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Hassan Qudrat-Ullah
Editor

Energy Policy Modeling in the 21st Century

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The Diffusion of Eco-Technologies: A Model-Based Theory

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Introduction

On the road toward ecological sustainability, technological change in general and innovations in particular play a crucial role. In fact, in many domains progress toward sustainability has been brought about by the replacement of a relatively inefficient, pollution-intensive technology with a more efficient, less polluting technology. In line with other contributions in the literature (Giannetti et al. 2004; Kemp and Pearson 2007; Kemp 2009; Kemp 2011), we refer to such technologies as "eco-technologies," or as "eco-innovations." Specifically, an eco-innovation may be defined as "the introduction of any new or significantly improved product (good or service), process, organizational change, or marketing solution that reduces the use of natural resources (including materials, energy, water, and land) and decreases the release of harmful substances across the whole life-cycle" (Eco-Innovation Observatory 2012, p. 8). In line with this definition, we identify a technology as an "eco-technology" if it is cleaner or more efficient compared to most commonly used

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technology.[1] Examples of eco-technologies are highly energy-efficient buildings (compared to buildings without insulation) and solar-warmed water (compared to electric boilers powered by coal-generated electricity). In this chapter, we have in mind mainly low-emission and energy-efficient technologies. Yet, the arguments we present are likely to apply to many other types of eco-innovations, such as water-saving innovations or exhaust filters.

This leads to the questions "How do eco-technologies diffuse?" and "What can be done to accelerate their diffusion?" Starting with the seminal work by Rogers (2003) on the diffusion of innovations, several streams of research have provided insights into these issues. Rogers defines the diffusion of innovations as a process "in which an innovation is communicated through certain channels over time among the members of a social system" (Rogers 2003, p. 5). Rogers's work has inspired a large body of research and influenced other disciplines such as marketing, sociology, communication sciences, and computer sciences. However, classical innovation diffusion studies have an implicit focus on individual adopters (such as persons or organizational units). Recent contributions on sustainability transitions, such as studies based on the multilevel perspective (Geels 2004; Geels and Schot 2007), provide stronger integration of microlevel with macrolevel developments.

The recent literature on sustainability transitions is interesting and inspiring, and we acknowledge its crucial contributions to the understanding of transitions toward sustainability. There are, however, two domains in which we depart from current thinking. First, we think the role of public policy in the successful diffusion of eco-technologies is crucial, and that it has been underestimated in the literature. Second, we propose that the application of modeling and simulation methodologies enhances current theorizing based on "natural language" (Hanneman 1988). In what follows, we further elaborate on both domains.

a) The central role of public policy

Promoting eco-technologies is a key aspect of public policy,[2] both as a solution to specific environmental problems as well as an approach to increasing the sustainability of a country as a whole. Technology is a preferred policy lever, as the other two main policy levers for sustainable development (reducing the size of the population and its affluence) are of questionable value: The forced reduction of the size of the population is outside consideration from a moral and ethical point of view. Voluntary birth control policies are slow to take effect, and they also raise difficult moral and ethical questions. Promoting reductions in a population's affluence for environmental reasons would not be a winning platform for any politician. Hence, promoting sustainable development by way of fostering eco-technologies is arguably the most favored approach to decreasing the environmental impact of economic activities.

This means that while most technological innovations need to stand the test of a free market environment in order to diffuse successfully, eco-innovations are likely to get public policy support that accelerates their diffusion. In this chapter, we present an analysis of the relationships between the market, technology, policy change, and public policy interventions. The theory described in this chapter results from generalizing findings of an in-depth study of the diffusion of energy-efficient renovations (Müller 2012, 2013). A preliminary version of this framework was described in Müller (2012, p. 350–353). In this chapter, we follow up and provide a more elaborated framework. The chapter's second contribution is to reflect on the strengths and limitations of building theories with the assistance of modeling and simulation methodologies.

b) Methodology

Research on sustainability transitions typically uses descriptive theorizing and relies mostly on natural language rather than simulation methods (Ulli-Beer, in press). Therefore, such research is generally not well equipped to link structures of causalities and behaviors in the presence of interacting feedback loops that cause dynamic complexity (e.g., nonlinear behaviors). In consequence, Ulli-Beer (in press, Chap. 2) concludes that this literature does not determine "which and how causal structures influence system behavior."

An alternative conceptual-theoretical viewpoint proposes that the link between structure and behavior can be better understood by employing semimathematical languages (Hanneman 1988), such as those offered by modeling and simulation methodologies (e.g., discrete-event simulation, agent-based modeling, and System Dynamics). In several recent studies, we have applied System Dynamics modeling and simulation to the analysis of specific eco-technologies (e.g., Müller 2013; Ulli-Beer et al. 2006; and the research documented in Ulli-Beer in press). System Dynamics[3] is more appropriate to our research endeavor than alternative methodologies for the following reasons:

- System Dynamics has a special strength in the analysis and synthesis of causal relationships and in the handling of delays. In these respects, System Dynamics is superior to the other two methodologies mentioned.
- Compared to discrete-event simulation methods, System Dynamics conceives of the systems modeled as continuous processes. This is in line with our

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[1] In this conceptualization it does not matter whether the eco-technology is a completely new technology or improvement of an existing technology. What is important is that there is a "better" configuration that has to overcome a "worse" configuration (also see "Model Sectors and General Setup"; in particular Table 1).

[2] In line with Knoepfel et al. (2007, p. 24), we define public policy as "a series of intentionally coherent decisions or activities taken or carried out by different public and sometimes private actors whose resources, institutional links and interest vary, with a view to resolving in a targeted manner a problem defined politically as collective in nature." Relying on this abstract term allows us to ignore the question which specific institutions are involved.

[3] System Dynamics is an interdisciplinary, scientific methodology that is used to describe the structure of causality driving change processes and to elicit the resulting behavior produced by that structure. Specifically, change processes are represented mathematically by differential equations. In order to obtain behavior, these equations are solved, by way of computer simulation. Any kind of change process can be represented as a simulation model, regardless whether it stems from the physical, ecological, or social domain. The methodology was developed by Jay W. Forrester in the late 1950s and early 1960s by applying principles of control (from electric engineering) to the management of real-world problems (Lane and Oliva, 1998, p. 219; Sterman 2000).

project, which addresses the patterns of behavior exhibited by the system under investigation.

- Compared to agent-based modeling, System Dynamics adopts a top-down view rather than a bottom-up view. For analyzing high-level aggregates, System Dynamics is more appropriate than a methodology that focuses on the behavior of single agents.
- Finally, System Dynamics strongly encourages an "endogenous point of view" (Richardson 2011, p. 219). Based on such a systemic perspective, more effective policies can be developed.

Summarizing this discussion, the following research questions can be formulated:

- How should the diffusion of eco-technologies be described in a generic way that goes beyond the particulars of specific technologies? In particular, in what generic way do the market, technological change, and public policy trigger the diffusion of eco-technologies?
- How should System Dynamics modeling and simulation support research and public policy activities in the diffusion of a specific eco-technology?

The remainder of this chapter is structured as follows. In "A Generic Theory of the Diffusion of Eco-Technologies", we present the main elements of our generic theory, in the form of a System Dynamics simulation model. With this model, we provide the cornerstones of a *middle-range theory*[4] *of the diffusion of eco-technologies* (Merton 1957; Schwaninger and Groesser 2008). In "Discussion: How Can System Dynamics Modeling Support Research and Policy Making in Support of the Diffusion of Eco-technologies?", we discuss how our results and the System Dynamics methodology can be used to conduct research and support policy making, and we outline how such a process could actually be implemented. In "Conclusions", we summarize our findings and offer a brief reflection on the benefit of using formal models in research and policy making.

A Generic Theory of the Diffusion of Eco-Technologies

In the social sciences, the result of theory building is often stated in natural language. In contrast, we present our theory in the form of a System Dynamics simulation model. In line with Schwaninger and Groesser (2008), we see the model itself as the theory. In general, it is good practice to discuss simulation models on the level of the equations as well as on the level of the feedback loops implemented by the equations. However, limited space as well as the nontechnical focus of this chapter motivated us to provide a more graphically oriented, high-level description.[5]

Table 1 Initial key characteristics of the two technologies

	Role	Market share	Technological maturity	Production costs	Environmental impact
Conventional	Incumbent	High	High	Low	High
Eco-technology	Innovation	Low	Low	High	Low

Model Sectors and General Setup

We assume that there are two generic types of technology (see Table 1). *Conventional technology* is the incumbent technology with a large market share. Due to learning effects and economics of scale and scope, it has achieved a high degree of technological maturity and low production costs. What makes such technology problematic from a sustainability perspective is its high environmental impact. In contrast, *eco-technology* represents innovations with low environmental impact. However, due to the recent advent of such technology, it has not had any chance of moving down the learning curve or benefiting from economies of scale and scope. Therefore, it initially has a low degree of technological maturity, rather high production costs, and hence a small market share.

Should a substitution of an eco-technology for a conventional technology take place, the environmental impact of the installed base could be reduced. However, at the beginning of the substitution process, the eco-technology faces high-diffusion barriers. As it has a low market share, there is only limited potential for industrial learning, and hence it remains at a low market share. In order to promote the diffusion of the eco-technology, public policy needs to support the diffusion process until it can compete with the conventional technology based on market incentives alone.

In order to organize our generic model of the diffusion of eco-technologies, we use six distinct model sectors (see Fig. 1). Sectors 1, 2, and 3 represent the extended economic subsystem. Through the dynamics of the market (sector 1), technological quality (sector 2), and production costs (sector 3), the economic system controls the installed base of the technology, and eventually determines the environmental impact (sector 6). However, in the diffusion of eco-technologies, public policy plays a crucial role. Hence, we model how public policy changes (sector 4) and how public policy intervenes in the economic system (sector 5). Note that while major drivers of policy change may be exogenous, there is still some feedback between the economic subsystem and public policy. For example, the impact of the current technological quality of the eco-technology influences public policy interventions.

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[4] The concept of middle-range theory was introduced by Merton (1957). It refers to theories that are located between universal theories ("grand theories") and micro theories. They integrate theoretical and empirical research. They consolidate different hypotheses or findings. Instead of all-inclusive efforts to develop a unified theory, they are limited to specific types of contexts, which allow for the formulation and testing of specific hypotheses. A middle-range theory is generic in that it holds for a whole class of systems. In contrast, a micro theory is less abstract, deals with relatively small slices of time, and covers small numbers of objects, e.g., individuals, interactions, or families.

[5] The model is electronically available in the Vensim model format from Matthias Müller.

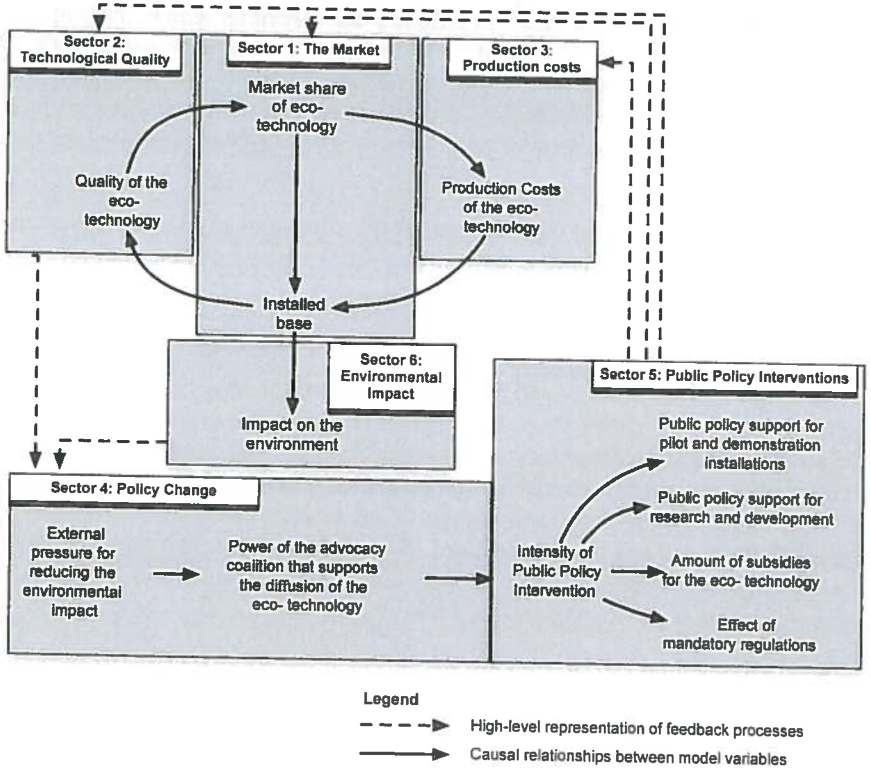

Fig. 1 Model sector diagram

In the remainder of this section, we provide a high-level description of these model sectors. Note that the actual model is subscripted. This means that in Fig. 2, for example, the equations are calculated once for the eco-technology and once for the conventional technology. In order to facilitate the communication of key model structures, the visualization contains only the most important structures. Structurally uninteresting calibration parameters and switches are omitted from this high-level description and need to be inspected in the actual model source code. We follow the convention of using <*brackets*> in the text to refer to variable names. <*Brackets*> in figures indicate that a variable was calculated in another model sector.

The Market and Its Effect on Installed Base

In our model, the market consists of two major feedback loops, demand and supply, that interact with one another. Through their interaction, these feedback loops control the installed base of the two technologies. Figure 2 shows a stock-and-flow diagram

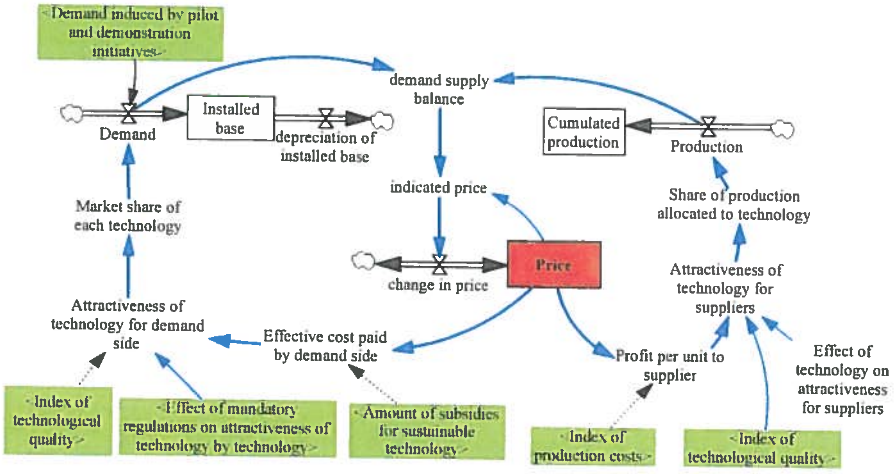

Fig. 2 Main feedback loops in the market sector. *Valves* represent flows and *boxes* represent stocks (integrations of flows). <*Variables set in single brackets*> in figures indicate that the variable is calculated in another model sector

of the two loops. In the middle, the price-setting mechanism is shown.[6] Whenever demand exceeds supply, that structure increases price. Whenever supply exceeds demand, that structure decreases price.

The basic logic of the two loops is as follows: When the <*price*> of a technology is reduced, then the <*effective cost paid by demand side*> is decreased as well, which in turn increases the <*attractiveness of technology for demand side*>. As the <*attractiveness of technology for demand side*> rises relative to the other technology, the <*market share*> of the corresponding technology rises too, eventually leading to increased <*demand*>. The<*installed base*> of each technology is modeled as a stock. This means that it is increased by the rate of <*demand*> and depleted by <*depreciation of installed base*>. As <*demand*> is increased, pressure mounts for prices to rise, thereby eventually dampening the whole demand loop.

On the supply loop, a similar basic pattern is shown. When the <*price*> of a technology is increased, the <*profit per unit to supplier*> is increased as well, thereby increasing the <*attractiveness of technology for suppliers*>. This in turn leads to an increased <*share of production* . . . > allocated to that specific technology and then to an increased <*production*> of that technology. Should<*production*> exceed <*demand*>, then the price mechanism will decrease <*price*> and thereby dampen the supply loop.

Figure 2 shows several other variables influencing the two market loops. For example, a measure of technological maturity (<*index of technological quality*>) influences both the <*attractiveness of technology for demand side*> as well as the <*attractiveness of technology for suppliers*>. Both the demand and the supply loop

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[6] See Ventana Systems (2012) for a discussion of strengths and limitations of various formulations of allocation.

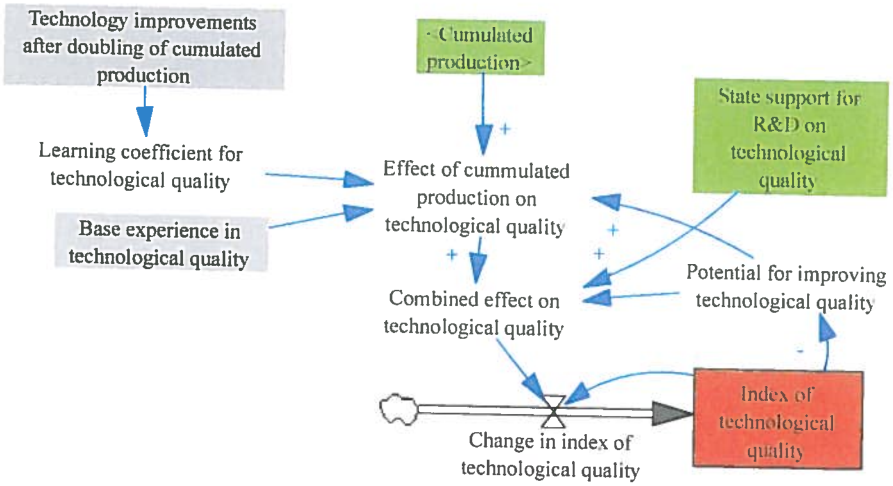

Fig. 3 Main elements of the model structure used to model improvements in technological quality

are also affected by the *<effect of mandatory regulations on attractiveness of technology>*. In order to model the effect of changes in production costs, the *<index of production costs>* is used to influence the *<profits per unit to supplier>*. Further, the *<effective cost paid by demand side>* (for the eco-technology) is influenced by the *<amount of subsidies for eco-technology>*. *<Demand>* (for the eco-technology) is increased by *<demand induced by pilot and demonstration initiatives>*. Note that these influences are not exogenous ones. Instead, they result from additional feedback loops. This means they are an integral part of the feedback structure that drives the diffusion of eco-technologies.

Changes in Technological Quality and Production Costs

Above, in "The Market and Its Effect on Installed Base", we argued that improvements in the technological quality of the eco-technology and decreases in its production costs increase the attractiveness of the eco-technology on both the demand and the supply side. In what follows, we argue that it is industrial learning and research and development (R&D) that bring about these changes. Figure 3 shows the main model structure used to model improvements in the *<index of technological quality>* as a function of the *<cumulated production>* and the *<state support for R&D on technological quality>*. As *<cumulated production>* is increased, experience with the technology is increased. This in turn increases the attractiveness of the technology on the market (see Fig. 2), thereby increasing demand and supply, which in turn contributes to technological improvements.

Initially, however, the technological quality of the eco-technology is so low that it has no chance to successfully diffuse based on market mechanisms alone. Therefore, we argue that a crucial initial step, *<State support for R&D on the technological quality>*, is an important contributor to technological progress. It helps to start up the industrial learning feedback loop that eventually makes eco-technology marketable (Fig. 4).

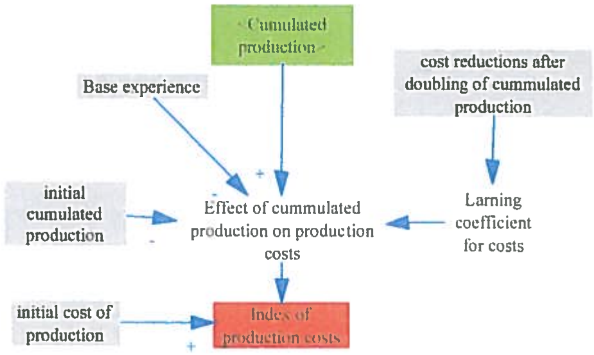

Fig. 4 Main elements of the model structure used to model reductions in production costs

Dynamics of Policy Change

In the Introduction, we argued that the diffusion of eco-technology is frequently the outcome of public policy. In particular, we argued that public policy promotes the diffusion of eco-technology as a way of achieving environmental policy goals. What has not been discussed is why public policy goes from ignoring a particular technology domain to actively promoting the diffusion of more sustainable alternatives. This can be addressed based on theories from political science. In fact, a range of explanations of policy change have been proposed (Easton 1957; Sabatier 2007). We rely on the advocacy coalition framework (Sabatier and Jenkins-Smith 1988; Sabatier and Jenkins-Smith 1993; Sabatier 1998) in order to explain and model long-term policy change, typically lasting a decade or longer.[7] In the advocacy coalition framework, actors in a policy subsystem are aggregated into different coalitions. Members of a coalition "(a) share a set of normative and causal beliefs and (b) engage in a non-trivial degree of coordinated activity over time" (Sabatier 1998, p. 103).

Typically, there are about one to five coalitions in a given policy subsystem (Sabatier and Weible 2007, p. 196). Further, such coalitions are typically highly stable, both internally and in terms of the power they hold relative to one another. Policy change is typically brought about by external events (Weible et al. 2009, p. 124), which may cause a decline in a formerly dominant coalition's power.

Figure 5 shows how we operationalize the advocacy coalition framework into a dynamic simulation model. We start by assuming the existence of two coalitions,

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[7] This description of the advocacy coalition framework substantially draws on previously published work reported in Müller (2012, Chap. 5.4.4.1; 2013).

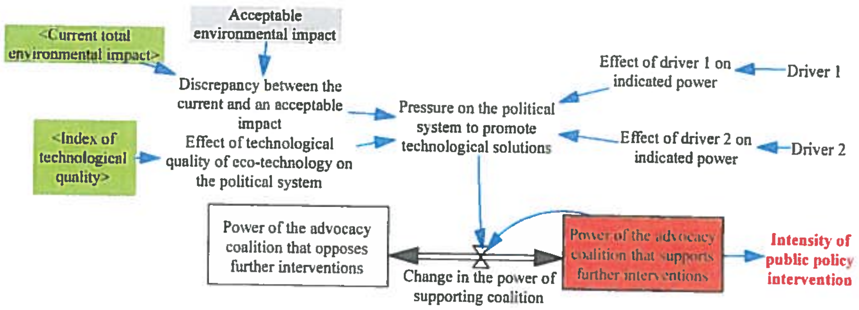

Fig. 5 Main elements of the model structure used to model policy change

one in support of and one opposed to further interventions. Empirically, we drew on studies of policy change in Switzerland's climate and energy politics (Ingold 2007, 2010; Jegen 2003; Kriesi and Jegen 2000, 2001; Lehmann and Rieder 2002). More specifically, we model the power of each of the two coalitions as a stock (e.g., *<power of the advocacy coalition that supports further interventions>*), and we model *<changes in the power of the supporting coalition>* as a flow connecting the two stocks. In line with the advocacy coalition framework, we assume that the drivers of policy change are mostly exogenous. Typical examples of exogenous drivers are the emergence of climate change concerns or energy security issues (see Müller 2012, p. 56 ff., p. 216 ff.). Such trends emerge from outside the policy subsystem, but they lead to the creation of a societal problem situation and create pressure on the political system. Technically, we implemented the effect of exogenous drivers by including two exogenous variables to operationalize such effects (*<driver 1>*, *<driver 2>*). These two variables are the main drivers of policy change, and cause the *<pressure on the political system to promote technological solutions>* to rise in the beginning.

In addition, we include two endogenous drivers of policy change. First, we assume that with a large discrepancy between the *<current total environmental impact>* and an *<acceptable environmental impact>* the *<pressure on the political system to promote technological solutions>* is large, thereby driving policy change. Second, we assume that a rising *<index of technological quality>* will reinforce the pressure on the political system. The rationale behind this is that in the context of a societal problem situation, the availability of better technology will weaken opposition to further regulations.

In the next section, we argue that in conjunction with a rising *<power of the advocacy coalition that supports further interventions>*, the *<intensity of public policy intervention >* rises.

Public Policy Interventions

Due to limitations of space, we refrain from describing the structures used to model public policy interventions in the same detail as the structures described above. Nevertheless, the logic implemented in this model sector can be derived by examining Fig. 1 (sector 5). As the *<intensity of public policy interventions>* rises, four distinct types of public policy interventions are implemented:

- Public policy supports pilot and demonstration installations of the eco-technology, with the goal of increasing demand, eventually speeding up the industrial learning loop (as shown in Fig. 2).
- Public policy supports research and development, with the goal of directly improving the technological maturity of the technology (as shown in Fig. 3).
- Public policy subsidizes market actors that implement the eco-technology, with the goal of increasing demand, eventually speeding up the industrial learning loop (as shown in Fig. 2).
- Public policy implements mandatory regulations, with the goal of regulating environmental impacts (as shown in Fig. 2).

The effects of these interventions can be seen in Figs. 2 and 3. The underlying logic of the simulation model now becomes more evident: Technologies that are of no particular interest to public policy would be subjected to the interplay of the demand, supply, technological progress, and production cost loops. This means that what is often called "free market economics" would determine whether a technology diffuses successfully—or not. In the case of eco-technologies, however, public policy actors are interested in ensuring that the process of replacing a conventional technology (with high environmental impacts) with an eco-technology (with low environmental impacts) actually takes place, and without avoidable delays.

Behavior of the Simulation Model in a Base Calibration

Generic theories cannot be calibrated against specific data. Nevertheless, we calibrated the model such that it yields a plausible behavior and generally reproduces model behaviors documented in Müller (2012). Figure 6 shows the behavior of key variables in a base calibration. Several issues should be highlighted:

- Demand and production are closely related in this model. Further advanced models might contain model structures that allow for stock keeping by the producing company. In its current version, however, the price mechanism assures that demand and production are in balance (Figs. 6a and 6b).
- For the base calibration, we assumed that the technological quality of the eco-technology rather quickly approaches the quality of the conventional technology (Fig. 6c). The production cost of the eco-technology, however, takes much longer to catch up. This is because it takes a long time to accumulate experience and the eco-technology's low-emission characteristics cause higher production costs (Fig. 6d).
- The intensity of public policy intervention rises more slowly than technological quality (Fig. 6e). This is because political processes take a great deal of time. Eventually, however, public policy rises to levels that allow the implementation

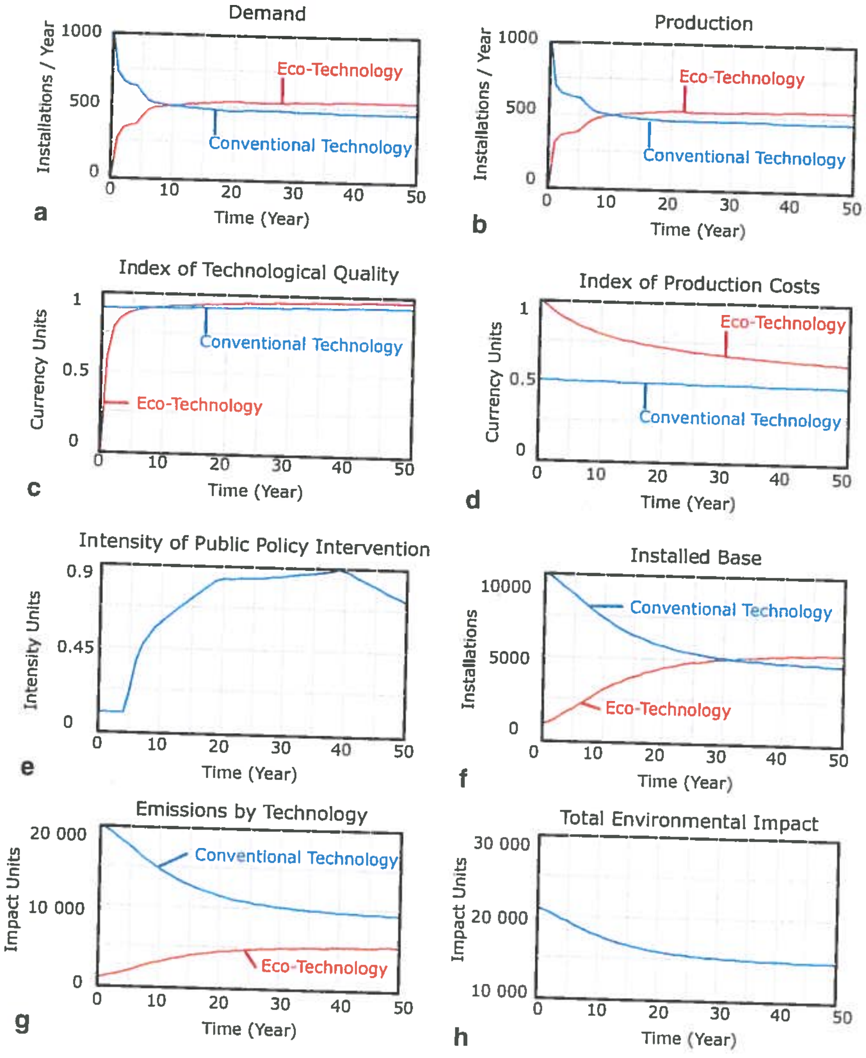

Fig. 6 Behavior of the simulation model in base calibration

of ambitious policies and instruments. Later in time, once the eco-innovation has reached a substantial market share and no longer needs public policy support to compete with the conventional technology, the intensity of public policy interventions starts to fall.

- The dynamics of the installed base (Fig. 6f) show that even when the eco-technology has the larger market share, it may take many years for the eco-technology to become the most frequently installed technology. The longer the service life of the conventional technology, the longer it will take to eventually replace it in the installed base.

- As the conventional technology gets replaced by the eco-technology in the installed base, total emissions are lowered (Fig. 6g) and the negative environmental impact is mitigated (Fig. 6h).

Model Validation

Model validation may be summarized as a systematic way of testing whether the structure and behavior of a simulation model provide a sufficiently accurate representation of the real system under investigation. Whenever a model fails a test, it needs to be changed to enhance its "fit" with the available information about the real system. A canon of tests and procedures has been proposed in the literature (Barlas 1996; Sterman 2000; Schwaninger and Groesser 2009). Hence, it is likely that the model presented here needs to be adapted and further developed when applied to the study of a specific eco-technology.

However, only a limited set of tests (e.g., unit tests, integration time step tests, etc.) could be carried out on the model in its current form. This is because we propose a generic theory rather than a substantive theory that addresses a specific eco-technology. Nevertheless, both model structure and model behavior were substantially derived from a study of the diffusion of energy-efficient renovations in Switzerland. The validation of that model is documented in Müller (2012). The tests described in detail there were applied equally to the model presented here.

Applying our generic model to a specific eco-technology will also reduce some of the challenges posed by using "qualitative" or "soft" variables (Luna-Reyes and Andersen 2003, p. 274). For example, while our generic model uses a qualitative variable called "index of quality", an applied model could rely on a more specific measure of quality and use empirical data to operationalize it. Modeling and validating more hard-to-observe variables (such as "power of the advocacy coalition that supports further interventions") still remains a challenge. Yet, "omitting structures or variables known to be important because numerical data are unavailable is actually less scientific and less accurate than using your best judgment to estimate their values" (Sterman 2010, p. 854). Also, the social sciences have a whole set of methods (e.g., expert interviews, literature analysis, discourse analysis) that can be applied to increase the empirically grounding of qualitative variables (McLucas 2003).[8]

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[8] Also see Müller (2012, Sect. 2.2.3 and 9.5.1) for further reflections on designing System Dynamics research that includes variables that are hard to measure.

Discussion: How Can System Dynamics Modeling Support Research and Policy Making in Support of the Diffusion of Eco-Technologies?

In "Using System Dynamics Modeling to Support Research and Public Policy Initiatives Aimed at Accelerating the Diffusion of Eco-Technologies", we discuss how System Dynamics modeling in general and our model in particular could guide research and policy making in support of the diffusion of eco-technologies. We do so by elaborating on a series of propositions. In "Implementing Diffusion-Support Processes Based on the System Dynamics Methodology", we then discuss how diffusion-support processes based on the System Dynamics methodology should be implemented.

Using System Dynamics Modeling to Support Research and Public Policy Initiatives Aimed at Accelerating the Diffusion of Eco-Technologies

Proposition 1: Our Model Is Valuable As a Starting Point for Studying the Diffusion of Specific Eco-Technologies Research into the diffusion of specific eco-technologies faces somewhat of a starting problem. Without theoretical knowledge about the diffusion process under investigation, it is not clear what empirical data should be collected. Yet, without empirical grounding, it may not be clear what theories are adequate. By using our generic theory as a starting point, this starting problem can be overcome by conceptualizing the causalities embodied in the model as hypotheses that need to be empirically tested. Insights from falsification testing may then be used to enhance the model's structure as well as its calibration. Further benefits of relying on our theory in the initial phases of research derive from its focus on a system rather than on isolated elements. Hence, using our theory as a starting point helps to overcome an overly narrow focus and supports the integration of different perspectives. When sufficient insights into the system governing the diffusion of a specific eco-technology have been assembled, the model can be expanded to include further effects, such as word-of-mouth effects or network effects.

Proposition 2: System Dynamics Modeling Is Well Suited to Integrate Findings from Research Projects Using Different Methods, and It Promises to Be a Valuable Tool in Managing Entire Research Programs Research aimed at providing action knowledge for accelerating the diffusion of an eco-technology may often be organized as a research program, consisting of several dedicated research projects. Particularly in an academic context, it may be very challenging to organize the research projects such that results from different projects can be synthesized with one another. In such a situation, there is great potential in using the System Dynamics methodology to synthesize the results from different research projects into a simulation model and in using insights from the simulations to guide individual research projects.

To illustrate this point, let us imagine a research program in which individual projects provide insights into the following issues: What is the installed base of the conventional technology and the eco-technology, and how does the ratio change over time? What is the environmental impact of the conventional technology and the eco-technology? What actors influence the diffusion process, and how should they be categorized? How do producers, consumers, or investors make decisions? What preferences do they have, and what attributes do they value? How does the current institutional framework (laws, regulations, government policies, etc.) influence the diffusion process? What are the causes of policy change? In order to integrate insights from different research projects, the development of a formal simulation model like the one presented above may prove valuable. For example, developing the simulation model is likely to indicate areas in which current knowledge is insufficient and areas in which further research needs to be undertaken to enhance the understanding of the diffusion process. Close coordination and communication between a System Dynamics modeling team and the more content-related research teams could yield both meaningful research into specific aspects of the diffusion of an eco-technology as well as an empirically and theoretically well-grounded simulation model that embodies a systems perspective.

Proposition 3: A Fully Developed, Empirically Well-Grounded Simulation Model Can Be Used to Identify Policy Levers and Investigate the Dynamic Implications of Policies Directed at Such Policy Levers Once a simulation model has been developed and tested to establish its consistency with the available knowledge, it can be used to support policy makers. In a first step, policy levers—variables that have a strong effect on the diffusion process—can be identified by systematically reviewing the simulation model. In a second step, policies and instruments can be identified by which such policy levers can be influenced in the real world. Third, the simulation model can be used to analyze the effect of policies and instruments over time. What is more, the simulation model can be used to estimate the intensity of the policies and instruments to be implemented. For example, a simulation model may be used to analyze the magnitude of a tax on fossil fuels or the optimal size of a subsidy. We have not yet tested the application of our model in a concrete decision situation with policy makers. However, we have shown how that model could, in principle, be used to support decision making (Müller 2012).

Proposition 4: Simulation Models May Become Part of a Joint Learning Process and Facilitate the Emergence of Consensus Across Different Advocacy Coalitions In essence, System Dynamics simulation models are "white box" models that can be inspected and understood by anybody. The ability to visualize complex systems can help policy makers' perspectives evolve toward a shared systemic perspective and away from a narrow, nonintegrated view of the diffusion process. This can be illustrated by findings from our recent study of the diffusion of energy-efficient renovations of buildings: In our research projects, we found that actors from industry, public policy, and civil society typically know a great deal about their narrow fields of specialization. Yet even with decades of experience, they were not particularly skilled in developing a systems perspective that could take in the whole diffusion process.

Finally, simulation models promise to facilitate joint learning processes among actors from different backgrounds. To avoid debating fragmented perspectives and vague fundamental values, simulation models could be used to debate policies and instruments based on a systemic understanding of the diffusion process.[9] This holds the potential for identifying win-win solutions and moving toward consensus on policies that perform well in the simulation model.

Implementing Diffusion-Support Processes Based on the System Dynamics Methodology

How could a diffusion-support process based on the System Dynamics methodology be implemented? In our experience, it is good practice to start by modeling the installed base of the conventional technology and the eco-technology and by capturing their dynamics over time. This may entail modeling car fleets or building stocks and tracking various characteristics such as fuel consumption, heating systems, and CO_2 emissions. Based on a rather small yet empirically well-grounded model of the installed base, preliminary policy recommendations can become evident.

In a second step, researchers should focus on the feedback loops that control the installed base and drive the technological substitution process. We expect that all the feedback loops included in our generic model are present in most technological diffusion processes. Yet, including additional feedback loops in a simulation model of the diffusion process may prove insightful and rewarding. Identifying additional feedback loops may entail both empirical research (e.g., face-to-face interviews, desktop research, analysis of quantitative data) and a review of theories that shed light on particular aspects of the system under investigation.

Along with the analysis of feedback loops driving the diffusion process, actors should be analyzed. Which actors are relevant? What part of the feedback structure do they control? What are the interests of the various actors, and how can they be influenced to contribute to the diffusion of the eco-technology rather than block it?[10]

As the understanding of the system under investigation deepens, a quantitative simulation model should be built that adequately represents the diffusion process of a specific eco-technology. Through iterations of model testing and subsequent model improvements, the quality of the model will be improved (see Barlas 1996; Schwaninger and Groesser 2009). When there is a lack of knowledge, further empirical research should be conducted.

In a next step, the simulation model should be used to identify policy levers that have a substantial impact on the diffusion rate of the eco-technology. We expect that such sensitivity analysis will rule out many potential policy levers. However, a set of potentially powerful policy levers will remain. Together with representatives of relevant actors, a dialogue on policies and instruments should be started. The goal of such a dialogue should be to identify pragmatic policies and instruments that make use of highly sensitive policy levers. As a result of collaboration with representatives of relevant actors, the quality of public policies would be improved and policy resistance would be reduced, thereby enhancing the effectiveness of diffusion-support policies.

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[9] A pertinent example for the case of municipal waste management is documented in Ulli-Beer (2006).

[10] See Müller et al. (2011) and Müller (2012, Chap. 5) for further insights on identifying and representing relevant actors.

Conclusions

In the Introduction to this chapter, we presented two research questions. First, we asked how eco-technologies diffuse. In particular, we were interested in what generic causalities associated with the market, technological change, and public policy drive the diffusion of eco-technologies. In the main part of this chapter ("A Generic Theory of the Diffusion of Eco-Technologies"), we argued that changes in technological quality and production cost influence supply and demand on the market. The diffusion process of technologies that are of no special interest for public policy is controlled by the technology and market loops that we described (see "The Market and Its Effect on Installed Base" and "Changes in Technological Quality and Production Costs"). However, technologies that are promoted as a means of achieving public policy goals are not subjected to the interplay of technology and market forces alone. In addition, public policy provides diffusion support by way of interventions like pilot and demonstration installations, support for research and development, subsidies, and mandatory regulations. We described this logic of intervention and argued that our model could be used as a starting point for research and policy initiatives aimed at supporting the diffusion of specific technologies. We claimed that our model is, in principle, applicable not only to one kind of technology but to a whole class of eco-technologies. If that assertion is justified, our model embodies a theory of the middle range.

This leads to our second research question, which asks how modeling and simulation could support the diffusion of a specific eco-technology. We showed that the System Dynamics methodology is well suited to integrate a broad range of insights and perspectives into a more complete, systemic perspective. Furthermore, we argued that a fully developed, empirically well-grounded simulation model can be used to derive robust policy recommendations.

Finally, we indicated how System Dynamics modeling might guide policy making in settings characterized by multiple actors as well as value and interest conflicts. Future research might take our generic model as a starting point and attempt its application to different eco-technologies. Furthermore, it would be promising to explore the potential of using System Dynamics modeling to guide and integrate larger research networks.

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