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# Towards modelling of innovation systems: an integrated TIS-MLP approach for wind turbines

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# Abstract

Meeting sustainability challenges requires not only innovations but also transitions towards sustainability paths. Studies which use technological innovation systems and multi-level-perspective approaches show that the development of innovation systems is a complex process, with many direct and indirect interdependencies of the different variables. The paper looks into the feasibility to support such analysis with system dynamics models. It is analysed how a combined TIS-MLP approach could form the conceptual basis for analysing the dynamics which drives the development of the system to be modelled. The feasibility of such a concept is further investigated by implementing it for China and Germany using wind energy as a case study. In order to develop a perspective how to build the model in technical terms, the dynamics of the innovation systems is translated in software based causal loop diagrams. In addition to methodological insights about the feasibility of modelling, the paper also yields insights into differences and similarities in the drivers of system dynamics in both countries. Furthermore, general conclusions for the potential of regime shift in countries catching up and the relation to leapfrogging are drawn. Thus, the paper augments more general conceptual advances with an evidence based case study and extends theoretical analysis towards empirical modelling.

Keywords: sustainability transitions; system dynamics; wind energy; technological innovation systems; multi level perspective; system dynamics

# 1 Introduction

Meeting global challenges requires not only a higher level of innovations but also changes in direction of innovations. However, it is still a big challenge how to build an innovation system which supports such far reaching societal goals, and a thorough analysis of the dynamics of innovation systems would benefit such an endeavour. The last years have seen both numerous applications of technological innovation systems (TIS), many of them in the field of sustainability technologies, and studies which look into niche development and regime shift from a multi level perspective (MLP). Each of these approaches has merits and limitations in contributing to a dynamic analysis of transitions towards sustainability. The existing case studies all show that the development of innovation systems is a complex process. This requires accounting for numerous interdependencies, which take place directly and indirectly, some of them immediately, others with considerable time delay.

This complexity puts additional burden on the scientists to keep track of all the repercussions which might result from changes in a framework condition or a policy design variable. We see a trend in applied policy studies to support such analysis with quantitative models. The models do not aim at forecasting the future development, but support answering questions such as what the effect of changing framework conditions or policy designs on the outcome might be, by rigorously accounting for all of the interdependencies which are modelled. Thus, they augment (but do not substitute for) case study analysis, and can provide an additional view which puts special focus on the endogeneity of development caused by the numerous interdependencies. These models require the scientists to spell out explicitly the assumptions and conclusions on the interdependencies of the variables. Typically, this kind of modelling must be able to account for many feedbacks, must be able to deal with non-linearities, and should be flexible with regard to the different sources and types of data. System dynamics has become a wide used methodology for these kinds of models (Richardson 1991; Sterman 2001a and b; Ghaffarzadegan et al. 2011), and a community on its own has been developing.

Developing such policy models is a far reaching long-term goal. In a first fundamental step, it requires definition of a system boundary, development of a mental model and its transfer into causal-loop diagrams; further steps require specification of variables, development of mathematical functions and calibration of parameters. This paper describes the results of the first step. Thus, it can also be interpreted as a feasibility analysis towards modelling, which looks at the following aspects:

- A feasibility analysis should contain the conceptual basis for analysing the dynamics which drives the development of the system to be modelled.

- A feasibility analysis should show that the system can be framed such that it is suited for modelling. This requires not only definition of system boundaries, but also a mental model of the causes and effects to be modelled. Furthermore, such an analysis should also show the level of detail, which is required for modelling.
- Feasibility also requires to develop a perspective how do build the model in technical terms. Thus, it is investigated how the dynamics of the innovation system can be translated in software based causal loop diagrams. We also discuss data requirements. However, specification of numerical values for variables, specific form of functional algorithms and calibration of parameters are beyond this paper.

In order to ensure compatibility with real world problems, we perform such a feasibility analysis for a case study, for which we have chosen wind energy development in Germany and in China. Therefore the analysis not only yields methodological insights, but also allows comparing the drivers of wind energy innovation system development in China and Germany. Thus, the paper augments more general conceptual advances with an evidence based case study and extends conceptual analysis towards empirical results.

The paper is structured as follows: Chapter 2 starts with background information on the state of the art of TIS and MLP analysis, respectively. It continues with outlining the concept how to build on the dynamics which can be derived from the TIS and MLP approach, and how this relates to the requirements of system dynamics modelling. Chapter 3 develops the conceptual model approach for the wind energy innovation system in Germany. Starting with an overview of performance indicators of German wind energy industry, the development of the innovation system and how it is influenced by both internal dynamics and landscape and regime of fossil fuel based electricity is analysed in a dynamic setting for three phases. For each phase, a diagram showing the dynamics and feedback loops is developed. Chapter 4 deals with the development of the Chinese wind energy innovation system and is structured in parallel to chapter 3. Chapter 5 compares both developments and identifies similarities and differences. It also takes up the perspective of augmenting case study analysis with system dynamics based simulation tools, by building causal loop diagrams with a system dynamics computer language and by discussing data requirements. Chapter 6 finally summarizes the experience and presents the overall conclusions.

# 2 State of the art

## 2.1 Technological Innovation Systems

The heuristics of systems of innovation has been developed for national, sectoral and technological systems (see e.g. Lundvall et al. 2002; Edquist 2005; Malerba 2005; Carlsson et al. 2002). The innovation system concept also has great potential to analyse sustainability-oriented innovation systems. Innovations in such systems are typically more influenced by public needs and public discourse than "traditional" sectoral or technological innovation systems. Regulation must address environmental externalities, and long time horizons of sunk costs into infrastructure, supported by traditional economic sector regulation, leads to a triple regulatory challenge (Walz 2007).

It has been suggested that a technological innovation system can be analysed by looking at how the different functions it is supposed to carry out are fulfilled (Hekkert et al. 2007; Bergek et al. 2008a,b; Hekkert and Negro 2009; Suurs and Hekkert 2009). Abstracting from differences in wording, the following categories of an innovation system's functions can be distinguished:

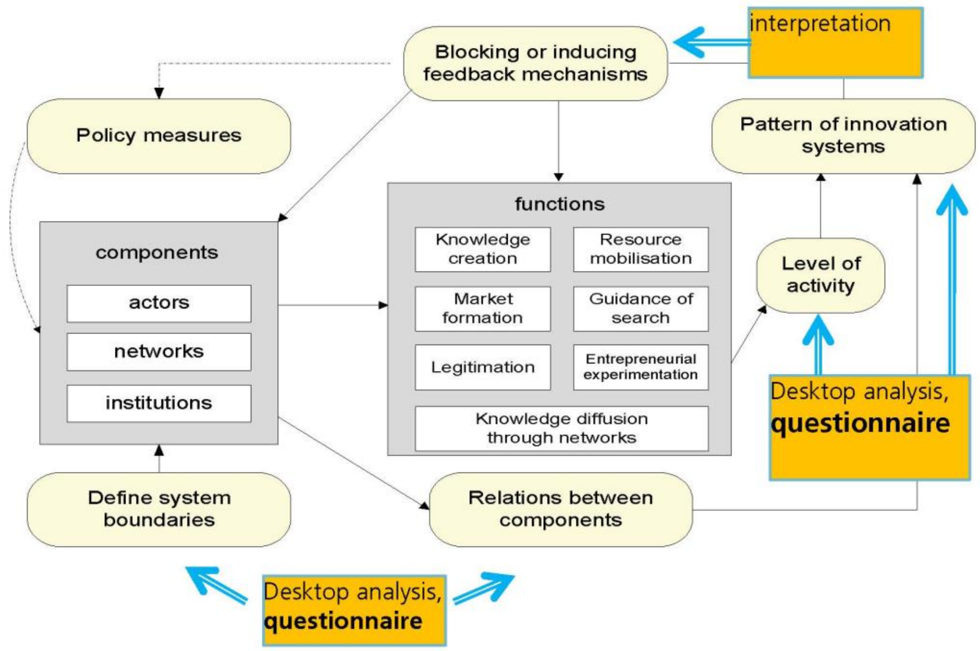
- *Knowledge generation* (F1),
- *knowledge diffusion* (F2) through exchanging information in networks, but also along the value chain (including supplier-user interaction),
- *guidance of search* (F3), that is directing R&D and search for new solutions with respect to technology and market,
- *entrepreneurial experimentation* (F4), leading to diversity and a variety of solutions in order to allow for a sufficiently large stock of technologies enabling the selection process to result in a dominant design.
- facilitation of *market formation* (F5), which enables learning in the market and scale effects.
- *Legitimization* (F6) of a new technology, which is closely connected with recognising a growth potential for the technology and the ability to counteract political resistance and to push for political support.
- *Resource mobilisation* (F7), which is especially important for new technologies associated with a higher risk of failure.

These functions are not disjunctive. Bergek et al. (2008c) point out that the mechanisms and interactions of the actors of an innovation system, and the feedback loops between the different functions need to be taken into account to properly understand the innovation process. These feedback mechanisms can induce an increase in innovations but also block further development (Bergek et al. 2008b; Hekkert and Negro

2009). It is within these dynamic relationships that the development of an innovation system takes place. Thus, the feedback mechanisms between the functions provide for the internal dynamics.

So far, the majority of applications of technological systems of innovation on green innovations have been case studies in the renewable energy field. Some of them have been performed for emerging economies (e.g. Mohamad 2011; Lema and Lema 2012; Walz and Delgado 2012; Lema et al. 2015b). Typically, such case studies are based on desktop research, interviews and questionnaires. They analyze the components of a TIS and their interrelationship, research the level of activity with regard to the different functions, and derive the pattern of the innovation system (Figure 1).

Figure 1: Implementation scheme for a TIS case study




Source: Walz and Delgado (2012), adapted from Bergek et al. (2008c)

The empirical evidence suggests a strong impact of policy on innovations in renewable energy technologies for power generation. Both public R&D spending as well as policies which induce domestic demand increase the innovation activities. Likewise, policy factors such as introducing targets for renewable energy and providing stable policy support lead to higher innovation output. There is also empirical evidence that success on international markets seems to foster further innovations.

However, the innovation systems approach has also been criticized for being inward looking, and not taking wider systems perspective into account. Thus, aspects such as embedding into societal development, and competition with existing technologies are seen as not being represented enough (Markard et al. 2012; Weber and Rohracher 2012).

## 2.2 Multi level perspective

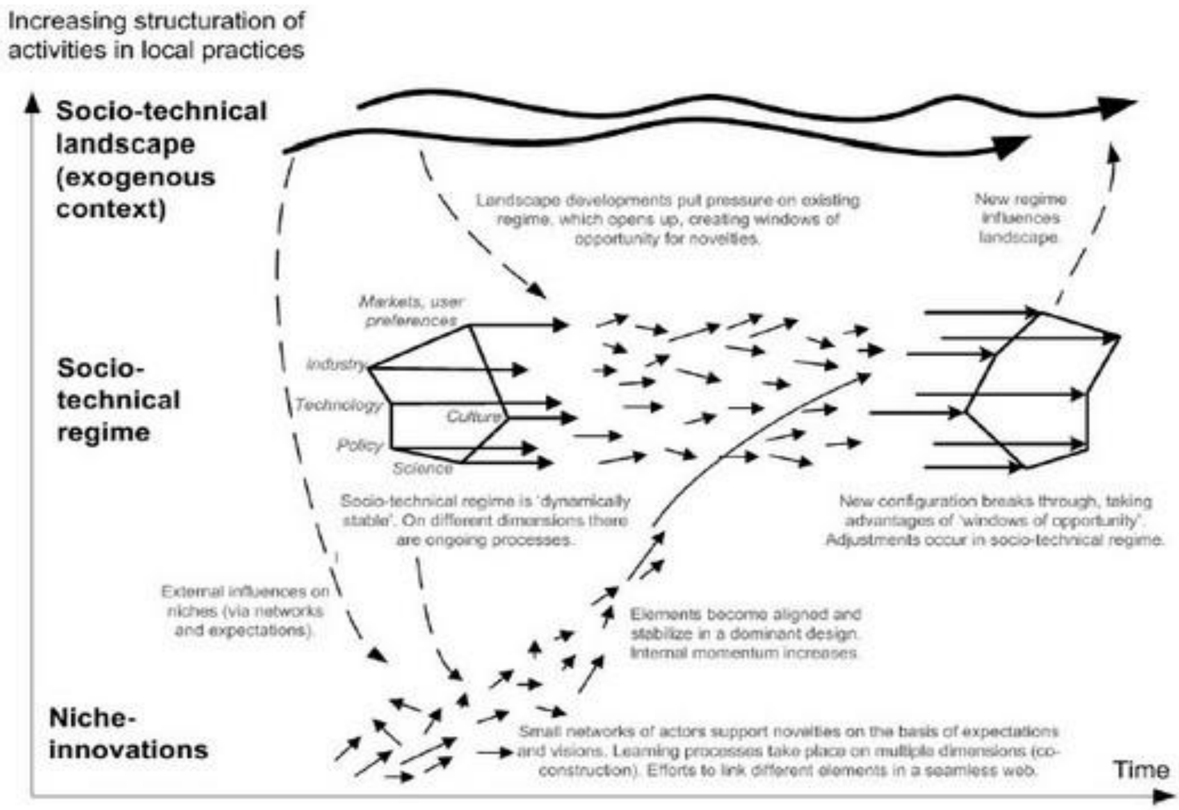
The innovation process is embedded in institutions, production of knowledge, and socioeconomic development. Thus, innovation follows certain paths, which can even lead to path dependencies and problems of moving towards new technological solutions. Innovations require organizational adaptations and the co-evolution of institutions supporting the further development of the technologies. Dosi (1982) explains the existence of path dependency of innovation processes, which has been taken up in the climate change literature by Unruh (2000) under the label of carbon lock in. At the beginning of a radical innovation, the selection processes towards a dominant design are important, but also availability of diverse solutions to select from. In later phases, market formation and feedbacks between users and producers are becoming more important, and the co-evolution of technologies and institutions supports further incremental innovations. However, the co-evolution between technology and the surrounding institutions can also lead to path dependency. A new technology has not only to compete against a traditional one, but against a system consisting of a traditional technology together with institutions which have been co-evolved around this technology.

The notion of path-dependency and co-evolution also shows up in the multi-level perspective, which is advocated by scholars such as Geels and Schot (2007) or Geels (2011). It distinguishes landscape, regime and niche. The landscape represents the broader picture of socioeconomic system, the regime consists of the established technological paradigm. A radical alternative has to grow in a niche together with a social network surrounding it, before it is able to compete with the established paradigm.

The notion of co-evolution in the tradition of evolutionary scholars such as Dosi (1982) or Nelson (1995) shows up at various levels of the multi level perspective. It can be horizontal co-evolution within the regime between the established paradigm and institutions. Furthermore selection processes lead to an adaptation of strategies or routines of companies towards the paradigm. Co-evolution can also take place on vertical levels, e.g. between the paradigm and the regime. Another form of vertical interaction is the competition between new and established paradigm, with the latter using the surrounding institutions to fight the success of the new paradigm. However, it might also be that the landscape can benefit the growth of the niche.

According to MLP, niches gain momentum after a dominant design, powerful actors and networks have emerged. The niche is growing, and starts to become an important economic component (Figure 2). It can be closely associated with empowerment, which Smith and Raven (2012) are advocating as a specific function of niches as protective space.

Figure 2: Process of regime shift in MLP




Source: Geels (2011)

The MLP approach has been criticised in the past for being too functional, and not putting enough emphasis on power and actor aspects (Smith et al. 2005; Geels and Schot 2007; Smith and Raven 2012). Furthermore, it has been suggested that transition research needs to take space into consideration (Markard et al. 2012), and calls for integrating MLP with economics of geography.

Walz and Köhler (2014) see a sustainability transition characterized by various niches developing, which share a common systemic relationship with a regime. For electricity supply technologies, the regime is based on fossil fuel and large central nuclear power stations, around which institutions have been co-evolving. Green energy technologies such as renewable energies form niches, which however addresses the core of socio-technical regimes (Figure 3). There are common features of the energy technologies which justify distinguishing them from other technologies. Energy innovations share the double externality problem described by Rennings (2000). In addition to the regulation of protection of knowledge and R&D, energy innovations in addition also face the externality of environmental costs. There is not much demand for green energy innovation, unless some form of environmental regulation leads to a level playing field between new and old, environmentally more harmful innovations. Thus, demand is highly policy driven, and policies such as standards, emissions trading systems, feed-in-tariffs or quota systems are simultaneously both environmental and demand led innovation policies. Furthermore, changes on the landscape level such as increasing environmental awareness, changing perceptions of man-environment relationships, or development of a political system placing a higher priority on green issues effect all the green energy innovation technologies. Thus, the different regimes and niches of green energy innovations are all affected by the same specific changes on the landscape level.

Renewable energies for generation of electricity belong to infrastructure related regimes. The specificities within each class leads to similar selection environments. Electricity technologies and related technologies share the following specificities (see Markard 2010 and Lema et al. 2015b):

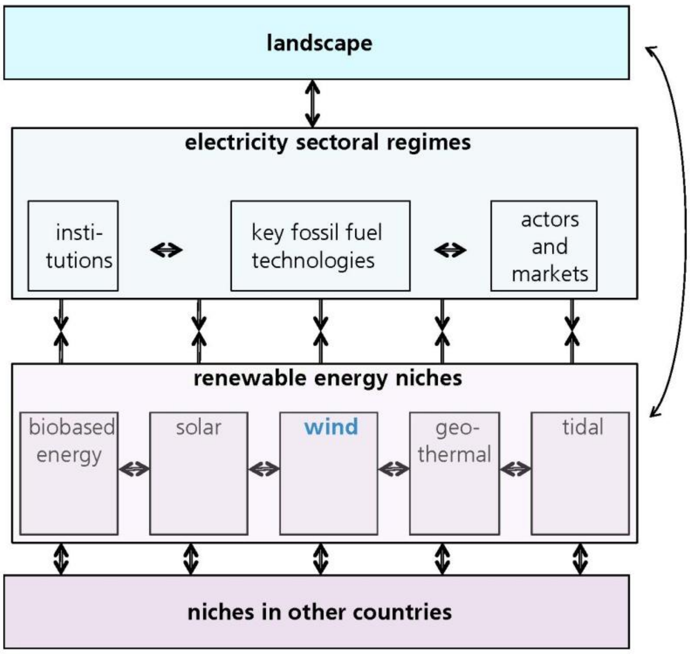
- Asset durability: A lot of these technologies are characterised by a very long lifetime (e.g. power stations, investments in related infrastructure such as electricity or water grids, roads and rail). Thus, the high asset durability limits the opportunity for reinvestments. Furthermore, the investments in infrastructure related technologies tend to be very capital intensive (Markard 2010). Thus, it would be very costly to substitute them before they have reached their end-of-life. Both factors support "technical path dependency" and technological lock in.
- Technical systemness of physical networks: If the technologies are physically connected with each other, via a grid, technical systemness (Markard 2010) increases path dependency. Problems of integration of renewable electricity supply, for example, can arise from a grid structure which is optimized towards the existing carbon intensive power system. If the grid structure is not suited, even large investments in low carbon electricity supply do not necessarily increase the market share of low carbon alternatives, unless they are supported by vast investments into a new grid structure. Thus, the specific features of technical systemness lead to a comparatively high level of path dependency.
- Cultural significance: access to energy, water and transportation are all related to basic needs, which shows up, for example, in their prominence among the future global challenges.
- Monopolistic bottleneck: Despite the call for deregulation and liberalisation, it is still acknowledged that monopolistic bottlenecks characterised by both sunk cost and

natural monopoly cost functions should be regulated. Clearly, infrastructure systems based on physical networks such as electricity/gas, water supply and sewage treatment, or railways include such a monopolistic bottleneck. Even potentially competitive stages, in general, require access to the monopolistic bottlenecks. This also holds for power produced by independent power producers, e.g. the operators of renewable energy, or railway operators. However, the way of economic sector regulation also influences the speed and direction of related technology innovations. From the point of view of innovation, these infrastructure sectors pose a third regulatory challenge (Walz 2007).

- Actor structure and political economy: Infrastructure innovation systems are characterised by a specific structure of actors. The incumbents which drive the existing regime, such as public utilities or multinational energy companies, are typically very powerful and sometimes influence government. Many of the actors which drive the niches, however, are small and medium enterprises, and are often newcomers. However, in addition to this actor constellation – which can also be found for other innovation systems – there are also community based groups and NGO-type actors, which are among the key proponents for eco-innovation niches. This reflects the characteristic of infrastructure systems as a social need, which cannot put to individual market based decisions alone. To sum up the argument, important actors in infrastructure innovation systems are different from the typical actors in other innovation systems. Thus, it can be expected that their behaviour also differs. Furthermore, the regime-niche constellation can be characterised as an arena with a very uneven power structure: Large companies, which profit from existing lock in, sometimes directly linked to government, versus drivers of eco-innovation, which very often are not part of the established innovation system, and do neither possess capital reserves nor experience in upscaling innovation.

These specificities of infrastructure technologies point towards the fossil fuel based regime being rather strong. Geels and Schot (2007) have been proposing that depending on the state of development and the timing of transformations taking place, the interplay between niche and regime can lead to different transition pathways. This leads Walz and Köhler (2014) to expect that a transition pathway which Geels and Schot (2007) have called "technological substitution", will emerge more often in case of renewable energies: Radical innovations, which have developed in niches, remain stuck because the regime is stable and entrenched. Only after strong disruptive changes in the landscape the regime will be challenged. Strong growth of the niche, brought forward by policy measures, might prove to be expensive, which again reduces the legitimacy of further growth of the niche. In such instances, the narrative of transition typically points towards future cost reduction through learning of the niche technologies (Smith and Raven 2012). The link to niche growth in other countries can strengthen such a narrative: Export success in the radical new technologies becomes an important argument to counterbalance the critique of rising economic costs. If the niche technologies promise to reduce or even to phase monopolistic bottlenecks, this can also add to further bolster up the transition narrative.

Figure 3: Level of aggregation of technological innovation system within multi level perspective




Source: adapted from Walz and Köhler (2014)

## 2.3 Conceptual basis for modelling

A feasibility analysis for modelling of energy innovation systems should contain the conceptual basis, which is able to provide for the dynamics which drives the development of the system. The previous sections have shown that both TIS and MLP approaches offer good starting points for an analysis of the dynamics of an energy transition. The following four aspects form the conceptual core on which mental models for the modelling of the dynamics of innovation system are based on:

- First, authors such as e.g. Bergek et al. (2008a and b) or Hekkert and Negro (2009) see the development of innovation systems influenced by virtuous or vicious circles among the different innovation functions. Thus, the feedbacks between these functions allow to account for the internal dynamics of innovation system dynamics (Smith and Raven 2012).
- Secondly, the MLP approach sees the development of a sustainable niche influenced by the interaction of a niche with landscape and regime, which puts the development of a specific technology into a wider perspective of transition pathways

and regime shift (Geels and Schot 2007; Geels 2011). Thus, drawing on the MLP approach allows for taking the external dynamics into account.

- Third, both approaches have been criticized for neglecting advocacy, political economy, and also spatial dimensions of importance of interaction of IS on a global scale (Markard et al. 2012; Smith and Raven 2012). However, the elements of a socio-political environment (Geels 2014) are also used in order to make the approach more actor specific. Thus, aspects of political economy could be used to translate the dynamics between niche and regime into the logic of actor behaviour within a TIS.
- Fourth, a combination of TIS and MLP can be achieved by interpreting a specific renewable energy TIS as a niche within a broader, fossil fuel dominated energy system. This niche draws on the common systemic relationship between renewable energy niches and the fossil fuel based regime described above.

Taking these findings into account, the method of system dynamics (SD) seems to be a valuable tool for modelling and analyzing the dynamics of innovation systems. System dynamics (SD) is a methodology and modelling technique for framing, understanding, and discussing complex issues (for detailed description of system dynamics methodology see Sterman 2001a or Bossel 1994). System dynamics goes back on systems theory, which was originally developed and described by the biologist von Bertalanffy in the 1950s (compare e.g. von Bertalanffy 1948; 1968). From this, the so called cybernetics originated, a mathematical theory for communicating and controlling technical or social systems over time including feedback loops and developed as a method for understanding the dynamic behaviour of complex systems. Meanwhile cybernetics is seen as the theoretical framework and conceptual background of system dynamics.

System Dynamics itself was developed in the late 1950s by Jay W. Forrester at the Massachusetts Institute of Technology (MIT). It allows that the dynamics of socio-economic systems may be analysed, modelled in qualitative and/or quantitative structures, and for their long-term trends to be simulated via computer-aided runs for supporting decision makers. Therefore, beneath cybernetics, two further important methodological features are provided by Descriptive Decision Theory and computer-aided simulation (see Forrester 1968a; 1971; Milling 1984).

Alike to the paradigm of cybernetics, System Dynamics also ensures that each information-based decision calls for a feedback within the system, whereby the current system state is changed. Common approaches of decision theory assume that the decision maker always decides rationally. Such an assumption, however, by no means corresponds to reality and may distort the result. System-dynamic models are based on Descriptive Decision Theory and postulate that the human being as the decision maker will not inevitably make rational decisions. System-dynamic models are able to account for such descriptive decision systems, which especially refers to uncertainty and incomplete information in social innovation processes. Moreover, the method also enables reliable assessments despite complex effects from feedback coupling structures, time delays, and aggregations as well as general cases of non-linearity, and thus overcomes the natural tendency of man towards "linear thinking" (Dörner 1989; Sterman 1989; Paich 1993; Sterman 2001b).

By means of continuous computer-based simulation however, the dynamic behaviour of a system and the individual parameters can be analysed, whereby the system's understanding of the effects of past decisions is deepened and the interaction of the individual variables becomes more transparent (Forrester 1968a; Stumpfe 2002; Milling 2002). System Dynamics is thus a method through which the long-term impact of decisions on a system and the existing interactions within the system under different environmental developments can be examined and evaluated ex-ante. The possibility to evaluate decisions based on if-then analyses and hence, creating various scenarios and future trends, constitutes an additional benefit.

Due to its configuration, System Dynamics enables a holistic picture of innovation system processes to be represented in one model by using differential equations to describe all relevant material, financial, and information flows, their interactions and dynamics and the impact of decisions from relevant decision makers (Forrester 1971). Therefore SD can be tailor-made specified to a great variety of problems including for example matters of business, but also questions of social, economic, biological and ecological nature (Sandrock 2006).

Due to these features, system dynamics is widely used in management, natural sciences but also increasingly in economics. It accounts for the influence of random effects, does not necessarily lead to equilibrium solutions like traditional economic models, and highlights the adaptation processes. The core variables of system dynamics are stocks and flows, with the flows determining the levels of the stocks. Essential to this methodology is the use of time delays and feedback loops (with feedback loops being a consequence of time delays). Thus, a level variable can directly or indirectly influence itself. The system behaviour is influenced by both exogenous factors, which by definition are not affected by the system, and endogenous factors, which are modelled with various feedback mechanisms within the system. Feedback mechanisms can be either positive (the influenced variable changes in the same direction as the influencing variable) or negative (the influenced variable changes in the opposite direction to the influencing variable).

The general assumption of the method is the recognition that not only the components of a system itself, but also the structure of the system is determining system behaviour (Forrester 1968b). The dynamic within system dynamics arises from the combination of time delays with feedbacks, and is able to explain nonlinearities. Thus, system dynamics, similar to the evolutionary thinking which forms the basis of TIS and MLP, puts an emphasis on the cumulative and time dependent pattern of system development, and on a system behaviour which depends on the interplay of components and their interaction. Indeed, there are already a few approaches which have used a systems dynamics approach within innovation studies: Lee and van Tunzelmann (2005) used it to analyse the integrated circuit development in Taiwan; Maldonado (2012) modelled the Brazilian software sector by looking at aspects such as adoption of technology, learning and financing. Walz and Krail (2012) analysed innovation driven export shares of wind energy turbines by building a system dynamics model which includes knowledge creation, economies of scale, policy style etc. However, to the best knowledge of the authors, none approach exists which developed a system dynamics approach for energy transition based on the functions of TIS or the MLP approach.

For developing models, we follow the generic approach of Forrester (1968b), delivering a structured procedure for evolving from a mental model to a quantitative one with mathematical structures. The mental model of a system is represented as a causal loop diagram, which is a map of a system with its components and their interactions. By capturing interactions and consequently the feedback loops, a causal loop diagram reveals the structure of a system. By understanding the structure of a system, it becomes possible to ascertain the behaviour of a system over a certain time period. To perform a more detailed quantitative analysis, a causal loop diagram is transformed to a stock and flow diagram. A stock and flow model helps in studying and analyzing the system in a quantitative way. A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in a stock. The final step of building a quantitative model involves the writing of equations that determine the flows and the estimation of the parameters and initial conditions.

The feasibility analysis has to show that the dynamics of the innovations system can be framed such that it is suited for modelling with system dynamics. We look at the feasibility of the modelling approach by framing the development of renewable energy innovation systems in terms which can be taken up by systems dynamics. Thus, we apply the concepts of TIS and MLP to capture internal and external dynamics of the case study, and map the interaction and feedbacks in a diagram. Furthermore, we translate this dynamic into a causal loop diagram. By doing this for a well researched topic, we assure that the feasibility of the modelling is not analysed for an artificial problem, but is indeed capable of dealing with the real transition issues which have been identified in numerous case studies. However, it is beyond the scope of this feasibility study to build a quantitative model with written equations.

The concept of modelling is elaborated for the case of wind turbine innovations in Germany and China. Applying the concept to a specific case helps to test the feasibility of combining the elements described above, and makes it more specific to define the challenges lying ahead with regard to specifying and estimating a model. Wind energy has been chosen because it is one of the most thoroughly analysed sustainable TIS, and provides a good example for successful TIS development.

In case of transition of electricity system, various forms of renewable energy technologies each form a niche (Figure 3). They face a common regime characterized by centralized, fossil fuel based power stations, around which a complex web of institutions, complementary technologies, and markets has been co-evolving, which perpetuate carbon lock-in. It is assumed that regime-niche interaction follows a disruptive transition path. There is an internal dynamic within each niche, described e.g. in various TIS case studies. In this case study, the focus is on wind energy. There are also influences of the landscape on both regime and niches. Furthermore, one niche might be directly or indirectly influenced from development in the niche in another country, or from internal development of other renewable energy niches. However, the latter internal dynamics are neglected in order to reduce complexity of the analysis.

# 3 Application to wind energy in Germany

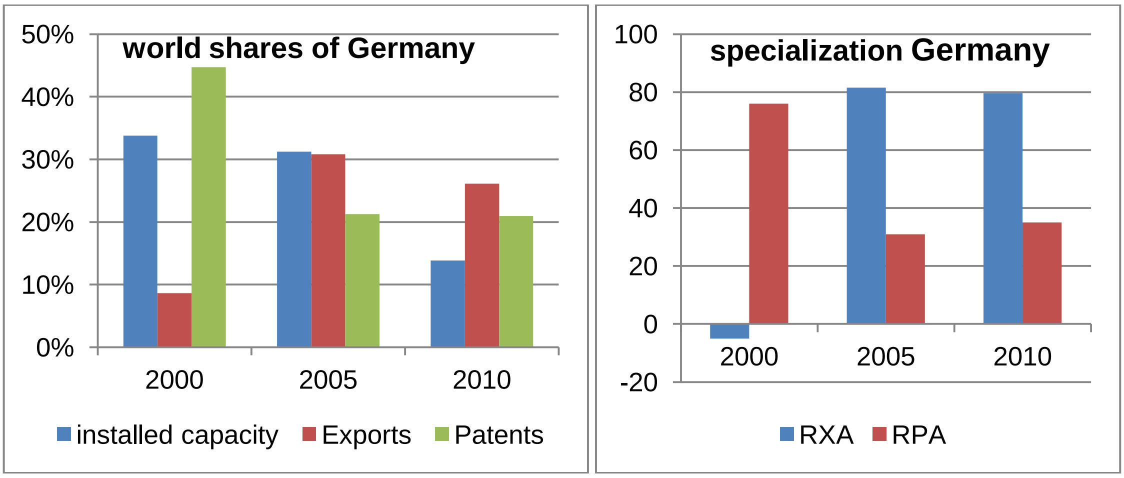
## 3.1 Overview of German wind energy industry performance

The German wind energy development is widely seen as a success story. Various analysis about the creation and functioning of the German innovation system have been performed, such as Bergek and Jacobsson (2003), Walz (2007), or Lema et al. (2014), to name just a few. The importance of supply side measures such as subsidies to R&D, the effect of the German feed-in-tariffs, and the interplay with various framework conditions (e.g. planning law) have all been described by these studies in greater detail. The most notable innovation output of the German wind energy innovation system is presented in Figure 4.

After introducing feed-in tariffs in 1991 (Stromeinspeisegesetz), diffusion of wind energy in Germany rose continually. In 2000, Germany roughly accounted for one third of worldwide accumulated installed capacity. Knowledge generation, measured with transnational patents[1] reveals a very strong position in technological competences. However, the focus of the industry was still inward looking, and most of the capacity of the wind turbine industry was used to supply soaring domestic demand.

With other countries pushing diffusion, most notably the U.S. and China, the share of Germany at accumulated installed capacity started to decrease, and was already below 15 % in 2010. With other countries picking up, the share of patents stabilized at around 20 %. However, giving Germany's overall performance in patenting this is still equivalent to a strong positive patent specialization in the technology (Figure 4). At the same time, Germany developed into a strong exporter of wind turbines, holding a word export share in of 25-30%. Even in light of the strong overall export performance of Germany, this still translates into a very strong export specialization. Thus, the development of exports signals that Germany was able to use her first mover advantage to establish a successful lead market position (Walz and Köhler 2014).

Figure 4: World shares and specialization of Germany's wind power industry




Source: calculation of Fraunhofer ISI

1 For the concept see Frietsch and Schmoch (2010).

## 3.2 Development of German wind energy innovation system

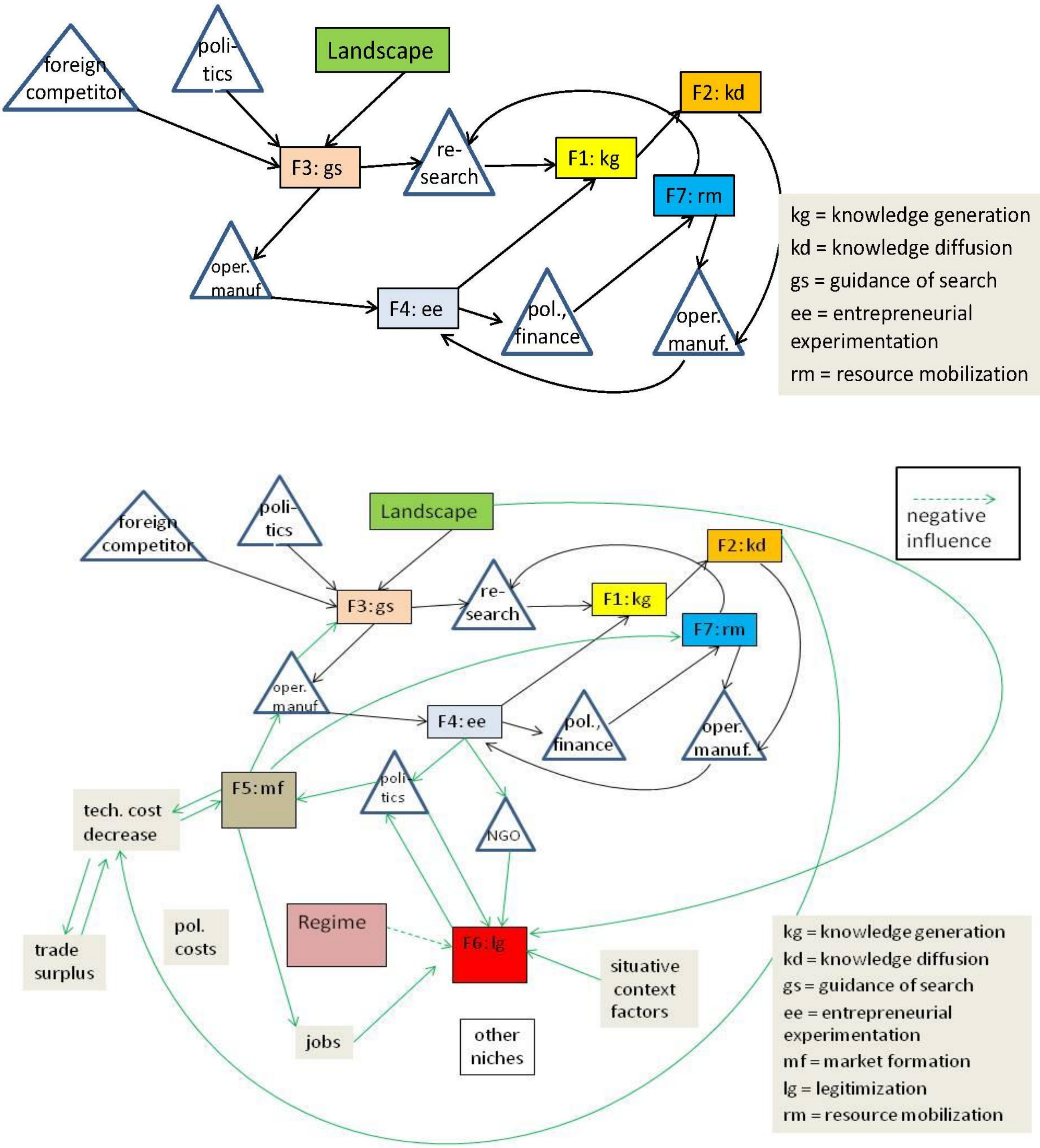
Bergek and Jacobsson (2003) emphasize that the development of IS runs through different phases. Following this notion, we see the development of wind energy innovation system in Germany characterized by three different phases, which trigger additional feedback loops between the elements. Figure 5a-c shows the dynamics and the main feedback loops within each phase; in addition, the triangular symbols indicate which type of actors might be involved.

The formative phase was characterized by establishing a positive feedback loop, which increased the level of activity of actors in manufacturing, research, and R&D policy, and led to interaction between these actors (see black arrows in Figure 5a). Landscape development towards greening society, earlier experience of Danish producers and nuclear phase out debate after Tschernobyl started the formation phase and gave "guidance to search" (F3). This influenced in particular research and manufactures of turbines, and led to an increase in knowledge generation (F1) and entrepreneurial experimentation (F4). An increased level of entrepreneurial activity further fostered knowledge generation (F1) and subsequent knowledge diffusion (F2). This positive feedback loop was further fueled by the resource mobilization (innovation function F7) brought forward by public and private research programs.

The second phase is characterized by growth of the niche in protective space. This was initiated by interaction towards additional innovation functions. In particular, the function legitimacy (F6) was influenced by the landscape (climate change becoming an important issue). The network building among manufacturers, but also results of entrepreneurial experimentation and knowledge generation and diffusion gained attention among policy makers and NGOs and increased legitimacy for wind power. This increase in legitimacy resulted in legislation ensuring market formation (F5), and led to substantial diffusion of wind turbines. Market formation itself (F5) led to various feedbacks, which drove down technology cost, and increased the competitiveness of the domestic manufacturers. Imports from foreign producers were reduced, and Germany developed a position as net exporter. This development had important consequences for the political economy debate. With Germany being a traditional technology exporter, the development of an additional export industry (wind turbines) furthermore strengthened legitimacy of the technology as an alternative of the established fossil fuel based paradigm. Furthermore, manufactures and operators received additional guidance of search and ideas for entrepreneurial activity, strengthening the positive feedback cycle established during the formative stage.

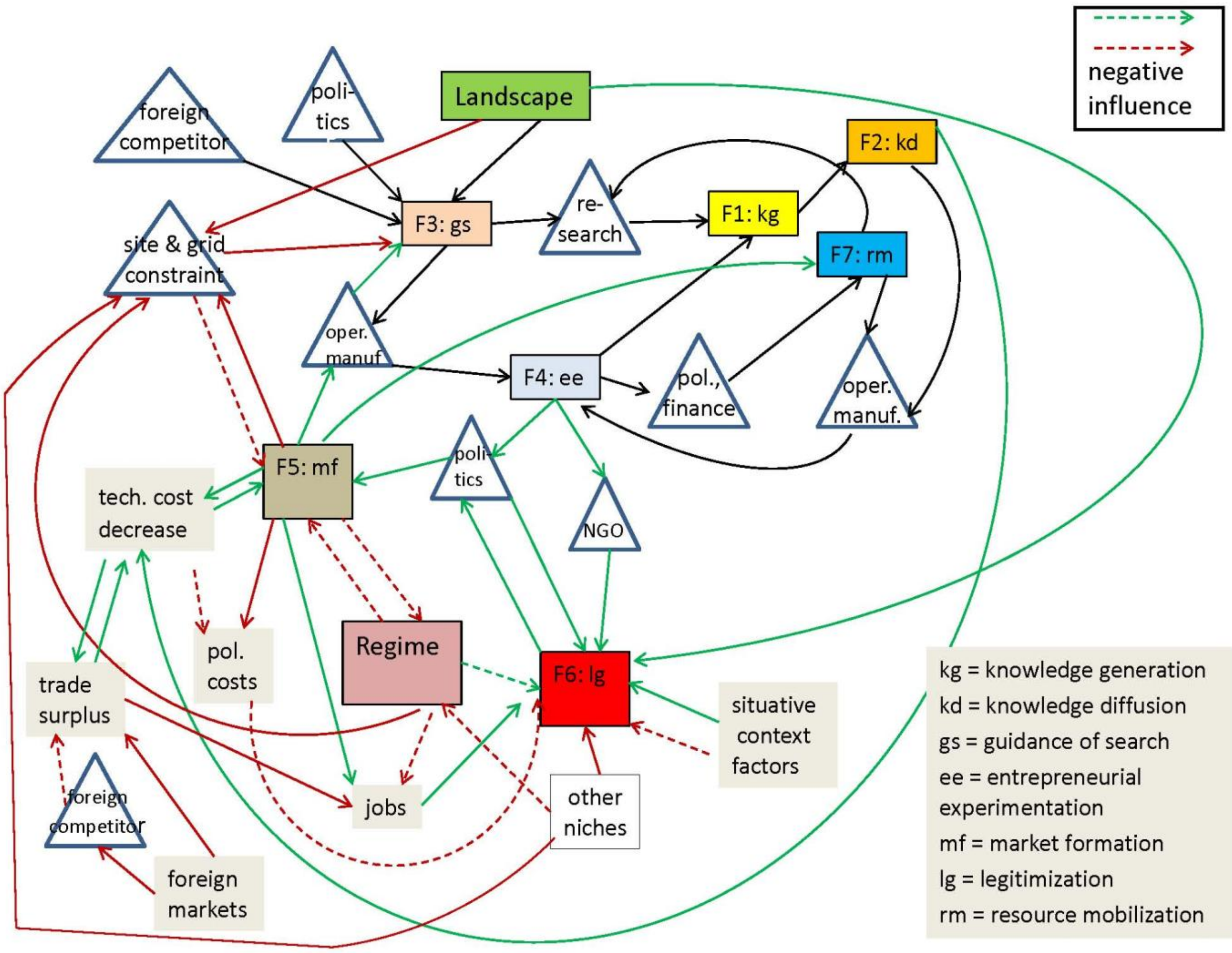
The third phase is characterized by new challenges which are caused by enlarging a niche towards a new regime, and which are ambiguous in their effect and even might threaten further development (red arrows in Figure 5c). Landscape factors (importance of environment) make protection of nature an important topic; this makes availability of additional sites for wind turbines more difficult. The capacity of existing grid, which has been built in the past according to the need of the existing regime, is forming a bottleneck for further expansion. New foreign players, which have been developing due to domestic policies in other countries, enter the world market and threaten the prospects of domestic technology suppliers. Thus, the political economy argument in favour of wind energy is weakened. The rapid expansion of renewable has led to rising policy cost of the feed-in tariff, which shows up in rising electricity prices. In order to avoid negative effects on export intensive industries, these cost increases have to be borne by the other consumer groups, especially households. This makes the political acceptance also more difficult especially in the short run, since learning and scale effects take time until they drive the costs down further. Thus, there is a delicate balance between technology cost decrease and increasing policy costs of expanding diffusion. If a decrease in legitimacy follows from these effects, policy is more likely to scale back policies which would result in reversing the dynamics of IS growth. If, on the other hand, the retarding effects are overcome, the regime is likely to be weakened furthermore, and co-evolution will remove some of the aforementioned obstacles. Thus, the current situation can be framed as a potential valley of death of regime substitution, which policy makers have to address in their decisions on changes in policy. In terms of system analysis, there are positive and negative feedback loops, and their relative strength and the timing sequence will decide whether the system will further expand or contract.

Figure 5a and 5b: Feedback loops and actors involved in the first two phases of German wind energy innovation system development




Source: Fraunhofer ISI

Figure 5c: Feedback loops and actors involved in the 3 phases of German wind energy innovation system development




Source: Fraunhofer ISI

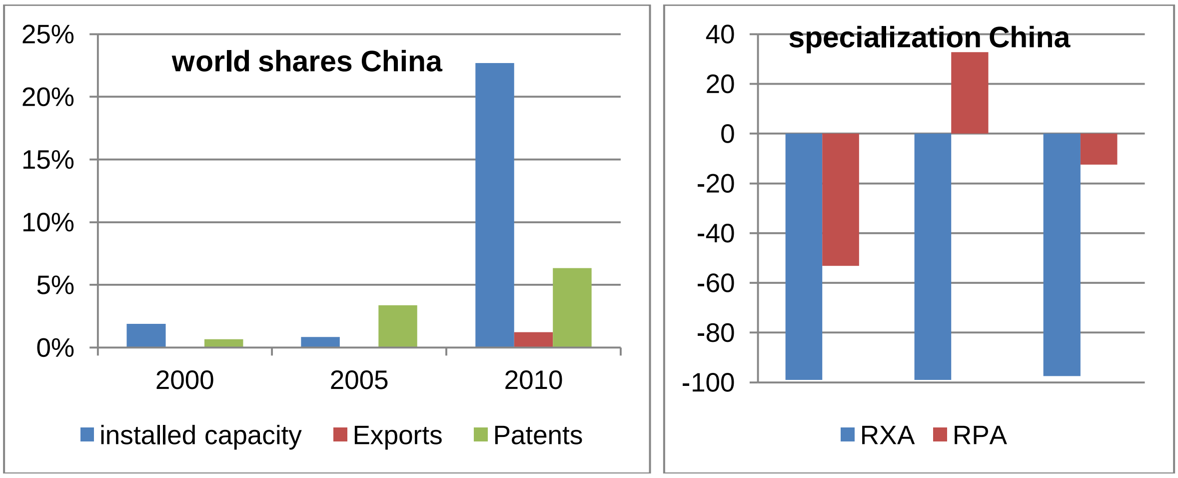
# 4 Application to wind energy in China

## 4.1 Overview of Chinese wind energy industry performance

The Chinese wind energy development is widely seen as a success story for diffusion of renewable energy in an emerging economy. The development of the Chinese wind energy industry, and the analysis of the innovation system, has been studied intensively lately (e.g. Walz and Delgado 2012; Klagge et al. 2012; Zhao et al. 2012; Ru et al. 2012; Wang et al. 2012; Zhang et al. 2013; Zheng et al. 2013; Gosens and Lu 2013; 2014; Dai et al. 2014; Lema et al. 2015a, Schmitz and Lema 2015; Koch-Weser and

Meick 2015). Figure 6 shows the impressive development of wind energy in China lately. China's share of worldwide accumulated installed capacity rose from a mere 2 % in 2000 to over 20 % in 2010, and this increase is still continuing. Patents started to rise too, and reached a word wide share of 6 %. However, exports are still very low, indicating that China's wind turbine industry hasn't reached full international competitiveness yet. This is underlined by a gap between China and the world leaders with regard to size of installed wind turbines, and the perception of China's wind turbine of being not top quality. The data on specialization of patents and exports further corroborate that despite the success story wind energy does not belong to the specific technological strengths of China's economy.

Figure 6: World shares and specialization of China's wind power industry




Source: calculation of Fraunhofer ISI

## 4.2 Development of Chinese wind energy innovation system

The assessment of the Chinese wind energy innovation system draws on the results of the papers on China mentioned above. Among the various studies on Chinese wind industry development, especially Walz and Delgado (2012), Klagge et al. (2012), and Gosens and Lu (2013 and 2014) use a TIS approach and employ the concepts of innovation functions. Thus, these papers were in particular helpful to allocate the various effects towards the different functions of Chinese wind energy innovation system.

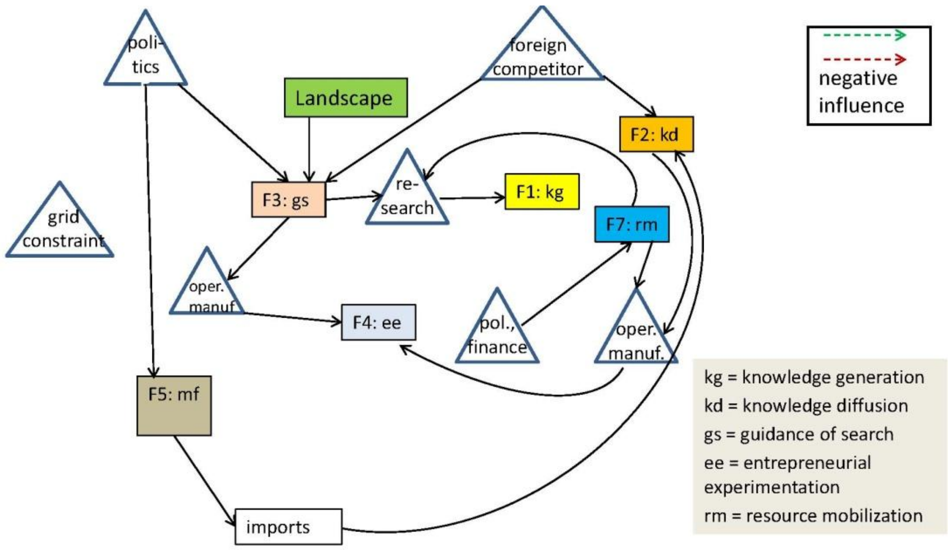
The development of wind energy innovation system in China is also characterized by three different phases, which reflect the different context and early follower strategy of Chinese producers. Figure 7a-c shows the main feedback loops within each phase, and indicates which type of actors might be involved.

The formative phase, which lasted from the late 1990's to approximately the early 2000's was characterized by the influence of the success stories of wind energy in other countries. The experience in other countries gave guidance of search (F3). This was supported by government programs aiming at transfer of knowledge, which perhaps reflected the overriding goal of Chinese policy to catch up technologically and to increase energy security (landscape factors). The program led to an increase in resource availability (F 7) and increase in absorption of foreign knowledge. Government also initiated a small scale diffusion program (market formation F5) of wind energy (ride the wind). The import of turbines from abroad supported further diffusion of (foreign) knowledge (F2). The increased level of knowledge diffusion triggered domestic entrepreneurial experimentation (F4). However, the link between entrepreneurial experimentation and knowledge generation remained rather weak. Thus, no positive feedback loop was initiated (see black arrows in Figure 7a).

The second phase (early 2000's to 2007) is characterized by growth of the niche in protective space. Landscape factors (export based growth paradigm), which led to supportive policies such as local content requirements of installed turbines, increased legitimacy (F6) and supported entrepreneurial experimentation (F4) of domestic companies. Market formation (F5) was further increased by de facto renewable portfolio standards, which led to the wind base projects of the large state owned utilities. Thus, the regime was involved in implementation of government policy. These developments led to learning in the market giving additional guidance of search (F3) and triggered entrepreneurial experimentation (F4) towards absorbing foreign knowledge and using it for own manufacturing via licensing. Increased profits from deployment and market prospects also increased resource availability, which was also used to increase domestically produced new knowledge (knowledge generation F3, as indicated by rising patents during this time). The increased domestic knowledge started to diffuse, which closed the positive feedback loop and led to acceleration of the innovation system development and increased importance of joint ventures instead of licensing as mode of technology transfer.

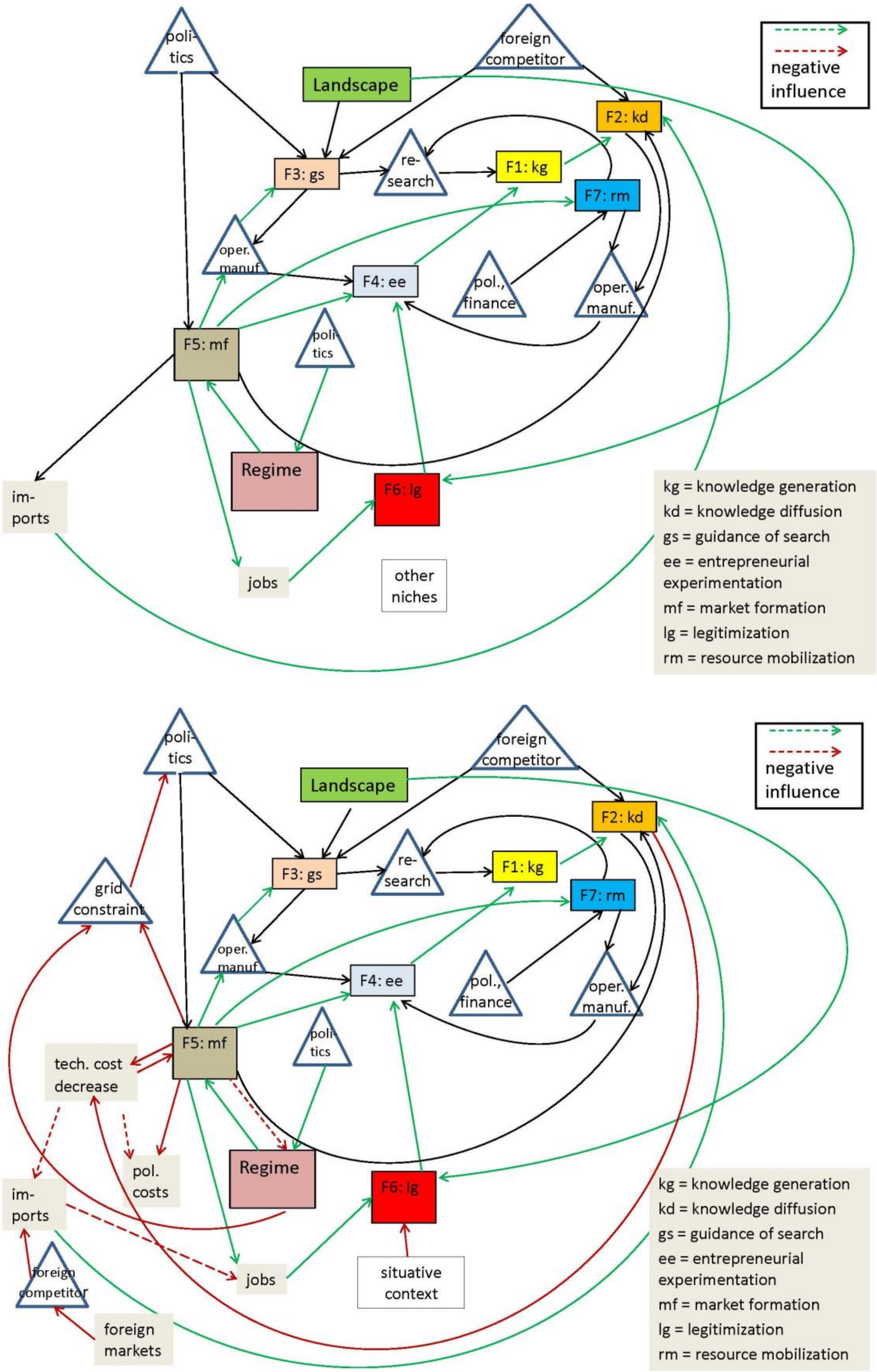
In the third phase, acceleration of growth and diffusion of knowledge lead to decrease in costs of newly installed wind turbines, which fell dramatically after 2007. However, the incentive system put the focus on installing capacity (MW), not on feeding electricity to the grid. Perhaps this also suited the interests of the coal dominated regime not to reduce the importance of the traditional coal based power plant system (interplay with regime). This development is in line with the surprisingly high level of installed capacity not linked to the grid, and is also made responsible for Chinese manufacturer's strategy not to put higher emphasis on increasing quality of the turbines (as there was no incentive for doing so). Thus, Chinese turbines gained in cost competitiveness compared to foreign ones, and as quality – showing up in higher levels of kWh per installed KW - was not rewarded very strongly in the home market, also gained rapidly in market shares in China. This also allowed the Chinese government to remove local content requirement. The success in domestic buildup of industry, supported by naming renewable energies as one of the emerging strategic technologies in the Five Year Plan, further increased legitimacy (F6) and accelerated positive feedback cycles even further (red arrows in Figure 7c). Situative context factors such as the financial packages in the aftermath of the financial crisis and financing available via CDM also benefited green technologies. The same applies to growing concern about rising levels of local air pollution (situative context factor in combination with landscape factor). In a virtuous cycle, knowledge generation and subsequent knowledge diffusion of domestic generated knowledge increases strength of domestic companies. The correction of incentives (feed-in-tariffs) gives new guidance of search, and an increase in quality of Chinese wind turbines can be expected. However, the time lag until a first positive feedback cycle was established, and guidance of search towards low cost installation, has been also responsible for China not being able to realize higher exports of its technology.

Figure 7a: Feedback loops and actors involved in the first phase of Chinese wind energy development




Source: Fraunhofer ISI

Figure 7b and c: Feedback loops and actors involved in the 2nd and 3rd phase of Chinese wind energy development




Source: Fraunhofer ISI

# 5 towards modelling: Lessons learnt and next steps

The paper shows that the approach of modelling the dynamics of transitions with a system dynamics approach is highly promising: It is able to integrate the internal dynamics of TIS with the external dynamics of MLP. The case of wind energy in Germany and China shows feedback loops, which explain the internal dynamics between the innovation functions. Landscape is important for starting positive cycles; however, in the case of Germany, it can also be a retarding influence in later stages of development. There are various tipping points of dynamics, which are characterized by counteracting influences of internal dynamics and regime resistance. In Germany, these tipping points raise the question whether or not the system further gains momentum. In China, it is decisive whether or not wind energy enters a higher level of quality weakening the regime. Situative context factors and landscape influence play an important role in deciding which way the dynamics is continuing. The German case also signals that the dynamics changes over time, with legitimacy and market formation becoming more prominent in later phases. Aspects of advocacy and political economy play an important role, and are connected with effects of globalizing value chains. In Germany, this can be seen by the importance of exports for legitimacy and the nexus with jobs, in China by the importance of build-up of domestic production capacities supported by local content requirement and building on absorption of foreign knowledge. The importance of these arguments is rooted in general paradigms of economic strategies for both countries, which can be assigned to the landscape level. Thus. political economy considerations link aspects of landscape, and of regime niche-interaction to specific innovation system functions. This can be interpreted as political economy acting as a link to connect MLP and TIS approaches.

The comparison between dynamics in Germany and China also reveals differences:

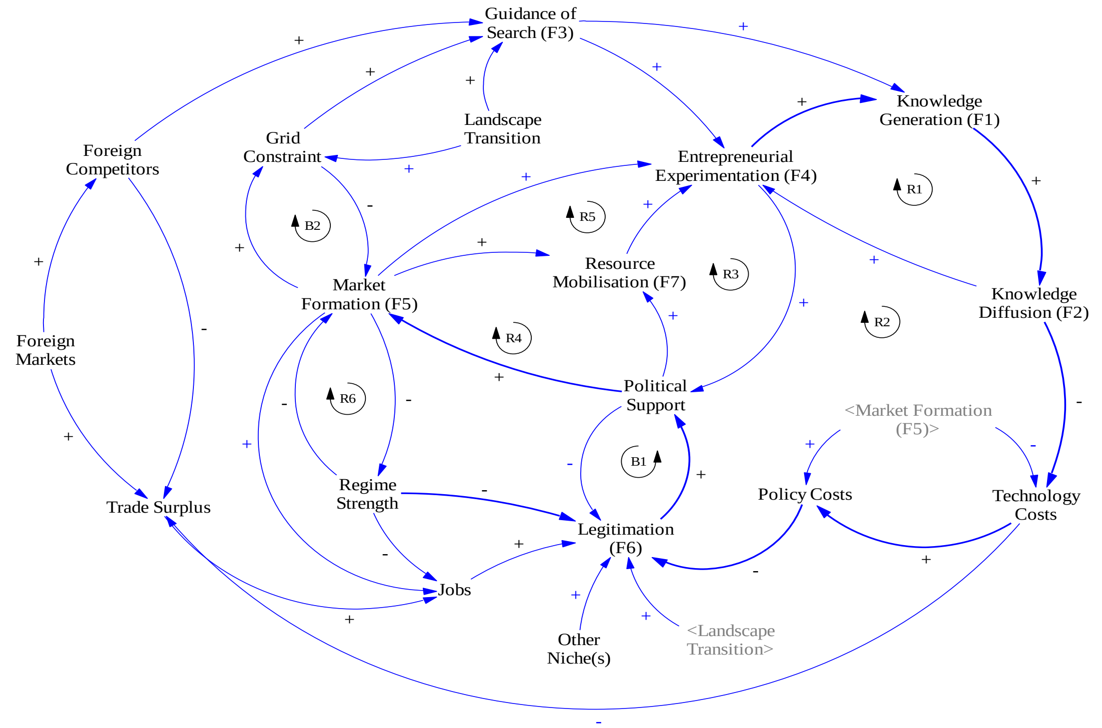
- Germany established positive feedback loop early on;
- The build-up of capacities to absorb knowledge in China makes knowledge diffusion F2 more important in the beginning;
- So far, no strong negative feedback loop has been developing for China; thus, the system is likely to expand furthermore; the effects of rising policy costs are not as visible and not so pronounced in China.
- There seems to be no pressure from landscape on sitting in China;
- The German development seems to be stronger influenced by political concerns (legitimacy more important; debate about jobs) than the Chinese, perhaps reflecting different cultural and political landscape factors.

- German development has reached a valley of death for further expansion, which reflects the growing need to finally adjust co-evolutionary institutions. China seems not to have reached that point yet, wind energy still can grow within the protected space.

Even though the analysis of the dynamics only concentrated on the most important aspects, Figure 5c and 7c already indicate that such an analysis becomes very quickly extremely complex. Thus, a typical case study based methodology quickly runs into problems of keeping track with all effects in such a complex analytical framework, and perhaps missing important implications of the systems structure, which might lead to increasing or faltering dynamics. Furthermore, it becomes difficult to judge how changes in a particular part of the system, which are related to one specific function (e.g. change in a policy) impact the overall dynamics. From a methodological point of view, this is an argument for supporting such a case study analysis by modelling tools.

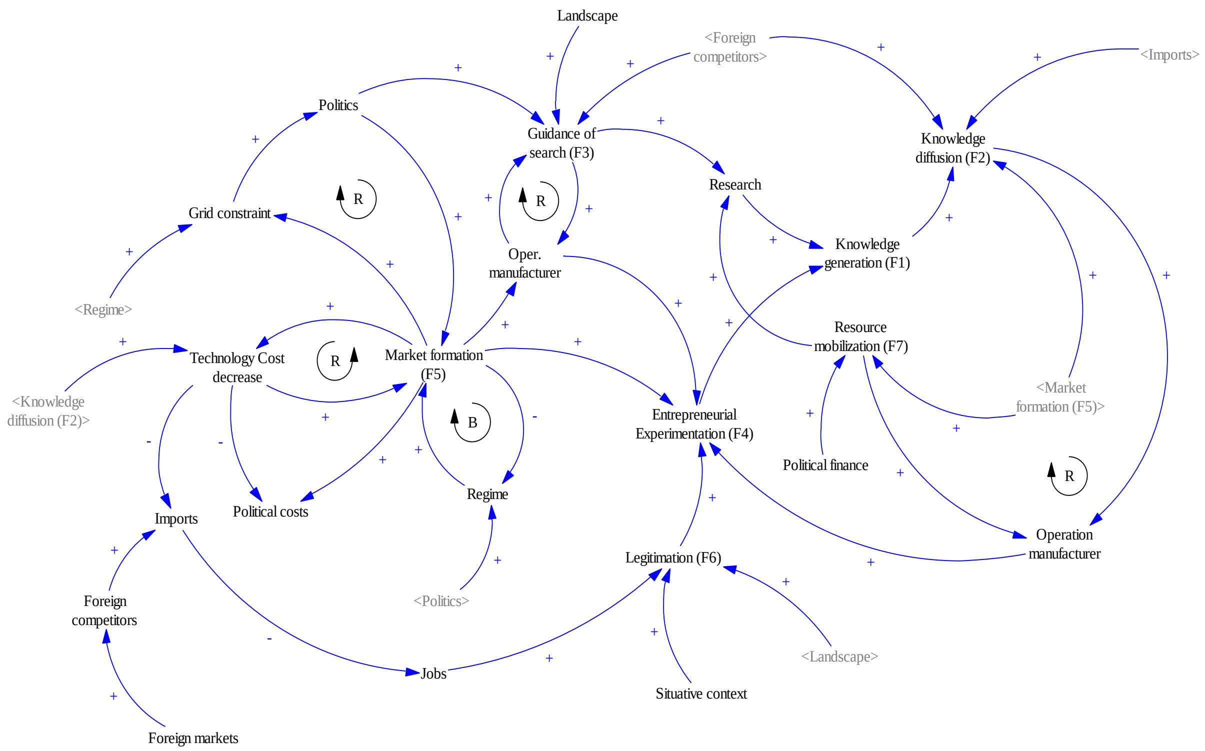
Such a modelling tool could be based on system dynamics, which has a long tradition in empirically analyzing system behaviour. System dynamics translates the qualitative system structures into formalized structures. The previous sections have shown that the complex case study results indeed yield feedback mechanisms and time delays, which form the first important step of system dynamics modelling. These structures can be further processed into causal-loop diagrams for computer-based simulations. The VENSIM software provides a flexible and simple platform for building simulation models (Ventana Systems, 2003). Figure 8 presents the results of the modelling exercise for Germany. Basically, Figure 8 is a translation of Figure 5c into system dynamics modelling which has been implemented by using the VENSIM software. In a similar way, Figure 9 translates the Chinese experience into a cause-loop diagram. The signs indicate whether the influence of one variable on the next one is positive or negative. All in all, there are eight feedback loops in the German, and five feedback loops in the Chinese case, which drive the development of the system. The sign of a loop tells whether it is a positive (reinforcing) or negative (dampening) feedback mechanism. Some of the feedback loops are also negative feedback loops, which reduce or even might reverse expansion of the system. Furthermore, threshold values and expectations play an important role. Especially if realized market formation is below expected market formation, the dynamics of the system might be reversed.

Figure 8: Causal-loop- diagram of wind energy innovation system in Germany




Source: Fraunhofer ISI

Figure 9: Causal loop diagram of wind energy innovation system in China




Source: Fraunhofer ISI

The feedback loops in the diagrams show the feasibility of translating the mental models of innovation system development into a structure which can be modelled with s system dynamics approach. The principal dynamics can be expressed in various feedback loops and with time delays between cause and effect. The motion of system development is started by effects arising from landscape, but also from interaction with other countries. The landscape is modelled as exogenous variable, which is not influenced by feedbacks from the system. The regime is weakened by the increasing strength of the niche; thus, it is modelled as an endogenous variable. However, this process has not been studied in detail yet, and might deserve more attention in future work.

Regime-niche interaction is translated with political economy considerations into effects on the function of legitimacy. This requires introducing various auxiliary variables into the model, such as exports. There is additional room for making the modelling more explicit, e.g. by introducing feedbacks on the competitiveness of foreign competitors or by a more explicit modelling of technology transfer and technology absorption. The level of performance with regard to an innovation function is interpreted as a stock variable, while the change in this performance is interpreted as a flow variable.

In order to move from the feasibility of modelling to building models, various challenges arise with regard to measuring the variables. Using system dynamics implies that stocks and flows have to be measured. The methodological difficulties to come up with measurable variables differ within and between the different types of variables:

- For some innovation functions, measurable variables are used already for some time; market formation (F5), for example, can be measured in physical (e.g. MW installed) or monetary terms, resource mobilization (F7) in monetary terms (€) or number of persons with certain qualifications, knowledge generation (F1) in commonly used innovation output indicators (patents, literature). For entrepreneurial experimentation (F4), indicators might be number of projects, number of persons involved, or number of new companies entering the field.
- Other innovation functions are more difficult to measure with indicators; knowledge diffusion (F2) might be measured with number of conferences, citations, or indicators derived from social network analysis. Bergek et al. (2008c) suggest to measure beliefs in growth potential, incentives from factor/product prices or the extent of regulatory pressures as proxies for guidance of search (F3). Furthermore, they use historical content analysis, backed up by counting of articles dealing with certain issues, in order to measure legitimacy (F6). However, in both instances, there are still methodological questions how to transfer these items into indicator systems.
- Many of the auxiliary variables can also be measured by traditional variables (e.g. trade surplus, foreign markets, costs, employment).

- Additional challenges lie in the measurement of landscape influence and strength of regime. In some areas, indicators might be available which describe changes in overall values and perceptions, such as surveys indicating the importance of environmental topics in a society. There has been a debate starting about indicators of social innovations lately (Reeder et al. 2012; Krlev et al. 2014), and depending on the methodological advances in this area additional indicators might become available.
- Finally, additional challenges arise with regard to the functional relation between the variables. One of the advantages of system dynamics is that it is flexible with regard to estimating these relationships. These can be estimated using statistical methods, expert opinion, market research data or other relevant sources of information (Sterman 2001a).

Recently, there have been several studies on renewable energy which analyse the interrelationship between innovation determinants econometrically (Johnson et al. 2010; Walz et al. 2011). The flexible approach of system dynamics allows the inclusion of the relationships identified in these studies into the broader system dynamics approach, and to combine it with other forms of information. Nevertheless, it becomes clear that developing such models will require time and substantial manpower.

# 6 Conclusions

The approach of modelling the dynamics of energy transitions, which require a replacement of fossil fuel dominated energy supply towards renewable energy, with a system dynamics approach is highly promising: It is able to integrate the internal dynamics of TIS with the external dynamics of MLP. The case study on wind energy in Germany and China shows the feasibility of such an approach not only on an abstract level, but for detailed case studies.

The analysis performed, and the various feedback loops which link the different aspects with each other, lead to a highly complex and interdependent system. The use of system dynamics opens up a perspective to simulate the system behaviour. Thus, analyzing innovation system dynamics might be a promising field in which case study based methodologies could be supported by model based analysis.

In addition to the methodological insights, the paper also yields interesting similarities, but also differences in the internal logic of the dynamics of innovation system development in both countries. The results also offer interesting input into the question, whether countries catching up systematically differ with regard to MLP mechanisms. The role of the regime in Germany seems to be more disruptive than in China. Perhaps this is an indication that renewable energy in China follows another transition path than in Germany. This might be related to the still existing growth perspective for fossil fuel in China, which is also typical for other catch-up countries such as India or South Africa. Furthermore, lower policy costs might be explained by indicating a second mover advantage. Thus, countries catching up might be less locked into a fossil fuel based regime. From a general point of view, this raises the perspective that an integrated TIS-MLP approach might also contribute to explaining leapfrogging potential for catching-up countries.

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