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Architectural change in accelerating transitions

Insights from the German energy transition

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As transitions accelerate, they often increase in depth and scope. Transition dynamics may go beyond changes in core technologies to include architectural change at the system level. In this paper, we study actor preferences for system technologies that underpin different system architectures. System technologies are important as they can affect the pace and direction of transitions including system architecture. Our empirical case is the transition in the German electricity system where actors disagree about how decentralised the system architecture should become. In electricity, system technologies ensure stable supply by e.g. providing flexibility for the integration of variable renewable energies. We find that many incumbents mainly prefer established centralized system technologies but because these are difficult to expand, they reluctantly accept a role for novel and immature decentralized system technologies. As for challengers, there are important differences from incumbents in terms of when and to what extent new system technologies are needed and how they should be supported. We make two contributions to the literature: 1) we introduce system technology as a concept and use it to illustrate tensions between the pace and direction of accelerating transitions, and 2) we show how actor roles and positions become more fluid during acceleration.

Keywords: Sustainability transitions; Acceleration phase; Disruption; System architecture; Germany

1 Introduction

The aim of this paper is to propose a novel way of understanding and analysing architectural change during the acceleration phase of sustainability transitions.

Addressing grand sustainability challenges requires far-reaching transitions in socio-technical systems such as energy, transportation or food (Geels et al., 2017). To address the urgency of challenges, transitions must enter a new phase in which they accelerate and possibly grow in depth and scope. While early stages of transitions are characterized by innovations in some core technologies such as renewable energies, acceleration is different (Markard et al., 2020). It includes rapid diffusion of novel core technologies which leads to a decline of established technologies (e.g. coal) and it may also involve changes in system architecture, which are major shifts in entire system configurations (Geels, 2018b; Johnstone et al., 2020; McMeekin et al., 2019).

Transition processes are often contested. Actors have competing interests and conflicting preferences about the pace and direction of transition processes (Lindberg et al., 2019; Roberts et al., 2018). Confronted with potential disruption—e.g. a devaluation of organizational assets or threats to established business models—incumbent actors sometimes work actively against new technologies (Geels, 2014b; Lauber & Jacobsson, 2016; Smink et al., 2015). In the literature, the politics of transitions has emerged as a vibrant strand of research, which investigates these kinds of tensions over transition targets, policies, technologies, and pathways (Meadowcroft, 2011; Raven et al., 2016; Roberts et al., 2018).

When transitions accelerate, these tensions often intensify (Markard et al., 2020). Widespread diffusion of novel core technologies may generate ‘knock-on effects’ and structural tensions with repercussions for the entire socio-technical system (Andersen, 2014; Haley, 2018). Architectural changes, which are major reconfigurations in system architecture, can be particularly disruptive for incumbent actors because they require deep organizational changes e.g. in terms of business models and firm identity. Although there is scope for reorientation by incumbents (Ansari & Krop, 2012; van Mossel et al., 2018), they typically prefer changes that are less disruptive (Geels, 2014a). Consequently, architectural change is typically spearheaded by actors challenging the incumbents (Christensen & Rosenbloom, 1995; Henderson & Clark, 1990; McMeekin et al., 2019).

Even though the issue of disruption and actor struggles around system architectures is arguably important for the acceleration phase of transitions, it has so far not been addressed in the literature (McMeekin et al., 2019). To address this gap, we analyse preferences of key actors regarding system architectures in a transition in the acceleration phase. To accommodate this analysis, we mobilize insights from the theory of complex technological systems (Arthur, 2009; Murmann & Frenken, 2006; Tushman & Rosenkopf, 1992) to propose the concept system technology as the basis for a novel way of understanding and analysing system architectures. System technologies generate system-level complementarities such as stable and reliable power supply. The configuration of system technologies underpins a particular system architecture (e.g. centralized vs decentralized). Studying contestations around system technologies can therefore reveal actor struggles over system architecture.

System technologies are important for several reasons. First, they can affect the *pace* of a transition. If they are available when needed, the transition will progress smoothly, if not, they may create bottlenecks (Haley, 2018; Hughes, 1983; Markard & Hoffmann, 2016). Second, they may affect the *direction* of a transition in the sense of transition pathways (Lindberg et al., 2019). Major investments in established system technologies, for example, create strong complementarities but they may also generate lock-ins, making it harder for alternative innovations to break through (Klitkou et al., 2015). Third, as new system technologies may be immature and fit poorly with prevailing system architectures, they may require public policy support, e.g. through subsidies, regulations, or common standards, to compete with established system technologies. Due to their importance for system architecture, the choice of system technologies may be contested. Different actors may support different kinds of system technologies, as some are better aligned with their assets and interests than others. Against this background, our research question is *which actors—incumbents and challengers—prefer which system technologies in accelerating transitions and why?*

We seek to answer this question by applying our system technology approach to a case study of the ongoing transition in the electricity system. A key challenge in this transition is that variable renewable energy (VRE) technologies such as wind and solar (which we conceptualize as core technologies) are diffusing rapidly which creates a need for new system flexibility to balance power supply and demand at all times (Bird et al., 2013; IEA, 2017). System flexibility is provided by flexibility technologies that support the interplay of electricity producing technologies and consumption. In this case, flexibility technologies are the equivalent to the analytical concept of system technology. We focus on the situation in Germany, where VREs have expanded rapidly while resistance by local initiatives has significantly hindered transmission grid expansion (the main established flexibility technology). This opens opportunities for alternative system technologies and architectures.

Analysis of multiple technologies and their interactions increases the level of complexity in analysis which challenges the in-depth, single case study methodology dominant in transition studies (Köhler et al., 2019). We therefore combine techno-economic and socio-political analysis. Techno-economic research provides detailed accounts of multi-technology interplays (Cherp et al., 2018; Robinius et al., 2017) but often lacks contextualized insights about socio-political factors (Geels, Berkhout, et al., 2016; Turnheim & Nykvist, 2019). Our study therefore has two main parts. First, we provide a desktop analysis of flexibility technologies drawing on techno-economic energy systems analysis to understand complementarities between technologies. In a second step we analyse socio-political aspects of flexibility technologies via analysis of public consultation responses of industry actors complemented by desk research and interviews. The techno-economic analysis informs our socio-political analysis of actor preferences.

We find heterogeneity in the preferences of incumbents. We also find that many incumbents prefer established centralized flexibility technologies (old architecture) but because these are very difficult to expand to accommodate new VREs, incumbents accept a role for novel decentralized flexibility technologies. Their reluctance for new architecture manifests in preferences for a rather limited role for new flexibility technologies far into the future and preference for no policy support for immature flexibility technologies. Many challengers also prefer a mix of old and new flexibility technologies due to the realization that existing flexibility technologies have a role to play in a future decentralised system. However, they remain skeptical to transmission expansion and the current institutional setup.

We make two contributions to the transition literature. The main contribution of the paper is to introduce and qualify the concept of system technology that improves our understanding of architectural change in socio-technical systems. In particular, the concept is helpful for grasping when and why the acceleration phase of transitions entails higher levels of disruption to incumbents and associated resistance and slow-down of transitions. Second, the paper shows that in the acceleration phase, actor roles and positions become more fluid beyond the incumbents-challengers dichotomy. We illustrate the range of incumbents' different strategies in the acceleration phase in relation to shifts in system technologies as well as how the strategies of challengers move from focusing on single technologies towards the functioning of the wider system.

2 Theoretical background

In this section we elaborate on the role of system technologies and system architecture in socio-technical systems and discuss how core and system technologies typically change as a transition unfolds through different stages of development. We also discuss how changes in system architecture affect, and potentially disrupt, incumbent actors.

2.1 Socio-technical systems, system technologies and system architecture

Socio-technical systems are complex arrangements of different kinds of elements (technologies, actors, institutions), which, together, provide societal services such as energy, water, or transportation (Köhler et al., 2019). During a transition, socio-technical systems change fundamentally. Changes may affect both the elements of the system and its architecture. In the following, we i) explain our understanding of socio-technical systems, ii) we take a closer look at, and define, two types of system elements (core and system technologies) and iii) introduce the concept of system architecture.

First, socio-technical systems can be understood as a nested hierarchy of subsystems (Geels, 2005; Holtz et al., 2008; Sandén & Hillman, 2011; Stephan et al., 2017). In this perspective, technologies can be studied at different levels of analysis (Murmann & Frenken, 2006). Take the electric vehicle, for example. The vehicle itself could be defined as a core (or focal) technology, its engine or battery as components at a lower level, and the wider transportation system as a higher-level system. In this paper we distinguish two hierarchical levels, system, and subsystem. The system level is where societal services such as electricity supply or transportation are provided. At the subsystem level, there are specific socio-technical arrangements such as electric vehicles or power plants charging stations, which, in combination, contribute to the functioning of the system, and its service provision at the higher level.

Second, at the subsystem level, we distinguish two types of technologies: core and system technologies. *Core technologies* directly help the system serving its societal function. Examples of core technologies are vehicles in the transport system or power plants in electricity supply.

System technologies are different: they facilitate and guide the interplay of multiple core technologies to form a larger, seamless system. System technologies thus *indirectly* help the system serving its societal function. System technologies must be defined in relation to a focal system and its core technologies. Converter technologies that allow AC and DC equipment to work together in the same grid can serve as an example (David & Bunn, 1988; Tushman & Rosenkopf, 1992).[1]

System technologies generate system-level complementarities (Markard & Hoffmann, 2016) with the purpose of improving overall system performance. The role of technological complementarities or externalities is widely acknowledged in historical studies of technology. For instance, work on techno-economic paradigms has emphasized the role of new or redefined infrastructures (e.g. canals, oil ducts, or the internet) for the diffusion of a new technologies and the emergence of a new paradigm (Perez, 2002, 2009). Infrastructures are a typical example of system technologies. However, infrastructures are typically viewed as "lumpy" technologies, i.e. large, capital-intense, long-lasting units (Andersen, 2014; Smith, 2005; Wilson et al., 2020). This view does not capture the full diversity of system technologies as they may also be modular and small-scale.[2] In our definition, system technology is solely understood in functional terms i.e. providing system-level complementarities.

Third, to understand the new challenges that arise when transitions accelerate, it is important to not just look at changes at the subsystem level (e.g., changes in core and system technologies) but also at system level changes. For these, we use the concept of system architecture. We understand *system architecture* as a specific configuration of multiple core and system technologies, actors, and institutions. Architecture is about the fundamental logic of how core technologies interact, division of labour and positions of actors, customer interfaces and preferences, and performance criteria for competition (Christensen & Rosenbloom, 1995; Colfer & Baldwin, 2016; Henderson & Clark, 1990).[3]

Our conceptualization of system architecture is inspired by the complex systems approach to technology anchored in management studies (Arthur, 2009; Murmann & Frenken, 2006; Tushman & Rosenkopf, 1992). The functioning of a technological system depends on the interactions of its subsystems. Interdependencies between subsystems define a technical architecture or dominant design of the system which is "mirrored" in a social architecture (actors and institutions) responsible for development, operation, and transformation of the system (Colfer & Baldwin, 2016; Tushman & Rosenkopf, 1992). The architecture partly emerges from properties of the technology (e.g. complexity) and partly from its societal embedding including user interfaces and service characteristics of markets (Abernathy & Clark, 1985; Clark, 1985; Murmann & Frenken, 2006). A match between technical and social architectures is important for overall system functioning. The performance of actors operating within systems is typically better if their

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[1] Note that there are different terms in the literature describing technologies that underpins the seamless interplay of other technologies including architectural (Christensen, 1992), linking (Tushman & Murmann, 1998), and gateway technology (David & Bunn, 1988). With system technology, we emphasize this type of technology in socio-technical systems.

[2] We further note that in innovation studies, the term infrastructure has not been used consistently. It refers e.g. to institutions, knowledge bases and to technological hardware (Smith, 2005). In the broader technology studies literature, also energy generation plants are referred to as infrastructures (Linzenich et al., 2021).

[3] Note that we see system architecture as part of the socio-technical regime which, in turn, is broader than devising coordination and interaction among technologies.

organizational design also mirrors the system architecture (Colfer & Baldwin, 2016; Henderson & Clark, 1990; Jacobides et al., 2006).[4]

With this extension of the notion of architecture from the level of a particular technology or product to the level of socio-technical systems, two issues require further elaboration that we attend to in the following: (a) the role of system technology in socio-technical transitions (section 2.2) and (b) how different types of system change challenge incumbents with implications for the politics of transitions (section 2.3).

2.2 System technology and transition dynamics

Transitions are associated with changes in core and system technologies. These changes may be incremental or radical and they may involve core or system technologies, or both. We will discuss these options and the associated transition pathways in the next section. Here, we first look at the most radical transformation and how changes in core *and* system technologies unfold over different transition phases. Following Rotmans et al. (2001), we distinguish four main transition phases: predevelopment, take-off, acceleration, and stabilization.

In the *pre-formation phase*, established core technologies are complemented by established system technologies under a given architecture (e.g., combustion engine vehicles and gas stations), cf. Figure 1. In the *take-off phase*, novel core technologies start to challenge established ones. Their emergence does not (yet) affect established system technologies because the established logics of the old system architecture are still strong and force core technologies to adapt (e.g., electric vehicles can only be charged privately). In the *acceleration phase*, however, established system technologies may create bottlenecks if they cannot cope with the rapid expansion of novel core technologies (e.g., increasing calls for public charging stations to facilitate widespread use of EVs). Whether bottlenecks appear, partly depends on differences in core technology characteristics (in electricity, for example, many renewable energy sources are variable and small-scale) (Malhotra & Schmidt, 2020; Sahal, 1985). Sometimes, however, adaptations to or extension of established system technologies can be sufficient. For example, in the transition from sailing to steamships, ports (as system technology) were enlarged to accommodate larger ship sizes (Geels, 2002). It is also possible, that established system technologies may be bridging or “two-world” technologies that play a role both ex ante and ex post a transition. The transition toward sustainable transport, for example, might largely rely on the existing road network, while additional system technologies such as multi-modal mobility platforms, ICT-based traffic flow management or dynamic road-pricing may emerge as new system technologies (Pel & Boons, 2010). Furthermore, established core technologies can change function under a new architecture and for example become system technology (e.g. gas power plants are core technologies in fossil-energy electricity systems but become system technologies in renewable-based systems providing flexible back-up services rather than bulk electricity) (Davies, 1997; Perez, 2002). Acceleration, in other words, may involve hybrid forms of new and

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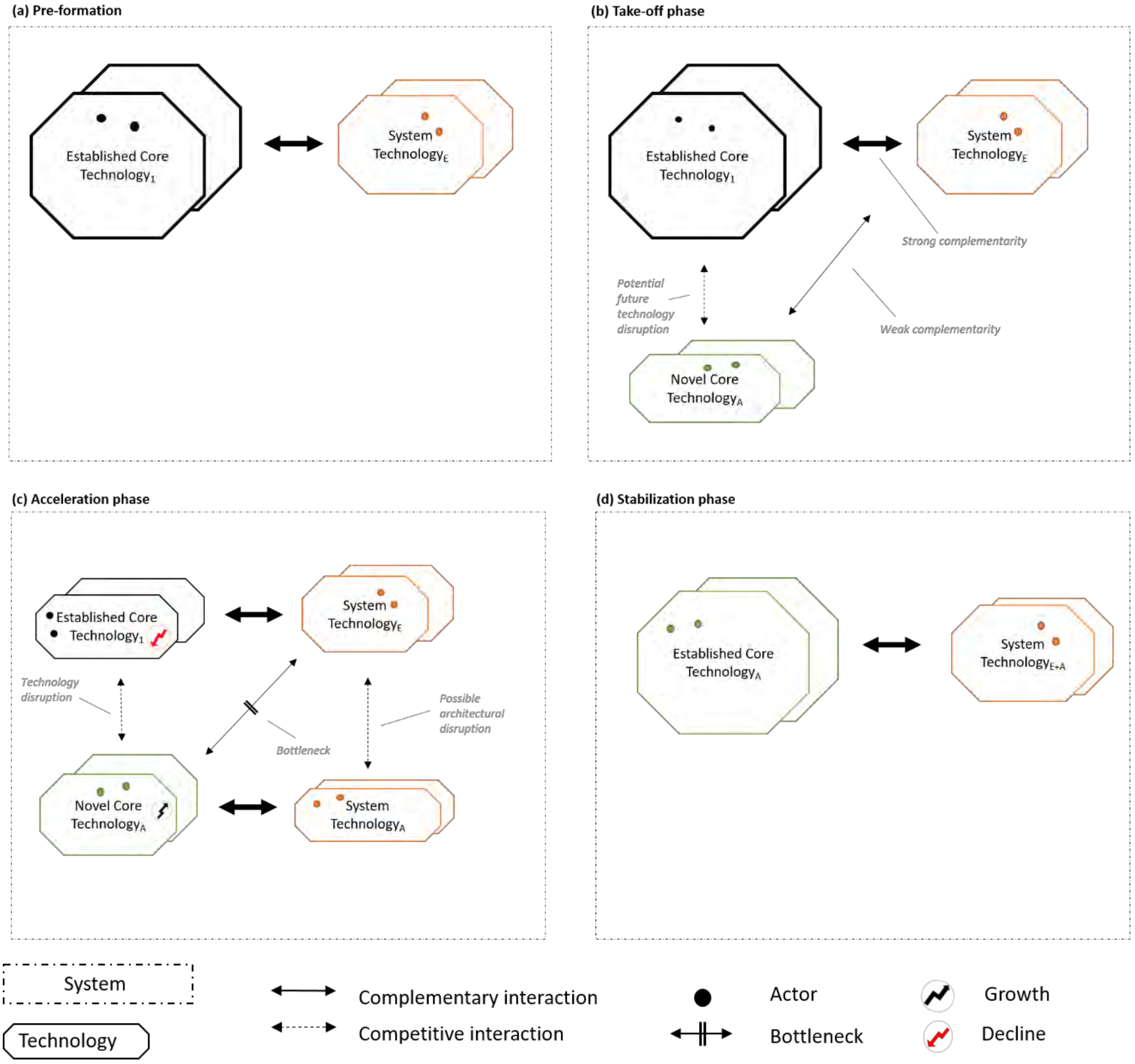
[4] Note that McMeekin et al. (2019) also define architecture as interaction between subsystems. However, they look at patterns of interaction between generation, distribution, and consumption subsystems. This approach does however not fit well for our empirical case. For example, there are architectural changes in electricity that would make the distribution subsystem obsolete (grid defection) and system technologies are distributed across all three subsystems which make them difficult to analyse. For these reasons we chose the approach outlined here.

established system technologies (David, 1997; Raven, 2007). In the *stabilisation phase*, a novel configuration of core and system technologies stabilize to under a new system architecture.

Figure 1: Role of system technologies across transition phases. Note that the illustration corresponds to the Radical Transformative Pathway in Figure 2 which includes system technology substitution and architectural change.



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Due to the strong complementarities between core and system technologies, system technologies may play a critical role in the formation of a dominant core technology. Think of a situation in which different core technologies and different system technologies compete, e.g., competition between battery-electric, hydrogen, and biofuel low-carbon transport (Klitkou et al., 2015; Magnusson & Berggren, 2018). Performance and innovation in new system technologies can therefore affect both the *pace* and the *direction* of transitions. Similarly, if some new core technologies have stronger complementarities with established system technologies, they will have an advantage against others. New system technologies may be immature and require dedicated *innovation policy support* to become competitive and useful, while existing institutions may discriminate against their emergence. From a policy perspective, it is therefore important to think both about core technologies and about the wider system.

2.3 Architectural change as a challenge for incumbents

Major changes in core and system technologies pose different challenges for incumbent actors. Based on previous sections we construct a two-by-two matrix including minor vs. major changes in core technologies and system technologies to distinguish four main transition pathways involving different degrees of system discontinuity implying different challenges for incumbents, cf. Figure 2.[5]

An *incremental innovation pathway* unfolds without major changes in core and system technologies, and thus has very limited discontinuity. It could involve making existing core technologies more sustainable through add-on innovations such as fossil fuel power production with carbon, capture and storage technology or using biofuels in internal combustion engines. For incumbents this involves competence enhancing innovations that reinforce competitive positions (Tushman & Anderson, 1986) and that can be managed via local search and learning-by-doing without major changes in strategy and firm identity (Geels, 2014a; Henderson & Clark, 1990).

A *modular substitution pathway* coincides with a ‘fit-and-conform’ change pattern where new and radically different core technologies are deployed while changes in system architecture remain limited (Geels, Kern, et al., 2016; Smith & Raven, 2012). For example, shifting from gasoline to electric vehicles can be done without fundamentally changing the overall configuration of the transport system (e.g., mobility practices and modes of transportation remain the same). For incumbents this involves competence destroying innovation (Tushman & Anderson, 1986) in core

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[5] We use discontinuity to describe change in the socio-technical system and disruption to describe influence on actors.

technologies even if there are only minor changes in system architecture. Incumbents typically must respond with ‘strategic re-orientation’ (Tushman & Romanelli, 1985) via higher-level learning including exploring and building new capabilities, target new markets and engaging in organizational change and strategic adjustments (Fiol & Lyles, 1985; Henderson & Clark, 1990).

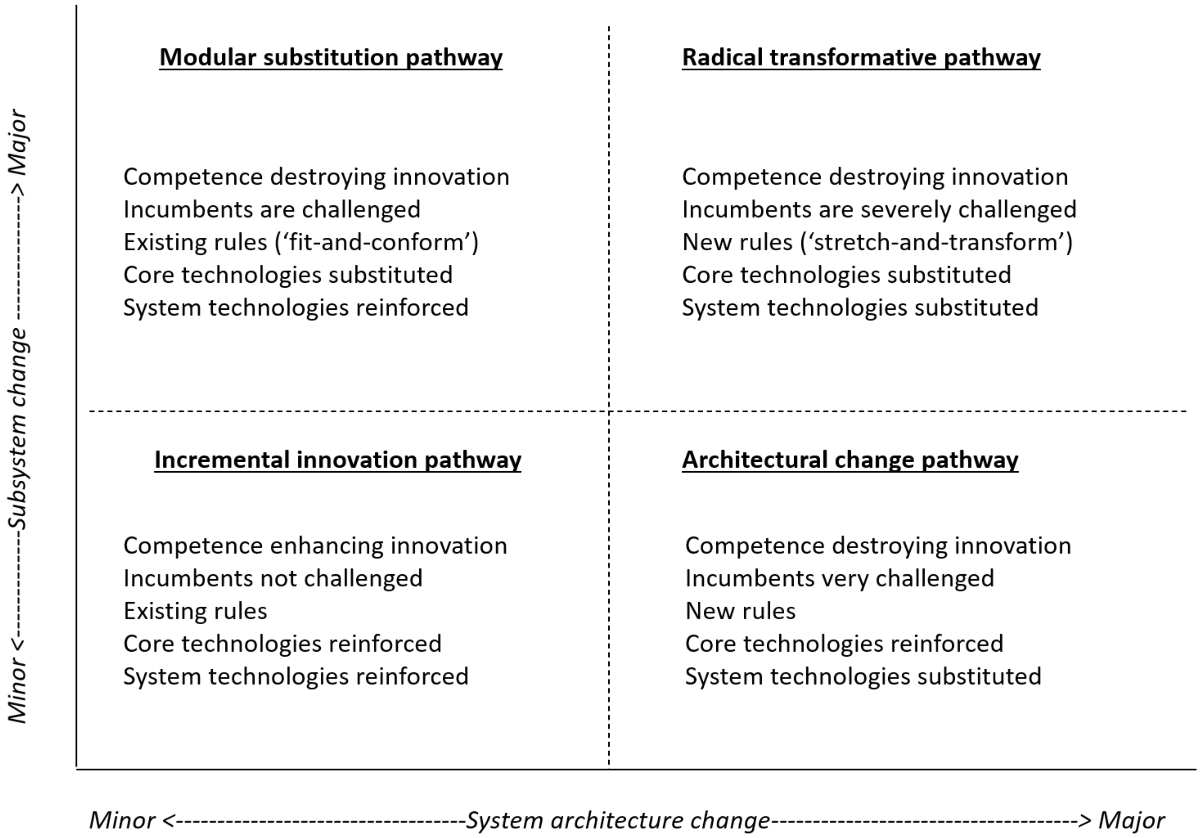
In an *architectural change pathway,* core technologies only undergo minor changes, but they are reconfigured under a new architecture. For example, less overall transport, shared mobility, and modal shifts towards more public transport and/or walking and cycling could foster a major shift in transportation systems without changing the internal combustion engine as a core technology. This shift would require new system technologies, e.g. digital platforms for inter-modal transport and for sharing cars and bikes, and new institutions supporting transportation as a service. For incumbents this involves competence destroying innovation in terms of system technologies and architecture even if core technologies are unchanged. Shifts in architecture are typically more challenging than changes in core technologies because it requires changes in organizational identity, vision and mindsets that underpin business models and strategy (Henderson & Clark, 1990; Tushman & Romanelli, 1985). Indeed, incumbents are rarely disrupted due to a lack of technological capabilities but due to their challenges in capturing value from those capabilities via new business models (O’Reilly & Tushman, 2008).

A *radical transformative pathway* comes with the highest degree of system discontinuity and is the most disruptive for incumbents. It reflects a ‘stretch-and-transform’ transition pattern where system architecture is transformed to fit the properties of novel core technologies (Smith & Raven, 2012). For example, a shift from decentralized (i.e. individual) and gasoline-fuelled transportation towards centralized (i.e. collective and shared) and electrified transportation. For incumbents this involves competence destroying innovation in terms of both core and system technologies. Incumbents thus must respond with ‘strategic re-creation’ (Geels, 2014a; Tushman & Romanelli, 1985) which includes both, on the one hand, building new capabilities and markets, and, on the other, changes in organizational identity and business models.

When only minor adaptations are needed, the reorientation process is easier (Teece, 1986; Tripsas, 1997). Although reorientation is certainly possible, it typically remains costly and risky (Bergek et al., 2013). Despite the potential of reorientation, we therefore expect that incumbents will, whenever possible, prefer transitions with least system discontinuity. For these reasons, the literature emphasize that architectural change is typically not driven by incumbents with central and dominant positions within the existing system architecture. Instead, it is often initiated by challengers that are peripheral actors in the system or newcomers (both ‘de novo’ and diversifying entrants) (Fligstein & McAdam, 2011). Challengers are the more likely to promote major changes because they are less embedded in, committed to, and bound by existing system architecture (Zietsma & Lawrence, 2010).

At the same time, research on the politics of transitions has shown that incumbents often proactively work against institutional and policy changes (e.g. influencing policymaking) (Geels, 2014b; Hess, 2014). The literature also highlights that resistance from incumbents intensify with the degree of discontinuity in existing systems (Geels, Kern, et al., 2016; Johnstone et al., 2020; Lindberg et al., 2019). Against this background, we expect resistance from incumbent actors against changes in system architecture. It can furthermore be expected that incumbent and challengers hold rather different preferences for both new and established system technologies as indicative of architecture preferences.

FIGURE 2: TYPES OF CHANGE AT THE SYSTEM LEVEL AND ASSOCIATED CHALLENGE TO INCUMBENTS (BASED ON LINDBERG ET AL. (2019), MCMEEKIN ET AL. (2019), TUSHMAN AND ROSENKOPF (1992), AND HENDERSON AND CLARK (1990))



In the case of the German energy transition, we already see major changes in core technologies and the current battle in the acceleration phase is about whether there will also be major changes in system architecture, or not. So, we are looking at a situation, in which actors find themselves between two pathways: modular substitution and radical transformation (Geels, Kern, et al., 2016). Against this background, we expect that incumbents prefer modular substitution and will be critical of a radical transformation pathway. We furthermore expect that challengers will be more positive to architectural change than incumbents. Such differences will manifest in diverging preferences for system technologies.

3 Methods

In this chapter we operationalize our theoretical concepts presented in the context of the pending renewable energy transition in the electricity system and explain our case selection, analysis, and data.

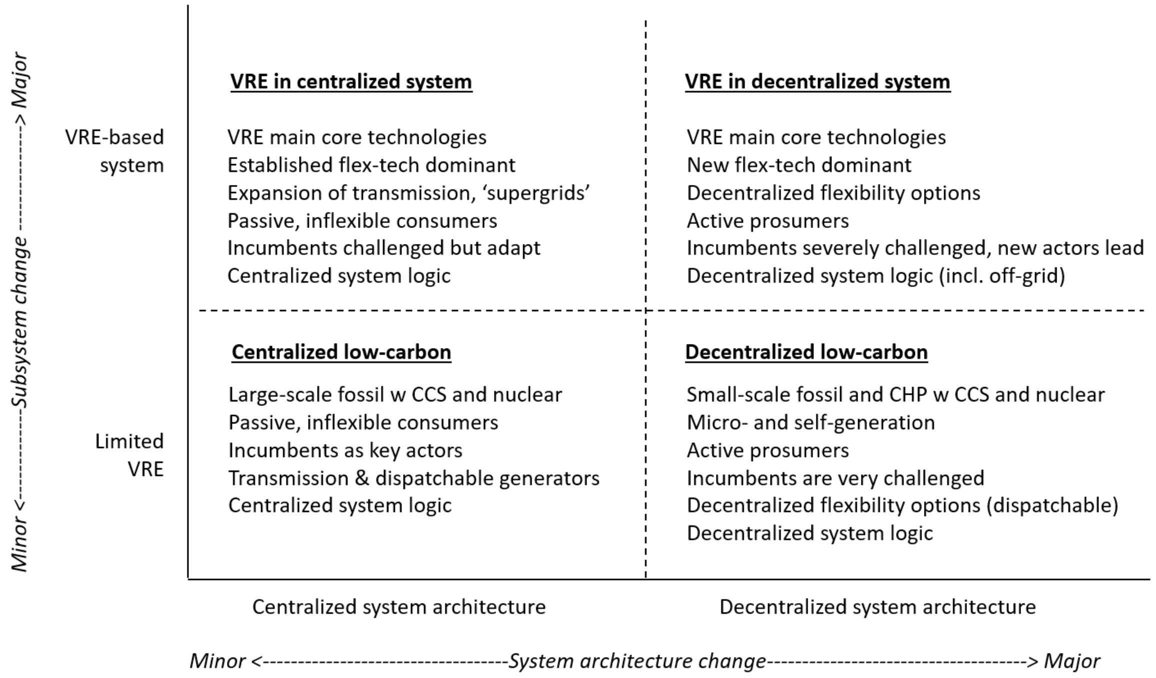
3.1 Research case: the electricity system

Core and system technologies. We conceptualize power generation technologies as core technologies and flexibility technologies as system technologies. Flexibility refers to the ability to always balance supply and demand. The traditional way to balance supply and demand is through dispatchable power supply (typically hydro and gas and coal power plants) as well as large transmission grids while demand has been largely considered inelastic and consumers passive. As VREs continue to grow, dispatchable supply decreases and new sources of flexibility are required (ETIP SNET, 2020; OECD/IEA, 2014). New flexibility functionalities that go beyond established flexibility technologies may also be needed. As (new and old) flexibility technologies are crucial for system-level balancing, functionality, and stability, we refer to them as system technologies.

System architecture and pathways. A transition to a VRE-based system is possible both under centralized and decentralized system architectures (Funcke & Bauknecht, 2016; Lilliestam & Hangera, 2016). The power system was traditionally organized in a very centralized way with large-scale generation (core) technologies such as coal and nuclear power plants whose balancing was supported by long-distance transmission grids. A system with such a centralized architecture can be decarbonised, e.g. with nuclear and carbon capture and storage technology (CCS) for fossil power plants (incremental innovation pathway / centralized low-carbon), see Figure 3. Another option is to move towards a VRE-based but still centralized architecture which involves many new core technologies but largely unchanged system technologies (modular substitution pathway / VRE in centralised system). However, the transition may also involve architectural changes towards a decentralized system. This typically happens due to a combination of demand-side changes and innovation in new system technologies that replace old ones (architectural change pathway / decentralised low-carbon) and/or because the characteristics of new core technologies do not fit well into a centralized system (radical transformative pathway / VRE in decentralised system). As the German energy transition is already based on changed subsystem technologies, we will focus on the pathways in the two upper quadrants in the following.

In this context, also flexibility technologies can fit better or worse with a centralized architecture (IEA, 2018). Centralized flexibility technologies (e.g. large-scale transmission grid, pumped-hydro power) are more compatible with the existing system architecture than decentralized flexibility technologies (e.g. distributed storage, demand response). Therefore, the analysis of system technologies and actor preferences for specific system technologies can be used as a proxy for analysing architecture preferences.

FIGURE 3: TRANSITION PATHWAYS, TYPES OF DISCONTINUITY IN THE ELECTRICITY SYSTEM, AND CHALLENGES TO INCUMBENTS



Minor <-------------Subsystem change -------------> Major	Centralized system architecture	Decentralized system architecture
VRE-based system	**VRE in centralized system** VRE main core technologies Established flex-tech dominant Expansion of transmission, 'supergrids' Passive, inflexible consumers Incumbents challenged but adapt Centralized system logic	**VRE in decentralized system** VRE main core technologies New flex-tech dominant Decentralized flexibility options Active prosumers Incumbents severely challenged, new actors lead Decentralized system logic (incl. off-grid)
Limited VRE	**Centralized low-carbon** Large-scale fossil w CCS and nuclear Passive, inflexible consumers Incumbents as key actors Transmission & dispatchable generators Centralized system logic	**Decentralized low-carbon** Small-scale fossil and CHP w CCS and nuclear Micro- and self-generation Active prosumers Incumbents are very challenged Decentralized flexibility options (dispatchable) Decentralized system logic

Minor <----------------------------------System architecture change-------------------------------------> Major

3.2 Case selection: Germany

Overall, our research design is to carry out an in-depth single case study because this is well suited for generating rich descriptions of empirical phenomena for which little theory exists—such as process understandings of architectural change in accelerating transitions (Eisenhardt, 1989).

The relevance of alternative flexibility technologies and political struggles about these should be particularly prominent in countries, in which 'classic' flexibility technologies such as hydropower or transmission grids are limited in their availability or expansion. In addition, we were looking for a case, in which VREs have progressed rapidly in recent years, covering a significant (and, likely, increasing) share of power supply. Finally, our case should be characterized by an ongoing but at the same time open-ended architectural changes such as development toward decentralization. Germany fulfils all three conditions and is therefore a good case to study.

Germany is relatively advanced in the transition towards a VRE power system. In 2019, approx. 42 % of power generation came from renewables, mainly variable wind and solar energy (German Environment Agency, 2020). The increasing share of VRE creates additional demand for flexibility (Bauknecht et al., 2020). The current lack thereof is reflected in an increasing curtailment of renewables, which went up to more than 6 TWh in 2019 (Bundetzagentur, 2019). Today, flexibility is mainly provided by conventional power plants (esp. gas-fired power plants) as well as pumped storage hydropower plants. While the former will be increasingly replaced by renewables, the capacity of the latter cannot be expanded.

What makes Germany a particularly interesting case is a strong regional and local resistance against the expansion of transmission lines, which would be crucial to connect regions with high wind production in the North with consumption centres in the South (Bertsch et al., 2016;

Kamlage et al., 2020) (Bundetzagentur). The resistance is related to conflicting visions of how the energy transition should look like, and this in turn is reflected in different preferences as to whether the energy transition should be more decentralised or centralised (Schmid et al., 2017). Yet there also arguments that transmission expansion could be reduced by more decentralised generation and alternative flexibility technologies (Prognos, 2016). For these reasons, the case provides a unique opportunity for studying contestations over architectural change in socio-technical systems during transitions.

3.3 Techno-economic analysis of flexibility technologies and system architecture

As preparation for our analysis of actor preferences, we operationalize and characterize those flexibility technologies that are most relevant in the German context. We look into their maturity, deployment scale, institutional fit with (de)centralized system architectures, and whether they have stronger technical complementarities with centralized or a decentralized system architecture. The latter involves assessing the technical complementarities between different flexibility technologies as well as how they interact with large- and small-scale VREs, respectively. We also describe how the functionalities of flexibility technologies differ in terms of duration of flexibility service and system problem addressed.

The analysis of technical factors is based on a review of the techno-economic energy systems literature. It provides consistent analyses of complex systems at the level of technologies together with an understanding of the functioning of the electricity system as a whole (Geels, Berkhout, et al., 2016). While this literature does not dig deep into the socio-political aspects of transitions, it provides us with a better understanding of the relevant technical interdependencies (Geels, Berkhout, et al., 2016; Winskel et al., 2014). Given that technical interdependencies must match the socio-political structures of the system, this is an important baseline for interpreting the results of the actor preference analysis. The results are summarized in Tables 4 and 5 in section 4. Details of the analysis can be found in Appendix A.

3.4 Socio-political analysis of flexibility technologies

We approached the case with an analysis of policy preferences of key actors at a time when there was an intense debate about the expansion of transmission and the ambitions and pace of the energy transition. We analysed publicly available documents submitted to a consultation process on the “Impulse Paper Power 2030” (translation), a report by the German Federal Ministry for Economic Affairs and Energy to sketch the future of power supply. The consultation ran from September 16 to October 31, 2016. On the Ministry’s website, 98 statements of firms, associations and private persons who agreed to publication are available for download.

While we also looked into more specific consultation processes on the future role of the power grid (Szenariorahmen 2017-2030, NEP 2017-2030), we focused on Impulse 2030 because of its unique combination of breadth (covering a broad range of topics beyond grid issues) and depth (sufficient prominence of the grid and other flexibility technologies). Of course, this approach creates trade-offs (e.g., we are not able to compare preferences across time) but as the phenomenon is rather new and unique, we decided to prioritise data quality (which allows us to compare across a broad range of actors and topics) over the ability to track changes through time.

For our analysis, we selected 22 firms, industry associations, NGOs and think tanks that play a crucial role in German energy politics and submitted a statement to the consultation. A particular focus is on organizations in the electricity system. We included both incumbents and challengers that we characterize in terms of position in system (generation, consumption, grid, or whole system) and technological assets, see Appendix B for details. This information is based on the authors collective insights to the German case and visits to actor websites. We use the information about actors to support our interpretation of results. For example, we infer that incumbency and ownership of large-scale, centralized assets are associated with actor preference for existing centralized architecture.

Our coding scheme covers four analytical dimensions regarding flexibility, see Table 3. The first dimension is about the general importance actors ascribe to flexibility for the future stages of the energy transition. The second dimension covers preferences regarding transmission grid expansion versus alternative flexibility technologies. It is a combined indicator based on the average of two sub-dimensions (grid expansion and other flexibility). As transmission grid expansion is so prominent in the debate about future flexibility options, we singled it out and compared it against preferences for all other technologies. With the third dimension we compare preferences for decentralized and centralized technologies. This dimension was coded based on the characteristics of flexibility technologies or, for technologies such as DSM or co-generation which can be both centralized and decentralized, on the context in which the actor was speaking about the technology. Again, this was a combined (average) indicator. The fourth dimension is about preferences for specific flexibility technologies which allows us to obtain a deeper understanding of the preferences.

Table 1: Main coding dimensions

Code	Indicative questions	Coding
General importance of flexibility	How important is flexibility for the energy transition?	1 (not important) – 4 (very important)
Transmission grid vs other flexibility technologies	How important is grid expansion and how important are other flexibility technologies?	Expansion (1 not – 4 very) Other (1 very – 4 not) Combined indicator
Decentralized vs. centralized flexibility	How important are decentralized flexibility technologies and how important are centralized ones?	Decentralized (1 not – 4 very) Centralized (1 very – 4 not) Combined indicator
Specific flexibility technologies	How important are specific flexibility technologies?	1 (not important) – 4 (very important)

For each (sub)dimension, we distinguished four categories and assigned values from 1 to 4: Not important (1), somewhat important / might play a role in the energy transition (2), important / will definitely be needed (3), and very important / precondition for the transition (4). For two sub-dimensions (Other and Centralized) this logic was inverted to allow for aggregation.

Next to the quantitative analysis, we also selected quotes from the consultation documents. These were chosen to illustrate specific findings. So, when we are reporting that a specific group of actors has a specific preference, we went back to the coded documents (of these actors), looked at all statements (on the topic) and selected a quote, which in our view was representative for this preference and group of actors.

To assist our interpretation of the results we furthermore conducted three interviews with energy experts in Germany, see Appendix C. We presented our results (i.e. Figures 3, 4 and 5), and asked for their interpretations. Interviews lasted about 1 hour and were carried out via online video software. Two authors attended all interviews and made notes and exchanged views after each interview. All interviews were recorded.

4 Techno-economic analysis of flexibility technologies and system architecture

In this chapter we provide an overview on the technical options that are available for providing system flexibility and how these interact with each as well as how their fit with different system architectures.

4.1 Flexibility technologies and system architecture

Globally flexibility capacity currently (2017) amounts to 3400 GW and mainly comes from established power generation technologies. The flexibility contribution of these technologies depends on how they ramp generation up and down. The main ones are gas (29%), coal (23%), and hydro (28%) plus pumped hydro (4%). Among non-generation flexibility technologies, the main established technology is transmission grid / interconnectors (5%), but new flexibility technologies increasingly play a role such as demand side management (DSM, 1%) and battery storage (0.1%). With a transition to a VRE-based power system, the need for flexibility will grow markedly and due to the phase-out of coal and possibly gas plants, new flexibility technologies are needed (IEA, 2018).

Table 1 summarizes relevant characteristics of selected flexibility technologies that will compete for market shares as new flexibility is needed in the energy transition. Note that transmission grid expansion is the main established non-generation option which also fits existing system architecture. Also, note that generation technologies can provide flexibility services if they are dispatchable. These technologies can create value with both generation and flexibility services. Indeed, in the German context it is expected that the role of gas and hydro will change functions from generation / core technologies to flexibility / system technologies as VREs diffuse (new core). Technologies can thus have different functions under different system configurations.

The mix of flexibility technologies in a given power system can influence the competitiveness of different VREs. The right side of Table 1 provides a broad overview of how different flexibility technologies combine with a (de)centralized system architecture approximated in form of large- and small-scale VREs.

We the following insights from this exercise. First, new transmission capacity improves the conditions for centralized VRE more than for decentralized VRE. Second, although P2G as a source of flexibility is immature and not part of the existing system, it is typically deployed at large-scale facilitates and can therefore improve conditions for large-scale VRE and it fits the logic of a centralized system. Third, modular storage technologies and DSM are very versatile and can improve the conditions for all VRE types. Battery storage goes especially well together with small-scale solar. Fourth, most new flexibility technologies are not mature and have low institutional fit with existing system institutions wherefore dedicated support may be required for them to play a prominent role. Lastly, established flexibility technologies have higher technical fit with a centralized system architecture than with a decentralized one. Novel flexibility technologies mostly also have a high technical fit with a centralized system architecture but have lower fit in terms of institutions.

TABLE 2: TECHNO-ECONOMIC CHARACTERISTICS OF FLEXIBILITY TECHNOLOGIES

Flexibility technology	Maturity	Scale (physical)	CEN-FIT (institutional)	CEN-DEC	Large-scale plants / Centralized*		Small-scale plants / Decentralized*	
					Wind	Solar	Wind	solar
Transmission	High	Large	High	CEN	+++	++	++	+
Large hydro storage	High	Large	High	CEN	+++	+++	++	++
Gas power plants	High	Large	High	CEN	++	++	+	+
Distribution grid flexibility	High	Large	Low	DEC	+	+	+++	+++
P2G (large)	Low	Large	High	CEN	+++	+++	++	++
Combined Heat and Power (CHP)	High	Large	High	BOTH	++	++	+++	+++
Batteries	Low	Small	Low	DEC	++	++	++	+++
DSM	Low	Small	Low	BOTH	+++	+++	+++	+++
VRE flexibility	Low	Varied	Low	BOTH	++	++	++	++

**Degrees of complementarity between flexibility and generation technologies: (+) = weak, (++) = moderate, (+++) = strong*

4.2 The relationship between flexibility technologies

Flexibility technologies compete but they can also be complementary because they can address different problems in VRE integration (Sinsel, Riemke, et al., 2020). First, there are flow problems as grids get congested because new VRE generation is in areas which have not been used for power generation before and which are far away from consumption centres. Moreover, flow problems result from the fluctuating nature of VRE as grids are unable to handle hours of peak generation. Transmission grids have typically been used to address this. As for flow problems, flexibility options like DSM or batteries can also be used to address this , thus partly making grid investment unnecessary or postpone it (competition) (Korpaas et al., 2003). Similarly the gas grid may partly replace the electricity network when congested (e.g. PtX).

TABLE 3: RELATIONSHIP BETWEEN TRANSMISSION AND OTHER FLEXIBILITY TECHNOLOGIES; NATURE OF INTERACTION BETWEEN FLEX TECHNOLOGIES: (-) COMPETITION, (+) COMPLEMENTARITY, (0) NEUTRAL

Flexibility technology	Nature of Interaction	Relation to Transmission
Large hydro storage	(+)	Hydro plants are remotely placed and needs transmission to be utilized
Gas power plants	0	Gas power plants can be placed near cities and therefore do not need much transmission. However, the gas plants are better utilized in an interconnected grid, e.g. to complement seasonal variations in hydro inflow
Distribution grid	(+)	Transmission and distribution are integral parts of electricity supply
P2X (large)	(-)	Large-scale P2X, especially P2G, has been launched as an alternative to transmission upgrades, using pipelines or tank ships as energy carriers instead of wires.
Flexible CHP	(-)	CHP can increase production flexibility near consumption centres, and thereby reduce dependence on external grid.
Batteries	(-)	Storage is an alternative to grid expansion. If transmission capacity is increased, there are less need for storage.
DSM	(-)	DSM can be alternative to grid expansion, especially for reliability purposes.
RES flex (e.g. VPP)	(-)	Flexible VRE operation may reduce the need for building power export capacity from areas with high VRE penetration.

Second, there are balance problems as generation and demand need to be constantly balanced. While flow problems depend on the geography of the system, balance problem are relevant for all systems and increase with a rising share of VRE. Flow problems can however also create balance problems (i.e. grid congestion limits flows). In this domain most flexibility options compete. As for transmission grids vs. other flexibility options, they compete to the extent to which transmission grids connect different generation and demand profiles, thus reducing the balancing problem. Yet they are also complementary as even in a perfect grid, there will be balancing problems to be dealt with by other flexibility options. Moreover, grids (transmission and distribution) are central for leveraging most other flexibility options.

Lastly, flexibility options only compete when they offer flexibility services with same time duration, cf. Appendix A. We illustrate these complex interactions by elaborating on the relationships between transmission and other flexibility technologies in Table 4.

4.3 Summary and expectations

The insights presented above lead us to a set of expectations regarding actor preferences in our case. First, we expect incumbents to prefer flexibility technologies that are mature (and thus well-known to them), large-scale, have high institutional fit with centralised architecture, and have strong technical complementarities with large-scale VRE. Reflecting this, we expect that incumbents will support incremental institutional changes that maintain or support a CEN architecture. Second, we expect that challengers prefer new, and decentralized flexibility technologies as well as major institutional changes. Third, because flexibility technologies differ in functionality, they are not fully excluding each other. For this reason, any VRE-based electricity system will require a mix of flexibility technologies. For this reason alone, we expect incumbents and challengers to hold overlapping preferences for flexibility technologies.

5 Socio-political analysis of flexibility technologies

A first result of our analysis is that nearly all the actors in our sample made statements that indicated that flexibility is important for the energy transition (average of 3.1 over all actors). Only two organizations, Statkraft (2.5) and the Association of the Chemical Industry (2.75), expressed somewhat lower importance. In contrast, the Association of Consumer organizations (4.0) and the Association for Co-generation (3.67) regarded flexibility as an indispensable precondition for the energy transition. This high level of general importance is a good basis to take a closer look at the specific preferences for flexibility technologies in the following.

5.1 Transmission grid expansion versus other flexibility options

Our findings show that, for most of the selected actors, transmission grid expansion is an important or very important flexibility option. At the same time, many actors are in favour of other flexibility options. So, for most actors, the issue of how to provide flexibility involves a combination of transmission grid expansion and other flexibility technologies, see Figure 4.

Among the vivid supporters of grid expansion is the German association of energy and water industries (BDEW), the association of the chemical industry (VCI), the transmission system operators (50hertz, Amprion, TenneT, TransnetBW), the Norwegian utility Statkraft, the German Energy Agency (Dena) and Next Kraftwerke, the operator of a virtual power plant.

> “The expansion of transmission grids is the cheapest option to integrate decentralized and mostly volatile power [supported by the feed-in tariff]. Other technologies such as

> storage will only be economically meaningful, in addition to grid expansion, if the share of renewables … is significantly higher [than today]. Grid expansion … is to be pursued with high priority." [50hertz]

> "[Transmission] grid expansion is the most cost-efficient flexibility option. Accelerating grid expansion is still necessary, e.g. licensing procedures. … In the long run, [transmission] grid expansion is the cheapest option for integrating renewable energies into the German and European energy system." [TransnetBW]

Only some actors, a group of oil and gas suppliers[6] and Eurosolar, regard grid expansion as less important. Eurosolar is a clear outlier here. They argue explicitly against grid expansion because they fear that the transmission grid is favouring central coal fired power plants.

> "The goal of the government regarding the construction of a gigantic, parallel HVDC [transmission] grid is beyond an objective discussion of real necessities. … The HVDC grid expansion is not a project of the energy transition but for the undisturbed continuation of coal fired power generation. Grid bottlenecks are not a result of high feed-in from renewables but a consequence of the simultaneous [operation of] … inflexible coal power plants." [Eurosolar]

Interestingly, also oil and gas suppliers are hesitant toward grid expansion but for very different reasons. They want to use the gas grid as an alternative to the power transmission grid and they promote gas fired power plants to provide flexibility.

> "The [transmission] grid expansion challenge is turning into an impediment for the energy transition. … many [local] protests [have] resulted in longer planning and construction times … In this context, the potential of the gas infrastructure needs to be used more [intensively]. … Gas infrastructure is energy transition infrastructure. Notwithstanding the degree to which heat and mobility sectors will be electrified, a better interplay of gas and electricity grids will be needed. The gas infrastructure comes with a huge potential for transport and storage. With power-to-gas, it will be possible to transport and store renewable energy electricity."
> [Oil and gas suppliers]

Another interesting result is that among those that support alternative flexibility options are even the four transmission grid operators.

> "We need suitable complementarities to volatile generation, [including] storage technologies …, small and micro installations (homes, vehicles)…, flexible loads (DSM) …, and the expansion of shiftable loads…" [TransnetBW]

The most vivid supporters of alternatives to grid expansion, however, are the German Energy Storage Association (BVES) and the Federation of German Consumer Organisations (Vzbv)

> "The German government is currently giving priority to grid expansion in order to promote the energy turnaround. It is already apparent today that this is not enough. … all existing options that can contribute to decarbonisation should be included and it should be possible to use them side by side across sectors. In a time of rapid technological progress and dynamic developments, rigid, one-sided approaches and the restriction of innovative concepts are not appropriate." [BVES]

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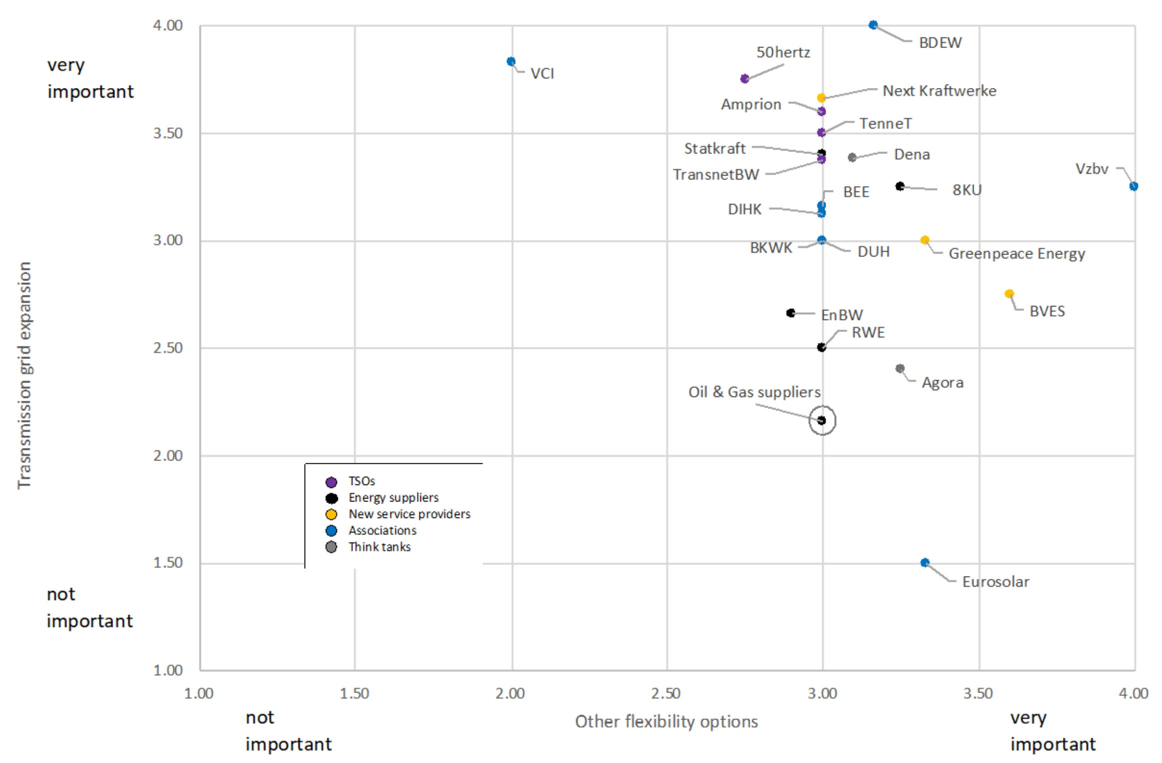
[6] Marked with an additional circle to highlight that this is a common position of 13 different firms.

The association of the chemical industry (VCI) has an opposite position. They see grid expansion as the cheapest way to provide flexibility and are somewhat reluctant toward alternatives even though they do see a merit in flexible gas plants, demand side management and cogeneration.

> “Swift advancement of urgently needed grid expansion ... will reduce overall costs in the long run. Overcoming acceptance problems with e.g. grid expansion and onshore wind is of key importance for realizing the energy transition.” [VCI]

FIGURE 4: IMPORTANCE OF TRANSMISSION GRID EXPANSION VS. OTHER FLEXIBILITY OPTIONS

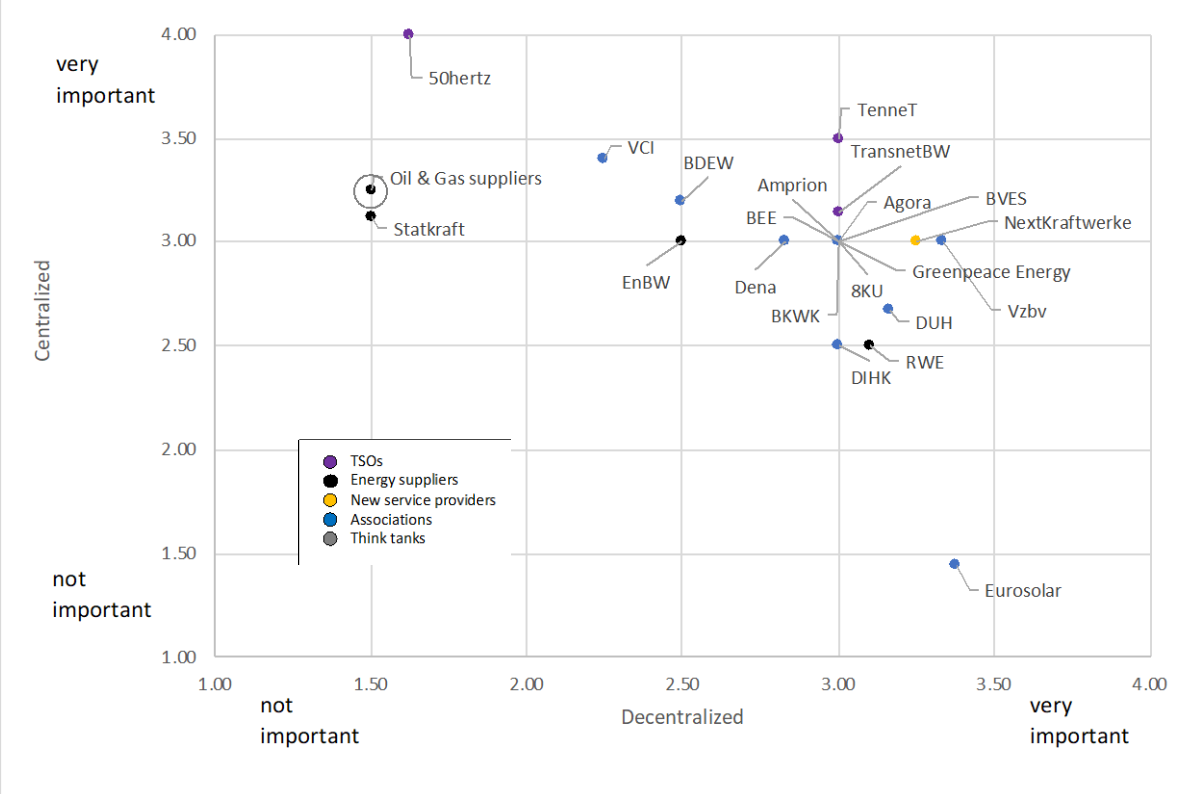


5.2 Centralized versus decentralized flexibility technologies

Taking a closer look at whether actors prefer centralized or decentralized flexibility options, we see a concentration around (3;3), which means that most actors consider both important. However, there are some outliers. 50hertz is most clearly in favour of centralized options, especially transmission grid expansion, and at the same time, they are reluctant towards storage options, for which they only see demand in long run.

> “Several studies have shown that there is no need for a large-scale expansion of storage. Other flexibility options are cheaper. Grid expansion is the cheapest way ... But storage options should be developed and researched for deployment in the long run.” [50hertz]

FIGURE 5: IMPORTANCE OF CENTRALIZED VS DECENTRALIZED FLEXIBILITY OPTIONS



The oil and gas suppliers as well as Statkraft are in favour of centralized flexibility solutions and see no need in supporting decentralized ones. The VCI holds a similar but less pronounced position.

> “Existing pumped storage [hydro power] should play a key role in a flexible energy system of the future dominated by renewable energies. … Statkraft opposes a separate treatment of aggregators [through legal regulations]. This will distort markets. … It is important to further push grid expansion across borders, e.g. to Norway. Hydropower reservoirs in Norway offer a vast amount of flexibility.“ [Statkraft]

Eurosolar is the antipode to these positions. It clearly opposes transmission grid expansion and argues strongly in favour of decentralized flexibility.

> “At various points, the impulse paper reveals the BMWi's clear reluctance to adopt decentralised solutions, whether in generation or in balancing supply and demand. However, this misjudges the elementary characteristic of renewable energies and thus misses the greatest efficiency and savings potential.” [Eurosolar]

However, these positions are exceptions and most actors assumes positions in the middle. It is particularly interesting to see three transmission grid operators holding intermediate positions.

5.3 Specific preferences for flexibility technologies

The actors in our study hold different positions regarding specific flexibility technologies. Figure 6 depicts preferences for eight flexibility alternatives, next to transmission grid expansion, which was already analysed in detail in section 5.1. Note that not all actors made statements for each option. Most alternatives are viewed as important by many actors, expressed by values of 2.5 and higher. Some views are shared by several actors (one line with several names to it). At the same time, there are only a few critical statements against specific flexibility technologies indicated by few values below 2.

We use these technology specific codes to explore further details of the concentration of actor preferences around a hybrid set of flexibility options in the future power system, i.e. upper right quadrant in Figure 5.

One insight from this analysis is that although many incumbent actors express support for decentralized flexibility options they maintain that the transmission grid is their preferred flex-option (Figure 4). However, they also acknowledge that transmission expansion is delayed due to public resistance. That is one reason why they find non-grid flexibility options important.

For example, although Amprion endorses VRE flexibility (score 3 in figure 6), DSM (2,75) and battery storage (2) as flexibility options, the TSO states:

> “Network expansion is a basic prerequisite for the success of the energy system transformation….The transmission system operators are working hard on the implementation of the legally approved grid expansion projects. In order to safely and efficiently manage critical grid situations arising from existing delays, the transmission system operators need appropriate and efficient measures. This includes a supra-regional optimization and coordination of countermeasures such as redispatch and feed-in management.” (Amprion)

EnBW similarly states that:

> “Exclusively relying on grid expansion is risky. Not only for wind energy but also for grid expansion, we see an increasing resistance against new construction projects. … Next to grid expansion, we need to create the option of an increasingly decentralized use [of energy]” (EnBW)

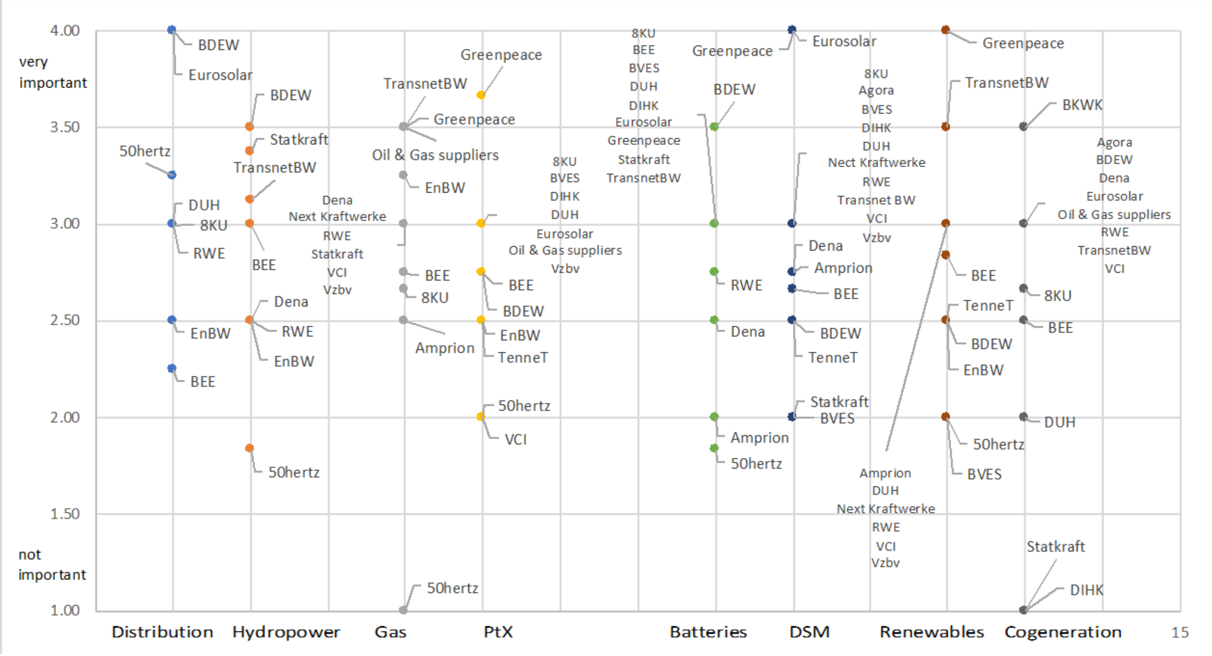
Tennet which expresses support for VRE flexibility (2,5) and DSM (2,5) also states:

> “Currently, the lack of acceptance for new [transmission] power lines is the largest obstacle for … the European energy transition. … [if] the energy transition continues to progress, grid expansion in AC and DC will be needed that significantly exceeds the projects currently [planned]…” (TenneT)

8KU which supports Battery storage (3), DSM (3), and distribution grids (3) as flexibility options argues that a both misled and failed focus on transmission grid expansion as main source of flexibility has left the system vulnerable.

> “As at the European level, the expansion of the transmission grids is certainly important here. However, it has not yet been successfully implemented. The concentration on network expansion and the neglect of regional and distribution networks has meant that regional (and cellular) flexibilities have not even come into being.” (8KU)

FIGURE 6: PREFERENCES FOR EIGHT FLEXIBILITY OPTIONS



A second insight is that some incumbents that support non-grid flexibility options, however, think they will be needed only well into the future. For example, BDEW which mentions battery storage (3,5) and cogeneration (3) as important sources of flexibility states that (also see 50hertz above):

> “Intelligent expansion of distribution grids, the national transmission grid and [international] interconnectors … will be of vital importance for a power supply system with ever increasing shares of renewable energies … The importance of storage technologies … will increase in the future.” (BDEW)

A third insight is that some actors emphasize the need for more modular flexibility options than transmission which is a large-scale technology. ENBW for example says that:

> “Gas fired power plants are, due to their technological characteristics (swift availability, short construction times, low investment costs, low CO2 emissions and flexible operation), the perfect addition to variable renewable energies.” (EnBW)

Similarly, DENA states that modular storage has several applications and is easier to deploy.

> “The assumption that storage [options] are more expensive than other flexibility options does not sufficiently take into account the possibility of multiple applications (e.g. power market, grid services, congestion management) and seems to be based on the – very optimistic – premise that grid expansion … can be realized as planned.” (DENA)

6 Discussion

In this section we summarize, discuss, and make sense of our empirical results in relation to previously formulated expectations regarding actor preferences and we discuss implications of the latter for our conceptual understanding of accelerating transitions.

6.1 Main findings

Regarding our expectation that *incumbents* would prefer a modular substitution pathway we have two main findings. First, we found heterogeneity among incumbents in terms of system architecture and flexibility technology preferences. Many incumbents, as expected, have a strong preference for transmission. We also found that many actors—both incumbents and challengers—prefer a mix of mature and immature, central and decentral flexibility options. This was also to be expected because, as we saw from the techno-economic analysis in section 4, grid expansion and other flexibility technologies partly compete against each other, but are partly complementary, too. However, this alone cannot explain the strong convergence in actor preferences, as the flexibility options are indeed both complementary and competing. This result therefore represents an interesting mismatch with our expectations based on theory.

Second, we found that many incumbents express preference for decentralized flexibility technologies because they accept that transmission grid expansion is likely to be insufficient as local resistance against projects is causing delays. In this situation, alternative flexibility options—especially more modular ones that are easier to deploy—receive more attention. In other words, incumbents are forced by circumstances to acknowledge the value of non-transmission flexibility options.

We find that the reluctant nature of incumbents' engagement with decentralised flexibility technologies manifest in three ways. First, in terms of the desired balance between decentralized and centralized flexibility technologies many incumbents express clear priority for centralized solutions but *due to circumstances* accept a *limited* role for alternatives. Second, in terms of when new flexibility is needed (now or later), several incumbents prefer that transmission grid expansion should be expanded first and that alternative flexibility technologies will only be relevant at a later stage. This preference for delay serves to maintain a centralized system architecture. Third, in terms of how flexibility should be provided (innovation support vs level playing field), many incumbent actors emphasize that cost-efficiency and competition among flexibility technologies should be the guiding principle for flexibility deployment (e.g. 50Hertz and Amprion). Accordingly, policy support for new and immature flexibility technologies is to be avoided (e.g. Statkraft). Instead they call for institutional change to accelerate the deployment of transmission expansion (e.g. TransnetBW and Amprion).

Regarding our expectation that challengers prefer new, and decentralized flexibility technologies as well as major institutional changes, we found the following. First, we also find heterogeneity among the preferences of challengers. We find that some challengers such as BVES and Eurosolar, as expected from theory, have strong preferences for decentralised flexibility technologies and are critical of transmission. Also, oil and gas suppliers do not support transmission (even though they prefer a centralized system architecture). However, most challengers prefer a mix of decentralised centralised solutions. We find that the challengers accept the value of centralized flexibility technologies because they will be important for the diffusion of more decentralised VREs. For example, Greenpeace Energy, even though remaining sceptical, acknowledged the value of transmission networks for VRE integration (Interview 2). Indeed, challengers such as BEE (renewables association) and Next Kraftwerke (virtual power plants) partly depend on transmission to realize value of their assets.

We find that challengers accept the value of centralized flexibility technologies only with several reservations. As with the incumbents, this manifests in three ways. First, in terms of the desired balance between flexibility technologies, some challengers strongly emphasise new flexibility options and want them to play a much more prominent role compared to today even if transmission remains an important part of the mix. Second, regarding the timing of flexibility deployment, several challengers argue that alternative flexibility options should be developed immediately, opening for alternative architectures now. Third, challengers see a need for innovation policies to help alternative system technologies to mature and grow (e.g. Greenpeace Energy, BVES, Eurosolar). Along with a few municipal utilities, they worry that grids will be over-prioritised under current regulation leading to neglect of decentralized flexibility options which, in their view, leaves the system vulnerable (e.g. 8KU, Next Kraftwerke). Indeed, it is widely agreed that existing regulations in Germany do not favour new flexibility technologies but rather transmission grids (Kemfert et al., 2016; Winfield et al., 2018).

Our results resonate with other studies of the German case. The main electricity incumbents were disrupted by VREs during the 2000s and gradually accepted that strategic reorientation was necessary in the late 2000s (Kungl, 2015; Schmid et al., 2016). In response they engaged in the early 2010s with new core technologies—especially large-scale VREs such as offshore wind (Clean Energy Wire, 2018b; Johnstone et al., 2020)—largely building on existing capabilities for managing large-scale projects and business models. All the main incumbents managed to build new technological capabilities in new core technologies as well as changing strategies and organizational structures (Interview 2; Ossenbrink et al., 2019; Richter, 2013).

However, the majority of VREs deployed in the 2000s were small-scale and owned by challengers. This new market with proactive and decentralized prosumers was quite different from what incumbents were used to and involved radically different business models. As the diffusion of decentralized VREs accelerated during the 2010s it started to influence the system architecture in terms of customer interfaces toward decentralization (Kungl & Geels, 2018; Ossenbrink et al., 2019). At this juncture, new flexibility technologies were still not an urgent issue (Bauknecht et al., 2016). Even so, incumbents started to respond to this development around 2015 by experimenting with new (decentralized) business models in form of research, development, and demonstration projects (Clean Energy Wire, 2018a, 2018b; Frei et al., 2018; Johnstone et al., 2020; Kungl, 2015). These attempts by incumbents were made difficult by capabilities and company culture rigged for large-scale projects with passive consumers (Ossenbrink et al., 2019; Richter, 2013).

This implies that at the time of our data points, incumbents were supportive of a renewable energy transitions, relatively successful in core technology changes with investments in large-scale VREs, and in the very early phase of experimenting with solutions for a decentralized system architecture and flexibility technology but still with strong uncertainty about how new business models could look like. This situation can explain that incumbents believe that decentralization is part of the transition but also that they would prefer that system architecture remains as centralized as possible because within that architecture they have a clear business model. As a consequence, decentralized and centralized configurations of VREs were developing in parallel both at the firm level and at the system level where it was driven by different kinds of actors (Funcke & Ruppert-Winkel, 2020).

6.2 Implications for theory

Our analysis and findings have implications for the relevance of the system technology concept for understanding the acceleration phase of transitions and for the dynamic role of actors.

6.2.1 System technology and accelerating transitions

The concept of *system technology* helps advance our understanding of transitions on, at least, two points. First, our approach and the distinction of innovation in core technologies and in system technologies and the resulting transition pathways typology have been useful to conceptualize the importance of system flexibility in the accelerating electricity system transition. A system technology approach, for example, directs attention to nuances in system architectures and it shows that different architectures can include different and partly overlapping combinations of system technologies. In that way, the system technology perspective opens a disaggregated view on architectures. Moreover, the latter is relevant for understanding variations in actor positions, especially when these positions vary depending on whether we look at architectural configurations as a whole or at specific system technologies. Compared to earlier studies, which showed more polarized conflicts around these issues (Lindberg et al., 2019; Markard et al., 2016), we were able to uncover (and explain) a higher degree of nuance.

Second, the concept of system technology improves our understanding of whether and how disruption to the status quo may deepen in the acceleration phase of transitions. Our results support the notion that incumbents are more challenged by architectural change (radical transformative transition pathway) than by subsystem change (modular substitution transition pathway). Since potential deeper disruption leads to higher levels of resistance (Lindberg et al., 2019), we expect that whether the level of resistance from incumbents is higher in the acceleration phase depends on the extent of change to system architecture. We suggest three degrees of change to system architecture that are associated with deeper disruption to incumbents including: (i) when established system technologies have to expand (e.g., to accommodate higher levels of diffusion of new core technologies), (ii) when entirely new system technologies in a limited role are required to complement existing ones, and (iii) when there are major disruptions in system architecture such that new system technologies come to dominate. Given that high levels of resistance from powerful actors is likely to slow down transition processes (Pel, 2021), the acceleration phase of transitions may in fact be a very slow process if major changes to system architecture are involved. In more general terms, the notions of system architecture and system technologies provide a new way of thinking about tensions and trade-off between the directionality (i.e. pathway and degree of disruption) and the pace of transitions.

6.2.2 Actor dynamics in the acceleration phase

In term of actors and architectural change our study shows that dichotomy of incumbents-vs-challengers becomes blurred in the acceleration phase as actors start shifting positions. Although we did not look directly at the strategies of actors, our analysis of their preferences for system technologies serves as reasonable a proxy. In our case, many incumbents already engaged with *strategic reorientation* by embracing a renewable energy transition and by adapting to new core technologies in form of large-scale VREs. Yet, we also observed that many incumbents subsequently engaged with *strategic recreation* by experimenting with business models and company identity for a decentralised system architecture. The latter was however very challenging and it is still too early to know if they succeed (Ossenbrink et al., 2019). Our case thus supports the notion that strategic reorientation is less challenging than strategic recreation (Geels, 2014a; Tushman & Romanelli, 1985). Moreover, our framework can serve as a template for understanding the variety of strategies incumbents pursue in the acceleration phase of transitions. It seems a promising topic for further research to better understand whether and how incumbents engage with or resist strategic recreation in relation to architectural change in transitions both within and beyond electricity systems, e.g. how automotive incumbents engage with low-carbon mobility (core technology) and inter-modal shifts and shared mobility (architecture) (Costa et al., 2022).

We also saw challengers valuing established, large-scale system technologies such as transmission. This suggests that challengers are interested in building a new system by creating bridges between old and new system elements instead of just looking to overthrow the old system, which is often observed in earlier phases (Turnheim & Geels, 2013). It also suggests that as transitions progress, challengers shift perspective from individual new core technologies to appreciate the challenge at the system level (Geels, 2018a; Hockerts & Wüstenhagen, 2010). This is a novel aspect of challenger dynamics in transitions that merits more attention.

7 Conclusions

This paper was motivated by limited conceptualization and empirical analysis of architectural change in socio-technical systems—especially related to actor tensions and strategies—which we explored in the context of an accelerating sustainability transition. We introduced the concept of system technology to explore the specific role of technologies that generate system-level complementarities. System technologies complement core technologies and play an important role in transitions. They are particularly important in the acceleration phase when architectural changes at the system level are at stake. We illustrated the usefulness of the system technology concept for studying potentially disruptive architectural changes, and the preferences of different types of actors, in the German electricity system.

Our main finding is that many incumbents prefer established centralized system technologies (old architecture) but because these are very difficult to expand, incumbents reluctantly accept a role for novel decentralized system technologies. Their reluctance for new system technologies is reflected in preferences for a rather limited role for new system technologies only at a very late stage of the transition, and their preference for no policy support for immature system technologies. Many challengers also prefer a mix of old and new system technologies due to the realization that existing system technologies have a role to play in a future decentralised system. Challengers, however, remain sceptical to further expanding established system technologies and the current institutional setup that supports them. As the actors continue to change and adapt their businesses and interests, their positions become more fluid. Overall, we see that actor shifts are not the end of actor tensions, but rather a dynamic process that also unfolds in the acceleration phase.

As we have studied only the electricity system, a few words of caution are in order. First, while it has emerged as the 'frontrunner' system in the low-carbon energy transition, it is also a highly complex system (e.g., due to the need of constant load balancing). The relevance of system technologies for system performance may therefore be higher than in other settings. It is also a slowly changing system (e.g., due to long-lasting infrastructures), which is why reorientation of actors may be more slow-motion than elsewhere. Moreover, it is a system, in which (so far) much of the transition has concentrated on the supply side, while changes on the consumer side have remained very limited. Accordingly, flexibility technologies such as demand side management, which depend on higher user involvement, did not play a prominent role in the discussions in our data. Future studies on system technologies and system architecture may want to explore other systems and places to better understand whether and how the particularities of context affect the disruptive effects of different system architectures. We also see merit in exploring other transition phases (emergence and stabilization) to better understand when actor tensions over system architecture typically emerge and when they are settled (if at all).

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Appendix A

Table 1 describes a template for our analysis of flexibility technologies. In this appendix A we go through each focal flexibility technology accordingly. The results are summarized in Tables 4 and 5 in section 4. Note that our assessment of flexibility technologies is not universal but depends (to a certain extent) on the particularities of the German electricity system. For example, although gas power plants in principle can be small-scale, in the German system they are large-scale. Similarly, battery storage can in principle be both large- and small-scale installations, but in Germany these are predominantly small-scale and behind-the-meter. These issues influence the strength of technical complementarities between flexibility technologies and (de)centralized renewables, and between different flexibility technologies (Sinsel, Markard, et al., 2020).

TABLE 4: TEMPLATE FOR DESCRIBING FLEXIBLE TECHNOLOGIES

	Dimension		**Content**
A	Flexibility technology		Name of flexibility technology / flexibility option
B	Description		Short tech description of how the technology is considered as a source of flexibility.
C	Maturity		*Maturity* refers to whether a technology via learning processes has improved performance and/or reduced cost in the system costs compared to alternatives, and how it is presently used. It indicates whether additional innovation and support is needed for the technology to diffuse. It also indicates whether incumbents are familiar with it (Azar & Sandén, 2011). Maturity can either high or low.
D	Scale		*Scale* refers to the typical physical scale of the technology when deployed. It indicates how big an intrusion a project is to a given landscape and thus the extent of public opposition to be expected as well as length of deployment time (Dahlgren et al., 2013; Lovins, 2002). We denote scale as small, large, or varied which means that the technology is used both as small and large-scale installations.
E	CEN-FIT Institutions		How well does the technology fit with centralized (traditional) power system planning and regulations? Would wide diffusion of a technology require major institutional changes to a centralized architecture? This indicator is based on maturity and scale and can be either high or low. Immature and small-scale flexibility technologies have low fit while mature and large-scale technology has high fit.
F	CEN-DEC Technical		In technical terms, does the flexibility technology have stronger complementarity with a centralized (CEN) or decentralized (DEC) architecture? Complementarities can also be of equal strength (BOTH). The guiding question underpinning each assessment was "how does expansion of flexibility technology X influence the deployment conditions for VRE technology Z? The indicator summarizes insights from rows I, J, K and L.
G	Flexibility service duration		What is the physical ability of the technology to provide flexibility over time
H	System problem addressed		Which power system problems does the technology help to solve
I	Large-scale plants / Centralized	Wind	How well does the flex technology match large-scale (centralized) wind power
J		Solar	How well does the flex technology match large-scale (centralized) solar PV
K	Small-scale plants / Decentralized	Wind	How well does the flex technology match small-scale (distributed) wind power
L		Solar	How well does the flex technology match small-scale (distributed and rooftop) solar PV
M	Key references		Main sources of information

TABLE 5: TRANSMISSION

Flex technology		Transmission
Description		Transmission facilitates generation, which is far away from consumption centres, offshore wind in particular but also many onshore wind plants are built in remote areas[7]. Transmission provides flexibility by connecting regions with different weather and consumption patterns in one market. Hence, the bigger, the better.
Maturity		High; Transmission grid technology is relatively mature although important innovations are happening in HVDC and grid management
Scale		Large; Transmission projects are typically large-scale installations with very long lead times of up to 10-15 years
CEN-FIT		High; Transmission fits very well with a centralized system. It is operated on a centralized way by one or a few TSOs that are tasked with maintaining system stability above all else.
CEN-DEC		CEN: It can be considered a centralized flexibility option that is pivotal to a centralized system configuration.
Flex service duration		Almost Continuously – AC power flows are immediately changed because of changed production or consumption, according to Ohm's law. Power flows can be controlled using FACTS devices (Flexible Alternating Current Transmission System). HVDC connections uses power converter stations at each side to control the direction and magnitude of power transfer. Stability requirements in the AC grids can limit the flexibility provided by HVDC.
System problem addressed		Flow : New transmission links increases the power transfer capacity between two areas Balance: Transmission indirectly improves the balancing between generation and consumption by smoothing power fluctuations and making more flexible resources available over a greater geographic area.
Large-scale plants / Centralized	Wind	Offshore wind deployment largely depends on building of new transmission capacity.
	Solar	Greenfield solar (i.e. large-scale projects) and CSP (concentrated solar power) need transmission but is somewhat more flexible with respect to location of the plants.
Small-scale plants / Decentralized	Wind	More transmission capacity does indirectly improve conditions for decentralized renewables by increasing the export possibilities
	Solar	Rooftop- and small-scale PV can be considered as relatively independent of transmission expansion, since the PV is installed at the low or medium voltage grids and often close to consumption, and their development are first and foremost limited by distribution grid limitations and not transmission.
Key references		(Ackermann, 2005; Andersen & Markard, 2020; Bayer et al., 2018)

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[7] Grids are built up by different voltage levels, from Transmission (typically from 66 kV to 500 kV) to Distribution (below 66kV). In European countries, transmission grids are normally owner and controlled by one or a few central Transmission System Operators (TSO), while there are a vast number of Distribution Grid Operators (DSOs) with responsibility for their local distribution grids.

TABLE 6: HYDRO POWER STORAGE

Flex technology		Hydro power storage
Description		Comprises pumped storage and reservoir hydro. Traditionally been used to cover daily to seasonal load variations to improve fuel efficiency of thermal power plants.
Maturity		High: Hydro power technology has been commercially available for many decades.
Scale		Typically large-scale. Takes long time to build. In Europe most potential exploited already
CEN-FIT		High: Already established as part of the traditional power system
CEN-DEC		CEN: Most reservoir hydro is large-scale connected to the central grid and built under traditional centralised power system planning regime. Small-scale hydro also exists, but more often as run-of-river without storage.
Flex service duration		Minutes-days (central Europe): Flexibility services limited by reservoir volumes Minutes-months (Nordic area): Many hydropower plants have seasonal storage. Power capacity is the limiting flexibility factor more than energy storage capacity.
System problem addressed		Balance: Reservoir hydropower with and without pumping are traditionally used as low-cost balancing option.
Large-scale plants / Centralized	Wind	Large hydro storage has strong operational benefits in connection with wind power but also more generally with large amounts of onshore wind, solar PV, and offshore wind in Europe
	Solar	
Small-scale plants / Decentralized	Wind	Reservoir hydro helps balancing the country/region net load and will thus indirectly also improve integration of small-scale VRE although not as efficient as for large-scale VRE which is directly connected to the transmission grid.
	Solar	
Key references		(Castronuovo & Lopes, 2004; Graabak et al., 2019; Lindberg et al., 2016)

TABLE 7: GAS POWER PLANTS

Flex technology		Gas power plants
Description		Gas power plants can be built to maximize efficiency (CCGT for base-load and mid-merit plants) or to maximize flexibility (OCGT for peak plants and smaller systems).
Maturity		High: Gas power plants without CCS have been commercially available for many decades. CCS for (flexible) gas power plants) is still in the R&D phase.
Scale		Large; typically, large-scale, but in principle also applicable for small-scale systems. But these are predominantly used in isolated island grids and rarely in the normal system due to economies of scale advantages. Large-scale plants take long time to build. Can in principle be built anywhere as opposed to hydro and wind.
CEN-FIT		High: Already established as part of the traditional power system
CEN-DEC		CEN: Gas power plants are typically in the 400-1000 MW range and connected to the central grid as part of a centralised system design. CCS will push this option even further in the centralised direction due to the need for CO2 infrastructure.
Flex service duration		Minutes-days: Gas power plants responds quickly to changes in the power system balance (i.e. the AC frequency), but energy losses increase for lower operating points. OCGT are more flexible than CCGT but with higher operating costs.
System problem addressed		Balance: CCGT where typically built for baseload operation but has gradually shifted towards more flexible operation as more VRE sources are entering the production mix. OCGT are typically installed as flexible peaker units.
Large-scale plants / Centralized	Wind	Flexible power plants are suitable to balance mismatch between VRE output and load. But its operation with large amounts of VRE can be challenging due to minimum run-times, varying efficiency, and minimum power constraints.
	Solar	
Small-scale plants / Decentralized	Wind	Same as above but are rarely deployed in decentralized systems, cf. above.
	Solar	
Key references		(Kubik et al., 2012; Montañés et al., 2016)

TABLE 8: DISTRIBUTION GRID

Flex technology		Distribution grid
Description		The distribution grid connects the transmission system to the end-users. Traditionally one-way flow, but recent years see reverse power flows due to local surplus VRE generation
Maturity		High : Distribution grid technology is relatively mature although there are some developments of FACTS devices for increasing grid capacity and improving stability
Scale		Large; although this concerns local projects, building grids is nearly always a big project that takes years.
CEN-FIT		Low; although building distribution grid is not a new thing, the distribution grid was not previously considered a source of flexibility. Mobilizing this solution requires that DSOs become more active and potentially challenges the dominant role TSOs enjoy today.
CEN-DEC		DEC:A properly designed and operated distribution grid could facilitate local flexible resources to integrate new VRE capacity and new electric demand with less need for flexibility from the overlaying (central) grid
Flex service duration		Continuously: Power flows responds instantaneously to changes in production and consumption.
System problem addressed		Flow (local): Distribution grid expansions make it possible to utilize more local VRE sources and to connect new electric loads and reduces the need for local storage like batteries.
Large-scale plants / Centralized	Wind	Distribution grid expansion does not affect conditions for large-scale plants.
	Solar	
Small-scale plants / Decentralized	Wind	Distribution grid expansion helps integrating small- to medium scale wind power and (aggregated) rooftop PV
	Solar	
Key references		(Seguin et al., 2016; Tande, 2000)

Table 9: P2G

Flex technology		P2G (large)
Description		Power-to-gas and back to power refers to the conversion between electric power system and gas systems, e.g. hydrogen
Maturity		Low; Still on RD&D stage, but with increasingly number of demonstration projects.
Scale		Large; large-scale, e.g. conversion and re-conversion of hydrogen with large-scale storage and possible blending into natural gas networks. Power-to-gas variants are flexible and modular regarding sizing, placement and operation but suffers from low round-trip efficiencies (hydrogen). Note we focus on large-scale P2G even though small-scale and decentralized electrolyser plants are possible because the latter is what was discussed in the consultation responses, we analysed
CEN-FIT		High: Although its deployment can require changes to regulation, it fits well into a centralized architecture
CEN-DEC		CEN: Large scale infrastructure for gas and liquid energy carriers Energy process site
Flex service duration		Minutes-months. Depending on gas storage technology (Compressed hydrogen tanks: Days. Underground storage: Months)
System problem addressed		Balance: P2G with properly sized and operated power interface (electrolysers) and storage may be used as flexible load seen by the power system Flow: P2G offer an alternative route for energy to be transported from a production site to consumers, typically as an alternative to grid extensions that can be expensive or difficulty due to environmental or social factors.
Large-scale plants / Centralized	Wind	Suited for balancing wind variations, due to the relatively low cost of long-term storage compared to e.g. batteries.
	Solar	As wind, but less benefits as solar typically needs more high-power low-energy capacity storage
Small-scale plants / Decentralized	Wind	Same as above with the caveat that channelling P2G flexibility into decentralized systems from large-scale plants is associated with further and significant round-trip efficiency losses. It is possible but not ideal
	Solar	
Key references		(Jafari et al., 2020; Varone & Ferrari, 2015; Wulf et al., 2018)

TABLE 10: CHP

Flex technology		**CHP**
Description		Combined heat and power (CHP) links power systems to heat systems and can therefore increase the inflexibility in the power system if heat supply is driving the operation. With thermal storage, CHP plants can operate primarily based on the electricity demand while the heat is stored. This adds flexibility to the power system. This is relevant both for large- and small-scale CHP plants
Maturity		High: CHP technology has been commercially available for decades. However, improvements can still be seen with respect to flexible operation
Scale		Large. While plant size varies, operation of CHP requires building and connecting both electricity and district heating grids. It therefore involves big projects with long construction time.
CEN-FIT		High: Part of the traditional power and heat supply system
CEN-DEC		BOTH: CHP can be part of centralized heating systems in cities but can also serve individual heating demands at e.g. industrial sites.
Flex service duration		Minutes-days: Depending on heat storage and fuel flexibility
System problem addressed		Balance: CHP is be operated to follow either heat demand or electricity demand, and can be used for balancing local VRE production by increasing operation flexibility through more thermal storage
Large-scale plants / Centralized	Wind	CHP is usually connected to the distribution grid level and is therefore most suited for flexible operation in connection to decentralized systems where it can provide balancing and power flow control. The aggregated flexible operation of CHP also has a positive effect on the transmission system level, improving indirectly the integration of large-scale RES
	Solar	
Small-scale plants / Decentralized	Wind	
Key references		(Beiron et al., 2020; Streckienė et al., 2009; Szarka et al., 2013)

TABLE 11: BATTERIES

Flex technology		Batteries
Description		Modular technology which can charge and discharge electrical power. It can in principle can be installed in conjunction with any type of VRE
Maturity		Low; while battery technology (Li-ion) is maturing and experiencing rapid cost declines, its application as energy storage systems is still rather limited. Especially at larger-scale projects
Scale		Small; Batteries are flexible with regards to size, but more readily available for smaller systems. Up to 250 MW is installed. Can be deployed very fast and can be moved geographical after installation if needed.
CEN-FIT		Low: if small-scale battery storage is to play a big role, it would not fit well with a centralized architecture. It can support transmission networks under a centralized architecture but typically only in an ad hoc and limited way.
CEN-DEC		DEC: Batteries are very attractive supplement to solar PV, being modular and easy to install by independent market actors, at low voltage levels.
Flex service duration		Seconds-hours: Batteries responds extremely quick to power flow changes and can deliver high power (MW) flexibility in both directions (charging and discharging). Storage over time is limited by the size of the battery itself, as opposed to hydrogen storage (or other P2G) where the energy storage (pressure tank etc) is physically detached from the conversion devices (electrolyser and fuel cell)
System problem addressed		Balance: Batteries are excellent devices for short-term balancing but becomes very expensive for storing energy over many hours or days. Flow: Batteries are increasingly being used as alternative to grid extensions for areas which experience increased electricity demands
Large-scale plants / Centralized	Wind	Batteries are well suited to balance wind variations but even better with PV. Batteries are very well integrated with solar PV. This is because the diurnal variation patterns of solar energy opt for storage systems with high power capacity, but the energy does not need to be stored for longer periods. Battery storage connected to the transmission grid can help with VRE integration at that level
	Solar	
Small-scale plants / Decentralized	Wind	Same as above but battery storage is, for flexibility provision, in general better suited for small scale installations because it enables extended production and consumption at the same location which is more efficient because you avoid transport and conversion losses
	Solar	
Key references		(IEA, 2018; Jafari et al., 2020; Sylvia, 2020)

Table 12: Demand Side Management

Flex technology		**Demand Side Management**
Description		DSM covers different forms of consumption flexibility, such as load shifting (consuming the electricity at a later stage), and load shaving (e.g. lowering the electricity for heating with lower indoor temperature as result). In terms of effect, it can be large-scale (industrial), small-scale (residential), and comprises different activation principles (direct control, automatic, manual, market-based)
Maturity		Low; Immature for distributed, aggregated, and automatic services. Technically mature for reserves provision from large industrial users. Still, the latter is not used much in Northern European including German power systems
Scale		Small; Varied in terms of effect but small-scale in terms of required physical installations as it primarily concerns digitalization and enhanced flexibility of existing technologies. DSM can therefore be installed rapidly
CEN-FIT		Low: Extensive DSM requires that users become very active and flexible something which is largely alien to the traditional organization and regulation of a centralized system
CEN-DEC		BOTH
Flex service duration		Minutes-hours: DSG could be activated even than minutes from a technical point of view, but its response time depends on the type of market/contract arrangement and communication system that is used for its activation. Some DSM options has a physical “rebound” effect, which causes the electricity consumption to increase as a later stage after the flexibility activation.
System problem addressed		Balance: DSM can respond to quick changes in the balance, either through direct (centralized) control by the System Operator or based on a market decision by an independent flexibility provider (decentralized decision) . Flow: DSM is a highly attractive alternative to grid constraints, both at transmission scale and distribution scale.
Large-scale plants / Centralized	Wind	DSM has many benefits in connection with integration of renewables, as it is available wherever there is electricity demand, as well as the relatively low-cost of investment compared to e.g. batteries. The main drawback is that DSM provides no power generation opportunities by itself. Large-scale solutions are typically industrial facilities but aggregated local DSM can also provide system-wide flexibility services. Local DSM can be used as an alternative to storage and grid expansion for integration of distributed RES
	Solar	
Small-scale plants / Decentralized	Wind	
	Solar	
Key references		(Strbac, 2008; Stötzer et al., 2015; Wolfgang & Doorman, 2011)

TABLE 13: VRE FLEXIBILITY

Flex technology		**VRE flexibility**
Description		Operation of VRE plants in a flexible manner, individually or as part of a larger generation fleet. One example is to operate a wind power plant at lower level than optimal (for the given wind speed), to avoid overloading of power lines or to provide balancing power. Another category of VRE flexibility is to operate a larger fleet of wind and PV together as a virtual power plant. The aggregated output is smoothed out, which can reduce overall intermittency in the system and facilitate more efficient operation of VREs
Maturity		Low; VRE flexibility is a novel way of providing flexibility which is not used much. However, technology and grid codes for flexible operation of wind power has been existing for years, but much less taken in use for PV
Scale		Varied; varies with the size of VRE plants
CEN-FIT		Low: VRE flexibility is an alternative to traditional means of balancing and congestion management
CEN-DEC		BOTH: VRE flexibility can in principle be activated at all levels in the system, and by a centrally coordinated wind farm controller to an individual rooftop PV owner.
Flex service duration		Seconds to Minutes: Solar PV can react instantaneously to a control signal by witching of the DC power supply. Wind farms are
System problem addressed		Balance: Although readily available technology, reduction of VRE output should be not the first flexibility source to activate since it leads to loss of curtailed energy. However, it is attractive for e.g. improving stability in case of grid faults. Flow: To have the option to curtail VRE production can be an attractive alternative to overinvesting in grids for export of surplus VRE from remote areas.
Large-scale plants / Centralized	Wind	Both wind turbines and solar PV systems can be equipped with power conversion technologies and operating systems which makes it possible to control active power and reactive to a certain extent. Limited flexibility due to the variations in energy input
	Solar	
Small-scale plants / Decentralized	Wind	
	Solar	
Key references		(Hulle et al., 2014; Pudjianto et al., 2007)

Appendix B

Actor (N = 22)	Actor description / type	System domain	Actor type	Asset base
50hertz	TSO	Grid	Incumbent	Transmission
8KU	Association of 8 municipal utilities	Generation/Distribution	Challenger (Peripheral Incumbent)	Generation/Distribution network
Agora Energiewende	Energy transition think tank	Whole system	Challenger (Newcomer)	None
Amprion	TSO	Grid	Incumbent	Transmission
BDEW	German Association of Energy and Water Industries	Generation	Incumbent	All electricity and gas assets
BEE	Association for renewable energy producers	Generation	Challenger (Newcomer)	Mix of renewables
BKWK	Association for CHP operators	Generation	Incumbent	CHP
BVES	German Energy Storage Association	Whole system	Challenger (Newcomer)	Storage technologies
Dena	German Energy Agency	Whole system	Incumbent	None
DIHK	German Chamber of Commerce	Consumption	Incumbent	Consumption
DUH	Environmental NGO	Whole system	Challenger (Newcomer)	None
EnBW	Utility	Generation/Distribution	Incumbent	Conventional generation, renewables
Eurosolar	Association	Generation	Challenger (Newcomer)	Renewables
Greenpeace Energy	Green electricity and gas supplier	Generation	Challenger (Newcomer)	Renewables, Power-to-Gas
Next Kraftwerke	Aggregator, Operator of a virtual power plant	Generation	Challenger (Newcomer)	Virtual Power Plant, decentralized renewables
13 Oil & Gas actors	Sells oil and gas. Exonmobil, Equinor, Shell, Total, etc.	Adjacent system	Challenger (Diversifying entrant)	Oil and gas resources
RWE	Utility	Generation	Incumbent	Conventional generation, renewables
Statkraft	Utility from Norway	Generation	Incumbent	Renewables (mainly hydro), gas plants
TenneT	TSO	Grid	Incumbent	Transmission
TransnetBW	TSO	Grid	Incumbent	Transmission
VCI	German Chemicals Industry Association	Consumption	Challenger (Peripheral Incumbent)	Chemical plants that require high voltage and stable power supply to avoid fluctuations
Vzbv	The Federation of German Consumer Organisations	Consumption	Challenger (Peripheral Incumbent)	Consumer interests / empowerment

References

Abernathy, W. J., & Clark, K. B. (1985). Innovation - Mapping the Winds of Creative Destruction. *Research Policy, 14*(1), 3-22. doi:Doi 10.1016/0048-7333(85)90021-6

Ackermann, T. (2005). *Wind Power in Power Systems*: John Wiley & Sons, Ltd.

Andersen, A. D. (2014). No Transition without Transmission: HVDC Electricity Infrastructure as an Enabler for Renewable Energy? *Environmental Innovation and Societal Transitions, 13*, 75-95. doi:10.1016/j.eist.2014.09.004

Andersen, A. D., & Markard, J. (2020). Multi-technology interaction in socio-technical transitions: How recent dynamics in HVDC technology can inform transition theories. *Technological Forecasting & Social Change, 151*.

Ansari, S., & Krop, P. (2012). Incumbent performance in the face of a radical innovation: Towards a framework for incumbent challenger dynamics. *Research Policy, 41*(8), 1357-1374. doi:http://dx.doi.org/10.1016/j.respol.2012.03.024

Arthur, W. B. (2009). *The Nature of Technology: What It Is and How It Evolves*: Free Press.

Azar, C., & Sandén, B. (2011). The elusive quest for technology-neutral policies. *Environmental Innovation and Societal Transitions*, 135-139.

Bauknecht, D., Heinemann, C., Koch, M., Ritter, D., Harthan, R., Sachs, A., . . . Langanke, S. (2016). *Systematischer Vergleich von Flexibilitäts- und Speicheroptionen im deutschen Stromsystem zur Integration von erneuerbaren Energien und Analyse entsprechender Rahmenbedingungen*. Öko-Institutenergynautics. Freiburg, Darmstadt. Retrieved from https://www.oeko.de/fileadmin/oekodoc/Systematischer_Vergleich_Flexibilitaetsoptionen.pdf

Bauknecht, D., Heinemann, C., Matthias, K., & Vogel, M. (2020). Demand flexibility and what it can contribute in Germany. In F. Sioshansi (Ed.), *Variable Generation: Flexible Demand*: Academic Press.

Bayer, B., Matschoss, P., Thomas, H., & Marian, A. (2018). The German experience with integrating photovoltaic systems into the low-voltage grids. *Renewable Energy, 119*, 129-141. doi:https://doi.org/10.1016/j.renene.2017.11.045

Beiron, J., Montañés, R. M., Normann, F., & Johnsson, F. (2020). Flexible operation of a combined cycle cogeneration plant – A techno-economic assessment. *Applied Energy, 278*, 115630. doi:https://doi.org/10.1016/j.apenergy.2020.115630

Bergek, A., Berggren, C., Magnusson, T., & Hobday, M. (2013). Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation? *Research Policy, 42*, 1210-1224. doi:10.1016/j.respol.2013.02.009

Bertsch, V., Hall, M., Weinhardt, C., & Fichtner, W. (2016). Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for Germany. *Energy, 114*, 465-477. doi:https://doi.org/10.1016/j.energy.2016.08.022

Bird, L., Milligan, M., & Lew, D. (2013). *Integrating Variable Renewable Energy: Challenges and Solutions*. Retrieved from Golden, Colorado:

Bundetzagentur. Why is grid expansion necessary? Retrieved from https://www.netzausbau.de/EN/background/why/en.html;jsessionid=721283837F1345178BA84804C43F6BC4

Bundetzagentur. (2019). *Quartalsbericht Netz- und Systemsicherheit - Gesamtes Jahr 2019*. Retrieved from https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Berichte/2020/Quartalszahlen_Gesamtjahr_2019.pdf?__blob=publicationFile&v=6

Castronuovo, E. D., & Lopes, J. A. P. (2004). On the optimization of the daily operation of a wind-hydro power plant. *IEEE Transactions on Power Systems, 19*(3), 1599-1606. doi:10.1109/TPWRS.2004.831707

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research & Social Science, 37*, 175-190. doi:https://doi.org/10.1016/j.erss.2017.09.015

Christensen, C. M., & Rosenbloom, R. S. (1995). Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. *Research Policy, 24*(2), 233-257. doi:https://doi.org/10.1016/0048-7333(93)00764-K

Clark, K. B. (1985). The interaction of design hierarchies and market concepts in technological evolution. *Research Policy, 14*(5), 235-251. doi:https://doi.org/10.1016/0048-7333(85)90007-1

Clean Energy Wire. (2018a). Germany's largest utilities at a glance. Retrieved from https://www.cleanenergywire.org/factsheets/germanys-largest-utilities-glance

Clean Energy Wire. (2018b). Power production at sea re-emerges as Energiewende cornerstone. Retrieved from https://www.cleanenergywire.org/dossiers/offshore-wind-power-germany

Colfer, L. J., & Baldwin, C. Y. (2016). The mirroring hypothesis: theory, evidence, and exceptions. *Industrial and Corporate Change, 25*(5), 709-738. doi:10.1093/icc/dtw027

Costa, E., Wells, P., Wang, L., & Costa, G. (2022). The electric vehicle and renewable energy: Changes in boundary conditions that enhance business model innovations. *Journal of Cleaner Production, 333*, 130034. doi:https://doi.org/10.1016/j.jclepro.2021.130034

Dahlgren, E., Göçmen, C., Lackner, K., & van Ryzin, G. (2013). Small Modular Infrastructure. *The Engineering Economist, 58*(4), 231-264. doi:10.1080/0013791X.2013.825038

David, P. A. (1997). Path dependence and the quest for historical economics: one more chorus of the ballad of QWERTY. *Souls*.

David, P. A., & Bunn, J. A. (1988). The economics of gateway technologies and network evolution: Lessons from electricity supply history. *Information Economics and Policy, 3*(2), 165-202. doi:https://doi.org/10.1016/0167-6245(88)90024-8

Davies, A. (1997). The life cycle of a complex product. *International Journal of Innovation Management, 1*, 229-256.

Eisenhardt, K. M. (1989). Building theories from case study research. *The Academy of Management Review, 14*, 532-550. doi:10.2307/258557

ETIP SNET. (2020). *Sector Coupling: Concepts, State-of-the-art and Perspectives*: ETIP Smart Networks for Energy Transition.

Fiol, C. M., & Lyles, M. A. (1985). Organizational Learning. *The Academy of Management Review, 10*(4), 803-813. doi:10.2307/258048

Fligstein, N., & McAdam, D. (2011). Toward a General Theory of Strategic Action Fields. *Sociological Theory, 29*(1), 1-26.

Frei, F., Sinsel, S. R., Hanafy, A., & Hoppmann, J. (2018). Leaders or laggards? The evolution of electric utilities' business portfolios during the energy transition. *Energy Policy, 120*, 655-665. doi:https://doi.org/10.1016/j.enpol.2018.04.043

Funcke, S., & Bauknecht, D. (2016). Typology of centralised and decentralised visions for electricity infrastructure. *Utilities Policy, 40*, 67-74. doi:http://dx.doi.org/10.1016/j.jup.2016.03.005

Funcke, S., & Ruppert-Winkel, C. (2020). Storylines of (de)centralisation: Exploring infrastructure dimensions in the German electricity system. *Renewable and sustainable Energy Reviews, 121*, 109652. doi:https://doi.org/10.1016/j.rser.2019.109652

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*, 1257-1274.

Geels, F. W. (2005). *Technological Transitions and System Innovations. A Co-Evolutionary and Socio-Technical Analysis*: Edward Elgar.

Geels, F. W. (2014a). Reconceptualising the co-evolution of firms-in-industries and their environments: Developing an inter-disciplinary Triple Embeddedness Framework. *Research Policy, 43*(2), 261-277. doi:10.1016/j.respol.2013.10.006

Geels, F. W. (2014b). Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory, Culture & Society, 31*(5), 21-40. doi:10.1177/0263276414531627

Geels, F. W. (2018a). Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective. *Energy Research & Social Science, 37*, 224-231. doi:https://doi.org/10.1016/j.erss.2017.10.010

Geels, F. W. (2018b). Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016). *Energy Research & Social Science, 46*, 86-102. doi:https://doi.org/10.1016/j.erss.2018.07.008

Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. *Nature Climate Change, 6*(6), 576-583. doi:10.1038/nclimate2980

Geels, F. W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., . . . Wassermann, S. (2016). The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014). *Research Policy, 45*(4), 896-913. doi:http://dx.doi.org/10.1016/j.respol.2016.01.015

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science, 357*(6357), 1242-1244. doi:10.1126/science.aao3760

German Environment Agency. (2020). Renewable energies in figures. Retrieved from https://www.umweltbundesamt.de/en/topics/climate-energy/renewable-energies/renewable-energies-in-figures

Graabak, I., Korpås, M., Jaehnert, S., & Belsnes, M. (2019). Balancing future variable wind and solar power production in Central-West Europe with Norwegian hydropower. *Energy, 168*, 870-882. doi:https://doi.org/10.1016/j.energy.2018.11.068

Haley, B. (2018). Integrating structural tensions into technological innovation systems analysis: Application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada. *Research Policy, 47*(6), 1147-1160. doi:https://doi.org/10.1016/j.respol.2018.04.004

Henderson, R. M., & Clark, K. B. (1990). Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly, 35*(1), 9-30.

Hess, D. J. (2014). Sustainability transitions: A political coalition perspective. *Research Policy, 43*(2), 278-283. doi:http://dx.doi.org/10.1016/j.respol.2013.10.008

Hockerts, K., & Wüstenhagen, R. (2010). Greening Goliaths versus emerging Davids - Theorizing about the role of incumbents and new entrants in sustainable entrepreneurship. *Journal of Business Venturing, 25*, 481-492. doi:10.1016/j.jbusvent.2009.07.005

Holtz, G., Brugnach, M., & Pahl-Wostl, C. (2008). Specifying “regime” — A framework for defining and describing regimes in transition research. *Technological forecasting and social change, 75*(5), 623-643. doi:https://doi.org/10.1016/j.techfore.2007.02.010

Hughes, T. (1983). *Networks of Power. Electrification in Western Society 1880-1930*: Johns Hopkins University Press.

Hulle, F. v., Pineda, I., & Wilczek, P. (2014). *Economic grid support services by wind and solar PV. A review of system needs, technology options, economic benefits and suitable market mechanisms*. Retrieved from

IEA. (2017). *Status of Power System Transformation*. Paris: International Energy Agency.

IEA. (2018). *World Energy Outlook*. Paris: International Energy Agency.

Jacobides, M. G., Knudsen, T., & Augier, M. (2006). Benefiting from innovation: Value creation, value appropriation and the role of industry architectures. *Research Policy, 35*(8), 1200-1221. doi:https://doi.org/10.1016/j.respol.2006.09.005

Jafari, M., Korpås, M., & Botterud, A. (2020). Power system decarbonization: Impacts of energy storage duration and interannual renewables variability. *Renewable Energy, 156*, 1171-1185. doi:https://doi.org/10.1016/j.renene.2020.04.144

Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020). Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom. *Energy Research & Social Science, 59*, 101287. doi:https://doi.org/10.1016/j.erss.2019.101287

Kamlage, J.-H., Drewing, E., Reinermann, J. L., de Vries, N., & Flores, M. (2020). Fighting fruitfully? Participation and conflict in the context of electricity grid extension in Germany. *Utilities Policy, 64*, 101022. doi:https://doi.org/10.1016/j.jup.2020.101022

Kemfert, C., Kunz, F., & Rosellón, J. (2016). A welfare analysis of electricity transmission planning in Germany. *Energy Policy, 94*, 446-452. doi:https://doi.org/10.1016/j.enpol.2016.04.011

Klitkou, A., Bolwig, S., Hansen, T., & Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. *Environmental Innovation and Societal Transitions, 16*, 22-37. doi:https://doi.org/10.1016/j.eist.2015.07.005

Korpaas, M., Holen, A. T., & Hildrum, R. (2003). Operation and sizing of energy storage for wind power plants in a market system. *International Journal of Electrical Power & Energy Systems, 25*(8), 599-606. doi:https://doi.org/10.1016/S0142-0615(03)00016-4

Kubik, M. L., Coker, P. J., & Hunt, C. (2012). The role of conventional generation in managing variability. *Energy Policy, 50*, 253-261. doi:https://doi.org/10.1016/j.enpol.2012.07.010

Kungl, G. (2015). Stewards or sticklers for change? Incumbent energy providers and the politics of the German energy transition. *Energy Research & Social Science, 8*, 13-23. doi:https://doi.org/10.1016/j.erss.2015.04.009

Kungl, G., & Geels, F. W. (2018). Sequence and alignment of external pressures in industry destabilisation: Understanding the downfall of incumbent utilities in the German energy transition (1998–2015). *Environmental Innovation and Societal Transitions, 26*, 78-100. doi:https://doi.org/10.1016/j.eist.2017.05.003

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., . . . Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions, 31*, 1-32. doi:https://doi.org/10.1016/j.eist.2019.01.004

Lauber, V., & Jacobsson, S. (2016). The politics and economics of constructing, contesting and restricting socio-political space for renewables – The German Renewable Energy Act. *Environmental Innovation and Societal Transitions, 18*, 147-163. doi:https://doi.org/10.1016/j.eist.2015.06.005

Lilliestam, J., & Hangera, S. (2016). Shades of green: Centralisation, decentralisation and controversy among European renewable electricity visions. *Energy Research & Social Science, 17*, 20-29.

Lindberg, K. B., Dyrendahl, T., Doorman, G., Korpås, M., Øyslebø, E., Endresen, H., & Skotland, C. H. (2016, 6-9 June 2016). *Large scale introduction of Zero Energy Buildings in the Nordic power system.* Paper presented at the 2016 13th International Conference on the European Energy Market (EEM).

Lindberg, M. B., Markard, J., & Andersen, A. D. (2019). Policies, actors and sustainability transition pathways: A study of the EU's energy policy mix. *Research Policy, 48*(10), 103668. doi:https://doi.org/10.1016/j.respol.2018.09.003

Linzenich, A., Arning, K., & Ziefle, M. (2021). Acceptance of energy technologies in context: Comparing laypeople's risk perceptions across eight infrastructure technologies in Germany. *Energy Policy, 152*, 112071. doi:https://doi.org/10.1016/j.enpol.2020.112071

Lovins, A. (2002). *Small is Profitable. The Hidden Economic Benefits of Making Electrical Resources the Right Size*: Rocky Mountain Institute.

Magnusson, T., & Berggren, C. (2018). Competing innovation systems and the need for redeployment in sustainability transitions. *Technological forecasting and social change, 126*, 217-230. doi:https://doi.org/10.1016/j.techfore.2017.08.014

Malhotra, A., & Schmidt, T. S. (2020). Accelerating Low-Carbon Innovation. *Joule, 4*(11), 2259-2267. doi:https://doi.org/10.1016/j.joule.2020.09.004

Markard, J., Geels, F. W., & Raven, R. (2020). Challenges in the acceleration of sustainability transitions. *Environmental Research Letters, 15*(8), 081001. doi:10.1088/1748-9326/ab9468

Markard, J., & Hoffmann, V. H. (2016). Analysis of complementarities: Framework and examples from the energy transition. *Technological forecasting and social change, 111*, 63-75. doi:http://dx.doi.org/10.1016/j.techfore.2016.06.008

Markard, J., Suter, M., & Ingold, K. (2016). Socio-technical transitions and policy change - Advocacy coalitions in Swiss energy policy. *Environmental Innovation and Societal Transitions, 18*, 215-237.

McMeekin, A., Geels, F. W., & Hodson, M. (2019). Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016). *Research Policy*. doi:https://doi.org/10.1016/j.respol.2018.12.007

Meadowcroft, J. (2011). Engaging with the politics of sustainability transitions. *Environmental Innovation and Societal Transitions, 1*(1), 70-75.

Montañés, R. M., Korpås, M., Nord, L. O., & Jaehnert, S. (2016). Identifying Operational Requirements for Flexible CCS Power Plant in Future Energy Systems. *Energy Procedia, 86*, 22-31. doi:https://doi.org/10.1016/j.egypro.2016.01.003

Murmann, J. P., & Frenken, K. (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy, 35*(7), 925-952. doi:http://doi.org/10.1016/j.respol.2006.04.011

O'Reilly, C. A., & Tushman, M. L. (2008). Ambidexterity as a dynamic capability: Resolving the innovator's dilemma. *Research in organizational behavior, 28*, 185-206. doi:https://doi.org/10.1016/j.riob.2008.06.002

OECD/IEA. (2014). *Power of Transformation - Wind, Sun and the Economics of Flexible Power Systems*.

Ossenbrink, J., Hoppmann, J., & Hoffmann, V. H. (2019). Hybrid Ambidexterity: How the Environment Shapes Incumbents' Use of Structural and Contextual Approaches. *Organization Science, 30*(6), 1319-1348. doi:10.1287/orsc.2019.1286

Pel, B. (2021). Transition 'backlash': Towards explanation, governance and critical understanding. *Environmental Innovation and Societal Transitions, 41*, 32-34. doi:https://doi.org/10.1016/j.eist.2021.10.016

Pel, B., & Boons, F. A. (2010). Transition through subsystem innovation? The case of traffic management. *Technological forecasting and social change, 77*(8), 1249-1259. doi:https://doi.org/10.1016/j.techfore.2010.04.001

Perez, C. (2002). *Technological Revolutions and Financial Capital. The Dynamics of Bubbles and Golden Ages*. Cheltenham (UK) and Northampton (USA): Edward Elgar.

Perez, C. (2009). Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics, 34*(1), 185-202. doi:10.1093/cje/bep051

Prognos, F.-A. (2016). *Dezentralität und zellulare Optimierung – Auswirkungen auf den Netzausbaubedarf: Kurzfassung des Endberichts.* . Retrieved from N-ERGIE Aktiengesellschaft, Nürnberg:

Pudjianto, D., Ramsay, C., & Strbac, G. (2007). Virtual power plant and system integration of distributed energy resources. *IET Renewable Power Generation, 1*(1), 10-16. Retrieved from https://digital-library.theiet.org/content/journals/10.1049/iet-rpg_20060023

Raven, R. (2007). Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls. *Energy Policy, 35*(4), 2390-2400. doi:https://doi.org/10.1016/j.enpol.2006.09.003

Raven, R., Kern, F., Smith, A., Jacobsson, S., & Verhees, B. (2016). The politics of innovation spaces for low-carbon energy: Introduction to the special issue. *Environmental Innovation and Societal Transitions, 18*, 101-110. doi:https://doi.org/10.1016/j.eist.2015.06.008

Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy, 62*, 1226-1237. doi:http://doi.org/10.1016/j.enpol.2013.05.038

Roberts, C., Geels, F. W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B., & Jordan, A. (2018). The politics of accelerating low-carbon transitions: Towards a new research agenda. *Energy Research & Social Science, 44*, 304-311. doi:https://doi.org/10.1016/j.erss.2018.06.001

Robinius, M., Otto, A., Heuser, P., Welder, L., Syranidis, K., Ryberg, D., . . . Stolten, D. (2017). Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling. *Energies, 10*(7), 956.

Rotmans, J., Kemp, R., & van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight, 3*(1), 15-31. doi:doi:10.1108/14636680110803003

Sahal, D. (1985). Technological guideposts and innovation avenues. *Research Policy, 14*(2), 61-82. doi:https://doi.org/10.1016/0048-7333(85)90015-0

Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy, 40*(3), 403-414.

Schmid, E., Knopf, B., & Pechan, A. (2016). Putting an energy system transformation into practice: The case of the German Energiewende. *Energy Research & Social Science, 11*, 263-275.

Schmid, E., Pechan, A., Mehnert, M., & Eisenack, K. (2017). Imagine all these futures: On heterogeneous preferences and mental models in the German energy transition. *Energy Research & Social Science, 27*, 45-56. doi:https://doi.org/10.1016/j.erss.2017.02.012

Seguin, R., Woyak, J., David Costyk, Hambrick, J., & Mather, B. (2016). *High-Penetration PV Integration. Handbook for Distribution Engineers*. Retrieved from Golden, CO (United States): https://www.nrel.gov/docs/fy16osti/63114.pdf

Sinsel, S. R., Markard, J., & Hoffmann, V. H. (2020). How deployment policies affect innovation in complementary technologies—evidence from the German energy transition. *Technological forecasting and social change, 161*, 120274. doi:https://doi.org/10.1016/j.techfore.2020.120274

Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. *Renewable Energy, 145*, 2271-2285.

Smink, M. M., Hekkert, M. P., & Negro, S. O. (2015). Keeping sustainable innovation on a leash? Exploring incumbents' institutional strategies. *Business Strategy and the Environment, 24*, 86-101. doi:10.1002/bse.1808

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Research Policy, 41*, 1025-1036. doi:10.1016/j.respol.2011.12.012

Innovation infrastructures (Purdue University Press 2005).

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017). The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy, 46*(4), 709-723. doi:https://doi.org/10.1016/j.respol.2017.01.009

Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy, 36*(12), 4419-4426. doi:https://doi.org/10.1016/j.enpol.2008.09.030

Streckienė, G., Martinaitis, V., Andersen, A. N., & Katz, J. (2009). Feasibility of CHP-plants with thermal stores in the German spot market. *Applied Energy, 86*(11), 2308-2316. doi:https://doi.org/10.1016/j.apenergy.2009.03.023

Stötzer, M., Hauer, I., Richter, M., & Styczynski, Z. A. (2015). Potential of demand side integration to maximize use of renewable energy sources in Germany. *Applied Energy, 146*, 344-352. doi:https://doi.org/10.1016/j.apenergy.2015.02.015

Sylvia, T. (2020). World's largest battery storage system now operational. *PV Magazine.* Retrieved from https://www.pv-magazine.com/2020/08/20/worlds-largest-battery-storage-system-now-operational/

Szarka, N., Scholwin, F., Trommler, M., Fabian Jacobi, H., Eichhorn, M., Ortwein, A., & Thrän, D. (2013). A novel role for bioenergy: A flexible, demand-oriented power supply. *Energy, 61*, 18-26. doi:https://doi.org/10.1016/j.energy.2012.12.053

Tande, J. O. G. (2000). Exploitation of wind-energy resources in proximity to weak electric grids. *Applied Energy, 65*(1), 395-401. doi:https://doi.org/10.1016/S0306-2619(99)00098-7

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy, 15*(6), 285-305. doi:https://doi.org/10.1016/0048-7333(86)90027-2

Tripsas, M. (1997). Unraveling the Process of Creative Destruction: Complementary Assets and Incumbent Survival in the Typesetter Industry. *Strategic Management Journal, 18*(S1), 119-142. doi:https://doi.org/10.1002/(SICI)1097-0266(199707)18:1+<119::AID-SMJ921>3.0.CO;2-0

Turnheim, B., & Geels, F. W. (2013). The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Research Policy, 42*(10), 1749-1767. doi:https://doi.org/10.1016/j.respol.2013.04.009

Turnheim, B., & Nykvist, B. (2019). Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. *Research Policy, 48*(3), 775-788. doi:https://doi.org/10.1016/j.respol.2018.12.002

Tushman, M. L., & Anderson, P. (1986). Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly, 31*(3), 439-465. doi:10.2307/2392832

Tushman, M. L., & Romanelli, E. (1985). Organizational evolution: A metamorphosis model of convergence and reorientation. *Research in organizational behavior, 7*, 171-222.

Tushman, M. L., & Rosenkopf, L. (1992). Organizational determinants of technological-change-toward a sociology of technological evolution. *Research in organizational behavior, 14*, 311-347.

van Mossel, A., van Rijnsoever, F. J., & Hekkert, M. P. (2018). Navigators through the storm: A review of organization theories and the behavior of incumbent firms during transitions. *Environmental Innovation and Societal Transitions, 26*, 44-63. doi:https://doi.org/10.1016/j.eist.2017.07.001

Varone, A., & Ferrari, M. (2015). Power to liquid and power to gas: An option for the German Energiewende. *Renewable and sustainable Energy Reviews, 45*, 207-218. doi:https://doi.org/10.1016/j.rser.2015.01.049

Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., & Zimm, C. (2020). Granular technologies to accelerate decarbonization. *Science, 368*(6486), 36-39. doi:10.1126/science.aaz8060

Winfield, M., Shokrzadeh, S., & Jones, A. (2018). Energy policy regime change and advanced energy storage: A comparative analysis. *Energy Policy, 115*, 572-583. doi:https://doi.org/10.1016/j.enpol.2018.01.029

Winskel, M., Markusson, N., Jeffrey, H., Candelise, C., Dutton, G., Howarth, P., . . . Ward, D. (2014). Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates. *Technological forecasting and social change, 81*, 96-114. doi:https://doi.org/10.1016/j.techfore.2012.10.015

Wolfgang, O., & Doorman, G. (2011). Evaluating demand side measures in simulation models for the power market. *Electric Power Systems Research, 81*(3), 790-797. doi:https://doi.org/10.1016/j.epsr.2010.11.006

Wulf, C., Linssen, J., & Zapp, P. (2018). Chapter 9 - Power-to-Gas—Concepts, Demonstration, and Prospects. In C. Azzaro-Pantel (Ed.), *Hydrogen Supply Chains* (pp. 309-345): Academic Press.

Zietsma, C., & Lawrence, T. B. (2010). Institutional Work in the Transformation of an Organizational Field: The Interplay of Boundary Work and Practice Work. *Administrative Science Quarterly, 55*(2), 189-221. doi:10.2189/asqu.2010.55.2.189

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We study the role of the energy system in the transition to the zero-emission society.