Towards The Assessment of Policy Impacts on System Transitions in Energy

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Abstract—The primary objective of Transition Management appears to be 'to manage transitions towards sustainability.' Since the emerging body-of-knowledge on system transitions to date remains largely descriptive, we propose a research agenda to develop a prescriptive system transition body-of-knowledge. This agenda is developed by focusing on energy systems. We conjecture it is always socio-technical systems that are the subject of transition and will provide policy makers with handles to push and pull transitions. Using a socio-technical systems perspective, we define *a system transition as a structural change in both technical and social subsystems.* Three items are identified on the (system transition) research agenda. Indicators for the successfulness of system transitions in the energy domain should be unambiguously defined and interpretable. Secondly, an understanding and recognition of the socio-technical design space is required. The design space for energy systems includes technological structure and content, policy, regulation and market design and social innovation. The combination and interrelation of these must be recognized and its use suitably underpinned, for example by exploratory simulation models and games that would allow ex-ante testing of transition policies and management. The case on carbon taxation as a transition instrument for emission reduction shows that it is possible to successfully identify a set of indicators, assess and compare transition instruments by simulations as a test method and come up with new insights in how transitions can be managed.

Keywords—System transition, Transition Management, Policy, Assessment, Energy

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I. Introduction

Transition Management appears to have as primary objective 'to manage transitions towards sustainability (see for instance Rotmans *et al.* 2000; Rotmans 2004)'. Geels states: "In recent years, there is increasing interest in transitions and system innovation, because of their promise to achieve jumps in environmental efficiency" (Geels 2005). Technical performance of energy infrastructures and its components exhibit only gradual, now approaching thermodynamic limits. Throughout the OECD, the environmental efficiency of energy systems with respect to SO_2, NO_x, soot and other harmful emissions has dramatically improved in the past decades. CO_2 emission, however, continues to increase globally and only a few countries have managed to stabilize their CO_2 emission (IEA 2005). The need for CO_2 reductions has been recognized by governments throughout the world by means of the Kyoto protocol (UNFCCC 1998) and other agreed targets (e.g. Intergovernmental Panel on Climate Change. Working Group III. 2001; 2007).

Generally speaking, the impact *I* of energy use (e.g. measured in total CO_2 emissions) is determined by population *P*, the per capita demand expressed as the affluence *A* and the system's technological characteristics *T*, as according to the well-known equation $I = P \times A \times T$ (Ehrlich *et al.* 1971; Ehrlich *et al.* 1972). To reduce the CO_2 impact of the energy system thus implies a change of population, of technology and/or in demand per capita. To date, in many a country government primarily focus on energy technology option - extraction, conversion. The EU has developed directives targeted at reducing energy-use by labeling energy-intensive products, which may be seen to affect life-style and affluence. For any given energy

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conversion technology, the fuel type and fuel consumption determine its CO_2 emissions, where fuel consumption is capped by the system's energy efficiency. Today, the need for a reduced CO_2 impact is clearly stated and acknowledged by many governments, i.e. by setting targets for GHG emission reductions by means of the Kyoto protocol (UNFCCC 1998) and through post-Kyoto measures. In the Netherlands, for instance, transitions are explicitly addressed in energy policy (Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer 2001; Ministerie van Economische Zaken 2005; Task Force Energietransitie 2006).

The energy infrastructure is characterized by huge sunk costs, which creates technological lock-in despite the re-regulation, liberalization and privatization of various energy sectors in the past decade. Transforming and improving this complex system therefore presents a huge challenge (Herder *et al.* to be published in 2008), let alone to develop a program suitable for managing its transition. The energy infrastructure is a large-scale system wherein the physical energy system is intertwined with an institutional, economic context and policy; change in the technical system is interdependent with change in that context. Moreover, since energy markets have been liberalized, change occurs as a result of series of decisions of independent actors – energy companies, regulators, governments etc.

This paper addresses *the design of system transitions for energy infrastructures*. It is argued for, that a design process, as generally used for artifacts, should also be applied on the design of transitions. Such a design should result in a transition that would let an improved infrastructure emerge with time.

First, an overview is given of key transition management literature (II). Secondly, the socio-technical systems perspective is introduced, adopted and related to complex adaptive system theory (III). Combining these, we conjecture the body-of-knowledge of design may provide suitable handles to develop a suitable recipe for transition management, notably the meta-model for design and support of a design process. Thirdly, the meta-model is explained and its applicability for transition management explored (IV). From this analysis, three items are identified for the transition management research agenda (V): the need for transition instruments, transition indicators and tests. Subsequently, these are elaborated by addressing the case of carbon policies to reduce CO_2 emissions in the power sector. (VI). In conclusion an outlook for research is given.

II. Overview of Transition (Management) Literature

Transitions can be 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). Societal transitions are defined as "structural innovations of societal systems in reaction to wicked problems threatening development" (Rotmans 2004; Timmermans accepted for publication).

Transition management approaches transition to be manageable by acknowledging the following five points (Rotmans *et al.* 2001):

- long-term thinking for framing short-term policy;
- multi-domain, multi-actor, multi-level;
- focusing on learning;
- aligning system innovation and system improvement
- keeping a large number of options open.

These are very abstract notions, which are operationalized descriptively in specific cases.

Presently, how transitions come about is conceptualized in two ways. First, literature on transitions uses three analytical and heuristic levels for system innovations (Geels 2002). The micro-level contains technological niches, in which new technologies can come into existence and be developed. The meso-level holds a patchwork of regimes in a dynamic equilibrium. The macro-level contains socio-technical landscapes, with global and normally slow developments. In this formalization, transitions occur when novelties on the micro-level evolves and is taken up to modify the patchwork of regimes and eventually transforms the landscape on the macro level (Geels 2005). Several papers and books have been using this conceptualization to describe and analyze past transitions (e.g. Rotmans *et al.* 2000; Elzen *et al.* 2004; Rotmans 2004; Verbong *et al.* 2007).

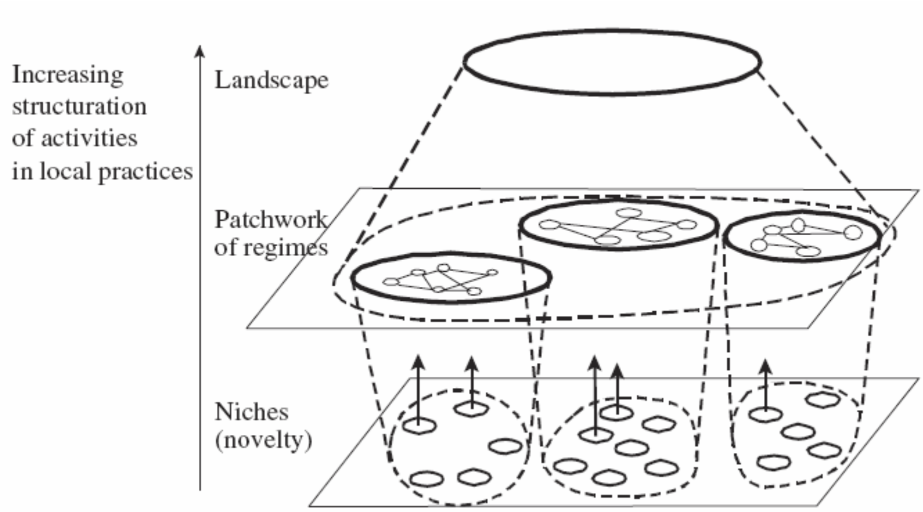

Fig. 1. Three analytical and heuristic levels for system innovations (Geels 2002)

Second, similar to the classic life-cycle of an innovation, four transition phases are identified in the pathway of transitions (Rotmans *et al.* 2001) (see Fig. 2). A phase of predevelopment (1) is one of dynamic equilibrium. In the take-off phase (2) change starts to occur. During the breakthrough phase (3) visible structural changes take place. A transition ends with a stabilization phase (4), where speed of change decreases and a new dynamic equilibrium is reached. Compared to the life-cycle of innovation, a fifth phase, decline, is lacking. Three system dimensions are identified, given a(n) (set of) indicator(s): the time period of a transition, the speed and the size of the change.

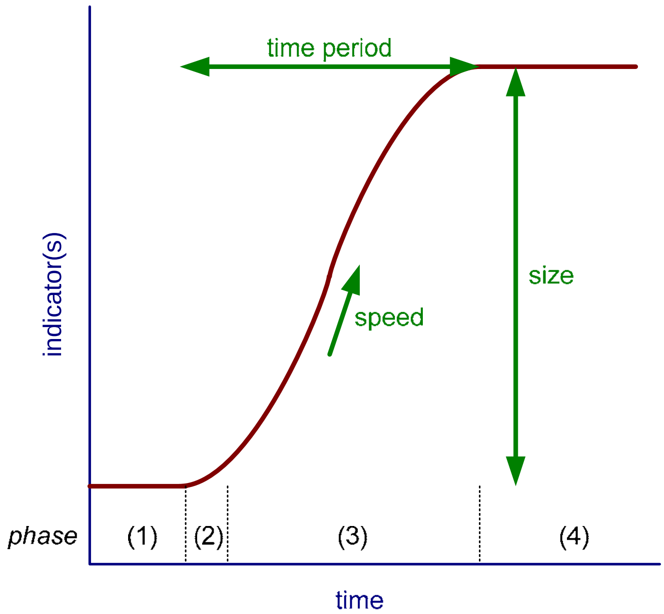

Fig. 2. Phases and indicators in transitions, adapted from figures in (Rotmans *et al.* 2001)

III. Large-scale Socio-technical Systems

Policy makers face the challenge to design policy in large-scale socio-technical systems (λ-systems) (Bijker *et al.* 1987; Hughes 1987; Ottens *et al.* 2006; Nikolic *et al.* in print) (See Fig. 3). These infrastructures contain many interdependent components: many different actors having specific goals and means to reach them, and technological subsystems with limited capabilities. λ-systems are evolutionary, they exhibit path-dependency; options in the future are shaped by current choices as well as current options have been shaped by the past. As a consequence, λ-systems were not designed as they are now but evolved to their present state (Nikolic *et al.* in print; Herder *et al.* to be published in 2008).

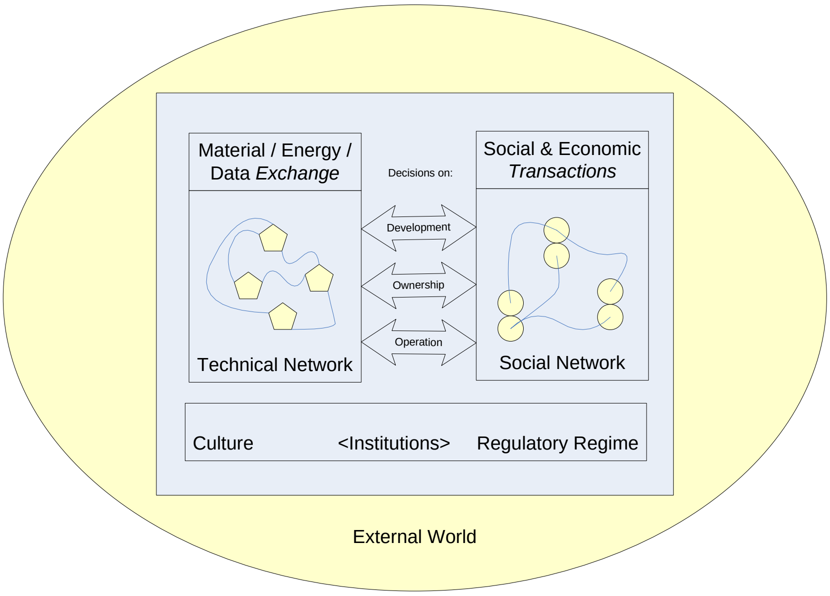

Fig. 3. Decision in λ-systems on development, ownership and operation are based on institutions. The social network comprises transactions, the physical network exchange.

Path dependency has many origins. Technological components realized years or decades ago are not necessarily equipped to meet present needs, in terms of sustainability, reliability or flexibility. They do present 'proven technology', however, which can and will impact the policy design process, not in the least because past investments represent current interests. Novel technical components of λ-systems must represent some advantage to "incumbents" or sufficient leverage to new-entrants. To create such favorable conditions often requires regulations and policy to change, which requires sufficient knowledge and recognition of policy-makers.

Infrastructure is another source of lock-in: many an infrastructure is a natural monopoly, its characteristics determining which novel components will fit, and which will not. Actions of policy-makers may well have to be targeted on breaking natural monopolies by introducing the nuclei for growth of alternative, competing infrastructure. It may thus be seen that breaking the cycle of path-dependency, in time will result in an improved system or even a system transition if the total system exhibits structural change (see Fig. 4). New policy thus eventually results in new actors and actor behavior, new system components and system structure, and eventually in transition. As indicated, however, rather than a single "grand policy" that creates the transition, policy also changes in discrete steps, with governments and parliaments stipulation few large and many small policy steps.

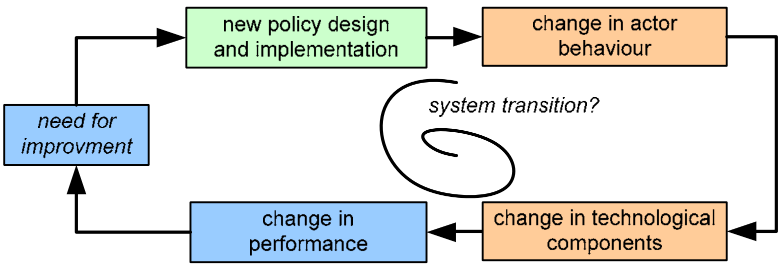

Fig. 4. From policy design to a change in performance in λ-systems

The eventual societal goal of transition management (TM) research is to support policy makers to manage a transition in sectors for which it is identified that structural change is needed. A key conjecture is that systems collapse and resulting chaos can be prevented, that a transition path can be engineered to avoid this unwanted system state. Recognizing all the factors that impede system change, it follows any transition must involve gradual and/or continuous change and that transitions are not only to be used as reaction the wicked problems that threatening development. Therefore, we prefer a definition of transitions and societal transitions to one that aligns with systems thinking: *a system transition is structural change in both technical* *and social subsystems* (see also Fig. 4).

The energy infrastructure is clearly a λ-system: actors live in a re-regulated and largely liberalized market; power generation, natural gas production, trade and supply and retail services are competitive markets that were unbundled from tasks such as grid and pipeline operation exhibiting natural monopoly characteristics; the sector is embedded in and strongly connected to several markets, i.e. fuel markets, emission-trading and spot markets. The players active in each of these markets have their own objectives and unique, competitive means to realize them by offering their products and services. The government sets the rules of the game, using policy and regulation as its main instruments. To meet public interests and meet policy goals, regulations must be designed in such a way that players exhibit behavior that contributes to public policy goals. Thus it may be seen that in the energy domain, *managing* a system transition implies the design of energy policy and regulation that invokes change by influencing the actions of stakeholders who are controlling energy technology – by ownership of intellectual property rights, tacit knowledge, by endeavoring and financing research and development, by investing in and deploying installations etc.

IV. System Design and Transition Management

Design of a complex system is a *contradictio in terminis*; these systems are complex because they cannot be designed, they evolve as a never ending series of discrete events and interactions, between each other and their surroundings. Let's assume we can position ourselves as an independent high-level observer that is detached from this process. We may then realize the design of system elements such as individual power plants, gas pipelines is lead 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 a system wherein a complex system may involve can at least partly be designed. It may be seen such meta-design and the design process thereof differs from the designing simpler systems (Maier *et al.* 2002; Dym *et al.* 2004). In the meta-design, in addition to the technological system content, the process of bringing the system into being is designed (Herder *et al.* to be published in 2008).

In order to develop such a meta-design whereby a complex system undergoes transition, we will use the conceptual model of a design process (See Fig. 5). As indicated, main steps in any design process are (1) the development of goals, objectives and constraints, (2) specify 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 can be selected for implementation.

Let us now assume we are a meta-designer who is again detached from the transition itself and who is in need of a meta-design for system transition. We may then proceed to apply the general design process to arrive at a suitable meta-design.

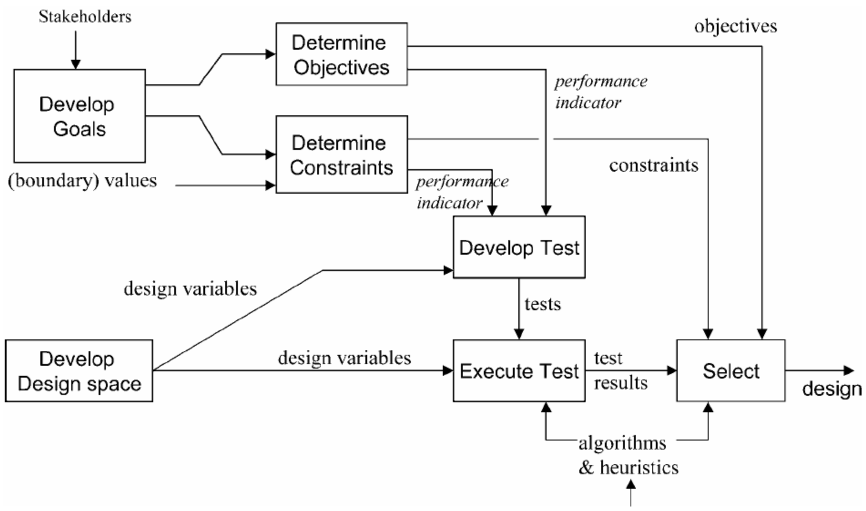

Fig. 5. Conceptual model of a design process (Herder *et al.* 2004)

A. Develop goals

The first step in the design process is the development of goals for the meta-design. Since eventually we want to select the best design, i.e. the meta-design that best fulfils these goals. Therefore, goals should be unambiguous and complete, which clashes with transition management guidelines stated in the literature. TM claims it is preferred to state ambitions above objectives, to have qualitative rather than quantitative objectives and recognize that all objectives maybe subject to re-adjustment (see for instance Rotmans *et al.* 2001). In many a design approach, however, goals are formulated as functional requirements, must-haves and should-haves, which appears to match with TM guidelines. For system transitions in energy, transition managers claim as main functional requirement that the energy infrastructure should must be sustainable (Rotmans *et al.* 2000). A proper design of a system transition for energy should contain functional requirements for the meta-design wherein the system transition itself develops. Sustainability is both a goal for the (meta-)design of a transition, as for the system itself: it reflects what the outcome of transition should be as well as its pathway. Sustainability is well-defined (Brundtland Commission 1987). 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 all involved actors agree that sustainability is the only goal. Other actors have different goals in this design process and since they are involved, they will impact the goals resulting from this step. 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.

B. Determine objectives and constraints

In determining objectives and constraints, one makes explicit the previously defined goals. 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 on different designs of system transitions. Actors will put in effort to make sure that for them relevant objectives and constraints are put in or left out according to their own preferences and means.

Two notes should be made here. First, designing λ-systems result in a huge set of constraints and objectives, possibly including conflicting ones. That would trouble 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 systems 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 analyzing 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: constraints for a transition could be that it transition should lead to continuous welfare growth or to limited welfare decrease. Additionally, an objective for the economy domain is 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 that irreversible emissions with a global or local environmental impact should be avoided, which can be measured by emission levels of substances of which it is known that they harm the environment or by uptake of limited resources. Another is that biodiversity should not go down, which is measurable as number of affected species. For the same goal, objectives could be that irreversible emissions that harm the environment should be minimal or that negative biodiversity effects during the transition should be minimized.

C. Develop the design space

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

The multi-level perspective (Geels 2005) 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 Fig. 2): for the identification and use of transition pathways, unambiguous and measurable performance indicators are a necessity. Both perspectives do not focus on how impact system transitions and are rather equipped for analyzing and describing past transitions.

Design variables rather come from transition management (TM) literature: methods for invoking transitions might be useful as design variables for system transitions. The transition instruments discussed here (Rotmans *et al.* 2001) are:

- transition objectives;
- interim objectives;
- transition visions;
- evaluating and learning
- creating public support.

Transition objectives and interim objectives rather belong to developing goals (and after that determining objectives and constraints) then being design variables. (Note that they were discussed earlier at those sections). Transition visions are also not part of the design space, because they are a means to explicate and visualize the result of a system transition. However, these far-future visions can be used to derive transition steps that can lead to that result. Next, by creating public support (through the involvement of actors in decision-making and through education) in the process one can create a momentum for change. That also relates more to earlier parts of the design process, i.e. determining objectives and constraints. Final is that by supporting technological niches innovative concepts can mature and, if successful, diffuse into society.

Rotmans (Rotmans *et al.* 2001) states that TM uses a systems approach: "The system approach implies thinking in terms of stocks and flows". And therefore "a transition is the result of long-term developments in stocks and short-term developments in flows." … "During the quick period of growth, acceleration is mainly the result of positive feedback mechanisms". This top-down view is of course useful but just one side of the story. Complex systems and complex adaptive systems theories tell us that change in λ-systems is the aggregate result of decisions and actions by individual entities. We therefore argue that it is disaggregate actions of actors that should be the focus of transition analysis, rather than the regime in order to come to a design of system transitions. For instance, CO_2 emissions occur on a disaggregate level: an increase in the CO_2-concentration in the atmosphere is the result of many smaller and larger sources in which (for the part that mankind is responsible of it) control of these sources is by many different actors. This conceptualization has consequences for the design space for system transitions and can enlarge it dramatically by including design variables that impact these disaggregate decisions. However, one must note that the successfulness of deriving design variables is interdependent with the identified set of performance indicators.

D. 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 can not be tested in reality: only one test could be executed, afterwards the system was changed by the test itself. As a consequence, the TM literature is thick on historic cases. Best practices are identified analogous to those cases, rather than identifying design alternatives and test beds for them. For real testing of design alternatives one can use the power of modern computers to imitate real systems in simulations. As we adopted a socio-technical systems 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*" refer to the more classic top-down systems view, which is too narrow to lead to meaningful simulation results of λ-systems when the object of study is transitions. Simulation exercises rather need to be well focused and have tailored designs to come to results that are meaningful. This especially true for models on system transitions, since the λ-system 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 behavior, and policy. Simulations can be used to better understand the functioning of λ-systems, to explore and identify determinant components and their interplay and, what for this section would be its main aim, to test the impact of design alternatives without implementing them. This can all be done without having the ambition to predicting the future, rather predicting the variety of trajectories and future states for a λ-system, given a set of well-chosen assumptions. To enrich the codification process of actor behavior, one can use serious gaming. By observing the outcomes and motivations of real players in a serious game, one can extract actors' behavior 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.

E. Select

The selection is made based on the outcome of the executed tests. If the performance indicators are well defined and the tests well developed, than one find out what design alternatives meet all constraints. Those are still feasible. If there is more than one design alternative left, one can select based on the objectives. Comparing objectives is subjective and it is probable that actors weigh the objectives differently. Selection for a design of a system transition therefore might prove very difficult. However, in that selection process indicating the performance of alternatives is crucial, 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 more transparently choose between alternatives.

V. Research Agenda for Assessing System Transitions

By addressing transition management using a system design perspective, three items have been identified for the transition management research agenda: the need for transition instruments, transition indicators and tests.

A. The need for Transition Instruments

Design variables for system transitions in the energy domain should be discovered by using insights in technology, policy and economy from literature on system transitions, design, complex systems thinking, energy technology and energy policy. Transition instruments should be identified to come to feasible designs.

CO_2 emissions as a byproduct of energy use (through e.g. power generation, combustion of natural gas and oil products), are an externality. Reducing CO_2 emissions through a transition of the energy infrastructure is internalizing external costs. Since energy infrastructure is extremely capital intensive, significant change is through investments in different technologies and system innovation (e.g. clever combination of the generation of heat and electric power (Dijkema 2004)). For internalizing the externalities of CO_2 emitting activities Pigou prescribes a unit tax equal to the marginal social damage (Pigou 1947). However, for most pollutants, as for CO_2, we do not have any reliable measure for this damage (Bimonte 1999). The systems structure implies extremely high transaction costs, since the impact of high CO_2 levels is global, rather then local. Internalizing the costs for CO_2 emissions is not efficient according 'The Problem of Social Cost' (Coase 1960) since it might be affected to the definition of rights (Coase 1988) under high transaction costs. These transaction costs exist because competitors for the same resource choose to operate as different firms (Demsetz 2003; McChesney 2006).

B. The need for Transition Indicators

Since design teams need to assess the characteristics of their designs, the goals must be made explicit as objectives and constraints for which measurable performance indicators can be defined. As argued in the previous section, in transition management literature such performance indicators are lacking or ill-defined, which leads to and obvious research agenda item: research on developing shared definitions of and 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, effectively share this information and over time create a body-of-knowledge on what works and what does not work for transition management.

C. The need for Transition Tests

Third, tests should be developed whereby different system transition designs can be compared. We argued that simulation models and gaming are needed as tools to compare the performance of different designs. These tests should contain relevant elements in the λ-system under study by incorporate the interdependency of technology, policy and economy.

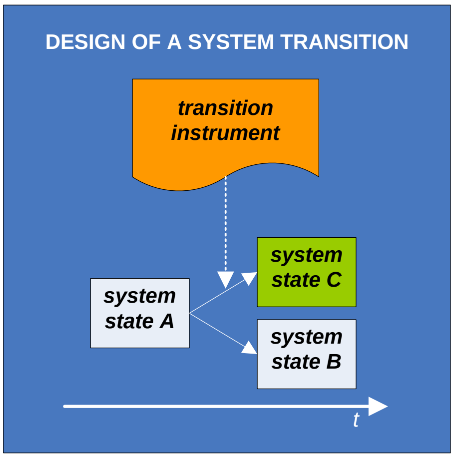

Fig. 6. Design of a system transition

VI. Case: Carbon Taxation (CT) as Transition Instrument

In this section, we will describe an exploratory case in which these agenda items – the need for transition indicators, transition instruments and transition tests – are addressed. The domain under study is the power production sector. This sector must undergo some transition in order to reduce its CO_2 emission by 20% in 2020. Immediate cause is that in Europe currently one of the main policy instruments to meet these reduction targets is CO_2 emission-trading (CET). The European Emission Trading System (ETS) was implemented as of January 2005 by Directive 2003/87/EG (CEC 2003; Europese Unie 2004). In the ETS companies active in specific sectors as listed in 2003/87/EG Annex I (CEC 2003) must be in the possession of CO_2 emission rights equals to the amount of CO_2 they emit (EnergieNed 2006). Any surplus can be sold; any deficit must be compensated for by acquiring rights.

The ETS is proof of the shift in the European Union from "command-and-control" instruments in environmental policy to incentive-based instruments (Egenhofer 2003). By introducing emission-trading a market is created wherein the price for the property right to emit a ton of CO_2 will be set by 'the invisible hand' (Smith 1776). The alternative is to impose a direct limit to any emitter, e.g. through an environmental permitting system or by carbon taxation. In both cases the solution and cost distribution of CO_2 reduction is not optimal – a flat tax does not cater for cost difference for CO_2 reduction, while permitting imposes a need for detailed information with the permitting authorities. Within the ETS all emitters are subject to a collective cap set by the competent authority (the EU in this case). More important, transactions of emissions rights between emitters have been made possible. Following Coase this will lead to the most cost-effective emission reduction (Smith 1776; Coase 1960; Svendsen 1999; Ehrhart *et al.* 2003; Svendsen *et al.* 2003).

We have previously assessed the combined effect of economic agents in the Dutch power sector subject to ETS. To this end we developed and used an agent-based model that allowed us to outplay the operation and evolution of the E-production sector socio-technical system with time (Chappin 2006; Chappin *et al.* 2007a; b; Chappin *et al.* 2007c). In order to allow simulation of transitions that amongst others allows a quantitative comparison between the long-term effects of emission trading versus taxation we have embarked on the development of an expanded model. Using the meta-design perspective we can specify not only ETS and taxation as transition instrument, but also developed specific energy system transition goals and objectives, alternatives and tests.

A. Carbon Taxation as Transition Instrument

As stated, a classic command and control instrument is the introduction of carbon taxation (CT), a regular Pigouvian tax (Pigou 1947). By taxation of CO_2 emission its negative external effects are (partly) internalized to the economy. A producer of electricity who employs carbon-intense feedstock/technology combination will experience additional costs. Thus, in a world with CO_2 tax, electricity producers will endeavor to reduce CO2 related cost by selecting less CO_2 intense feedstock/technology combinations. Over time, the technology portfolio employed changes. It may thus be seen that carbon taxation qualifies as a transition instrument. Its effectiveness to create a transition towards sustainability should be tested. The tax level is an important parameter to be set for this transition instrument. To explore and test, two policy settings are compared: a carbon tax of 20 €/ton versus 100 €/ton.

B. Potential evolution of portfolio and related CO_2 emissions as Transition Indicators

The second issue to be addressed is the definition of suitable indicators for transition. Since the main objective of carbon taxation is to reduce CO_2 emissions, a logical performance indicator is the level of CO_2 emission. An alternative would be to use CO_2 reduction as indicator, which would be in line with the Kyoto Protocol agreement (8% reduction in the EU compared to 1990 level).

Another type of indicator is to monitor power sector structure or technology portfolio. In any CO_2 reduction scheme, operational flexibility and efficiency will be used first. Measures by operators could include buying other quality coal or gas, have a different utilization of their facilities or to put in small modifications to increase energy efficiency. Such changes are easily reversed, however, in view of changing economic circumstances such as increasing demand or price. In case the pressure of tax is sufficient, operators will invest serious money in new, less CO_2 intense installations. Such changes are not easily to bring about or to reverse. It may be seen therefore technology portfolio is an indicator of transition.

C. An Agent-Based Model to perform ex-ante Transition Test

The proof of the pudding is in the eating. It is, however, hard to outplay transitions in reality. The built model contains a set of acting and interacting agents. Power producing agents decide on operations of and investment in power plants. In addition, a government agent decides on policy changes, a consumer agent decides on power demand. These agents interact and engage into contracts. Subsequently, a physical system is modeled containing relevant physical apparatus (power plants, consumer technology) and physical flows of goods (fuels, power, CO_2). The system evolves based on the actions and interactions of the agents but also on exogenous scenarios to outplay a potential transition. Simulations under different scenarios and policy are executed and outcomes are assessed with mathematical and statistical methods.

The assessment is done by simulations with an agent-based model, reusing the largest part of the emission-trading model. A broader discussion on the model and its outcomes can be found elsewhere (Chappin *et al.* Forthcoming in 2008). 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 *et al.* 1996; Axelrod 1997). An ABM contains a set of interacting ‘agents’ with certain properties, acting based on a set of rules, reacting upon factors coming from outside. A schematic overview of the role of the agent-based model is presented in Fig. 7. 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), of which the core components are:

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

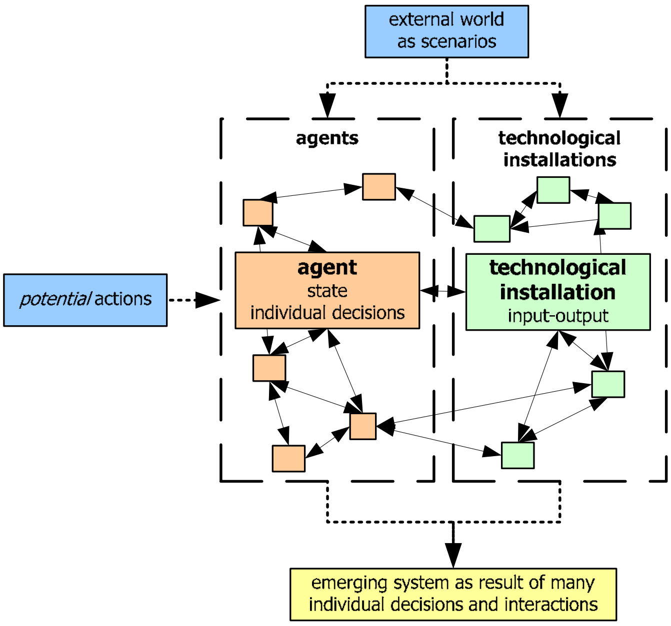

Fig. 7. A schematic overview of agents in the agent-based model (Chappin *et al.* 2007b)

By means of an ontology (formalization of concepts and an agent language) the agents and physical installations are formalized as nodes in a multi-dimensional network. Agents in this model own physical apparatus that are on the level of physical assets. Physical assets do not act themselves as they are passive and controlled by agents owning them. This ontology is combined with a model of the socio-technical system itself to a multi-dimensional network of agents and their physical assets: a level of contracts, physical material flows and control (see Fig. 8). Actors in the real world are modeled as agents that manage on a strategic level and on an operational level. Social nodes are called agents; agents act by strategic management to change its identity and its ownership of physical nodes, also called technologies. Agents act by operational management to engage in contracts and physical installations constitute a physical network in which materials are exchanged. Actions are based on economic, physical and design properties of the agents and physical installations.

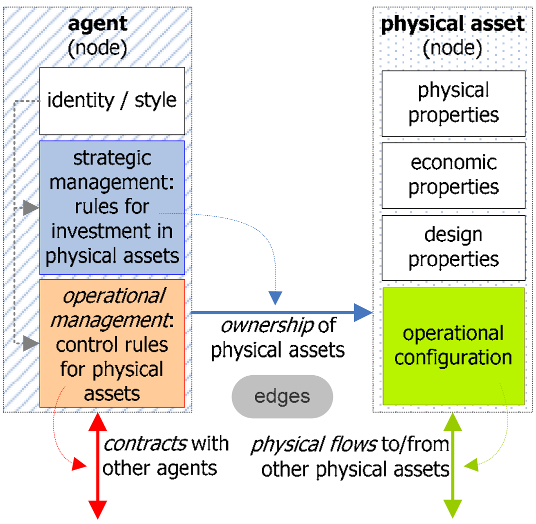

Fig. 8. Ontology as formalization of agents, physical installation and their multi-dimensional networks (Chappin *et al.* 2007c)

The main agents in the model produce power. Power producing agents' strategic management is the decisions to invest or disinvest in power plants and the criteria to do so. In reality this is a process in which preferred type and timing of investments and disinvestments are made together. For practical reasons, it is chosen to split this process in three consecutive parts. The following decision scheme is constructed:

1. deciding what power plants should be dismantled
    a. because the technical lifetime is passed
    b. or because it is a cause for continuous losses;
2. deciding if investing in a new power generation facility is needed
    a. because old power plants should be replaced
    b. or because there is need for portfolio expansion (e.g., to accommodate growing demands);
3. deciding which type of electricity generation plant is preferred, only after the decision was made to invest.

Besides strategic behavior, electricity producing agents also must exhibit operational behavior. As said in conceptual terms, by operational actions agents engage in negotiation and contracts. In general, a choice is made for demand-driven trade: negotiation always starts by the party that has demand for a good or service. Negotiation can lead to contracts and use the concepts defined in the ontology as language. For instance, if an agent needs coal, it will ask around for contracts for the delivery of the good called coal (all these concepts are defined in the ontology, recall the previous section). Electricity producing agents perform the following consecutive steps:
1. bid on power exchange
2. acquire resources
3. pay carbon tax

Power plants can be characterized by their fuel-type, costs, lifetime and fuel usage. Power plant data is used from several sources. Data for wind, biomass, nuclear comes was earlier collected (Chappin 2006). Data for coal and natural gas plants, with and without carbon capture and storage were collected and adapted from (Davidson 2007). Operational flexibility in power plants is limited. Since reductions by changes in existing power plants are assumed to be of limited impact, in the model emission reduction can only be realized by a shift in the power generation portfolio used.

The agents' decisions are based on factors, not influenced by the model. System developments are analyzed by using a set of well-chosen indicators (see the next section). Those factors are modeled as 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 influences 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). The three scenario axis together build a scenario space – a cube – in which each point is represents set of values of trends, in other words, a scenario. A full factorial design of this scenario space leads to 8 scenarios.

D. Potential evolution of portfolio and related CO_2 emissions as Transition Indicators

The third issue was the definition of indicators for transitions. The indicator is the basis for decision-support. Since the main objective of carbon taxation is to reduce CO_2 emissions, it was logical to take the CO_2 emission-level as an indicator. Note that another option could be to take the CO_2 reduction as indicator. Since governments' main policy setting is the carbon tax level, the indicator for emissions is for the three chosen options, 20, 100 and 200 €/ton CO_2. Since there are many circumstances and there is much uncertainty modeled as stochasticity, the outcomes vary as well. Measures to represent evolutionary pathways are not defined in the literature. It is not enough to plot the expected CO_2 emissions levels, also the variety should be taken into account. In order to accommodate this need, we use and adapt several statistical methods. For plotting variance a box plot was adapted in the below presented visualization of the outcomes (see Fig. 9).

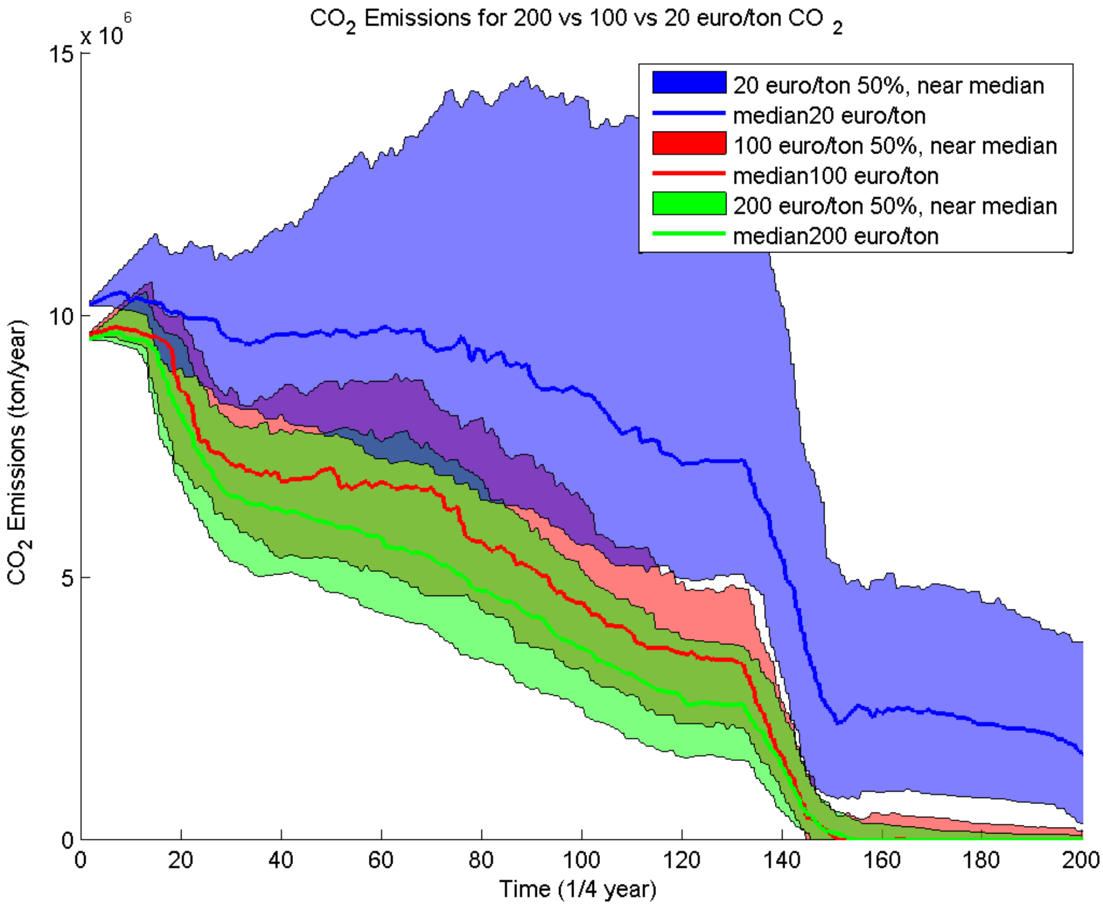

Fig. 9. CO_2 emissions as transition indicator applied to compare three policy settings: carbon tax of 20 and 100 and 200 €/ton. This is based on a box plot, adapted to make it evolutionary (see the legend). The dark areas contain 50% of the models outcomes for each tax level. The dark lines inside these areas are the medians (the value that occurs the most) for the corresponding tax level.

The main point is that the medians are reasonably far apart in the largest part of the graph which could be a strong argument in favor of a high tax level, since it clearly makes a difference. But there is a relatively large amount of uncertainty in the outcomes, resulting in overlap in outcomes between the various tax levels. Especially the overlap in 100 and 200 €/ton is notable. However, whether this difference is statistically significant, is difficult to determine visually. Therefore, another statistical method is applied (see Fig. 10). Here, we applied series of Student-T tests over time for differences between the tax levels 20 and 100 €/ton, and between the tax levels 100 and 200 €/ton. The parts inside the gray area are indifferent, so are two time periods in which 100 and 200 €/ton are indifferent. The difference in impact of 200 €/ton over 100 €/ton is therefore only between 5 and 30 years. In contrast, 100 €/ton is expected to lead to statistically more emissions reduction than 20 over the complete simulated time. The effectiveness of a higher tax level is thus for a big part a consequence of external factors and uncertainties inside the model. Using such a graph, one can – once the indicator is well defined – grasp the variance in the outcomes over time.

E. Conclusion of the modeling exercise

Based on agent-based simulations, it was found that the impact of a higher tax rate, will lead to a larger improvement over time. Emission reduction is given the assumptions in the model (of which an important one is the feasibility of large-scale use of bio-based power) achievable, but only on long term and with relatively high carbon taxes (around 100 €/ton). However, it is likely that governments, if they decide on implementing carbon taxes, phase-in the tax level, which means starting out with a lower tax level. That would imply a significant delay in reduction, but might increase acceptability. It is crucial to note that emission reduction on short term is not guaranteed by this policy instrument, because of the inflexibility of operational equipment.

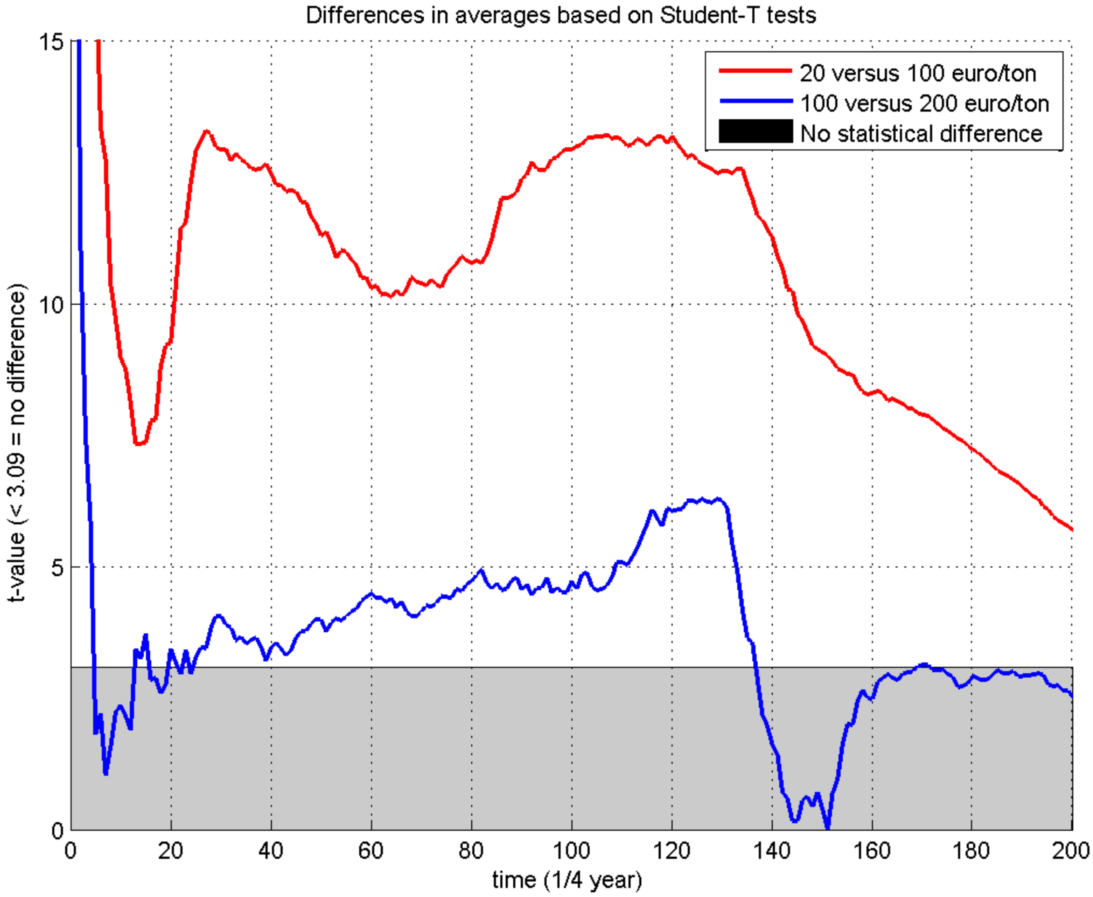

Fig. 10. Student-T tests for differences in outcomes for different tax levels. The two series of tests refer to a comparison of 20 and 100 €/ton (the red line) and 100 and 200 €/ton (the blue line). The significance level is 0.001, which means that there is a chance of 0.1% that the conclusion that there is indeed a difference is wrong. The test value t is presented, based on the formula $T = \frac{\overline{X} - \mu}{\sigma / \sqrt{n}}$

VII. Conclusions and Outlook

A design of a system transition should lead to the optimal structural change by taking the preferred transition pathway in a large scale socio-technical system (λ-system, recall Fig. 6). The complexity in the energy infrastructure shows in difficulties in designing system transitions in the energy domain. We believe that proper design of system transitions is a necessity to achieve a less carbon intense energy infrastructure. In order to come to an optimal design of system transitions, a process design approach should be used. This requires new policy, law, and corporate strategies. To provide decision support for better policies and strategies, we developed a research agenda for a body-of-knowledge on system transitions that is prescriptive, which will underpin transition management for sustainability. Three issues were identified in applying such an approach: the need for the development of transition indicators, transition instruments and transition tests. Those issues are on the research agenda. A case was presented to illustrate these findings and provide a first example of the new insights one can obtain by addressing those issues. That case was on carbon taxation as transition instrument. Statistical methods were adapted in order to provide unambiguous and appropriate indicators. The impact of this transition instrument on the system was assessed by means of agent-based simulations.

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