Governing Competing Technological Innovation Systems for Sustainability Transitions – Lessons from the German Energy Transition

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Short Abstract

Mission-oriented policies require instruments reacting on the dynamics of innovation and exnovation processes. This paper offers conceptual ideas on those process dynamics and the related governance challenges. First conclusions from the case of the German energy transition demonstrate its relevance for policy making.

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1. Introduction

Economic and innovation policy objectives have experienced a significant evolution in recent years. Apart from economic growth via the generic support of innovation activities, the public and academic debate as well as the policy making itself introduced further policy objectives aiming at the resolution of societal challenges via innovation (Gassler et al., 2008). The implementation of the Sustainable Development Goals, the Horizon 2020 Strategy of the European Union (EU) or the German Hightech-Strategy are crucial examples for this innovation policy shift to the so called “New Mission Orientation” (NMO). Mission-oriented innovation policy pursues policy objectives via a reflexive, technology-open governance through a policy instrument mix (Dachs et al., 2015). Even though these instruments directly address specific technological options for the mission accomplishment, the NMO is supposed to be technology-open as the support aims at experimenting with several technological options in market niches until the optimal technological path has been revealed (Aghion et al., 2009).

Sustainability transitions represent the most appearing example in the debate on mission-oriented innovation policy mixes (e.g. Grubb et al., 2017; Kivimaa and Kern, 2016; Rogge et al., 2017; Rogge and Reichardt, 2013; Wieczorek et al., 2010). Transitions consider the systemic change of established structures of consumption and production via technological innovations and changes in behavior. Systemic change in this sense involves two key processes: The innovation process aiming at the development and diffusion of new sustainable technological alternatives and the exnovation process focusing on the phase-out of established technological structures, which is only possible if either a technological substitute emerges or the use of old technologies is widely obviated (David, 2017; Kemp and van Lente, 2011).

The innovation and exnovation side of sustainability transitions are often not only related to just one technology: In the electricity sector, for instance, several renewable energy technologies are supposed to innovate the power production in order to overcome several incumbent technologies such as coal or nuclear power plants. Following Dreher et al. (2016), this study conceptualize the relation between the different old and new technological alternatives within sustainability transitions as a competition between Technological Innovation Systems (TIS). The TIS analysis framework is introduced in order to detect the specific stages of the technology life cycle for each technology as this is relevant for understanding the potential of the different technological options for the Sustainability Transitions (Bergek et al., 2008; Hekkert et al., 2007; Huenteler et al., 2016).

In the recent literature, innovation policy analyses for sustainability transitions often focused on the policy mix for the dynamics of the political support for one specific technology and its development and diffusion (Hoppmann et al., 2014). However, the principle of technology openness within the NMO claims the consideration of several technological alternatives and, hence, a governance that considers the state of maturity of the different options and guides to those options which guarantee at most the dynamic efficiency of the sustainability transition (Geels et al., 2008; Klein, 1984; Mazzucato, 2016).

It is the objective of this paper to conceptualise the challenges of a challenge-driven innovation policy referring to the NMO. Considering Sustainability Transitions as a combination of innovation and exnovation processes, this paper presents three main challenges for policy makers: The *innovation diversity challenge* for the equitable, but not equal support of all relevant technological options, the *exnovation challenge* of connecting the support of the new with the phase-out of the old technological paths, and the *timing challenge* of policy implementation and adaption to the dynamics of sustainability transition processes.

By presenting the implications of each of these governance challenges for policy makers the theoretical base for the analysis of mission-oriented innovation policy mixes and its dynamic adaption be demonstrated. The relevance of the conceptual ideas is then presented in the case study on the implementation and the dynamics of the renewable energy feed-in tariffs (FIT) in Germany as a typical example for mission-oriented innovation policy: They support different technological options for a green energy transition, but this support is dynamically adjusted to the evolution of the innovation process of each technology.

Furthermore, the study examines in how far the FIT adjustment in Germany has been combined with exnovation policies, notably for nuclear and coal energy. The observed time period begins with the implementation of the Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG) in 2000 and ends in 2017. In that way, this study expands the analysis of Hoppmann et al. (2014) on policy learning in the deployment of solar photovoltaic power by considering all supported technological alternatives (solar photovoltaic, wind onshore, wind offshore, biomass, geothermal and hydro energy technologies) as well as the established technological structures for the phase-out (nuclear, hard coal and brown coal technologies).

The course of this study begins with a review on the Sustainability Transitions literature with respect to governance issues in section 2. By providing a framework for the relevant timing decision of policy makers for both the innovation and the exnovation side of sustainability transitions, this section ends with the basic challenges for a dynamic governance of innovation and exnovation processes - also reflecting the basic research questions of this study. Section 3 describes the case of the German Energy Transition and the examined data sources giving the basis for the methodological thoughts presented in section 4. Section 5, then, analyses the quantitative and qualitative evolution of the German feed-in tariffs for all supported technologies in order to see in how far policy makers reacted to the innovation process dynamics. By reflecting not only the FIT for renewable energies, but also the implementation and adjustment of exnovation policies so far, it is, moreover, examined whether policy makers coordinated innovation policy adjustments with exnovation measures. Preliminary conclusions and hypotheses for future qualitative case study research with expert interviews are presented in the last section 6.

2. Theoretical perspectives on the governance of sustainability transitions

2.1 Sustainability transitions as a disruptive process

Sustainability transitions by definition aim at a disruptive change (Christensen, 1997): As current economic activities in production or consumption are supposed to damage the environment, a sustainability transition represents the process of overcoming these activities by a technological substitute or the abolition of these activities – or both to a certain degree. Thus, the disruptive character of sustainability transitions is inevitable for achieving sustainability transitions in firms or the economy (Boons et al., 2013: 3; Kivimaa and Kern, 2016: 205-206).

Sustainability transitions at the societal level often concern the change of entire socio-technical systems like the energy or the transportation system. Socio-technical systems are defined as networks of different actors (individuals, firms, other organization or collective actors) and institutions (cultural or technical norms etc. for regulating the relation between actors) aiming at providing a specific product or service for society. In contrast to socio-technological transitions, technological transitions, alone, do not include changes in user practices or in formal or cultural institutions (Carlsson and Stankiewicz, 1991; Geels, 2002; Markard et al., 2012).

In contrast to other socio-technological transition mainly aiming at a higher efficiency, competitiveness and economic growth, sustainability transitions follow the resolution of another kind societal challenge: The transformation of economic activities from an environmental damaging to a sustainable mode guaranteeing the same environmental conditions for future generations (Cagnin et al., 2012; Daimer et al., 2012; Kemp and van Lente, 2011; Kuhlmann and Rip, 2014; Nill and Kemp, 2009: 669-770). As these kinds of transitions require a change at the systemic level leading to higher costs and losses for those profiting from predominant technological structures (consumers and producers), sustainability transitions are subject to a prisoner's dilemma problem: The sustainability transition is in the interest of society on the long run, but almost nobody has an incentive to change behaviour and the use of technologies in the short run.[3]

2.2 The role of policy making

For overcoming the prisoner's dilemma problem, the state is supposed to use economic and innovation policy instruments providing the guidance towards sustainability. Concrete politically set objectives in international treaties and national legislation provide a forward-looking guidance for economic actors in demonstrating that policy making will impose a certain degree of sustainability transition in a defined period of time. By defining and following environmental objectives such as the reduction of greenhouse gas (GHG) emissions policy makers influence or even force economic actors to prepare for shift their production and consumption structures in a sustainable manner (Burke and Stephens, 2017: 37-38; Lindner et al., 2016; Weber and Rohracher, 2012; Wydra, 2015).

Neoclassical economics provide rationales for such policy instruments that internalize the negative external effects of GHG emitting economic activities by disincentivizing them (Jaffe et al., 2005). For example, a Pigouvian tax (Pigou, 1932) introduces a fixed price on GHG

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[3] An alternative view on costs and benefits of sustainability transitions for firms and economies has been postulated by Porter and van der Linde (1995): Environmental regulation also creates incentives for sustainable innovations strengthening international competitiveness of a country which might be able to achieve a new lead market status as the first exporter of green innovations. Therefore, profiteers of a stronger environmental regulation are all firms and sectors related to the development and production of sustainable innovations.

emissions or the use of fossil fuels such that economic actors are forced to reduce the GHG emitting activities or to adopt to sustainable technological alternatives. Another prominent instrument, the emissions trading system, follows the idea of Ronald Coase (1960), that individuals are able to negotiate the use of scarce public resources (or the publicly intended reductions of GHG emissions) without any policy regulation, if the state clearly defines the property rights on the concerned good. The emission trade system defines the property right on GHG emissions by the ownership of GHG emission certificates. It defines the overall amount of emissions, the society accepts for a certain time period, and allocates this amount in the form of certificates to economic agents either via grandfathering or via a price. For the defined time period, economic agents can sell or purchase certificates, if they want to reduce or augment their GHG emitting activities – the certificate price can be found in a market equilibrium (Jenkins, 2014: 467-469; Lehmann, 2012; Lehmann and Gawel, 2013).

Both instruments are able to achieve GHG reduction objectives – the cap-and-trade system just defines the allowed amount of emissions via the certificate allocation and the Pigouvian Tax can be adjusted in the way, that economic agents are forced to comply to the policy objective. The related market mechanism guarantees static efficiency in the sense of the neoclassical Pareto criterion[4] and addresses both market failures coming from negative environmental external effects and positive external effects of innovative activities fostering the development of new knowledge for sustainable technologies (Jaffe et al., 2005; Lehmann, 2012).

However, the postulated instruments do not give guidance for technology-specific decisions on the abandon of old and the development and diffusion of new technologies (Aghion et al., 2009; Gawel et al., 2017). This technology-neutral and static approach of neoclassical environmental economics leaves all fundamental questions regarding the technological direction of the sustainability transition to the market, or more precisely: to the current market ruled by incumbent firms. Therefore, with these instruments only aiming at the internalisation of the external effects sustainable product and process innovations can only emerge and diffuse, if the related incentive to a more sustainable production and consumption is high enough to compensate the price and cost differential resulting from the different stages of maturity between new and old technological paths (Arthur, 1989).

From a systemic perspective, the additional costs of transition for consumers and producers are more complex than a pure neoclassical perspective can imagine: Zundel et al. (2005) have well elaborated all the factors stabilising the established dominant design and, hence, the incumbent firms and technologies at the expense of high market entry barriers for new technological alternatives. For example, typical market failures basing on neoclassical innovation economics such as risk and asymmetric information on financial markets as a problem for new technological paths or subadditivities and economies of scale favouring established technologies which have already reached a sufficient degree of mass production (Schmidt et al., 2016: 1966-1969; Unruh, 2000). Moreover, Zundel et al. (2005) and other scholars with a more systemic view point out that other non-price-based barriers for new technologies exists: The knowledge development and diffusion for new technological paths are still in process,

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[4] Efficiency in the sense of Pareto Optimality means that nobody can be better off without harming another.

infrastructures may not be compatible with new technologies, regulation and institutions are often created for the established socio-technical system and interest groups of the incumbent firms and technologies are normally much more powerful (Foxon and Pearson, 2008; Negro et al., 2012; Unruh, 2000, 2002).

In consequence, a technology-neutral approach for fostering sustainability transitions aims at the cheapest solution in present (Jacobsson et al., 2009: 2144) – without considering in how far new technologies in an early-stage of the life cycle might by efficient on the long run. This idea of dynamic efficiency lies in the core of innovation economics, notably the evolutionary, neo-schumpeterian school of innovation studies (Del Río and Bleda, 2013). Dynamic efficiency exists if firms, sectors and entire economies are always able to shift their production towards more profitable technological paths (Klein, 1984). But because of the inherent uncertainty (Knight, 1921)[5] about the technology development, it is not sure whether an efficient technology in present will also be efficient in the future compared with other existing or new, emerging technological alternatives (Nill and Kemp, 2009).[6]

Following the perspective of dynamic efficiency, evolutionary innovation economics puts emphasis on the existence of several technological paths and the role of experimentation: Trial-and-error is the source of evolutionary processes meaning that the experimentation with different technological alternatives for the resolution of problems or challenges are inevitable for discovering a suitable technological solution as a new dominant design (Dosi, 1982; Dosi and Nelson, 2010; Metcalfe, 1994; Nelson and Winter, 2002). Zundel et al. (2005) define this kind of competition between different technological alternatives “new-vs.-new”: Technological transitions are often subject to the experimentation with competing technological options. This is considered by the idea of technology-openness within the NMO innovation policy conception: Not only one, but all relevant technological alternatives are supported in order to guarantee the variety of experiments which is necessary for dynamic efficiency. However, different technologies at different stages of maturities require an innovation policy basing on its specific needs and requirements in order to preserve a true competition between the different technological options. Therefore, technology-openness of the NMO crucially differs from technology-neutrality by using technology-specific policy-mixes for each technological option (Dachs et al., 2015: 25-26; Gassler et al., 2008).

2.3 Challenges for the governance of sustainability transitions

This NMO challenges policy making in the way that policy makers inevitably have to choose between different competing technological options: At first, policy makers have to choose which technologies might contribute to the resolution of a societal challenge. At a later stage of the transition, policy makers have to abandon supported experimental niches in order to

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[5] Uncertainty in this sense refers to the concept of Knight (1921) that uncertainty in contrast to risk is subject to incomplete information about the possible outcomes and the related probabilities of a random variable.

[6] Nill and Kemp (2009: 670-672) consider the disadvantages of both, static Pareto efficiency as difficult to use for the analysis of innovation processes as well as the idea of dynamic efficiency which is rather usable as an effectiveness criterion. Therefore, we refer to the idea that the governance of technological transitions is subject to a trade-off between both, Pareto optimality and the effectiveness of technological change, between static and dynamic efficiency.

lock-in to the most promising technological paths. If policy makers follow a technology-neutral approach, this can be seen as a decision for the lock-in to the cheapest option in present. If policy makers support the development and partial diffusion of several technologies for a certain amount of time, they have to decide which technological paths are considered as possible alternative for the transition, how policy mixes can be designed in order to create an equitable treatment for a true “new-vs.-new” competition and which technological path should finally become the dominant design of the transition (Arthur, 1989; Mazzucato, 2016; Zundel et al., 2005). We call this challenge for the governance of new mission-oriented technological transitions the *innovation diversity challenge*.

Technological transitions usually have a disruptive character as with the emergence of new technological paths the old paths have to be left. Sustainability transitions, particularly, aim at a disruption because the inherent motivation behind the transition is the overcoming of technological structures and behaviours damaging the environment (Markard et al., 2012: 955-956). However, due to the systemic character of technological transitions, innovation policy strategies only supporting the development and diffusion of green innovations do not necessarily lead to a beginning of the phase-out of the old polluting technologies. For the ordinary case of full competition markets the support of new, environment-friendly technologies immediately disturbs competition to the disadvantage of the incumbent polluting technologies. But if, for example, a socio-technological system is concerned by infrastructures as a natural monopoly or a high degree of state regulation within the market, the phase-out of the old requires a policy shift away from the old in order to move towards new technological paths (David, 2017; Kivimaa and Kern, 2016).

Referring to Zundel et al. (2005), technological transitions are subject to one more dimension of competition called “old-vs.-new”. Established technological structures still have a high economic value and importance, notably for specific regions and firms, such that the related interest groups will try to stop, to delay or to shape the transition as close to the needs and requirements of the incumbents undermining the idea of technological-openness idea of NMO. The existing NMO literature often omits or underestimates the importance of an innovation policy conception that also directly addresses the phase-out of the old technological paths by specific policy instruments. We therefore want to highlight this as an important aspect of the governance of technological transitions, especially for the case of sustainability transitions, and, therefore, define it as the *exnovation challenge* of NMO innovation policy making (David, 2017; Turnheim and Geels, 2013).

As mentioned above, dynamic efficiency requires time and variety of experiments such that there exists a trade-off between static and dynamic efficiency concepts for innovation policy makers: Often new possible technological alternatives will not enter the market without a technology-specific support “from niche to paradigm” (Geels, 2002, 2010; Nill and Kemp, 2009). This begins with the support of research and development (R&D) and first experimental business models in order to test in how far an invention can become marketable. In later stages of the transition, new technological alternatives often require subsidies for mass production as well as the adaption of existing socio-technological systems in order to create the conditions for a mass diffusion of new technologies. Thus, the technology-specific innovation policy mix for each option has to be adapted to the dynamic development of each innovation process (Jochem et al., 2009: 35-41). Moreover, the period of experimentation with different technologies is limited, as dynamic efficiency finally requires the abandon of unsuccessful alternatives and a lock-in to the most promising technological path(s) at a suitable point in time. Only this lock-in will, finally, achieve static efficiency gains in the form of specialisation of entire sectors and economies of scale such that the transition leads to a new transformed market in which further state innovation policy interventions are not necessary after the mission has been achieved (Mazzucato, 2016).

Thus, the NMO innovation policy conception demands for a dynamic understanding of policy making which stands in contrast to a static role of economic and innovation policy only aiming at providing a good and long-term regulatory market framework as well as stable macroeconomic conditions. This immediately concerns the governance of the new-vs.-new competition with the inherent uncertain character of innovation processes regarding the future technology development. But the dynamic policy making character holds true, as well, for exnovation processes: In the beginning of the phase-out, policy instruments are designed in order to creatively disturb the incumbents by setting incentives and a clear political guidance for the phase-out of the old technological paths. Later stages of the exnovation process can only take place if either technological alternatives have sufficiently emerged or political decision making accepts a significant shut down of polluting activities without substituting them. As this decision making is depending on the urgency of environmental goals, on the one hand, and on the speed of innovation processes, on the other hand, exnovation processes, as well, require a dynamic policy making. The call the problem of dynamic policy making for both, the innovation diversity and the exnovation challenge, the timing challenge of mission-oriented policy making for sustainability transitions.

After having delineated the three governance challenges of dynamic and disruptive sustainability transitions, the following subsection gives further conceptual hints on how researchers and policy makers should respond to these governance challenges.

2.4 A dynamic perspective of innovation and exnovation policy making

The conceptual answer on the governance challenges for sustainability transitions cannot be given without noticing the simultaneous development of each of the concerned old and new technologies. The challenge for policy makers relies in the simultaneous governance of the coevolution (Geels, 2014) of these different technologies. In order to react to this kind of challenge, policy making requires conceptual ideas of the dynamic adjustment of innovation and exnovation policy strategies to the dynamics of innovation and exnovation processes. For the governance challenge mentioned above, this paper proposes the conceptualisation of competing Technological Innovation Systems (TIS) for both the new-vs.-new and the old-vs.-new competition.

Based on the conceptual idea of Hekkert et al. (2007) a TIS is defined as “a network of agents interacting in the economic/industrial area under a particular institutional infrastructure (…) and involved in the generation, diffusion, and utilization of technology” (Carlsson and

Stankiewicz, 1991: 93). We refer to a competition not between technologies, but TIS, because not technologies themselves, but the underlying involved actors stand in competition by following the same objective: the further development and diffusion of a technology. It is called not only a technological system, but a TIS because the technology is considered to develop over time via knowledge created by R&D as well as tacit forms of knowledge generated in the application and diffusion of the related technology. The systemic perspective – including researches, firms, consumers, regional actors as well as all other related stakeholders – gives the opportunity to consider all relevant actors participating in the competition between different TIS.

This competing TIS approach (Dreher et al., 2016) is not only applied on the new-vs.-new competition. Existing dominant technological structures form an established TIS with ongoing incremental and radical innovation activities on this path. Related actors profit from the dominant technological path and therefore do not have any interest to leave it. The stabilisation of established TIS does not only consider innovation activities aiming at a better economic competitiveness for example via lower costs. The stabilisation of existing paths also means a mission-oriented search of ways how established TIS can contribute to societal missions without leaving them. Hence, established TIS have the strong interest to mitigate the disruptive potential of sustainability transitions or to slow down the transition which obviously contradicts to the interests of new TIS.

Thus, the TIS competition concept is applicable on both the diversity innovation and the exnovation governance challenge of mission-oriented innovation policy strategies. But as both of these governance challenges are subject to the timing challenge, a further understanding is required what the specific stages of innovation and exnovation processes imply for policy making. This is the reason why innovation and exnovation processes require a heuristic model as the basis for the discussion which timing questions are relevant for which of the old and new TISs. For the conceptualisation of the innovation process, the idea of double-boom dynamics (Schmoch, 2007; Schmoch and Thielmann, 2012) is preferred to a simple s-curve (Adner and Kapoor, 2016) as the double-boom-cycle idea puts emphasis on the uncertainty of innovation processes: Not every rise in R&D or diffusion means a sustainable progress of the innovation process which can always experience phases of re-orientation. The Science-Technology-Cycle of Meyer-Krahmer and Dreher (2004) in the following illustration 1 integrates both the science and the technology market dimension of innovation processes. The level of activity considers different innovation indicators such as patents or publications as indicators for scientific activities as well as sales as an indicator for the market diffusion. By the scope of activities, it is meant how diverse applications and designs of technologies might be.

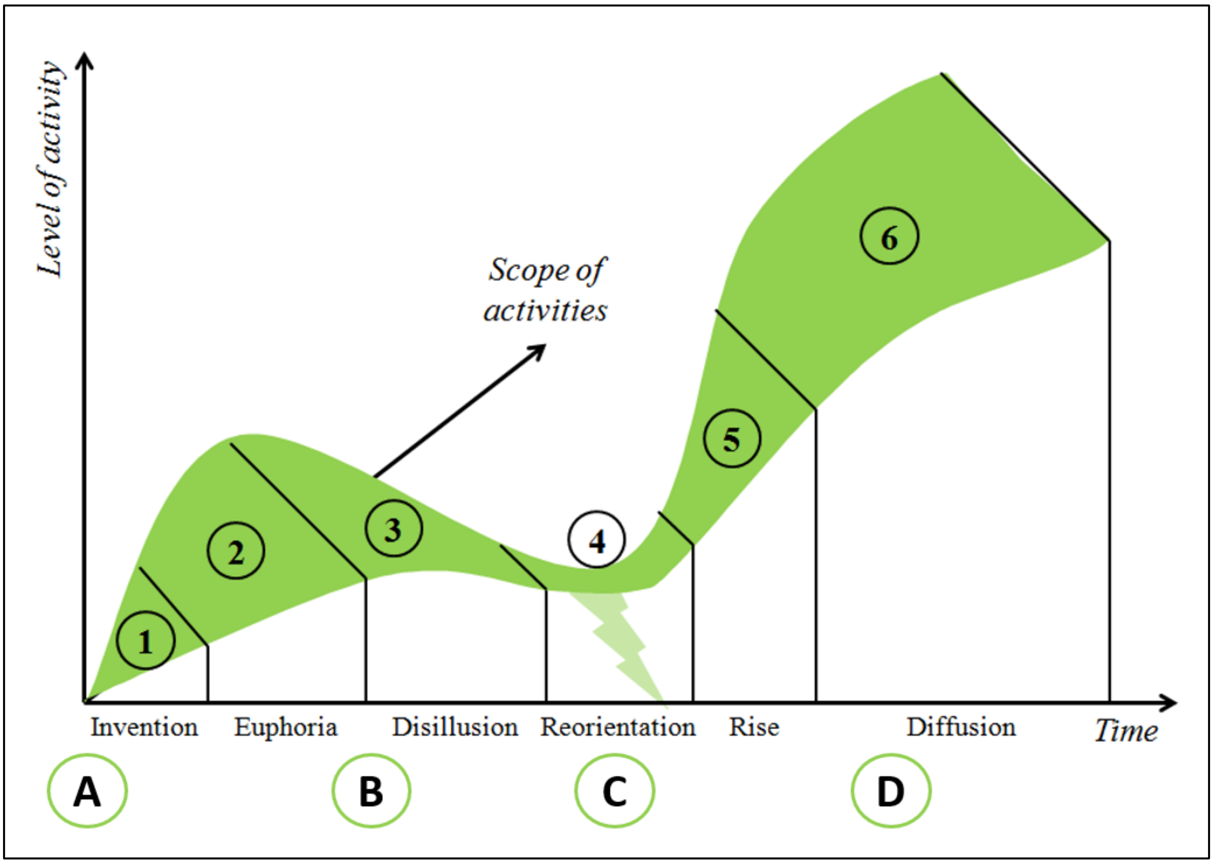

Illustration 1: The Science-Technology-Cycle.

Source: own depiction following Meyer-Krahmer and Dreher (2004: 29)

Invention and exploration (1) is characterised by scientific activities regarding new technological inventions motivated by curiosity, scientific reputation or political priorities in the financial support of basic R&D. After the successful introduction of a new technology, the scope of activities increases because of new possible application fields and further design ideas. This phase of *euphoria (2)* considers basic research and applied R&D in public institutes and firms. While big companies tend to focus on R&D activities, new start-ups try to apply the technology within a new business model. As first efforts in the development of new products often fail or require a broad extension of financial and personnel resources, a phase of *disillusion (3)* follows the euphoria. The scope of activities is reduced only on promising ideas, some stop their R&D activities, some new start-ups are forced to leave the market.

In the following phase of *reorientation (4)* the innovative technology will either experience an early sunset or become a convincing novelty with disruptive potential for the market. The remaining industrial and applied research actors play a crucial role. SMEs and new start-ups can only enter the development at this stage if the other players have made a mistaken assessment of the capabilities of the new technology. A successful reorientation leads to the *rise (5)*. First users impose a dominant design for the later adopters. Quality and reliability of the product represent the main competition parameters. Further developments of other companies, applied research and the complementary services supply reinforce competition. Prices have an increasing importance if not quality, but cost reduction largely influences the competitiveness of the innovation. Finally, the broad *diffusion (6)* of the innovation creates a lock-in often related to an irreversible shift of technological structures often accompanied with an adapted regulation. Possibly, new application fields are discovered due to the availability and shrinking production costs through learning curves and the intensive competition. At this stage the innovation reaches maturity in case of shrinking diffusion rates and a constant number of adopters (Meyer-Krahmer and Dreher, 2004: 30-32; Schmoch, 2007: 1009-1011).

This ideal-typical heuristic of an innovation process describes how the development and diffusion of an innovation process takes place. At different points of this Science-Technology-Cycle different problems for the innovation process and, hence, different rationales and requirements for a mission-oriented governance occur[7]. Four different governance questions have been identified and are indicated by a letter in the course of the ideal-typical innovation process (illustration 1):

A: How should R&D or other innovative activities be supported in order to create knowledge and to search for technological options resolving a societal challenge?

In the invention phase nobody knows which technologies might occur such that a technology-specific support is not possible at this point in time. If policy makers have identified societal challenges but do not see concrete technologies (or suppose that further technological alternatives might be developed in the future), mission-oriented innovation policy instruments addressing the knowledge creation through formal R&D or through other innovative activities can foster the search process for new alternatives. One example are direct R&D funding programmes for projects aiming at the resolution of the related societal challenge (Foray et al., 2012).

B: Which of the emerging technologies have the potential to contribute to the mission achievement and should be supported as a possible technological alternative?

After the phases of searching and inventing specific technologies emerged with different potentials for the resolution of a societal challenge. Policy makers, now, have to decide which technologies are considered to be an alternative for the mission achievement. If scientific actors and firms do not independently build-up a TIS for a new invention, the state has to decide in how far the disruptive potential of a technology justifies a policy-driven TIS creation. This includes R&D support instruments e.g. by the foundation of technology-related research institutes as well as instruments creating market niches for a further applied experimenting with new applications and business models around the emerging TIS. As some technological alternatives might be more promising, at first, or closer to existing structures and incumbent firms an equitable new-vs.-new-competition requires a technology-specific support along the related needs and requirements of each technology (Dachs et al., 2015: 25-26).

C: Do costs and the effectiveness of the technology legitimise an ongoing support of the development and diffusion of a previously chosen technological alternative?

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[7] As the following insights on governance challenges do not only concern the dynamics of sustainability transitions, but mission-oriented transitions in general, it is referred to the more general NMO approach and societal challenges, to which sustainability transitions obviously belong.

In the course of the supported innovation processes, information is revealed on the cost structures and the effectiveness of the chosen technological alternatives as well as its potential for system integration and market diffusion. Some will show a higher, other a lower potential. By comparing the performance as well as the R&D and other innovative activities policy makers have to evaluate in how far a TIS is still worthy of support, require further innovation policy instruments (notably for better conditions at the demand side, e.g. via regulatory changes or financial incentives) or should be abandoned in order to favour other more promising ones.

D: Is the market diffusion sustained and a lock-in justified or do further significant risks still exist compared to the other supported technological alternatives?

After the selection and the further establishment of the most promising alternatives at the demand-side it is the time to ultimately chose the best option or mix of options for the lock-in. If the best effectiveness for the mission achievement coincides with the lowest cost structure in one TIS, the abolishment of support policies for other TIS will let the market decide for the optimal solution. However, if this is not the case, the policy makers are able to force the socio-technical system to adopt to the technological path which is considered to have the best mix between cost-efficiency and effectiveness for the mission accomplishment.[8] The time period which ultimately requires a decision for the mass diffusion and the lock-in depends on the time a society has for the achievement of a societal mission. If the technological transition urges, only little time will be left for experimenting and waiting for the choice of the optimal technology from a dynamic efficiency perspective.

The support and choice for a new technological path cannot be analysed without the dynamics between the old, established TIS – and vice versa. As long as no new, suitable technological alternatives emerge, the exnovation process cannot start.[9] Furthermore, a disruptive technological transition is not necessary unless the established technological structures may still be able to achieve the societal objective on the predominant path. In consequence, it is important to analyse the co-evolution of innovative TISs and established TISs. The exnovation process of established TIS is subject to dynamic developments as well. Therefore, the following proposed ideal-typical heuristic of an exnovation process is conceptualised as the inversion of the Science-Technology-Cycle above (illustration 2):[10]

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[8] This is considered as the formation of a new market because due to the lock-in the new technologies do not need further market-disturbing policy instruments such that the new market can develop towards the neo-classical understanding of static efficiency (Mazzucato, 2016).

[9] This holds true unless the economy the economy is not crucially depending on the established TIS. For example, even if policy making in energy transitions try to reduce energy consumption in order to make the exnovation process easier, energy in the form of electricity or heat is still the most important resource for hardly every economic activity. Therefore, it is of crucial importance that an exit of a fossil-fuelled energy generation can only be introduced with the simultaneous increase of alternative renewable energy sources.

[10] The following concept is still work in progress. In order to demonstrate the basic exnovation dynamics we omitted the third axis of the scope of activities so far. The aspect of the scope of activities is left to further discussions about and developments the exnovation process heuristic.

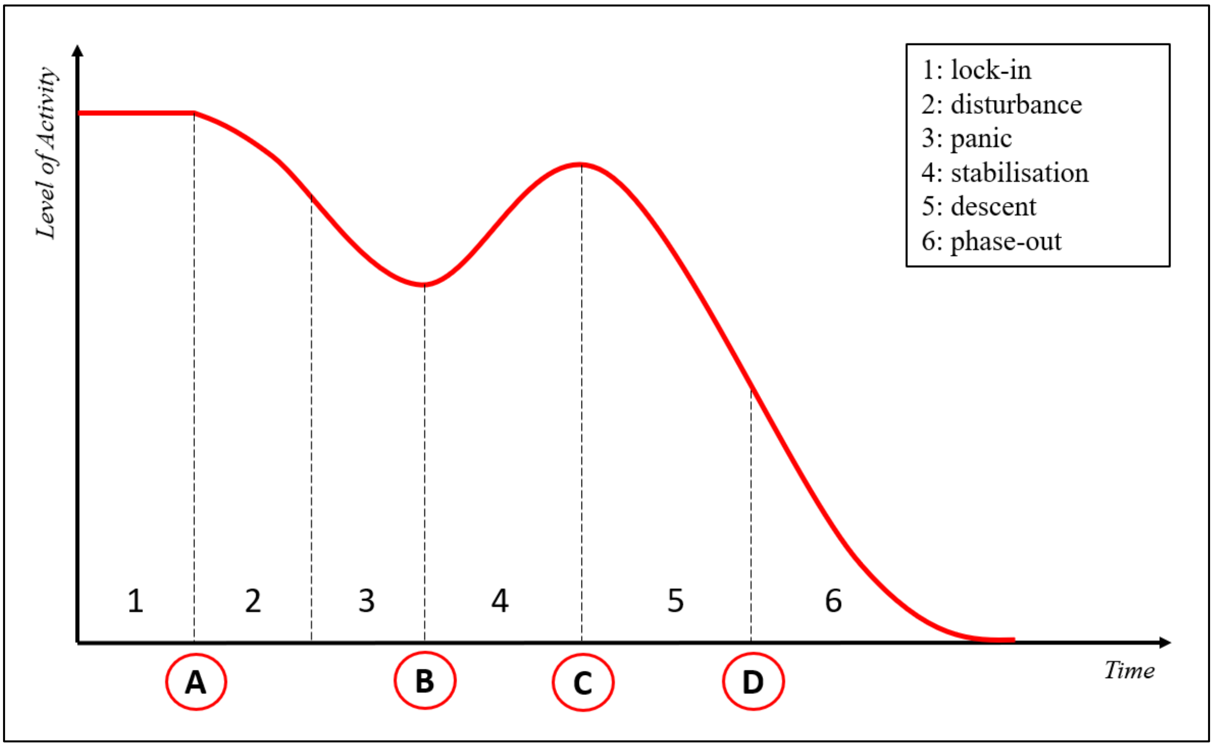

Illustration 2: The Science-Technology-Exnovation-Process.

Source: own depiction

The ideal-typical exnovation process begins with the phase of the established *lock-in (1)* to a dominant technological path (which represents the end of the Science-Technology-Cycle). A first *disturbance (2)* emerges if consumers or firms change their behaviour due to a shift in market preferences or policy guidance (e.g. to more sustainable production pathways). Early dropout firms experiment with incremental improvements of the established technology in order to cope with the changed demand conditions. If more actors decide to leave the dominant path, the phase of *panic (3)* will lead to further efforts for stabilising the existing technological structure. Bigger firms will spend more resources on R&D in order to adapt established technologies to the changed consumers' or political preferences.

The following *stabilisation (4)* is the result of incremental improvements done so far. Furthermore, due to failures in the development of improvements or alternative technologies the exnovation is considered to be far more difficult or even impossible. However, if preferences of the consumers or societal challenges are urgent the phase of the *descent (5)* occurs. Incumbent actors realise that the existing path cannot be stabilised any more. This process can be accelerated further by the existence of serious technological alternatives which might cause a disruptive transition away from the old and towards the new. Incumbent firms will try to enter those new technological paths which are closest to the predominant path in order to keep the risk and the costs of the transition as low as possible within. Moreover, it is in the incumbents' interest to slow down the process for profiting as long as possible from the established structures. In the last stage of the exnovation process, the *phase-out (6)* is planned and irreversible.

Similar to innovation processes, different governance questions arise as well at different stages of the exnovation process. Again, four different governance questions have been identified and are indicated by a letter in the course of the ideal-typical exnovation process (illustration 2):

A: Does a significant disturbance of an established path take place – either by a shift of consumer preferences or by political willingness?

A society cannot aim at the phase-out of specific technologies if not reasons have been fount yet. Possibly, consumers are tending to existing superior alternatives or are aware of environmental problems such that a part of them prefers other sustainable modes of production or a reduction in consumption. The first disturbance can also come from policy making for example indirectly by introducing economic incentives for the internalisation of negative external effects: GHG emission prices, for example, makes the established TIS actors to think about incremental improvements for lower emission levels.

B: Does the exnovation process accelerate seriously through the rise of alternatives or a further change in consumer or political preferences?

In the phase of panic, the exnovation process leads to a significant shift of activities within the incumbents in order to stabilise the predominant TIS. Incremental or radical innovations aiming at environmental improvements are introduced because of this struggle of survival. This can be supported via mission-oriented R&D programmes – but only in case of significant hints that the established path can possibly be maintained without neglecting the achievement of the societal mission. In case of no clear signs favouring the maintenance of the current path, policy making has to focus on the development of disruptive alternatives in order to avoid significant reductions in economic activities.

C: Should the exnovation process continue and accelerate or stop because of missing technological alternatives or serious improvement in line with the societal mission?

After disturbances and panics lead to the discussion of alternatives to and improvements of the current path, the state has to answer on the question if the current path should be left or not. Sometimes technology-neutral instruments aiming at the reduction of polluting activities are already enough for overcoming old technological structures. But if the stabilising factors for the established path are very strong, further steps of the exnovation process cannot be done without a strong policy shift for example via strong regulatory specifications.

D: When should the phase-out be completed?

At the later stages of the exnovation process the decision has been made to phase-out of the existing path. But if other alternative technologies are still not able to sufficiently replace the old technological path, the bridging technology arguments is used in order to legitimize the use of the established TIS as long as possible. In a special case, the exnovation process can be subject to an old-vs.-old competition as well: If several older technologies exist, policy makers are supposed to use those technologies with the lowest potential for further environmental damages. The case of the energy transition is a good example, as simultaneously exnovation processes consider nuclear power plants as well as hard, brown coal and gas power plants.

As a result, the derivation of governance questions from the innovation and exnovation process dynamics helps to understand that mission-oriented innovation policy mixes have to consider the specific dynamics of each concerned TIS and their co-evolution, as the dynamics of innovation and exnovation have mutual influences. In order to demonstrate the relevance of the conceptual framework, the research project use the following methodology.

3. Methodology and research question

The German energy transition at the electricity market has been chosen as a suitable case for innovation policy making following the idea of the NMO. Several technological alternatives (notable solar photovoltaic, wind onshore, wind offshore, biomass, geothermal and hydro technologies) have been supported via technology-specific FIT and other R&D support and regulatory measures. Furthermore, the German energy transition started from an industrial structure mainly permeated by nuclear power plants and fossil-fuelled electricity generation through hard coal, brown coal or gas. From a policy making perspective, the German energy transitions started to obtain a mission-oriented character with the implementation of the Renewable Energy Act (EEG) in the year 2000, which did not only introduce higher FIT, but also specific extension objectives for the renewables. Furthermore, the German GHG emission reduction objectives represent another mission claiming for a change in the electricity mix. Finally, the specific German decision for a nuclear phase-out makes this case even more interesting as differences in the phase-out strategies of the established electricity production paths can be examined. In order to analyse the dynamics of innovation and exnovation processes the research project focuses on the time period between the introduction of the EEG in 2000 and the current edge (2017).

Some work already exists on the dynamics of specific renewable energy TIS in Germany (e.g. Dewald and Fromhold-Eisebith, 2015; Dewald and Truffer, 2011), the coevolution of the renewable energy TISs in Germany (e.g. Dreher et al., 2016) or in the Scandinavian countries (Miremadi et al., 2018). However, regarding the analysis of policy making, case studies mainly focused on one technology, notably photovoltaic (Hoppmann et al., 2014; Quitzow, 2015) but do not systematically consider the coevolution of policy making and priority-setting in the course of the technological transition. This project wants to expand the foregone analyses by considering policy dynamics and policy learning referring to all relevant old and new TISs. Following the understanding of sustainability transitions as a process of competing old and new TISs, this study puts emphasis on a joint governance of competing TIS: Policy makers have to adapt the technology-specific policy mixes simultaneously in order to chose the suitable alternatives at each stage of the innovation and exnovation processes. Therefore, the main research question is: Did policy makers address the relevant dynamic governance questions in the course of the innovation and exnovation processes within the technological transition?

In order to answer this question for the case of the German energy transition at the electricity market, the methodological approach of Hoppmann et al. (2014) for the analysis of policy dynamics for the deployment of solar photovoltaic is adapted and expanded to the other relevant old and new TIS. A qualitative case study research approach is employed for a further understanding of the dynamic coevolution of policies for the different old and new technological alternatives (Yin, 2009). This methodology aims at the validation of the conceptual ideas on the dynamic governance challenge of innovation and exnovation processes in technological transitions. This inductive case study research shall demonstrate the importance of a further expansion of the theoretical discussion (Eisenhardt and Graebner, 2007).

In a first step, the collection of data from official reports and data sets as well as other studies on the dynamics of the TISs and the related policies are collected in order to overview the policy dynamics and policy learning for each of the relevant TIS. Regarding the policy analysis, the study mainly focuses on the dynamics of the FIT scheme based on the EEG and its amendments until 2017. For the governance of the old TIS, the study considers the German legislation on the nuclear phase-out as well as policy instruments aiming at a reduction or stabilisation of hard and brown coal nuclear power plants.[11]

The analysis of the different data sources aims at the formulation of hypotheses on the question, whether the different policy changes addressed the relevant dynamic governance question for the related TISs. After the formulation of hypotheses, the second step of the research project pursues the verification or rejection of the hypotheses by qualitative expert interviews as another relevant data source for an in-depth understanding of the policy dynamics and its purposes at the different phases of the processes.

In the current state of the research project, the first step of data collecting and analysing for hypothesis formulation is still in progress, such that, in the following, only a few hypotheses on the governance for the different old and new TISs in competition are delineated for a further discussion.

4. Insights from the evolution of policy making in the German Energy Transition

4.1 Innovation policy learning within the German feed-in tariff scheme

The support of renewable energy in the German electricity mix has mainly been supported by the FIT scheme of the EEG in the year 2000 as the main demand-sided financial instrument for the promotion of renewable energies. The technology-specific approach supported each chosen renewable energy technology by a specific FIT which is annually adjusted. Thus, by using the FIT scheme policy makers made a choice according to the governance question B and identified the technological paths considered to contribute to the resolution of the societal

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[11] One limitation of the focus on the competing TIS is the omission of further technological context structures important for this TIS competition (Bergek et al., 2015). In particular, a further analysis of the technological dynamics of the electric grid as the main infrastructure and the policy mix guiding the transition of the grid for the integration of the renewable energies might be insightful as well.

challenges coming from global warming and the decarbonisation of the economy. Furthermore, the German federal government introduced diffusion objectives for renewable energies, in general, such that the different renewables are still to an open new-vs.-new competition: The share of all renewable energies in the electricity mix should rise to at least 35 percent in 2020, 50 percent in 2030 and 80 percent in 2050 (BMWi, 2016: 13). The following illustration 3 shows the development of the German gross electricity generation by energy source technologies.

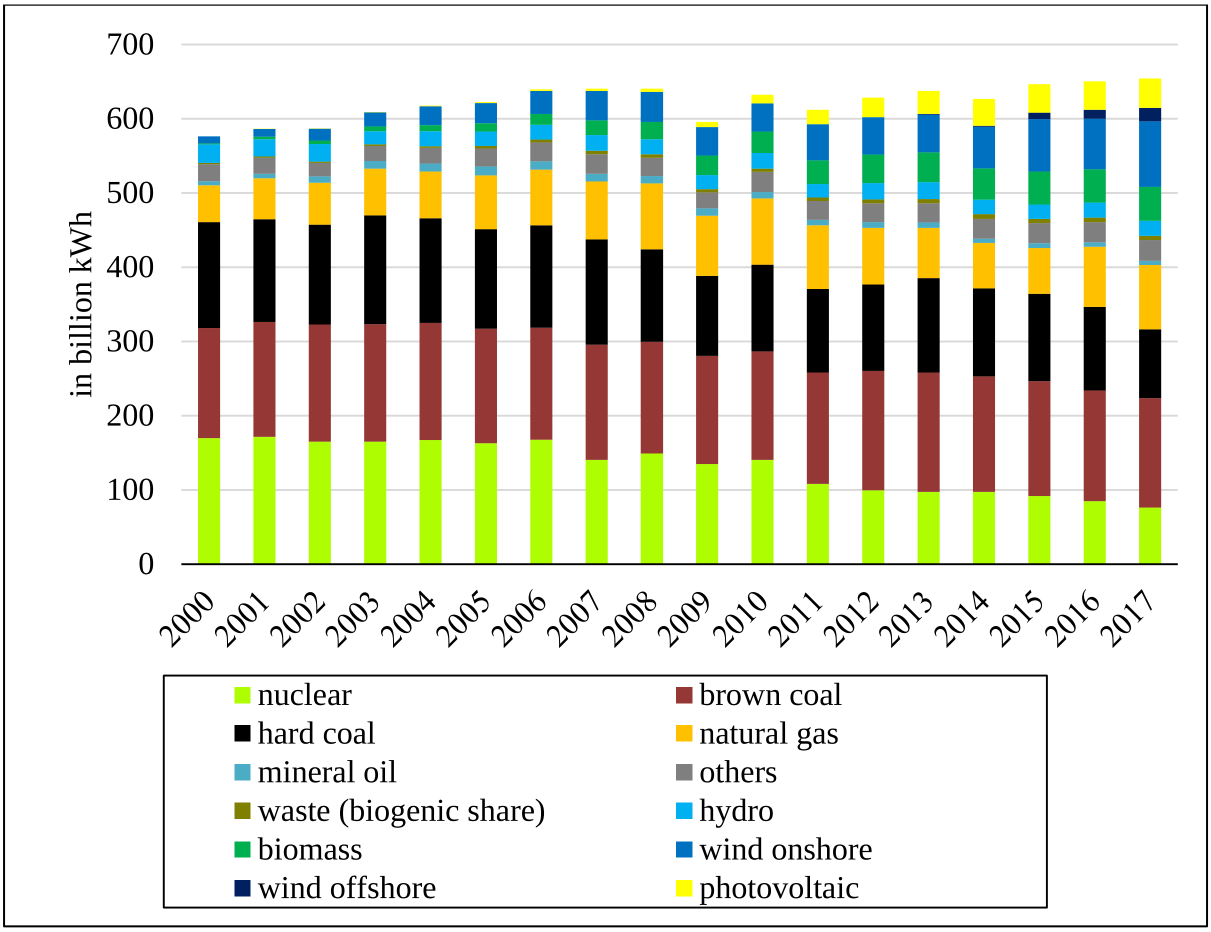

Illustration 3: Gross electricity generation in Germany in billion kW/h.

Data source: AG Energiebilanzen (2018)

Photovoltaic, wind onshore and biomass energy experienced a significant increase in the German electricity mix, whereas geothermal energy still does not develop or diffuse significantly. Despite the introduction of a FIT for hydro energy no significant increase resulted because of the limited geographical space for hydro energy capacities in German waters. Wind offshore as another renewable energy alternative emerged later and was supported by an own FIT since 2009. As a result of the innovation processes so far, 37 percent of the electricity mix in 2017 have been produced by renewable energies. The renewable energy extension objective for 2020 has already been achieved.

Due to the different dynamics of the renewable energy TIS some of them are now subject to other dynamic governance questions then others:[12] The photovoltaic, wind onshore and biomass TISs have already reached the governance question D, because due to the success of these renewables policy makers now have to decide whether further measures for a more substantial lock-in should be introduced or not. Wind offshore as a further technological alternative emerged, but it is still too early to think already about a possible lock-in. However, if policy makers decide to wait in order to see the future potential of wind offshore compared to the other grown renewables, this means that in order to guarantee an equitable competition it might be necessary to wait with a lock-in, until wind offshore could have revealed its innovative potential. This governance strategy also implies to wait with further exnovation accelerating policy adjustments (see 4.2).

As the extension objectives for renewables have already been achieved for 2020, there is no need for a further step towards a lock-in. As the potential of hydro power in Germany has probably been exploited, a further lock-in (question D) is not possible. For the geothermal TIS the question C rises whether the support should still be granted or adapted (e.g. towards a further R&D support in order to solve the related problems by the creation of additional knowledge). Otherwise, German policy makers might decide to stop the support of geothermal technologies because of the low potential and innovation dynamics compared to the others.

In how far the feed-in tariff scheme answered to these governance questions and to the dynamics of the innovation processes of the different renewable energy TISs can be analysed by considering the following illustration 4.

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[12] Apart from this diffusion indicator, further indicators and information have to be used in order to confirm these first hypotheses on the stage of the different renewable energy TISs in the innovation process. For the identification of the dynamic governance question for the TISs it is referred to the letters of the ideal-typical Science-Technology-Cycle in illustration 1.

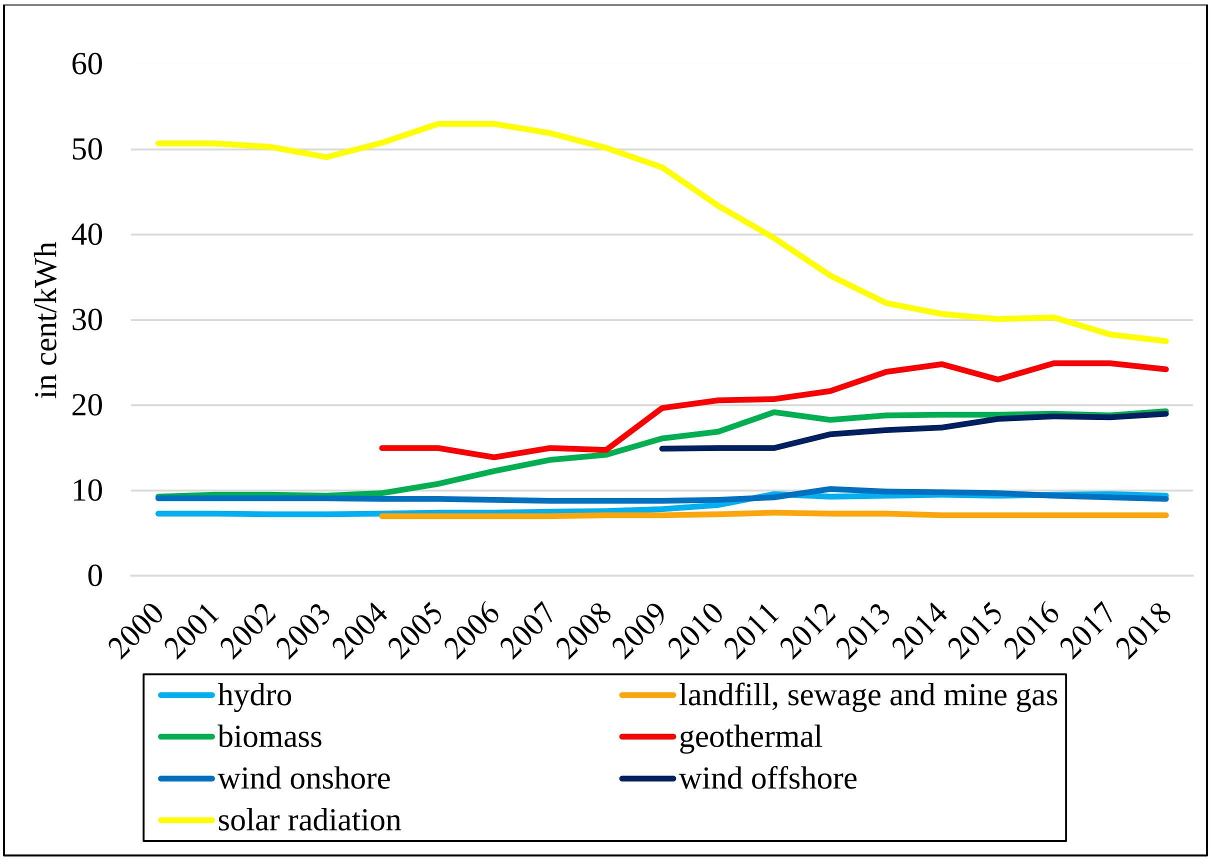

Illustration 4: Average renewable energy feed-tariffs in Germany by energy source in cent per kW/h[13]

Data source: BMWi (2017)

Compared to the other renewable energy FITs only photovoltaic experienced a huge decrease in the financial support. The other feed-in tariffs either remained constant (hydro and wind onshore energy) or even increased (biomass, geothermal and wind offshore). While the decrease of photovoltaic FITs shows that policy makers reacted on the diffusion dynamics and the higher state of maturity, the increasing other FITs show that policy makers still try to accelerate the development and diffusion of other renewable energy TIS. The further analysis will consider other indicators such as the cost structures or knowledge creation activities (patents etc.) as well as on further amendments of the FIT scheme concerning flexible caps and other policy design aspects. This leads to more insights on the question in how far policy makers have been able to identify the relevant dynamic governance questions and whether they reacted consistently by modifications of the policy mix.

In order to understand the general priority setting and the direction policy makers are following via the innovation policy mix, a closer look at the exnovation side and the coherence between innovation and exnovation policy mixes is required.

4.2 Exnovation policies for the phase-out of nuclear, but not coal power

Considering mission objectives as important for the NMO policy strategy for sustainability transitions, it is interesting to see, that extension objectives for the renewable energy TISs in

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[13] The data for the years 2017 and 2018 are forecasted values.

Germany have been implemented without technology-specific numbers, whereas for the phase-out of the conventional energies concrete exit plans have only been introduced for nuclear energy via legislation. Exnovation policy instruments for decarbonisation such as regulatory measures or the European Emission Trade Scheme (ETS) only indirectly concern the other fossil-fuelled conventional energy TISs in Germany (David, 2017; Renn and Marshall, 2016). However, considering the development of the installed capacities of conventional energy TISs, it can be seen that significant reduction has only been achieved for nuclear power. Gas, hard, and brown coal capacities remained at the same level over the last two decades (illustration 5):

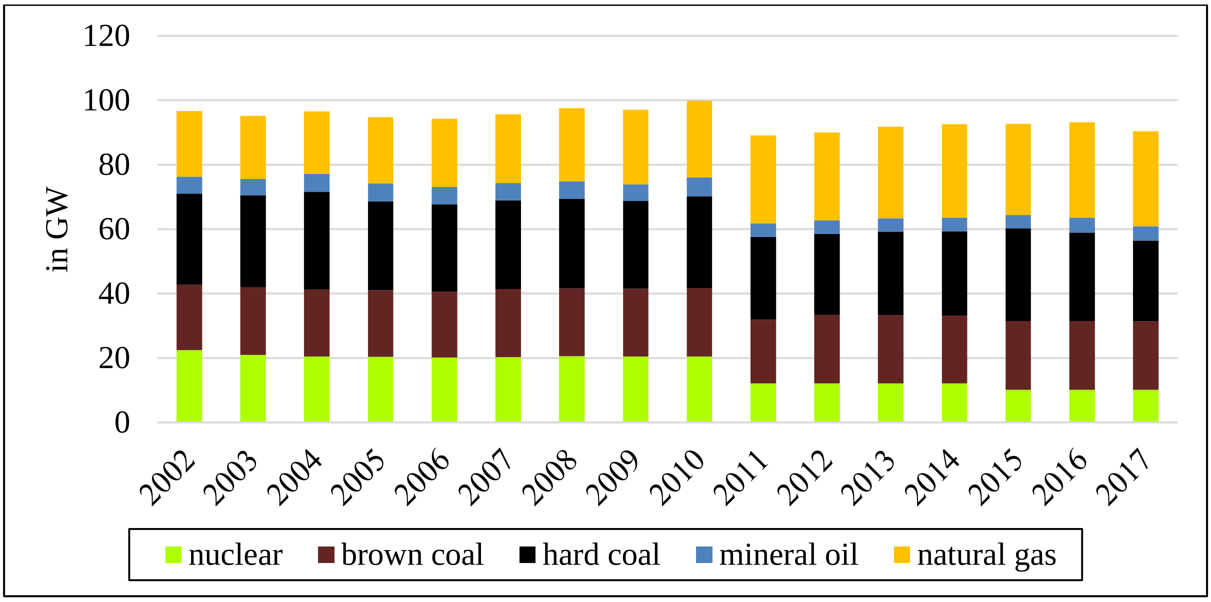

Illustration 5: Installed capacities of power generation of conventional energy sources in Germany.
Data source: Fraunhofer ISE (2018)

Regarding the governance questions for the conventional energy TISs it exists crucial differences between nuclear and the other fossil-fuelled technologies:[14] While the nuclear phase-out is already taken place and subject to a fixed exit date (policy makers already answered the exnovation governance question D), the decarbonisation of the electricity production has not yet begun significantly. Even if a little disturbance has taken place, gas, hard, and brown coal TISs are still subject to the governance questions A or B. No further disturbances have occurred neither by consumers nor by policy makers. Furthermore, innovation activities within the fossil-fuelled TISs still try to develop technological modifications such as CO_2 capture and storage (CCS) for stabilising the conventional technological paths (Hohmeyer and Bohm, 2015).

Regarding the treatment of gas and coal TISs, it is remarkable that German policy makers did not react on the different emission levels of coal and gas power plants. Although gas power plants are supposed to emit far less GHG emissions, no further efforts have been made for the use of gas power as a bridging technology such that more coal power plants could have been shut down. On the contrary, the introduction of capacity markets for guaranteeing the security

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[14] For the conventional energy TISs, the governance questions of the exnovation process are relevant, which are indicated as letters in illustration 2.

of supply stabilised the brown coal TIS such that a further discussion on how to shut down coal power production capacities stopped although Germany will probably not achieve its GHG reduction objective for the year 2020 (David, 2017).[15]

In consequence, it can be concluded that the different old and new TISs within the German energy transition at the electricity market are subject to different process dynamics and, hence, governance questions. As the innovation processes for an extension of renewable energy capacities is functioning well, whereas exnovation processes so far only significantly concerned nuclear and not the other fossil-fuelled power production technologies, this can be a hint on a lack of directionality as well as a lack of policy coordination failure (Weber and Rohracher, 2012) between the governance of innovation and exnovation processes.

5. Preliminary conclusions and subsequent research steps

Considering the theoretical properties of the New Mission Orientation (NMO) it has been demonstrated that mission-oriented innovation policy strategies require a dynamic innovation policy mix framework for innovation exnovation processes. In particular, sustainability transitions often cannot sufficiently be supported with a focus on the development and diffusion of green innovations. The phase-out of old technological structures often has to be addressed directly by further policy instruments.

Due to its systemic character, technological transitions are conceptualised as a competition between old and new technological innovation systems (TIS) – all of them subject to specific system dynamics. While existing literature on technology life cycles gives insights on the governance challenges of the innovation side, the exnovation side, as well, requires a further understanding of the different phases and dynamics. Therefore, this paper delivers a conceptual idea on the dynamics of exnovation processes and the related governance questions.

The presented dynamic innovation and exnovation concepts have been used for the analysis of the case of the German energy transition at the electricity markets. First insights illustrate the relevance of a joint analysis of innovation and exnovation processes from a dynamic perspective in order to adapt continuously the related innovation and exnovation policy mixes to the dynamics. Further analysis, notable on the exnovation side of the German energy transition is required in order to validate the hypothesis that German policy making lacked of a joint coordination of innovation end exnovation policy mixes.

This research project is still work in progress such that this paper delivers a first understanding of a conceptualisation of dynamic innovation and exnovation in the context of mission-oriented technological transitions. A further conceptualisation, notably on the relevance of the scope of activities for the exnovation process, is requires. Further research steps are the collection and analysis of relevant data such that the hypotheses formulation can be continued

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[15] The new government formed by the conservative and the social democratic party in Germany aims at the foundation of an expert commission which is supposed to propose objectives and strategies for a coal power phase-out without stating a concrete date for it.

and finished. After that, the formulated hypotheses will be validated by qualitative expert interviews.

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