatility on the CO_2 market. Under a taxation scheme with an average tax level equal to the CO_2-market price, emission reductions are accomplished faster and further, with less income transfer from consumers to producers. For the same case we developed a serious game in which the agents are replaced by human players, which was demonstrated to facilitate the knowledge transfer from the modellers to the target audience (chapter 8).

The second case addresses the liquefied natural gas (LNG) market, which is traditionally governed by long-term high-volume bilateral contracts (chapter 5). The question in this case is: *how can we simulate the LNG sector and let the transition to spot trade in the LNG market emerge?* In this case, we have not modelled a policy intervention. Instead, we identified four drivers for transition in the LNG market: growth of the market, uncommitted capacity, technological innovations, and the LNG spot market reinforcing itself. These drivers have been put to the test in an agent-based model of agents representing companies active in the LNG market. These agents engage into contracts on LNG trade by optimizing their expectations regarding future options based on their experience. We explored the potential of transition towards a market where flexible spot trading is pursued. We observed that a spot market for LNG is likely to evolve and found that the identified drivers growth, uncommitted capacity, and innovation are important for the development of spot trade. Contrary to many expectations, we have not observed that spot-trade reinforces itself.

The third case was on energy saving in consumer lighting (chapter 6). We asked the question: *what are the effects of government policies on the transition to low-electricity consumer lighting?* We simulated a network of heterogeneous consumer agents who replace failing lamps based on their individual preferences and exchange of perceptions within their social network. Various types of lamps with different properties allow agents to make their choice. Agents have memory and develop perceptions regarding lamps, technologies, and brands, and share these over their social network. The simulation results confirm that the implemented phase-out of incandescent bulbs in the EU is the most effective way of achieving a lower electricity usage for lighting. However, in the long run a taxation scheme is equally effective and relieves the investment peak imposed on consumers by the ban on bulbs. The third case was on energy saving in consumer lighting (chapter 6). We asked the question: *what are the effects of government policies on the transition to low-electricity consumer lighting?* We simulated a network of heterogeneous consumer agents who replace failing lamps based on their individual preferences and exchange of perceptions within their social network. Various types of lamps with different properties allow agents to make their choice. Agents have memory and develop perceptions regarding lamps, technologies, and brands, and share these over their social network. The simulation results confirm that the implemented phase-out of incandescent bulbs in the EU is the most effective way of achieving a lower electricity usage for lighting. However, in the long run a taxation scheme is equally effective and relieves the investment peak imposed on consumers by the ban on bulbs.

Model typology and analysis

The modelling framework has enabled us to discuss the notion of energy transition in a systematic fashion. This can be translated into the description of a simulation model. Furthermore, the framework helped us to identify the three criteria for tracing specific interventions.

Three criteria link the ability of a simulation model to trace specific interventions to *the way in which individual interventions are modelled*. First, it is required that the system is modelled in a way that it captures its evolution. Second, the system should be responsive to the intervention. Third, the system has to be flexible with regard to the various interventions modelled. When these criteria are met – for any type of simulation model, already existing or conceptual – the effects of specific interventions can be traced.

Using these criteria we have developed a *typology of transition models*. In level 1 models, only the first criterion (captures evolution) is required; level 2 models also meet the second criterion (responsiveness); level 3 models meet all three criteria (including flexibility). The typology can be used to show the potential ability of any model in assessing the effect of individual interventions based on a conceptual description of the model. An analysis of transition models existing in the literature revealed that they generally do not meet all three criteria.

We showed the need to address change in the system's structure in simulation models. An important element is how to assess such change and how to determine and analyse (change in) the structure of the system. In order to do so, we developed a *'dynamic path approach'* that identifies a path of causal relationships among the multiple variables in the evolving system and shows how they develop over time (chapter 7). The network of causal relations is a representation of the relevant mechanisms governing the system's behaviour. Results based on a simple causal diagram from the case on power generation and CO_2 policy show that the approach can indicate how the structure of the system changes over time. The results show that the developed approach prevents a flawed interpretation of the simulation results when the structure of the system changes.

Conclusions and outlook

We conclude that we *can* assess the long term consequences of policy interventions in evolving energy infrastructure systems. This can be done by analysing the outputs of agent-based models which have been systematically developed using the modelling framework we developed in this thesis.

In order to assess the viability of transition management, a necessary ingredient is that they represent the socio-technical system in a way that assessment of the effects of interventions is possible. In order to trace the effects of specific interventions, it is required that the system is modelled in a way that it captures its evolution, and is responsive and flexible to the interventions modelled. Existing simulation models of transitions do not meet these criteria and are, therefore, *not capable* of assessing the viability of transition management.

Agent-based models (ABMs) are suitable to simulate energy transitions, because they can capture change in the system structure and dynamics. Insights gained from ABM simulations show advantages and disadvantages of specific policy interventions in energy infrastructures, by showing the variability in the long-term effects on the affected energy systems.

With the models developed, we have shown cases where a specific intervention affects the many distributed decisions taken by relevant actors in a way that is likely to alter the dynamics and the structure of the socio-technical system along a desired trajectory. ABMs can determine likely effects of interventions without claiming to perfectly predict future states of socio-technical systems.

In future work, the viability of transition management could be further explored by tracing and assessing transition management instruments from the literature in case studies in which they are modelled as interventions in simulations. Subsequently, policy interventions could be modelled endogenously, i.e. where interventions are adapted, based on actual or expected system performance. The viability of transition management may be proven when the core aspects of management – intervening, monitoring, and adapting – can be simulated.

Another line of future work is that of developing a modular and generic agent-based energy markets model in a 'complexity modelling lab'. Such a lab could support strategic decision makers in decisions that are urgent.

At the end of the day, these efforts may help us to understand how our energy infrastructure systems can be changed in the course of the coming decades. By making a well-informed selection of interventions, the challenges ahead may be conquered and a disruption in the quality of the way we live our lives may be prevented.

Samenvatting

Energietransities simuleren

Evoluerende energie-infrastructuren

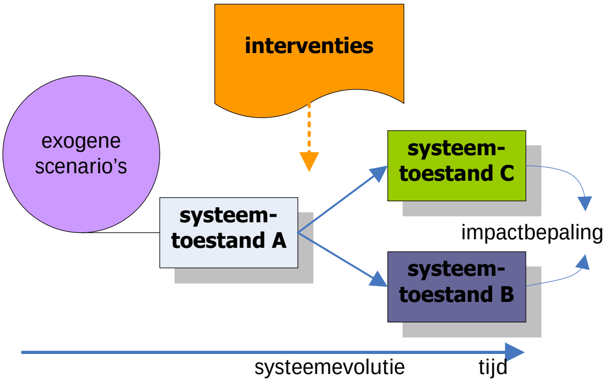
In de 21^{e} eeuw moeten onze energie-infrastructuren veranderen om de toegankelijkheid, de betaalbaarheid, de betrouwbaarheid en de kwaliteit van energieservices te garanderen. Dit is nodig vanwege de uitputting van traditionele grondstoffen, de dreiging van klimaatverandering en de mondiaal toenemende vraag. Dit proefschrift exploreert simulatiemodellen als gereedschap om vooraf de gevolgen vast te kunnen stellen van interventies, voorgesteld om structurele verandering in onze energie-infrastructuren teweeg te brengen. Dergelijke systemische verandering van onze infrastructuren naar een duurzamere energievoorziening staat bekend onder de term energietransitie.

Energie-infrastructuren zijn socio-technische systemen die aanbieders en consumenten van energieproducten en -services in staat stellen elkaar te bereiken, zowel in termen van fysieke verbindingen als in contractuele overeenkomsten. Veel autonome en heterogene actoren nemen strategische en operationele beslissingen met betrekking tot de delen van de infrastructuur waarvan ze eigenaar zijn, die ze reguleren of pogen te beïnvloeden. Deze beslissingen worden genomen in een dynamische en onvoorspelbare omgeving. Energie-infrastructuren zijn complexe systemen die worden gekarakteriseerd door de vele non-lineaire interacties tussen sociale en technische elementen over verschillende systeemniveaus. Op de lange termijn evolueren onze energie-infrastructuren. Elke strategische beslissing of beleidsinterventie is onderhevig aan diepe onzekerheid – we kunnen de exacte gevolgen van specifieke interventies niet voorspellen omdat we te maken hebben met complexe, evoluerende systemen. Het hoogst haalbare is om de lange termijn ontwikkelpaden van infrastructuren te exploreren en een poging te doen om patronen van evolutie als functie van interventies te bepalen.

Het doel van dit proefschrift is het simuleren van evoluerende energie-infrastructuursystemen en het simulatie- en modelleerplatform dat dit mogelijk maakt te ontwikkelen. De simulatieresultaten zijn bedoeld om publieke en private actoren in hun strategische beslissingen te ondersteunen. Uiteindelijk zou dit publieke en private actoren moeten helpen beter te anticiperen op de effecten die hun beslissingen teweegbrengen.

De centrale onderzoeksvraag is:

> *Hoe kunnen we de lange termijn consequenties van beleidsinterventies in evoluerende energie-infrastructuursystemen vaststellen?*



Figuur 1 – Modelleerraamwerk voor het simuleren van energietransities

Ondanks het feit dat definities van transitie in de literatuur sterk verschillen, wordt transitie doorgaans in verband gebracht met de lange doorlooptijd, het structurele en systemische karakter van de verandering en de betrokkenheid van vele actoren, elk met hun eigen voorkeuren en middelen. Op basis van een complex socio-technisch systeemperspectief hebben we transitie gedefinieerd als "substantiële verandering in de toestand van een socio-technisch systeem" (hoofdstuk 2). Hoewel veel auteurs claimen dat energietransities kunnen worden 'gemanaged', ontbreken geschikte tests en indicatoren om het verloop van de energietransitie als het gevolg van specifieke interventies – en daarmee de haalbaarheid van energietransitiemanagement – te bepalen.

Onze hypothese is dat we het inzicht in de mogelijkheden voor sturing van energietransities kunnen vergroten door het simuleren van de evolutie en het gedrag van (subsystemen van) de energie-infrastructuren. Dergelijke inzichten kunnen bijdragen aan het bepalen van de haalbaarheid van transitiemanagement, dat we definiëren als "de kunst van het vormgeven van de evolutie van socio-technische systemen" (hoofdstuk 2).

Het bouwen van simulatiemodellen

Tot op heden is niet bekend hoe simulatiemodellen kunnen worden gebouwd die ons toestaan de consequenties van interventies in energie-infrastructuren te traceren. Daarvoor is een raamwerk – een set van richtlijnen – nodig. Gebaseerd op het concept van energie-infrastructuursystemen als complexe, evoluerende socio-technische systemen hebben we *agentgebaseerd modelleren* geselecteerd om specifieke interventies (of het gebrek daaraan) in verschillende subsystemen van de energie-infrastructuur te simuleren: 1) elektriciteitsopwekking en CO_2-beleid, 2) de evolutie van de mondiale markt voor vloeibaar gemaakt aardgas (LNG) en 3) de regulering van consumentenverlichting. Dit heeft geleid tot een (conceptueel) raamwerk dat het debat rondom transities in energie-infrastructuren structureert (zie Figuur 1 en hoofdstuk 3). Met behulp van het raamwerk kunnen de reikwijdte, het systeem, de relevante eigenschappen en de resolutie van de resultaten worden gedefinieerd. Nadat ze zijn geïdentificeerd worden ze vertaald in een simulatiemodel. Daartoe kan agentgebaseerd modelleren worden gekozen als modelleerparadigma, maar dat hoeft niet. De volgende elementen zijn onderdeel van het raamwerk:

- *Systeemrepresentatie* – Het systeem wordt gerepresenteerd vanuit een socio-technisch systeemperspectief. De modelleur dient te kiezen welke actoren onderdeel zijn van het systeem en met welk detail hun toestand en gedrag worden beschreven. Daarnaast worden relevante fysieke elementen en hun eigenschappen geselecteerd.

- *Exogene scenario's* – De mogelijke ontwikkeling van de wereld exogeen tot het systeem in het model wordt gevangen in scenario's. De modelleur moet relevante aspecten in deze exogene wereld identificeren, karakteriseren en selecteren. Daarnaast moet hij bepalen hoe de dynamiek, de spreiding en de onzekerheid in deze aspecten worden gerepresenteerd. Scenario's kunnen statische waardes bevatten die worden gevarieerd tussen simulaties (zoals olieprijzen), trends of modellen die specifiek de relatie tussen een aantal parameters exogeen voor het gemodelleerde systeem beschrijven. Om relevant te zijn, moet het infrastructuursysteemmodel in staat zijn te reageren op de veranderingen in scenarioparameters.

- *Interventies* – De indentificatie van beleidsinterventies die mogelijk de evolutie van het energie-infrastructuursysteem beïnvloeden is een kernelement. Individuele interventies of een assemblage van interventies kunnen worden geselecteerd om *transitieontwerpen* te vormen. Deze worden expliciet onderscheiden van de exogene scenario's. *Hoe* de transitieontwerpen worden gerepresenteerd is sterk bepalend voor zowel de complexiteit van de modelleerexercitie als de mogelijkheid van het model om de effecten van de gemodelleerde interventies te simuleren.

- *Systeemevolutie* – Bij het uitvoeren van simulaties evolueert het socio-technische systeemmodel over de tijd. De beslissingen van actoren hebben effect op de systeemstructuur en -prestatie gedurende elk moment in de gesimuleerde tijd. De resultaten van verschillende simulaties worden verzameld om de scenario- en interventieruimte afdoende te beschrijven. De evolutie van elke parameter in elke run wordt vastgelegd voor de analyse. Daartoe moeten indicatorvariabelen van de systeemstructuur en -prestatie en van de onderliggende interacties worden geselecteerd.

- *Impactbepaling* – De effecten van interventies kunnen worden getraceerd en bepaald door analyse van de simulatiegegevens. Door middel van het ontwikkelen van grafische representaties van belangrijke systeemindicatoren kunnen patronen worden geïdentificeerd, die resulteren in een bepaling van de systeem*prestatie*. Daarnaast moeten de verandering in systeem*structuur* en de onderliggende causaliteiten worden bepaald.

Door het operationaliseren van de vijf onderdelen kunnen simulatiemodellen worden ontwikkeld van (subsystemen van) evoluerende energie-infrastructuren waarbinnen het mogelijk is de effecten van specifieke interventies te traceren.

Het bepalen van transitie vereist het bestuderen van structurele veranderingen als gevolg van beleidsinterventies. *Agentgebaseerd modelleren* is het enige modelleerparadigma waarbinnen een emergente systeemstructuur mogelijk is. In een agentgebaseerd model (ABM) worden de actoren gerepresenteerd als gecodeerde *agenten*, met eigenschappen die de individuele identiteit of managementstijl bevatten. Agenten zijn voorzien van gecodeerde beslisregels, sommige voor de strategische beslissingen en andere voor de operati-

Tabel 1 – Cases voor simulatiemodellen van energie-infrastructuren

Casus	Interventies
1 Elektriciteitsopwekking	CO_2-emissiehandel, CO_2-belasting, secundaire beleidsinstrumenten
2 LNG markt	Geen, via de markt
3 Consumentenverlichting	Verbod op gloeilampen, gloeilampenbelasting, LED subsidie

onele beslissingen. De term agent is daarom gereserveerd voor proactieve en autonome componenten in het systeem. Markten zijn ook agenten indien ze zijn geïnstitutionaliseerd met hun eigen regels waarmee bijvoorbeeld prijzen tot stand komen. Fysieke componenten worden gezien als objecten. Ze zijn gerepresenteerd als gecodeerde fysieke punten/elementen met eigenschappen met betrekking tot hun technische mogelijkheden en flexibiliteit. Zowel sociale als fysieke componenten interacteren. Elke interventie kan de beslissingen van agenten beïnvloeden. De structuur en dynamiek van het systeem zijn het emergente gevolg van de fysieke causaliteiten van het systeem en van de beslisregels van agenten die reageren op beleidsinterventies.

Simulatieresultaten

Drie subsystemen van de energie-infrastructuur – zelf complexe socio-technische systemen – zijn geselecteerd als cases. Elke casus bestrijkt een specifiek segment van de energiewaardeketen (productie, transport, consumptie) en specifieke beleidsinterventies (beleidsmaatregel, governance/geen interventie, regulering). Een overzicht staat in Tabel 1.

De eerste casus betreft het CO_2-vrij maken van de elektriciteitsinfrastructuur (hoofdstuk 4). Voor een significante reductie van CO_2-emissies zijn investeringen in schone(re) technologieën voor elektriciteitsopwekking vereist. De centrale vraag in deze casus is: *zal de transitie naar een CO_2-arm elektriciteitsopwekkingsportfolio succesvol zijn?* Agenten in het model representeren elektriciteitsproductiebedrijven, die gedurende decennia investeren in nieuwe centrales en hun elektriciteitscentrales beheren. De agenten zijn onderhevig aan ofwel een CO_2-emissiehandelsysteem, of een CO_2-belasting, of er is geen beleidsinterventie. Daarnaast is er onzekerheid betreffende het verloop van brandstofprijzen en de elektriciteitsvraag. De resultaten laten zien dat het emissiehandelsysteem zoals het geïmplementeerd is in de EU een investeringsrisico met zich meebrengt als gevolg van de prijsvolatiliteit op de CO_2-markt. Bij een CO_2-belasting met een gemiddeld belastingniveau gelijk aan de prijs op de CO_2-markt worden emissiereducties sneller behaald en wordt er meer gereduceerd, terwijl de inkomensoverdracht van consumenten naar producenten lager blijft. Voor dezelfde casus is een serieus spel ontwikkeld waarin de agenten worden vervangen door menselijke spelers. Het spel helpt bij de kennisoverdracht van modelleurs naar de doelgroep (hoofdstuk 8).

De tweede casus richt zich op de markt voor vloeibaar gemaakt aardgas (liquefied natural gas, LNG), traditioneel gekenmerkt door lange termijn, groot volume bilaterale contracten (hoofdstuk 5). De centrale vraag in deze casus is: *hoe kunnen we de LNG sector simuleren zodat transitie naar spothandel in de LNG markt kan ontstaan?* In deze casus hebben we geen beleidsinterventies gemodelleerd, maar zijn vier drijvende krachten voor transitie in de LNG-markt geïdentificeerd: de groei van de markt, de niet-gecommitteerde capaciteit, de technologische innovatie en spothandel die zichzelf versterkt. De effecten van deze drijvende krachten zijn getoetst in een agentgebaseerd model van agenten die bedrijven representeren die actief zijn in de LNG-markt. De agenten gaan contracten voor LNG-handel aan door het optimaliseren van hun verwachtingen van hun toekomstige opties en hun ervaring. Het potentieel van de transitie naar een markt waarin flexibele spothandel wordt nagestreefd is geëxploreerd. We hebben geobserveerd dat het waarschijnlijk is dat een spotmarkt voor LNG zal ontstaan en dat de geïdentificeerde drijvende krachten groei, niet-geommiteerde capaciteit en innovatie belangrijk zijn voor die ontwikkeling. Tegen de verwachting in, vonden we niet dat de spothandel zichzelf versterkt.

De derde casus gaat over energiebesparing in consumentenverlichting (hoofdstuk 6). De centrale vraag in deze casus is: *welke effecten zijn te verwachten van beleidsinstrumenten op de transitie naar energiezuinige consumentenverlichting?* We hebben een netwerk gesimuleerd van heterogene consumentenagenten die kapotte lampen vervangen op basis van hun individuele voorkeuren en de percepties die binnen hun sociale netwerk worden gedeeld. Agenten kiezen uit diverse typen lampen waarvan de eigenschappen verschillen. Agenten hebben een geheugen en ontwikkelen percepties over lampen, technologieën en merken. Ze delen die over hun sociale netwerk. De simulatieresultaten bevestigen dat de geïmplementeerde uitfasering van de gloeilamp in de EU de meest effectieve manier is een om het elektriciteitsverbruik voor consumentenverlichting te verlagen. Op de lange termijn is een gloeilampenbelasting even effectief, maar die voorkomt wel de grote investeringspiek, veroorzaakt door het verbod op gloeilampen.

Modeltypologie en -analyse

Het modelleerraamwerk maakt een systematisch debat over energietransitie, dat kan worden vertaald naar de beschrijving van een simulatiemodel, mogelijk. Daarnaast heeft het raamwerk ons geholpen om criteria te identificeren om specifieke interventies te traceren.

Drie criteria koppelen het vermogen van een simulatiemodel om specifieke interventies te traceren aan *de manier waarop individuele interventies worden gemodelleerd.* Ten eerste is het vereist dat het systeem zo wordt gemodelleerd dat de evolutie wordt gevangen. Ten tweede moet het systeem responsief zijn aan de interventie. Ten derde moet het systeem flexibel zijn met betrekking tot de verschillende interventies die zijn gemodelleerd. Indien aan deze criteria wordt voldaan – voor elk type simulatie, bestaand of conceptueel – kunnen de effecten van specifieke interventies worden getraceerd.

Met behulp van deze criteria hebben we een typologie van transitiemodellen ontworpen. Voor niveau 1 modellen is alleen aan het eerste criterium (vangt de evolutie) vereist; niveau 2 modellen voldoen ook aan het tweede criterium (responsiviteit); niveau 3 modellen voldoen aan alle drie de criteria (inclusief flexibiliteit). De typologie kan worden gebruikt om het vermogen vast te stellen van elk type model om de effecten van individuele interventies, gebaseerd op een conceptuele beschrijving van het model te bepalen. Een analyse van bestaande transitiemodellen in de literatuur laat zien dat deze doorgaans niet aan alle drie de criteria voldoen.

We hebben laten zien dat we de verandering in de systeemstructuur in simulatiemodellen moeten bestuderen. Een belangrijk element is hoe dergelijke veranderingen in de systeemstructuur kunnen worden bepaald en geanalyseerd. Om dat te doen hebben we een ‘dynamische padaanpak’ ontwikkeld die een pad van causale relaties identificeert binnen de verschillende variabelen in een evoluerend systeem en laat zien hoe deze zich in de loop van de tijd ontwikkelen (hoofdstuk 7). Het netwerk van causale relaties is een representatie van de relevante mechanismes die het systeemgedrag beheersen. Resultaten gebaseerd op een simpel causaal diagram binnen de casus over elektriciteitsopwekking en CO_2-beleid laten zien dat de aanpak een indicatie geeft hoe de systeemstructuur over de tijd verandert. De resultaten laten zien dat de ontwikkelde aanpak een foutieve interpretatie van simulatieresultaten kan voorkomen indien de systeemstructuur verandert.

Conclusies en vooruitblik

We concluderen dat we de lange termijngevolgen van beleidsinterventies in evoluerende energie-infrastructuursystemen kunnen bepalen. Dat is mogelijk door middel van het analyseren van de uitkomsten van agentgebaseerde modellen die systematisch zijn ontwikkeld met behulp van het raamwerk in dit proefschrift.

Voor het bepalen van de haalbaarheid van transitiemanagement is het noodzakelijk om het socio-technische systeem op een manier te representeren die het mogelijk maakt de effecten van interventies te bepalen. Om specifieke interventies te kunnen traceren is het noodzakelijk dat het systeem wordt gemodelleerd op een manier dat het de evolutie vangt en responsief en flexibel is met betrekking tot de gemodelleerde interventies. Bestaande simulatiemodellen van transities voldoen niet aan deze criteria en zijn als gevolg daarvan niet in staat om de haalbaarheid van transitiemanagement te bepalen.

Agentgebaseerde modellen zijn geschikt om energietransities te simuleren, omdat ze de verandering in de systeemstructuur en -dynamiek kunnen vangen. Inzichten van simulaties met agentgebaseerde modellen laten door middel van de variatie in de lange termijn effecten in het relevante systeem de voor- en nadelen van specifieke beleidsinterventies in energie-infrastructuren zien. Met de ontwikkelde modellen hebben we in cases laten zien dat specifieke interventies de gedistribueerde beslissingen van relevante actoren zodanig beïnvloeden, dat het waarschijnlijk is dat de dynamiek en structuur van het socio-technische systeem op een gewenst pad komen te liggen. Agentgebaseerde modellen kunnen de waarschijnlijke effecten van interventies bepalen zonder te claimen dat de toekomstige toestand van socio-technische systemen perfect wordt voorspeld.

In toekomstig onderzoek kan de haalbaarheid van transitiemanagement verder worden geëxploreerd door het bepalen van het effect van instrumenten uit de transitiemanagementliteratuur door ze als interventies te modelleren en te simuleren. Daarnaast kunnen beleidsinterventies endogeen worden gemodelleerd, hetgeen wil zeggen dat interventies worden, aangepast gebaseerd op behaalde of verwachte systeemprestaties. Mogelijk kan de haalbaarheid van transitiemanagement worden bewezen wanneer de kernaspecten van management – interveniëren, monitoren en aanpassen – kunnen worden gesimuleerd.

Een andere richting voor toekomstig onderzoek is het ontwerpen van een modulair en generiek agentgebaseerd energiemarktenmodel dat plaats kan vinden in een ‘laboratorium voor het modelleren van complexiteit’. Een dergelijk laboratorium zou strategische beslismakers ook in urgente beslissingen kunnen ondersteunen.

We hopen dat deze inspanningen ons uiteindelijk zullen helpen om onze energie-infrastructuursystemen gedurende de komende decennia te veranderen. Door het plegen van goed doordachte interventies kunnen we hopelijk de uitdagingen op ons pad overwinnen zonder dat de kwaliteit van ons leven aan te hoeven tasten.

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Curriculum Vitae

Émile Jean Louis Chappin was born on 27 November 1982 in Zoetermeer (The Netherlands). He completed pre-university education (VWO) in 2001 at Oranje Nassau College in Zoetermeer. Subsequently, he studied for his Master's degrees in Systems Engineering, Policy Analysis and Management at the Faculty of Technology, Policy and Management of Delft University of Technology. With an intern at TU Delft regarding a model of the transport of hydrogen, he specialized in energy systems. Emile obtained his Bachelor's degree with the thesis *The transition to a hydrogen economy*, presenting a causal analysis of public acceptance of hydrogen. In 2006, he graduated with the MSc thesis *Carbon Dioxide Emission Trade Impact on Power Generation Portfolio*, presenting an Agent-Based Model of the Dutch power generation sector implementing a CO_2 emissions trading scheme.

In 2007, Emile started his PhD project at the faculty of Technology, Policy and Management of TU Delft. As a member of the Energy and Industry group and as a researcher of the Next Generation Infrastructures Foundation he performed research on simulating energy transitions using agent-based modelling and serious games. In 2007, he worked part-time for the Centre for Environmental Sciences of Leiden University on a project commissioned by SenterNovem in which a calculator tool was developed for estimating the life-cycle greenhouse gas emissions of electricity from biomass.

The work of Emile's PhD project was the topic of several scientific articles, book chapters, conference papers, and articles in newspapers and brochures. Emile presented his work at conferences throughout Europe and America. In addition, his research was part of Delft TopTech courses (2009–2010), the Next Generation Infrastructures Academy (2009–2010), and a workshop at the 33rd IAEE conference in Brazil (2010). Finally, the work was presented in non-academic settings (e.g. the Dutch Ministry of Economic Affairs, Eneco, and Rotterdam Port Authority). As from February 2011, Emile has been a post-doc in the same research group.

Alongside his work as a researcher, Emile has gained experience as a teacher in a variety of courses on BSc, MSc and postgraduate level on topics related to energy, industry, life-cycle analysis, and data analysis. Furthermore, Emile writes a column for FD Selections. Finally, Emile chairs the non-profit *theaterorkest.nl*, managing orchestras for amateur theatre productions, and he is a professional pianist and conductor.

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Simulating Energy Transitions

Have you ever wanted to know whether a CO_2 tax outperforms the EU emissions trading scheme? Or how long it really takes markets to change and to let consumers choose differently? In this book, Emile Chappin explores simulation models to provide us with answers *before* policy interventions are implemented and shows that, by developing *agent-based models*, we can simulate energy transition.

Learn about a new framework that enables us to model energy infrastructure systems as complex socio-technical systems, which evolve as a result of distributed decision making by actors in the system. See how running agent-based models let the system structure and dynamics emerge from the interactions between actors and technologies. Understand how actors, who decide on operation and investment, are responsive to policy interventions, market rules, and technological development. Find out from simulations of the electricity production sector, the LNG market, and consumer lighting that interventions in these energy systems do alter their evolution they invoke structural, systemic change: transition.

This thesis thus demonstrates that agent-based models yield a powerful tool for governments and companies: they allow them to assess the long-term effect of their policies and strategies in our complex, interconnected world.

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