106 *Int. J. Critical Infrastructures, Vol. 6, No. 2, 2010*

Agent-based modelling of energy infrastructure transitions

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Abstract: Shaping energy transitions not only requires technical system innovation and redesign but also new policies, regulations, Research and Development (R&D) and investment strategies – a transition assemblage. Transition management thus equates to designing and implementing such an assemblage. Agent-Based Models (ABMs) may be used for *ex-ante* assessment of transition assemblage alternatives. To help determine whether the design of a particular model is fit for its purpose, we have developed a typology. Three models were assessed:

1 a model on the impact of CO_2 policy on the power production sector

2 a model on the transition of the global Liquefied Natural Gas (LNG) infrastructure

3 a model on the imminent transition caused by the arrival of Light-Emitting Diode (LED) lighting systems.

All three models can be used to compare transition assemblage alternatives and could be adapted to assess regulatory adaptability.

Keywords: agent-based model; ABM; energy infrastructures; energy modelling; transitions; transition management; power generation; carbon policies; LNG market; consumer lighting.

Reference to this paper should be made as follows: Chappin, E.J.L. and Dijkema, G.P.J. (2010) 'Agent-based modelling of energy infrastructure transitions', *Int. J. Critical Infrastructures*, Vol. 6, No. 2, pp.106–130.

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1 Introduction

Energy infrastructure systems are complex systems: they contain many interacting physical and social components. Due to a myriad of decisions and interactions, system structure, content and performance emerge over time. The power grid, for example, can be considered a large-scale sociotechnical system (Chappin and Dijkema, 2008c) or λ-system (Nikolic *et al.*, 2009). Sustainability of our energy infrastructure is another emergent property (Dijkema and Basson, 2009).

We define a system transition as "structural change in both technical and social subsystems" (Chappin and Dijkema, 2008b). Transitions emerge over time as a fundamental change of λ-systems. During transitions, the structure and the content of the physical subsystem change. While these changes are caused by the social subsystem which comprises actors and their interconnections, the body of rules and institutions that govern actor behaviour and decision making, and the mutual dependence of physical and social subsystems cause both to change in a complex web of interaction, feedback and feedforward relations. The idea behind transition management is that if a transition is wanted, actors could somehow manage its emergence in the system. What is lacking, however, is a basic understanding of the sociotechnical design space available for transitions and a recognition of the very complexity of many a sociotechnical systems which may imply that we only have a certain chance of success to steer λ-system towards some preferred state.

We postulate that policy design and implementation is part of the sociotechnical design space. A 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 indeed initiates a transition and leads to some optimal end state while additional requirements for the transition path often exist.

Transitions typically span decades wherein the combination of external influence, actor behaviour and actor interaction is dynamic and complex. Consequently, elucidating suitable design variables for shaping transitions is difficult and may even be impossible. In transition and transition management literature, the focus is on descriptive case studies on past transitions (Rotmans *et al.*, 2000; Geels, 2002; Rotmans, 2003; Geels, 2004). However, as we have argued elsewhere (Chappin and Dijkema, 2008a–b), where description leads to understanding, transition management implies that transitions should and can be steered and shaped. Transition managers design a coherent assemblage of policies, regulations, Research and Development (R&D) strategies, financing and so on. We define a transition assemblage as the all-inclusive set of transition instruments applied. A transition assemblage design is, therefore, a unique selection of transition instruments. The effectiveness of such a transition assemblage equates to the likelihood of meeting the designers' objectives.

During and after a transition, the components and interactions are different; being-in-transition is one of the emergent system properties. Thus, observing a transition is difficult and subjective, and complete understanding and management of energy infrastructure transition may be impossible. However, Axelrod (1997b) already argued that "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". Also, it has been demonstrated that physical subsystem models can be adequately incorporated in

Agent-Based Models (ABMs) to yield models that increase our understanding of energy infrastructures and industrial networks (Chappin *et al*., 2009b; Chappin and Dijkema, 2009; Davis *et al*., 2009; Nikolic, 2009).

Therefore, we conjectured that ABMs are suitable to assess transition assemblage 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 ABMs that show transitions in energy systems. We deem such models to be valid if they are 'fit for purpose'. 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 transitions in energy infrastructures and assess transition assemblage alternatives for transition managers.

In this paper, we present a framework for the use of ABMs as transition models. While we limit ourselves to ABMs, constructing these models still leaves many degrees of freedom. The purpose of the framework is to assist modellers of ABMs on transitions. The framework provides a cohesive overview of the building blocks available and presents the options and restrictions that model developers have. Thus, it should allow a balanced and sound model development. In addition, the framework may serve as a typology of transition models; it characterises existing and new models in terms of potential for elucidating transitions and transition management. We demonstrate the usefulness of this framework by three applications.

The structure of this paper is as follows: First, we elaborate system transitions in large-scale sociotechnical systems (λ-systems). Second, we introduce gent-based modelling as a suitable building block for models intended for *ex-ante* assessment of transition assemblage in energy infrastructure systems. Third, we present a typology for categorising models used to evaluate transition management. Fourth, the models reviewed using the framework are presented. These models include the following:

- a model used to analyse CO_2 policy and taxation for the power production sector and to assess these transition instruments
- a model used to elucidate the ongoing transition of the global Liquefied Natural Gas (LNG) infrastructure
- a model developed to assess the effect of a breakthrough technology, Light-Emitting Diode (LED) lighting systems.

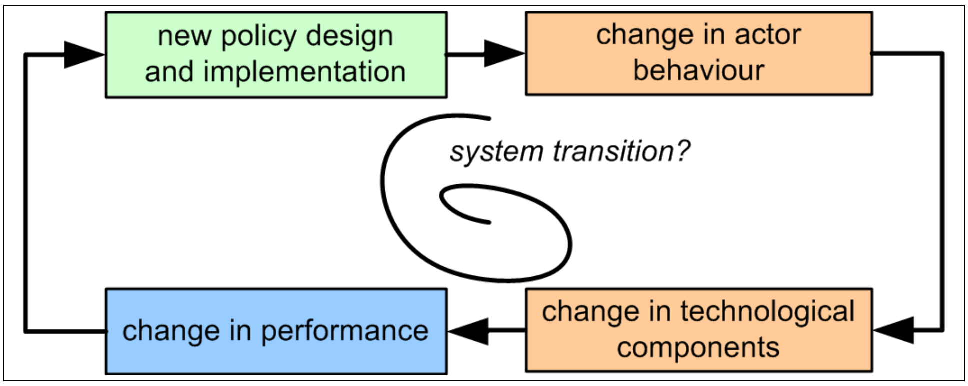
For each of these, the model setup and results are briefly presented and the model type is reflected upon, notably the degrees of freedom that were addressed in each modelling exercise. The paper ends with a conclusion and an outlook.

2 Designing system transitions in large-scale sociotechnical systems

2.1 Transitions of λ-systems

Energy infrastructure systems can be considered λ-systems that contain interdependent subsystems or components which are also considered systems (Asbjørnsen, 1992). They are evolutionary and they exhibit path dependency and lock-in. Current choices shape options for system structure and content in the future and the options, in turn, were shaped by the past. The λ-systems we observe today were not designed as such; they evolved to their present state (Herder *et al*., 2008; Nikolic *et al*., 2009). Because the needs of society change, technological components were not designed to meet the current set of requirements (*e.g.*, sustainability, reliability, flexibility and affordability). New or refined needs, emerging from society, affect the need for policy and regulation (see Figure 1). Only policy makers can design a policy that affects actor behaviour. A policy influences the conditions of an actor's decision making and, thus, it may change the outcomes of his/her decisions: Must we invest in a power plant or a wind farm? Shall we buy an LED or a conventional bulb? In other words, changes in the technical components of λ-systems and their interaction only materialise when actors change their behaviour and decide differently. Regulation will only affect the technical system content indirectly through the actors. Actors change their preferences or perceptions by adopting new strategies or by the introduction of a new policy. To add to complexity, changes may materialise at a time when perceptions and preferences have changed again.

Figure 1 From policy design to improvement (see online version for colours)



Over time, this process may result in a fundamental change of system structure; we call that process a system transition (see Figure 1). A system transition is, therefore, by definition, an emergent property of a λ-system.

2.2 *Policy design should incorporate system transitions*

Policy makers face the challenge of designing effective policies in and for λ-systems (Bijker *et al*., 1987; Hughes, 1987; Ottens *et al*., 2006). The energy infrastructure is clearly a λ-system; competitive tasks (power and natural gas generation and retail services) were unbundled from monopolistic tasks (grid and pipeline operators). The sector is embedded in and strongly connected to several markets, *i.e.*, fuel, emission trading and spot markets. Transport of energy (electricity, natural gas, oil, LNG, *etc*.) is, therefore, more and more separated from production and consumption. On the demand side, users increasingly get more options to join in the game, for instance, by the introduction of distributed generation and smart metering. The consumer is also more involved because of the renewed introduction of consumer-side incentives to change their consumptive behaviour.

All the actors active in these markets have their own objectives and means to realise them. The government optimises its objectives by setting the rules of the game, using policy and regulation as main instruments. Government affects the behaviour of actors who optimise their own objectives.

Incorporating the transition pathway and end state adds a new dimension to the challenge of policy design.

2.3 Knowledge gaps in the design of system transitions

Based on literature on the design process (Maier and Rechting, 2002; Dym and Little, 2004), a number of knowledge gaps on the design of system transitions has been identified. Since these have been described in detail elsewhere (Chappin and Dijkema, 2008b–c), we will only summarise them here. A design of a system transition encompasses a transition assemblage that is estimated by a certain performance based on transition tests.

First, there is a need for transition indicators which should unambiguously state the performance of system transitions – their pathway and their end state – according to the objectives and requirements of its designer.

Second, there is a need for a clear understanding of transition instruments, *i.e.*, the design alternatives, based on design variables, in order to come to the largest variety of possible designs for system transitions.

Third, one needs to be able to check the different designs with suitable tests to assess their performance, measured by performance indicators. Simulation models are tests for different transition designs using indicators to measure their performance.

The framework, described in the next section, intends to fill the three gaps mentioned above.

3 Framework for agent-based models of transitions in energy infrastructure systems

We postulate that assessing the performance of system transitions is an extremely difficult task. We believe that it is not sufficient to rely only on traditional assessment methods such as top-down and economic optimisation models. Those models often exhibit hidden assumptions (for example, being equipped for homogenous actors only). For testing the performance of system transitions, one rather needs to assess the evolution of λ-systems under different transition assemblage designs. Based on Axelrod (1997b), we argue for ABMs to assess the performance of transition assemblage designs for energy infrastructure systems. They fit the structure of λ-systems; the decision making of relevant actors is translated to behavioural rules of agents; the technical subsystems are modelled as physical networks of equipment and flows. When discussing transitions, alternatives to ABMs lose relevance because they impose a fixed system structure to the model preventing the observation of emergent transitions. The main necessities for observing transitions include a dynamic system structure and the use of entities (discrete and active). The main alternatives to ABMs are the other simulation schools. Computable General Equilibrium (CGE) models are static equilibrium models (Jones, 1965; Leontief, 1998) based on linear equations. As such, they are continuous and do not allow for discrete components. Also system dynamics (Forrester, 1958; 1969) only allows for continuous variables. Dynamic systems (Rosenberg and Karnopp, 1983) are continuous and are only applicable to physical systems and discrete event simulation (Gordon, 1978; Boer *et al*., 2002; Boyson *et al*., 2003; Corsi *et al*., 2006) assumes passive components not capable of acting.

We present a framework for building useful ABMs of transitions in energy infrastructure systems (see Figure 2). The five main components of that framework are as follows:

1 system representation

2 exogenous scenarios

3 design of transition assemblage

4 system evolution

5 impact assessment.

Let us have a closer look at each of these building blocks. We define different levels for exogenous scenarios and for the design of transition assemblage. Selection of those levels impact 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 does not restrict the modelling paradigm; it promotes the intelligent use of the strengths of different modelling paradigms for different parts of the system.

By introducing the levels of complexity for the transition assemblage, the framework serves as the typology for transition models (see Table 1). Used as such, one may come to the unfortunate conclusion that using the lowest levels is very common in the (small) body of transition models in the literature and that, because of implicit assumptions, such models cannot lead to insight into transitions.

Table 1 Typology of transition models

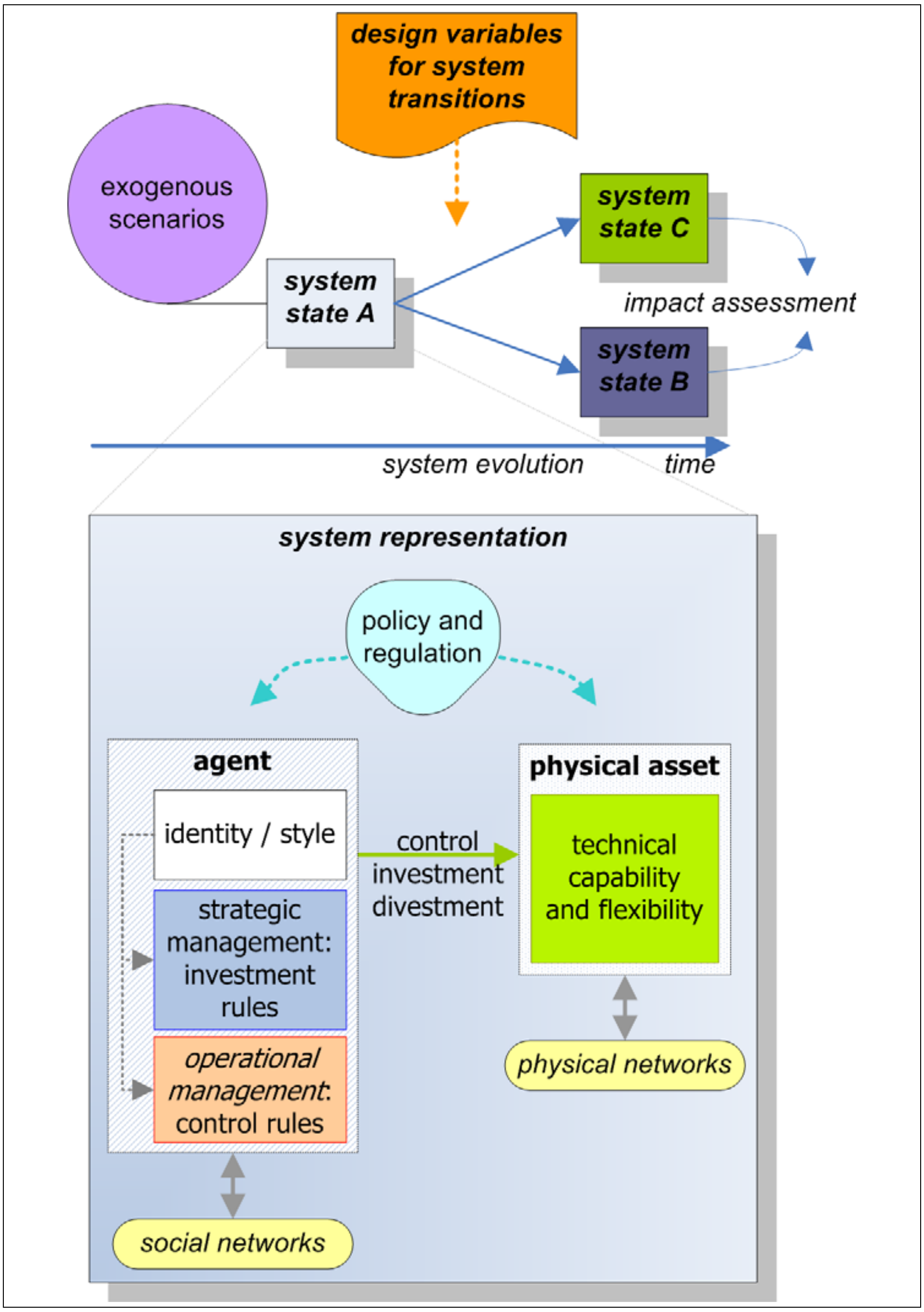
Ability of the model	*Level 1*	*Level 2*	*Level 3*	*Level 4*
Observe system evolution	x	x	x	x
Assessment of transition impact		x	x	x
Comparison of transition designs			x	x
Assessment regulatory adaptability				x

Let us now look at the five components.

3.1 System representation

Our framework intends to use ABMs as a modelling paradigm for building assessments of transitions in energy infrastructure systems. This implies that the ABM represents the energy infrastructure system. Therefore, we will define the ABMs and agents and provide the steps to come to agent-based system representations for studying the design of system transitions in λ-systems. In general, all subsystems or elements under relevant influence by other subsystems or elements need to be included in the system representation.

Figure 2 Framework for assessing system transitions with ABMs (see online version for colours)



Note: The main components are system representation, exogenous scenarios, transition assemblage design variables, system evolution and impact assessment.

An agent-based simulation model is often defined as “a collection of heterogeneous, intelligent, and interacting agents, which operate and exist in an environment, which in turn is made up of agents” (Epstein and Axtell, 1996; Axelrod, 1997a). An ABM contains a set of interacting ‘agents’ with certain properties acting based on a set of rules, reacting upon factors coming from outside. 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). Although in the literature, different sets of properties for agents are proposed (Bussmann *et al.*, 1998; Weiss, 2000), the core components of an agent are a set of goals, a working memory, a social memory and a set of rules for social engagement. Physical elements do not act themselves; they are passive. Therefore, properties and capabilities characterise elements in the physical subsystem.

Many tools and methods exist for operationalising 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 translation of this knowledge into the representation of the system. This follows the combination of using agents in ABMs and the chosen λ-systems perspective.

The model developer defines a conceptual model of the system containing all relevant elements. Consecutively, implementation of those elements is formalising 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, operationalisation is a tailored design process, specific to the domain under study and the researchers’ focus. Additional conventions or methodologies aid that process. For instance, one can use the system decomposition method (Nikolic *et al.*, 2006; 2009) designed to capture tacit knowledge of actors in an ABM. That 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 formalised and shared using ontologies (van Dam and Lukszo, 2009). Next, many suggestions are formulated that increase the efficiency of a model development process (Chappin, 2006, Chap. 9).

3.2 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. Every thing relevant but exogenous makes up the scenario space (Fahey and Randall, 1998; Enserink *et al.*, 2002). The scenario space can have one of the several levels of complexity. In all those levels, relevant but unaffected components are modelled as exogenous parameters. They can be static, be varied individually and be varied together.

3.2.1 Static parameter values

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

Most common is a range of values, sometimes with a nonuniform distribution. The need for data is limited; for each parameter, the minimum, maximum and interval values and possibly the distribution need to be determined. The range of available values reflects the parameter's uncertainty.

3.2.2 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, a natural gas. One representation is a start value and a change pattern, possibly stochastic. Modelling scenario parameters as trends has two consequences. First, this requires additional parameters: a probability distribution and its properties. Although more complicated to develop, this approach will enable the use of more realistic scenarios. The variability in the trends characterise the uncertainty in the parameter. This uncertainty can, with trends, 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 into account this trend, for instance by forecasting agents. Therefore, the use of varying trends leads to very different models.

3.2.3 Coupling with other models

Finally, one can develop or use existing models such as System Dynamics Models (SDMs) or mathematical models to provide exogenous parameters. SDMs are a collection of differential equations and are often considered an incompatible modelling paradigm to ABMs since ABMs are discrete and SDMs are continuous (Schieritz and Milling, 2003; Borshchev and Filippov, 2004). These models differ in the type of assumptions. That makes it hard to adapt SDMs to the agent-based paradigm. We postulate, however, that we should combine ABMs and SDMs into a hybrid to use the best of both worlds. A single SDM 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 SDMs or mathematical models to model exogenous scenario parameters should be considered if multiple scenario parameters are strongly correlated especially when well-designed SDMs are available. Mathematical models are often found in literature and can be used as an external world to the agents in the model.

3.3 Design of transition assemblage

Similar to exogenous scenarios, different levels of complexity exist for modelling the transition assemblage design. Table 2 presents an overview of those levels. They are discussed separately.

Table 2 Transition assemblage design alternatives

Level	*Description*	*Level of complexity*
1	Implicitly modelled	
2	Fixed system parameter	Model needs responsiveness.
3	Exogenous scenario parameter	Model requires flexibility.
4	Endogenous system parameter	Model requires regulatory adaptability.

We postulate that for adequate evaluation of transition assemblage designs, one should aim at Level 3 or 4. It is possible to start at Level 2 and upgrade later. However, Level 1 should be avoided since reusability in a higher level model will prove impossible. One should take notice that these levels are not exclusive and that different levels of policies and regulations can be in one model simultaneously.

3.3.1 Implicitly modelled

In this case, the structure of the model accommodates a certain policy and regulation. The assemblage is a fixed set of policy and regulation, the setting of which in the model is implicit. 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 transition assemblage. As a dreadful consequence, one can never assess the impact of the design assemblage. Therefore, models using this level will not lead to useful models of transition management. Consequently, we recommend not to apply Level 1 policy and regulation in transition models. The very selection and design of policy and regulation is *de facto* a transition assemblage design variable. If policy is not modelled as such, alteration of policy is impossible without constructing a new model.

3.3.2 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 ABMs, 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 2, it is still impossible to assess the effect of a transition assemblage. The only advantage of using this level over making it implicit is that the model is upgradeable to the Level 3. Upgrading implies adding agents’ responsiveness to other policy values while the model structure remains intact. Hence, we recommend to start at least at Level 2.

3.3.3 Exogenous scenario parameter

A policy can be a (set of) scenario parameter that is exogenous to the system in transition. In this setup, policy is one of the three levels of scenario parameters:

1 varying parameter values between runs

2 varying trends between runs

3 based on SDMs – all with their advantages and disadvantages (see the previous section on exogenous scenarios).

Only at this level and upwards 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 policy in this framework. However, as stated above, one may start with fixed system parameters (Level 2) as this will not limit model expansion.

3.3.4 Endogenous system parameter

At this level, policy development is endogenous. This implies that the government is an actor included in the system representation who decides during a simulation run on their policy and regulation. Government's 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 the agent's reaction to government's 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.

Modelling this level transition assemblage is modelling a form of adaptive governance which is considered a keystone of transition management (Rotmans *et al.*, 2000; 2001; Loorbach, 2007). We, therefore, conjecture that only this level can really assess transition management as referred to in the literature.

However, modelling policy and regulation as an endogenous system parameter that 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 data on government's responsiveness under different conditions. A solution is to model uncertainty on that data as (Level 3) exogenous scenario parameters. Adoption of that solution leads to models in which the adopted policy is the outcome of the interplay of the system's state, the decision rules of the government and the parameters of exogenous scenarios. This will lead to robust evaluations of designs since it acknowledges the evolution of policy as well as uncertainty in government's actions and responses.

3.4 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. As stated above, policy can also be emergent when modelled endogenously. Variety in 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. One needs an impact assessment by using different system evolutions at different locations in the parameter space in order to come to sound conclusions.

3.5 Impact assessment

Together, the above notions are the necessary ingredients for the impact assessment of the design alternatives. How do we decide which transition assemblage design is to be preferred? The impact assessment has to encompass a well-designed set of experiments and a solid analysis of their results.

3.5.1 Parameter sweep: experimental design

In order to assess and compare the performance of different transition assemblage design alternatives, one can use the 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 different factors of the model are varied between different 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 computing resources available.

The use of environment scenarios (Fahey and Randall, 1998; Enserink *et al.*, 2002) 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 that were 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 a 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 that 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 the factors in other groups.

3.5.2 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. The recorded parameters should include not only the selected performance indicators but also the input variables in order to allow testing for correlations.

Since the parameter space is large and modern computational power allows large sets of runs to be completed in reasonable time, this full record is often a huge amount of data. One can use visualisation 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 performance of different transition assemblage designs. However, statistical methods generally are of a static nature and are not capable of adequately analysing 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. One example is by making a series of student *T*-tests over time to assess differences in means (Chappin and Dijkema, 2008c).

3.6 Conclusion

In order to underpin transitions in energy infrastructure systems and the potential of transition design and transition management, we need to develop models that assess transition designs. We formulated, based on this line of thinking, a typology of transition models containing four levels. These levels have different requirements for the following five components of the model:

1 system representation

2 transition assemblage

3 exogenous scenarios

4 evolution

5 assessment.

The model typology is summarised in Table 1. On Level 1, only system evolution is observed in which transition assemblage is implicitly modelled and assessing transitions is impossible. Level 2 allows for transition assessment. On Level 3, the comparison of different transition designs also becomes possible, but keystone transition management principles can only be evaluated on Level 4. As a consequence, only Levels 2, 3 and 4 models are useful. Therefore, the most innovative results are to be expected from Levels 3 and 4 models.

4 Case on production: design for a model of transition in power generation

A quantitative 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, 2008b–c). The main objective is to get insights on the potential long-term impact of policy interventions such as a carbon tax or emissions cap on the power sector. A detailed analysis of this case and its results has been the subject of publications (Chappin *et al.*, 2009a–b). A schematic overview of how the ABM is set up is presented in Figure 4. This model can be called a Level 3 model. The model allows for evaluation and comparison of different transition assemblages. We are developing an upgrade to Level 4 which is discussed below.

4.1 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 an operational behaviour, *i.e.*, power producers need to negotiate contracts for feedstock, sales of electricity and, in the case of emissions trading, emission rights. They also exhibit a strategic behaviour, *i.e.*, 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 negotiated contracts and organised exchanges and the physical flows and their constraints and characteristics are modelled.

Figure 3 Case on production: the framework applied to carbon policies and power generation (see online version for colours)

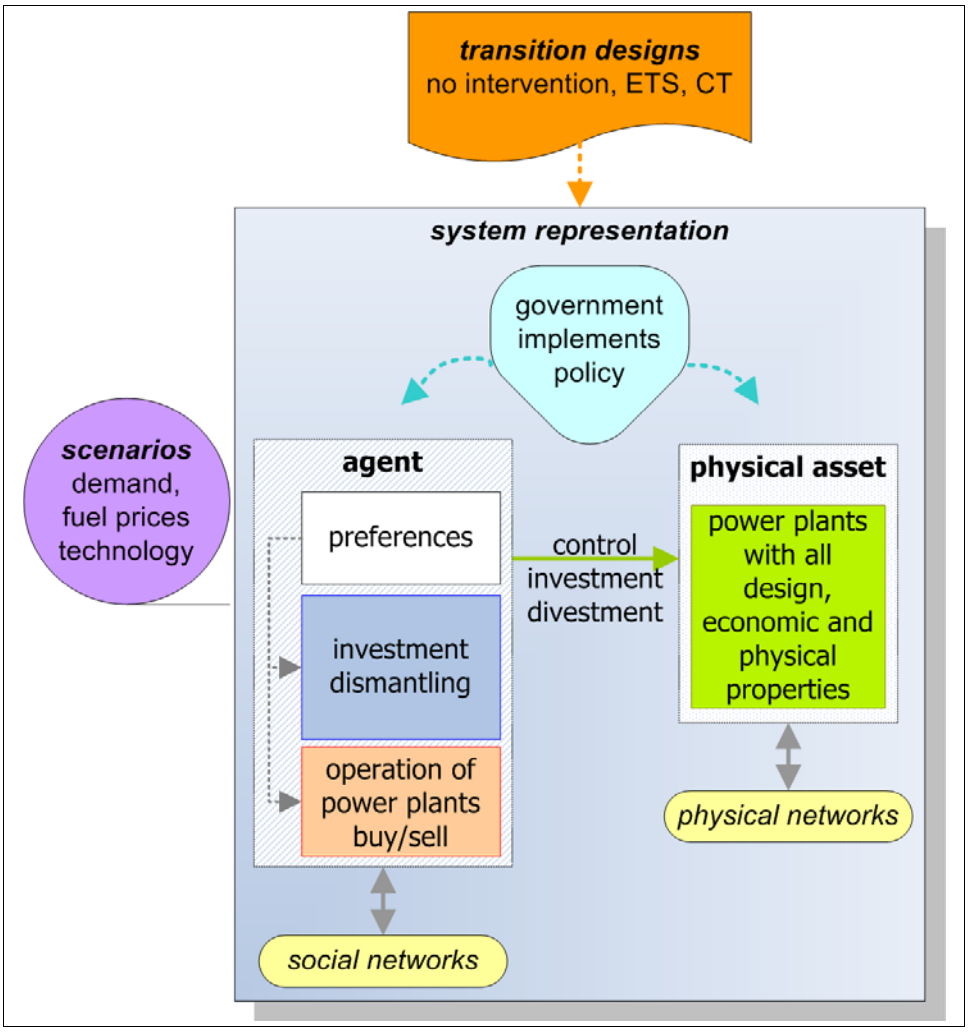
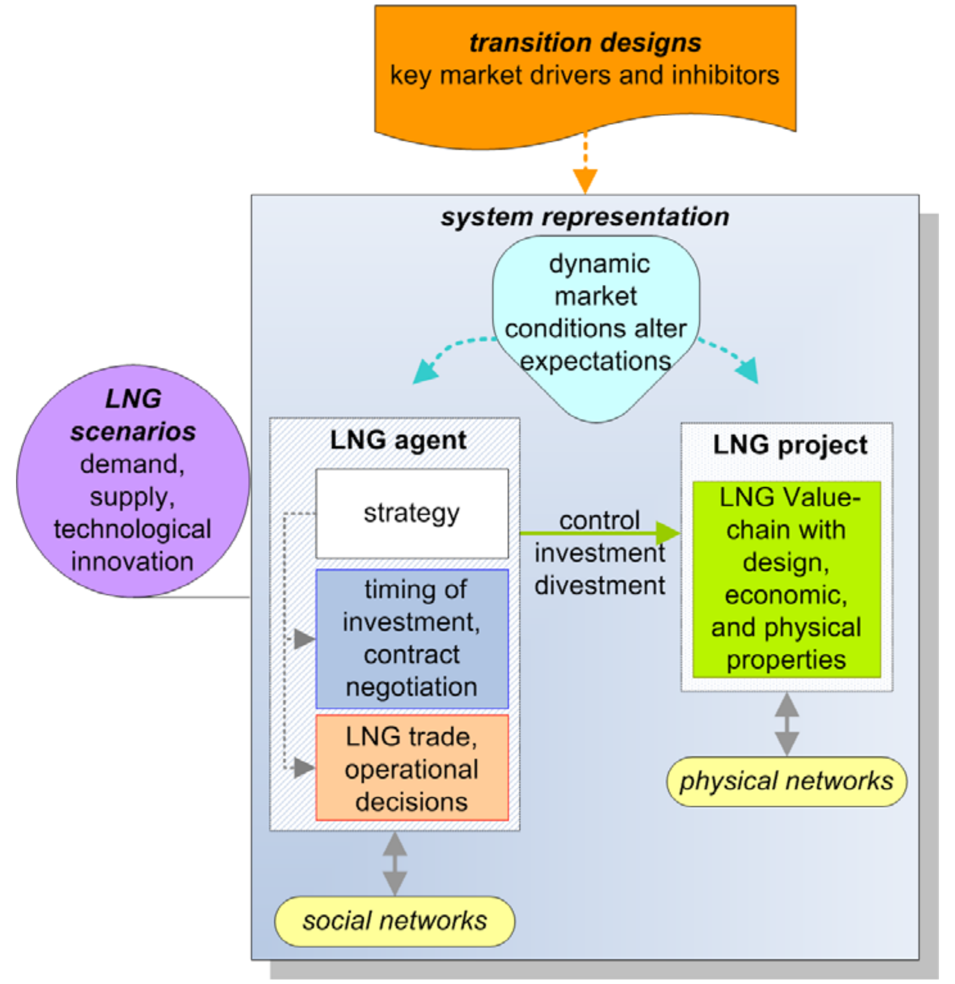


Figure 4 Case on trade: conceptual model for transition in LNG markets (see online version for colours)



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.

4.2 *Exogenous scenarios*

A range of scenario parameters is in Level 1. It is specific to the Dutch market. In addition, the electricity demand profile consists of ten steps per year that reflect a typical load duration curve and has a rising trend. The demand rises as a Level 2 trend. Fuel prices are modelled as a variety of Level 2 trends as well.

4.3 Design of transition assemblage

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 Emission Trading System (ETS) which is implemented in the EU and Carbon Taxation (CT) which has been implemented on a smaller scale in Norway. Next to those 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 the Phase 3 of the EU ETS in which the CO_2 cap is reduced every five years by 3 Mtonne for a market with the size of the Netherlands. With an initial cap of 50 Mtonne, a 50% reduction is achieved in a little more than 40 years. Another important policy variable is how many emission rights can be obtained through the Clean Development Mechanism (CDM).[1] This is set to 5 Mtonne per 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 per tonne which reflects the current CO_2 price under ETS. Over time, tax level increases to 80 per tonne. These values were estimated based on the runs under ETS.

The transition assemblage is, therefore, modelled at Level 3 using exogenous parameters, leading to strong requirements, *i.e.*, the agents need to be able to act under ETS and CT policies, for the other model components. We have plans to upgrade this model to Level 4 by advancing the role of the government agent. It could enhance the strength of the implemented policy based on past successes.

4.4 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 is implemented which will be repeated yearly:

- 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 a 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 noncompliance.[2]
- 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.

4.5 Impact assessment

Simulations have been done for the three transition designs: no-carbon policy, ETS and 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.

5 Case on trade: modelling transitions in the LNG market

The LNG market is subject to considerable changes, the most principal of which is the departure from long-term project specific sales and purchase agreements towards a truly global LNG market with flexible spot trading governed by master sales agreements. This is exemplified by the rise of the LNG spot market which was virtually nonexistent in the early 1990s (*e.g.*, 1.2% of the total trade in 1992) and represented 16% of the total LNG trade by 2005 (Morikawa, 2008). It is widely expected in the industry that this share will further increase to 30% within the next decade (Aissaoui, 2006; NGI, 2007) or less (IEA, 2004). To explore this imminent transition of this market, a sociotechnical system perspective (based on the ideas of Hughes, 1987) is combined with principles of transition management, institutional economics and the ABM paradigm. This model is being developed at the moment. We aim at a Level 3 model by implementing a variety of strategies for the core LNG agents in the model that may lead to a system transition.

5.1 System representation

In order to acquaint the reader with the complexity of the LNG trade and create a common understanding of the LNG market model at hand, a system representation is given in Figure 4. The central idea is that the LNG market contains LNG agents who invest in LNG projects and who operate them. In order to create value and to realise a return on investment, each LNG agent who owns an LNG project, for instance, a liquefaction plant, needs to negotiate a contract with another LNG agent who owns the complementing LNG project (a regasification terminal) to create a functional value chain. The result of this contract negotiation process determines the credit level of the LNG agent and its performance. This model seeks for quantification of the relation between the key market drivers and the inhibitors of the market on the one hand and the strategic behaviour of the LNG agents on the other. In this case, the focus is even stronger on the strategic behaviour than the first case discussed in this paper.

5.2 Exogenous scenarios

The demand profile for natural gas from LNG is derived from Global Insight (2007). Demand is set exogenously for the period 2005–2025. In addition, the availability of innovative technologies is exogenous and refers to potential innovations such as floating storage and regasification units and the construction of an LNG trading hub that enables LNG suppliers and buyers to store and trade LNG over an extended period of time.

5.3 Design of transition assemblage

Next to the rapid expansion of the LNG trade, there are other imminent market drivers that may facilitate a transition towards a spot market for LNG. These include, but are not limited to, decreasing capital costs, more flexible demand requirements, the rise of an uncommitted tanker fleet and the initiation of new liquefaction plants without the complete contractual coverage of the produced volumes. Examples of this trend are Malaysia LNG Tiga, Australia's Northwest Shelf (NWS) Train 5 (Tusiani and Shearer, 2007), and 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.

The momentum of the LNG spot market can act as a self-reinforcing loop wherein expectations about the future development influence the decisions on whether or not to become active on the LNG spot market. Brito and Hartley (2007) stated that "while exogenous changes in costs or demand are critical to promoting a change in market structure, there is also a substantial endogenous component. Expectations about the evolution of the market influence investments and trading decisions and can make the change in market structure much faster and more abrupt."

5.4 System evolution

The proposed LNG market simulation seeks to uncover the emergent behaviour of the LNG market as a whole by looking at the investment decisions and contract negotiation process of the individual and autonomous LNG agents. Accordingly, it interprets a change in the market structure as a departure from the traditional LNG market towards a global LNG market that actively pursues more flexible spot trading models. The model seeks to implement the following schedule of actions:

- investment decision
- timing of investment
- contract negotiation
- project realisation
- trade LNG.

5.5 Impact assessment

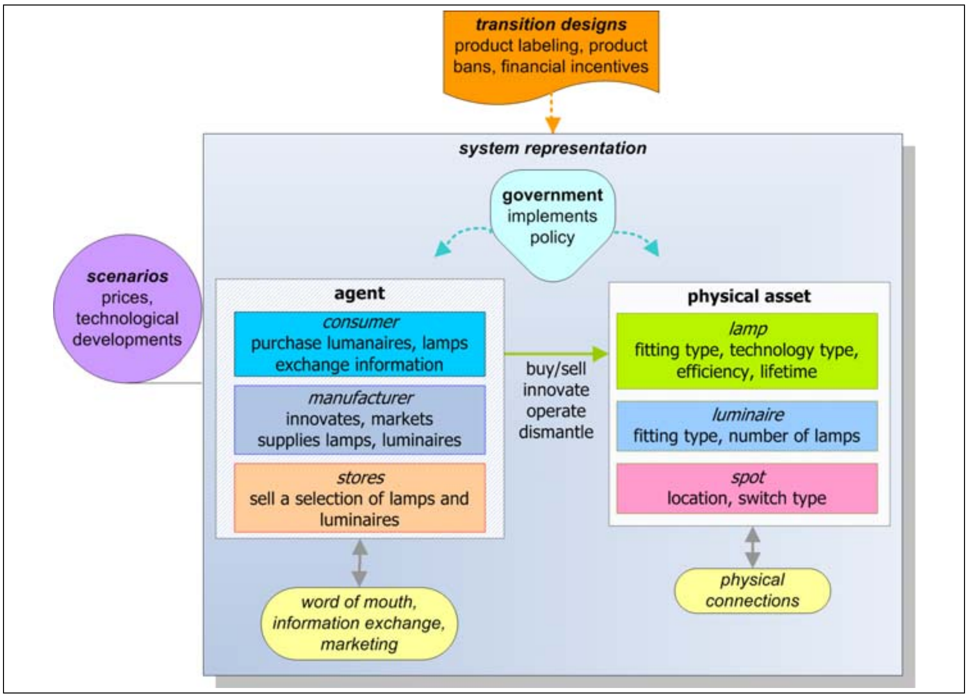
It is our belief that the interplay of exogenous forces and endogenous expectations can move the LNG market along the pathway of transition towards the breakthrough phase in which visible structural changes are the forerunners for a new market equilibrium. We expect to underpin this idea by implementing and operationalising this model and executing and analysing a vast parameter sweep.

6 Case on consumption: transitions in the consumer lighting sector

In consumer lighting, changes are forthcoming. The EU's phase out of incandescent lighting is a clear strategy that will change the sector by removing from stores the cheapest forms of inefficient household lighting (CEC, 2009). Although implied, it is uncertain whether or not the lighting sector will be efficient overnight; either consumers may switch to forms of inefficient lighting that are exempted from the phase out or consumers' behaviour will change. The precise dynamics within the sector are unknown.

A conceptual model is presented from which an ABM will be developed that is expected to lead to improved understanding of the dynamics of transitions that may occur in this sector (see Figure 5). 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 feasible transition assemblage designs. This model is still a conceptual design. We aim at a Level 4 model (including regulatory adaptability) where the government and lighting companies engage in adaptive strategy formulation.

Figure 5 Case on consumption: conceptual model for simulating transitions in the consumer lighting sector (see online version for colours)



6.1 System representation

The consumer lighting sector is a true sociotechnical system; the social part of the system contains a network of a variety of actors having strategic and operational behaviours. Consumers visit stores, buy luminaires and lamps, dismantle lamps when they break and communicate with other consumers through word of mouth. Stores sell new luminaires and replacement lamps; manufacturers innovate and supply the stores. The consumer's decision making regarding purchases of lamps and luminaires will be operationalised based on heterogeneous preferences for different characteristics and aspects of lamps like price, lifetime cost, colour and environmental aspects such as luminary efficiency.

The technical part of the system consists of the lamps people have in their homes. In the model, a consumer owns a number of luminaires. Attached to these are a number of light bulbs that match the socket type and wattage. The light output is controlled using either a switch or a dimmer.

6.2 Exogenous scenarios

Key parameters, such as prices of light bulb technologies, will be supplied by scenario trends. Technological improvements may be modelled endogenously, *i.e.*, relating innovation to adoption.

6.3 Design variables for system transitions

Government regulation is initially included as fixed parameters in the model. Later, it may be transformed to an endogenous system parameter so the model can be used to test several adaptive governmental strategies. Potential strategies to be tested are eco-labelling, forced phase out of all low efficiency alternatives, phase in of an eco-tax, *etc*. All transition assemblages can first be modelled as Level 3 exogenous scenario parameters, directly determining the strategies of the actors. One could also engage in interactive strategy formulation, modelling on Level 4 where the effect of the timing of intervention of parties can be studied and where the effect of the interaction of the transition strategies of different actors can be evaluated. This does require a more advanced model though.

6.4 System evolution

When a lamp fails, a consumer goes to buy a new one that fits the luminaire, but a consumer may also change his/her luminaire itself if he/she prefers to. The decision is based on the alternatives available and individual preferences. In a consumer's decisions, experiences with lamps of a certain kind are recorded in memory and influence the decision. Consumers also influence each other by communicating their experiences. Consumers are also influenced by marketing from stores or through other media.

Depending on the needs of consumers, manufacturers will respond by increasing the pace of innovation. If demand is higher for specific products, manufacturers will be tempted to supply these products. The interaction of the level of luminaries and bulbs on the one hand and innovation and purchase of consumers on the other hand is complex and is expected to lead to interesting dynamics.

6.5 Impact assessment

The model allows for testing governmental interventions. The model is set up in a modular way, allowing the introduction of new policies next to the ones formulated previously. On the other hand, marketing strategies of manufacturers can also 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.

7 Conclusion and outlook

Since transitions in energy infrastructure systems are to be 'managed', we developed a framework to use ABMs as transition simulation models for the assessment of transition assemblage design alternatives. To reflect the main components and interactions of energy infrastructure systems, this framework adopts a large-scale sociotechnical systems perspective and expands it to allow modelling transitions of and in such systems.

The proposed framework consists of a number of parts. First, the system representation is based on agent-based modelling and systems thinking. Second, exogenous scenarios use scenario analysis and/or system dynamics. Third, design variables for system transitions are based on policy making and transition literature. Fourth, system evolution reflects complex systems thinking. Fifth, the impact assessment can be a combination of experimental design, scenario analysis, statistics and data mining.

This framework functions as a typology for existing and new transition models by classifying the way in which the transition designs are modelled. Level 1 is modelling transition designs implicitly which is not useful for assessing the effect of the transition assemblage although it is often used. Level 2, using fixed system parameters, is better, but only in the sense that it easily facilitates upgrading to Level 3 which is using exogenous system parameters. Only Level 4 truly allows for assessing the merits of transition management by introducing regulatory adaptability and assessing its potential.

The framework brings together many research domains which fits the multidisciplinary approach needed to elucidate transitions and underpin transition management. Its intention is not to limit the researcher, but rather to structure and explicate his choices and build models that are not only useful but also reusable and modular.

To explore its applicability, the framework is currently being tested and elaborated upon in several case studies that will be the subject of future publications. In conceptual terms, three cases have been described in this paper. The framework allows for developing models of energy infrastructure transitions that focus on production, trade and consumption.

Acknowledgements

This work has been partially funded by the Next Generation Infrastructures Foundation.

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Notes

1 Under the pressure of the industry, the Dutch government acquires additional emission rights through the CDM. In the Dutch ETS allocation plan, it was announced that government reserved 600 million euros for this purpose, the equivalent of 20 Mtonne CO_2 rights (Ministry of VROM and SenterNovem, 2005).

2 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.