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Architectural change in accelerating transitions: Actor preferences, system architectures, and flexibility technologies in the German energy transition

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ABSTRACT

Despite growing research attention to accelerating transitions, the process of acceleration is not yet fully understood. It, for example, remains unclear whether or not acceleration requires deep changes in the architecture of sociotechnical systems and associated disruption to incumbents. We begin to unravel this issue by introducing a new framework for studying architectural change which foregrounds the role of actors. Based on a distinction between core and architectural technologies we outline four acceleration pathways that involve varying depths of system change and actor reorientation. Our framework suggests that incumbents want to avoid acceleration pathways with architectural change while challengers will promote them. The locus of actor contestation may thus shift from 'whether to transition' in early transition phases towards 'how to transition' (e.g., architectural changes). We apply the framework to study the transition in the German electricity system, where actors disagree about how decentralized the system architecture should become. To understand the nature of actor contestations around renewables integration solutions, we study actor preferences for different architectural technologies and system architectures. We find that incumbents prefer established centralized architectural technologies but, because these are difficult to expand, they reluctantly accept a role for emerging decentralized alternatives. Challengers support architectural technologies that are more disruptive. Our analysis suggests that accelerating transitions that include architectural change may, paradoxically, be very slow because they can alienate incumbent actors. This points to important trade-offs between the speed and depth of change in transitions.

1. Introduction

Despite growing understanding of the causes and consequences of global warming, emissions of CO2 continue to grow due to an array of systemic lock-in mechanisms [1,2]. The need for rapid low-carbon energy transitions is thus as urgent as ever. In response, sustainability transition scholars have started to analyse the characteristics of accelerating transitions, including multi-system interaction, niche diffusion, technology phase-out, and major shifts in system architectures [3,4].

Here we focus on architectural change in sociotechnical systems. System architecture is about institutionalized patterns of interaction between subsystems such as supply and consumption [5,6]. Architecture includes technological aspects (e.g., architectural technologies) and social aspects (e.g., institutions and how actors interact). Architectural change can be a source of major disruption to incumbent actors [7] and accelerated diffusion of innovations can have knock-on effects on system architecture [8].

We highlight two issues in need of more attention. First, despite some insights into acceleration and architectural change, we still know little about how processes of architectural change unfold and how different kinds of *actors* foster or resist architectural change [8]. Organizational scholars have shown that architectural change can be highly disruptive for incumbent actors due to a need for deep organizational changes and that it is therefore typically spearheaded by challengers [9,10]. At the same time, transition scholars found that incumbent actors can and do reorient [11,12] and that architectural change can also take place without major disruptions to incumbent actors [5,6]. Understanding challenges, preferences, and strategies of actors is important because the

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pace and direction of transitions is influenced by negotiations between actors with conflicting interests [13,14]. As a consequence, a next step for research is to explore in more depth the role of actors and their challenges and struggles in relation to architectural change [8].

Second, existing literature is ambiguous on the role of architectural change when transitions accelerate. For example, some scholars suggest that architectural change is integral to the acceleration phase because diffusion of new technologies causes deeper and deeper changes in sociotechnical systems [4,15,16]. Other studies report that transitions can accelerate without major architectural changes [8,17,18]. Such contrasting accounts reflect a need for both new theoretical perspectives and empirical studies to understand under which conditions architectural change is part of accelerating transitions.

We address both issues by conceptualizing architectural change in transitions and by studying (conflicting) actor preferences around architectural change.

To study the role of actors we suggest a more granular and disaggregated view on system architecture than previously applied. We draw on studies of complex technological systems [19–21] to introduce the concept of architectural technology to transition studies. We suggest that sociotechnical systems contain an array of core technologies and architectural technologies (that we understand as subsystems). While core technologies (e.g., electricity generation technologies) directly generate the services provided by sociotechnical systems, architectural technologies (e.g., electricity grid technologies) ensure a seamless interplay between them to ensure stability and efficiency at the system level. Any system architecture is thus underpinned both by a particular institutional logic [5,8] and by a set of architectural technologies. Major shifts in architectural technologies are thus indicative of architectural change. This approach enables us to articulate a set of transition pathways defined by varying degrees of change to core and/or architectural technologies that, in turn, pose different challenges to actors. Situating distinct portfolios of core and architectural technologies in alternative transition pathways allows us to study what actors think and do regarding system architectures such as how actors engage with architectural technologies. As existing literature is unclear about how different actor types—i.e. incumbents and challengers—engage with architectural change, we aim to contribute to this discussion by examining the following research question: *which actors prefer which architectural technologies in accelerating transitions and why?*

We explore this question with 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 are diffusing rapidly which requires new system flexibility to balance power supply and demand at all times [22,23]. System flexibility is provided by flexibility technologies that support the interplay of electricity production and consumption. In our case, flexibility technologies are the architectural technologies of the electricity system. We analyse 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 and more decentralized flexibility technologies which contrast the traditional centralized system architecture.

Analysis of interactions among multiple technologies is complex and challenges the in-depth, single case study methodology dominant in transition studies [24]. We therefore apply mixed methods by combining technoeconomic and sociotechnical analysis. Technoeconomic research provides detailed accounts of multi-technology interplays [25,26] but often lacks contextualized insights about actor preferences and institutions [27,28]. Drawing on literature from energy system researchers, we provide a rich description of the technical dimension of system architectures, and we also assess which flexibility technologies can be considered centralized and decentralized, as well as their technical complementarities with generation technologies. Our sociotechnical analysis focuses on the preferences of incumbents and challengers. It is based on public consultation responses of 22 industry actors complemented by desk research and interviews (see Section 3.3 for further details). Informed by the technoeconomic insights, we subsequently discuss to what extent actors' capabilities, resources, and mindsets can explain their preferences for system architecture (Section 5).

We find that incumbents and challengers largely hold contrasting preferences about system architecture but also observe some indications of convergence. Many incumbents prefer established centralized flexibility technologies (old architecture) but because these are very difficult to expand, they increasingly accept a role for novel decentralized flexibility technologies. Their reluctance against new architecture manifests in preferences for a rather limited role for new flexibility technologies, only far into the future, and preference for no preferential support for immature flexibility technologies. Many challengers, in contrast, prefer that new, decentralized flexibility technologies should play a more dominant role in the system, should be deployed now, and call for dedicated institutional support. In addition, they acknowledge the value of existing flexibility technologies as these often increase usefulness of new core and flexibility technologies.

We make two contributions to the transition literature. First, we provide a first exploration of the role of actors in architectural change in sociotechnical systems in the context of accelerating transitions. We provide a framework for understanding different challenges and varying depths of reorientation (incumbent) actors face when confronted with architectural change. Second, we introduce the concept of architectural technology which provides a new approach for understanding architectural change in socio-technical systems. In particular, the concept is helpful for grasping whether and why the acceleration phase of transitions involves architectural change. Transitions that include architectural change may, paradoxically, be slow because they can alienate incumbent actors. Transitions that do not, might be more rapid because it is relatively easier for incumbents to reorient and deploy their capabilities and resources in support of the transition. This points to potential trade-offs between the needed depth of reorientation and the possible speed of accelerating transitions.

2. Theoretical background

In this section we elaborate the concepts of architectural technologies and system architecture, discuss changes in them across different transition phases, and how changes in system architecture affect, and potentially disrupt, incumbent actors.

2.1. The architecture of sociotechnical systems

We conceptualize system architecture by mobilizing three distinctions: i) system vs. subsystems/technologies, ii) core vs. architectural technologies, and iii) technical vs. social dimensions of architectures.

First, socio-technical systems are comprised of three types of components: technologies, actors, and institutions. Systems of provision such as electricity, water or transportation rely on multiple technological artefacts to function such as electric vehicles or gas power plants. This leads to a distinction between system and technology/subsystem which reflect that socio-technical systems can be understood as a nested hierarchy of systems [29–31]. In this context, the architecture of sociotechnical systems affects how technologies/subsystems interact; if we find institutionalized patterns of interaction these patterns are a consequence of system architecture [8].[1]

Second, research on complex technological systems distinguishes between core and architectural technologies. Core technologies—e.g. vehicles in the transport system or power plants in electricity supply—directly help the system serve its societal function. Architectural technologies indirectly help the system serving its societal function by enabling and guiding the interplay of multiple core technologies. Architectural technologies generate technical compatibility and facilitate productive interplay among core technologies to form a larger, seamless system [19–21,32].[2] Converter technologies that allow AC and DC equipment to work together in the same grid can serve as an example [19,33]. Interactions between core technologies are supported by a set of architectural technologies that make up the system architecture. Architectural technologies generate system-level rather than technology-level complementarities and services with the purpose of improving overall system performance [system-level complementarities are discussed in detail by [34]. Note that architectural technologies must always be defined in relation to a focal system and its core technologies.

Third, we distinguish between a technical and a social dimension of architecture. The former is related to architectural technologies, while the latter is about coordination. The social dimension includes actors and institutions involved in the development, operation, and transformation of the system [33,35]. Following a sociotechnical approach [6,36], we view the social architecture as structured by formal (e.g., policies, regulations, standards) and informal institutions (e.g., norms, routines, worldviews) that shape and are shaped by actors. Established system architecture is underpinned by an institutional logic that outlines system purpose and the positions, social roles, and relationships of actors including problem framings, business models, and interaction with users [10,36,37]. Central and influential actors such as incumbents typically comply with, enforce, and reproduce these institutions and roles, and therefore become organizational carriers of the system architecture logic [38,39].[3] 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 organizational design and resources is aligned with system architecture [10,35,40]. Over time, actors therefore develop capabilities, resources, and mindsets matching the architecture. Consequently, it is important to actors how the architecture looks like. During periods of architectural change, mismatches between technical and social dimensions may occur.

2.2. *Architectural change in transitions as shifts in architectural technologies*

Although transitions do not always involve shifts in architectural technologies and architecture, cf. Section 2.3, we here focus on illustrating why and how architectural change can happen as a transition goes through different phases. Following Rotmans, Kemp [41], we distinguish four main transition phases: predevelopment, take-off, acceleration, and stabilization. Our illustrations resemble the radical transformative pathway, cf. Fig. 2.

In the *pre-formation phase*, established core technologies (e.g., large-scale, fossil-fuel power plants in electricity) are complemented by established architectural technologies (e.g., transmission networks) under a given architecture (e.g., centralized system operation), cf. Fig. 1. In the *take-off phase*, novel core technologies start to challenge established ones. Their emergence does not (yet) affect established architectural technologies because the established logics of the old system architecture are still strong and force core technologies to adapt (e.g., variable renewable energy technologies are curtailed or household generation not allowed into the grid).

In the *acceleration phase*, however, established architectural technologies may create bottlenecks if they cannot cope with or hinders the expansion of novel core technologies (e.g., increasing challenges of integrating large share of variable renewables with purely centralized system operation). Whether bottlenecks appear, partly depends on differences in core technology characteristics [42,43]. In the American transition from traditional factories to mass production, for example, new electric, precision machine tools (core technology) led to tensions with the direct-drive system and manual materials handling (old architectural technologies). As the new core technology diffused, this led to uptake of new architectural technologies such as continuous materials handling techniques (conveyor belts, the assembly line), electric distribution systems, and unit drive electric motors. With new architectural technologies came the fundamentally new institutional logic of mass-production and architectural change in the system [44]. Similarly, in electricity, many renewable energy sources are variable and small-scale and therefore may not fit well with a system architecture built for large-scale dispatchable plants. Sometimes, however, adaptations to or extension of established architectural technologies can be sufficient. Established architectural technologies may also be bridging technologies that play a role both ex ante and ex post a transition.

Furthermore, established core technologies can change function under a new architecture and for example become architectural technology [45,46]. For example, gas power plants are core technologies in fossil-energy electricity systems but can become architectural technologies in renewable-based systems providing flexible back-up services rather than bulk electricity. Architectural change may thus involve hybrid forms of new and established architectural technologies [47,48]. In the *stabilization phase*, a novel configuration of core and architectural technologies stabilize to under a new system architecture.

At any moment in time available architectural technology can thus influence diffusion of new core technologies. Due to different technology characteristics, some new core technologies can have stronger complementarities with established architectural technologies (e.g., large-scale renewable plants). This gives these technologies an advantage against other technologies that require new architectural technology to function optimally (e.g., small-scale renewables). The properties of established architectural technologies and innovation in new architectural technologies can therefore affect both the pace (how fast new technologies can diffuse) and the direction (i.e. which new technological options fit better with accessible architectural technologies) of transitions. New architectural 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 [49,50].

2.3. *Architectural change and actor preferences*

Different combinations of changes in core and architectural technologies pose different challenges for incumbent actors, which, in turn, shape their preferences for distinct technological solutions. We use a two-by-two matrix including minor vs. major changes in core technologies and architectural technologies to distinguish four main transition

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[1] The concepts of subsystem and architecture can be applied at different levels of aggregation. For example, the architecture of the electricity supply system concerns how electricity generating technologies / subsystems interact. However, every electricity generating technology also has subsystems that interact around an architecture. Also, electricity supply, distribution, and consumption can be seen as subsystems in the larger electricity system. We define subsystems at the level of technological artefacts (e.g., power plant or grid technology) and architecture at the level of the electricity system.

[2] Note that there are different terms in the literature describing technologies that underpins the seamless interplay of other technologies in a larger technological system including architectural [32], linking [20], and gateway technology [19].

[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.

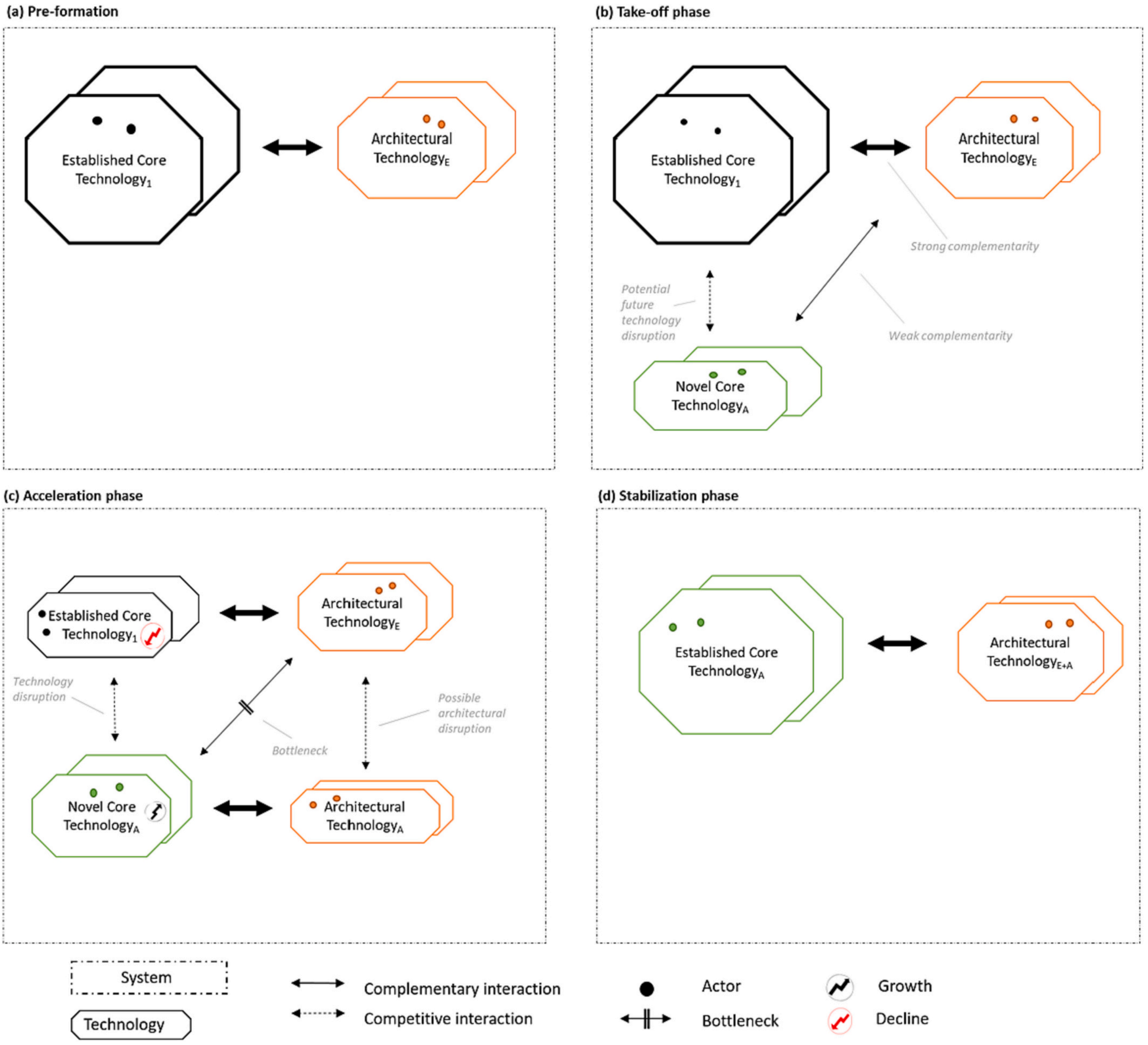

Fig. 1. Role of architectural technologies across transition phases. Note that the illustration corresponds to the Radical Transformative Pathway in Fig. 2.

pathways with different implications for the actors involved, cf. Fig. 2.[4]

To link pathways and organizational challenges, we draw on a configurational perspective on actor reorientation which outlines reorientation processes at different levels [51–53]. The main idea is that organizations can be viewed as hierarchical configurations of elements at three different levels: a) fundamental cultural-cognitive elements such as organizational identity, mission, and mindsets that shape how actors view and make sense of the world, b) capabilities, competence, and assets that actors use to perform tasks and roles, and c) organizational routines and habits which influence the way in which actors apply capabilities in practice.

[38,53]. Actor reorientation during a transition can remain moderate but it may also reach deeper levels of change [51,52]. The challenges posed to incumbents in our pathway types correspond nicely with the varying depths of reorientation identified in the literature. Below we introduce both the pathways and the implied level of reorientation in each pathway.

An *incremental innovation pathway* unfolds with only minor changes in core and architectural technologies. It could involve making existing core technologies more sustainable through add-on innovations such as fossil fuel power plants with carbon, capture and storage technology or using biofuels in existing internal combustion engines. For incumbents this involves reorientation at the level of organizational routines and habits. It involves competence enhancing innovations that reinforce competitive positions [54]. These can be managed without major changes in capabilities, strategy, or firm identity [10,12]. This is the least demanding type of reorientation.

A *modular substitution pathway* involves diffusion of radically different core technologies while changes in architectural technology and institutional logic are minor [55,56]. For example, shifting from gasoline to electric vehicles can be done without fundamentally changing the overall configuration of the transport system (e.g.,

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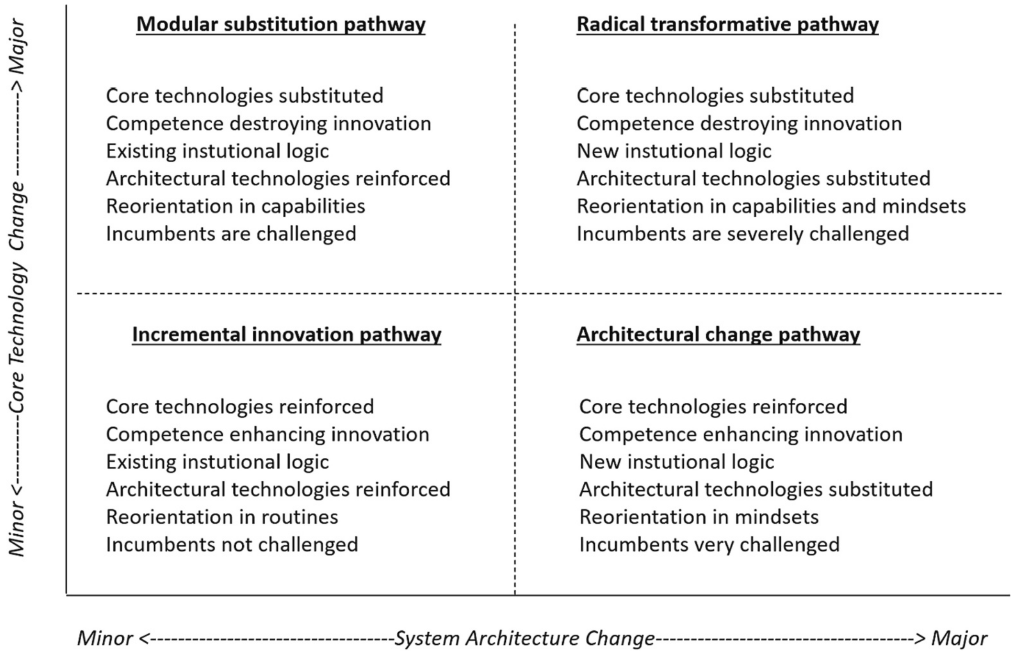
[4] We use discontinuity to describe change in the socio-technical system and disruption to describe the associated influence on actors.



Modular substitution pathway

Core technologies substituted
Competence destroying innovation
Existing instutional logic
Architectural technologies reinforced
Reorientation in capabilities
Incumbents are challenged

Radical transformative pathway

Core technologies substituted
Competence destroying innovation
New instutional logic
Architectural technologies substituted
Reorientation in capabilities and mindsets
Incumbents are severely challenged

Incremental innovation pathway

Core technologies reinforced
Competence enhancing innovation
Existing instutional logic
Architectural technologies reinforced
Reorientation in routines
Incumbents not challenged

Architectural change pathway

Core technologies reinforced
Competence enhancing innovation
New instutional logic
Architectural technologies substituted
Reorientation in mindsets
Incumbents very challenged

Fig. 2. Types of change at the system level and associated challenge to incumbents.

mobility practices, business model of automakers, and modes of transportation remain the same). This pathway requires that incumbents change core capabilities and resources and is thus more demanding. It involves competence destroying innovation in core technologies [54]. Incumbents typically respond by exploring and building new capabilities, resources, and engage in organizational change and strategic adjustments [10,57] [58].

In an *architectural change pathway,* core technologies only undergo minor changes, but how they interact changes more fundamentally. For example, less overall transport, shared mobility, and modal shifts towards more public transport and/or walking and cycling could foster a major sustainable shift in transportation systems without changing the internal combustion engine as a core technology. This shift would require new architectural technologies, e.g. digital platforms for intermodal transport and for sharing cars and bikes, and new institutional logics supporting transportation as a service. Shifts in system architecture are challenging for incumbents because they require reorientation at the level of organizational identity and mindsets that underpin business models and strategy and are aligned with the institutional logic of the system architecture [10,58]. This is an even more challenging type of reorientation for incumbents.

A *radical transformative pathway* comes with major changes in both core and architectural technologies. For example, a shift from decentralized (i.e. individual) and gasoline-fuelled transportation towards centralized (i.e. collective and shared) and electrified transportation. It requires the most radical form of reorientation which involves both building new capabilities and resources, plus changing organizational identity and business models [12,58].

While early research highlighted how incumbents oppose transitions [59,60]—e.g. by lobbying policy makers [61,62] working against institutional changes [63] or controlling market access [64]—more recent contributions show that incumbents many also be proactive and innovative [65–68]. Transition scholars are currently trying to integrate these contrasting findings by searching for a systematic understanding of when incumbents inhibit or promote transitions [69]. Suggestions of how to advance the field include integration with organizational theory [70], mobilizing the concept of social roles [71], or exploring plurality [11].

The configurational perspective helps to understand the plurality of strategies among incumbents. Proactive incumbents, on average, will prefer and work towards pathways that are least challenging and disruptive for them in a particular context. Embracing more disruptive pathways requires additional pressure from other social groups such as users, NGOs, or policymakers [51,52]. Indeed, reluctance towards transitions from incumbents tend to increase with the degree of envisioned discontinuity in existing systems [3,7,56]. Moreover, Geels and Turnheim [52] found that although many incumbents have reoriented significantly in the electricity, mobility and heating systems in the UK, they exclusively promote incremental innovation or modular substitution pathways. Similarly, many of the examples of proactive incumbents are about modular substitution rather than architectural change; i.e. where incumbents build directly on existing capabilities to develop new core technologies without big changes in system logics or business models such as electric heavy vehicles [17], electric ships [18], electric transmission [50], and modern gas turbines [72].

Against this background it is reasonable to assume that despite significant actor heterogeneity, architectural change is typically not driven by incumbents with central and dominant roles within the existing system architecture. Instead, it is initiated by challengers whose identities, mindsets, capabilities, and resources are not to the same extent aligned with existing architectural logic and technologies [37,73,74]. Challengers include 'de novo' entrants (i.e. start-ups) and adjacent incumbents from other systems [75]. They may also include peripheral incumbents which are fringe actors that operate in the system but are less powerful, smaller, and with less vested interests (e.g. capabilities and identity) as compared to core incumbents [12,76].

In the case of the German energy transition, there were already major changes in core technologies and actor struggles in the acceleration phase is about whether there will also be major changes in architectural technologies and architecture. So, we are looking at a situation, in which actors find themselves between two pathways: modular substitution and radical transformative pathway [56]. Moreover, all actors we analyse are in favour of a renewable energy transition albeit in different ways. On basis of the reviewed literature, we expect that incumbent actors in the German case prefer a modular substitution pathway while being in disfavour of changes in system architecture. Therefore, we also expect that incumbent and challengers hold different preferences for both new and established architectural technologies as indicative of system architecture preferences.

In the configurational perceptive on actors, the activities of actors (including investment decisions, publicly stated preferences, or partnerships) are the outcome of interactions between organizational identity and mindsets (cultural-cognitive elements), and actor capabilities and resources (strategic assets) [38,53]. Inspired by this, we study publicly stated preferences of actors for various architectural technologies (activities) combined with information about actors' roles in the system, actor resources, and the context to understand who prefers which architectural technologies and why.

3. Methods

In this chapter we explain our case selection, operationalize our theoretical concepts and describe our analysis.

3.1. Case selection: the German energy transition

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 [77] such as actor perspectives on unfolding architectural change in accelerating transitions.

The relevance of alternative flexibility technologies and actor struggles over 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 where the energy transition is already in an acceleration phase, i.e. in which VREs have progressed rapidly and cover a significant (and, likely, increasing) share of power supply. Finally, our case should be characterized by ongoing but at the same time open-ended architectural changes such as development towards decentralization. Given these criteria, there are very few relevant cases to study and the German energy transition constitutes a unique case in this context.

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 [78]. The increasing share of VRE creates additional demand for flexibility [79]. The current lack thereof is reflected in an increasing curtailment of renewables, which went up to more than 6 TWh in 2019 [80]. Today, flexibility is mainly provided by conventional power plants (especially 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 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 [81,82]. The resistance is related to conflicting preferences of whether the energy transition should be more decentralized or centralized [83]. Similarly, some actors suggest that transmission grid expansion should be reduced by alternative and more decentralized flexibility technologies [84]. For these reasons, the case provides a unique opportunity for studying conflicting actor preferences over architectural change in socio-technical systems during transitions.

3.2. The electricity system and key concepts

Core and architectural technologies. We conceptualize electricity generation technologies as core technologies and flexibility technologies as architectural technologies. Flexibility technologies are those that link generation technologies together and allow them to function seamlessly in a larger system by supporting the continuous balancing of supply and demand. In the Germany electricity system as in many other countries, the traditional way to balance supply and demand is with large transmission grid technologies aided by dispatchable power plants. As VREs grow, electricity supply becomes more volatile and new sources of flexibility are required [85,86]. New flexibility functionalities that go beyond established flexibility technologies may also be needed.

System architecture. A transition to a VRE-based system is possible both under centralized and decentralized system architectures [87,88]. Our baseline for thinking about pathways is the traditional way of organizing the electricity system in Germany which included a very centralized system architecture with large-scale generation (core) technologies such as coal and nuclear power plants, passive consumers, and with system balancing via flexible conventional plants and long-distance transmission grids (main architectural technology).

Transition pathways. The described system can be decarbonised without major architectural change e.g. with more nuclear and carbon capture and storage technology (CCS) for fossil power plants (incremental innovation pathway / centralized low-carbon), see Fig. 3. Another option is to move towards a VRE-based but still centralized architecture which involves major changes in core technologies but only minor changes in architectural technologies (modular substitution pathway / VRE in centralized system). Decarbonization in principle is also possible via architectural changes towards a decentralized system but without major changes in power generation (core) technologies. This typically happens due to a combination of demand-side changes and innovation in new architectural technologies that replace old ones (architectural change pathway / decentralized low-carbon). Finally, decarbonization can also happen through both architecture decentralization and new distributed VREs (radical transformative pathway / VRE in decentralized system). As the German energy transition is already based on changed core technologies, we will focus on the pathways in the two upper quadrants in Fig. 3.

Flexibility technologies can fit better or worse with a centralized architecture [89]. Centralized flexibility technologies (e.g. large-scale transmission grid, pumped-hydro power) are more compatible with the existing system architecture (e.g. few, large-scale generators) than decentralized flexibility technologies (e.g. distributed storage, demand response). This implies that ideal combinations of types of generation/core and flexibility/architectural technologies exist under distinct architectures.

Below we will assess which flexibility technologies can be considered (de)central or both based on how they fit with different types of VREs and system architectures based on technical complementarities. The assessment is based on a review of energy systems literature [90] which provides extensive technoeconomic analyses of multi-technology interplays and the functioning of the electricity system as a whole [28,91]. The methodological details and literature underpinning the assessment can be found in Appendix A.

3.2.1. Flexibility technologies, electricity generation technologies, and system architecture

Table 1 summarizes relevant characteristics of selected flexibility technologies that will compete for market shares as new flexibility is needed in the energy transition. It provides an overview of how well different flexibility technologies fit with centralized versus as decentralized system architectures, respectively.

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; especially if they are dispatchable. Indeed, it is expected that the role of gas will change function from generation / core technologies to flexibility / architectural technologies as VREs diffuse. Technologies can thus have different functions under different system architectures. What we define as core and architectural technologies thus partly depends on the system of interest.

First, the left side of the table provides information about whether technologies are established and mature as flexibility options in the system. This indicates whether incumbent actors are familiar with and understand technical functionalities of technologies, and whether

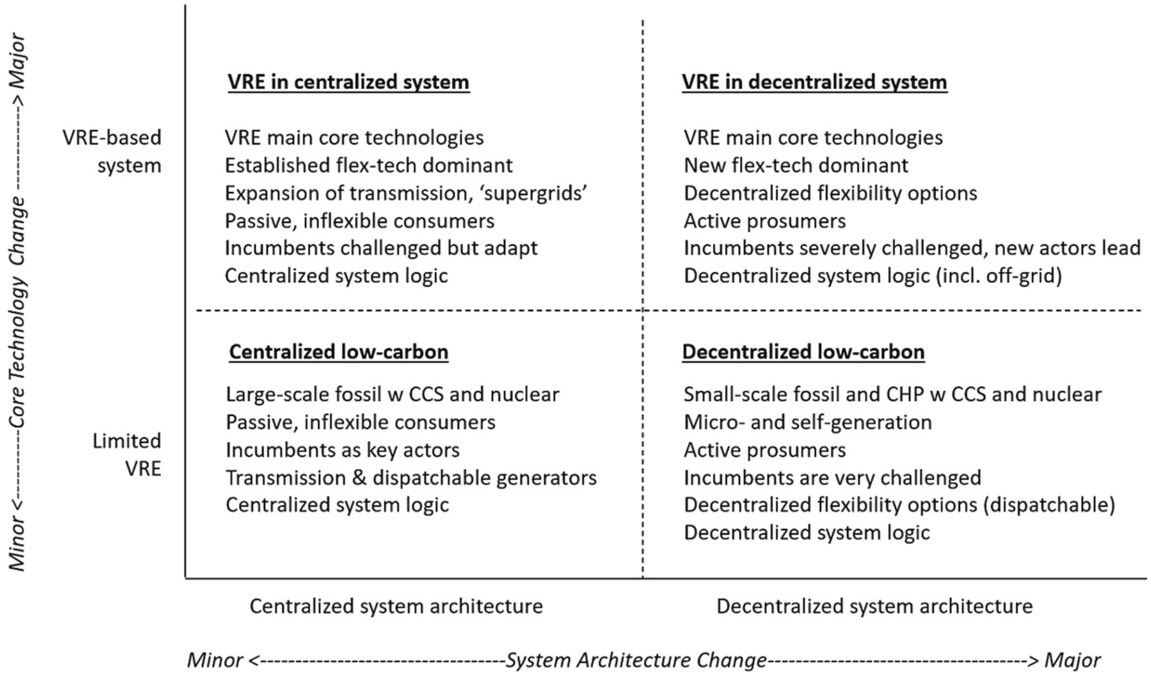


Fig. 3. Transition pathways, types of discontinuity in the electricity system, and challenges to incumbents.

Table 1
Characteristics of flexibility technologies.

Flexibility technology	Maturity	Scale (physical)	CEN-FIT	CEN-DEC	Large-scale plants/Centralized[a]		Small-scale plants/Decentralized[a]	
					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	++	++	++	++

[a] Degrees of complementarity between flexibility and generation technologies: (+) = weak, (++) = moderate, (+++) = strong. The strength of complementarity is based on the authors' assessment of the data presented in Appendix A.

existing institutions are conducive to their deployment. Based on this, we assess whether flexibility technologies have high or low socio-technical fit with existing centralized architecture (CEN-FIT). This assessment indicates how well flexibility technologies fit the social dimension of centralized system architecture, cf. Section 2.1.

Second, the right side of Table 1 provides a broad overview of the technical complementarities between different flexibility technologies, on the one hand, and centralized (indicated by large-scale VREs) versus decentralized system (indicated small-scale VREs) architectures (for simplicity we focus on solar and wind), on the other. Based on the strength of technical complementarities we assess under the CEN-DEC column whether flexibility technologies can predominantly be considered centralized (CEN), decentralized (DEC), or is technically equally compatible with both (BOTH). This assessment indicates the technical dimension of system architecture, cf. Section 2.1.

The main takeaways from the table are, firstly, that 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 and 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 however 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.

We further note that flexibility technologies can both compete and be complementary [92]. Competition for resources happens, for example, if transmission grid capacity is constrained and hinder sufficient flow of electricity, options like DSM or batteries at each end of the line can be used to address this (e.g. via virtual transmission lines). In this way, the new flexibility technologies reduce or postpone the need for investment in transmission [93]. Also, flexibility options only compete when they offer flexibility services with same time duration, cf. Appendix A. Complementarity takes place, for example, because grids (transmission and distribution) are often important for leveraging many other flexibility technologies such as flexible CHP or hydro power.

Any system architecture will therefore be characterized by a mix of flexibility technologies including (de)centralized, new and established ones. System architecture can therefore not be understood by looking at whether one or the other flexibility technology is in the system, but rather by looking at which flexibility technologies play dominant and peripheral roles within a broader mix.

3.2.2. Contextualized expectations

The particularities of the electricity system and the German context inform our expectations for the analysis. Overall, architectural change in the German energy transition would entail a major shift in flexibility technologies from a current dominance of mature, centralized technologies towards a mix of flexibility technologies dominated by novel, decentralized flexibility technologies. Regarding actor preferences, we expect incumbents to predominantly prefer centralized flexibility technologies that are mature, large-scale, have high institutional fit with centralized architecture, and have strong technical complementarities with large-scale VRE. Second, we expect that if new and decentralized flexibility technologies as well as new institutions are promoted, it is done by challengers. Third, because flexibility technologies can be both complementary and competing, it is possible that incumbents and challengers hold overlapping preferences for flexibility technologies.

3.3. Analysis of actor preferences

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 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 submissions of firms, associations and private persons who agreed to publication are available for download.

While we also investigated 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).

For our analysis, out of the 98 documents we selected 22 submissions of firms, industry associations, NGOs and think tanks that play a crucial role in German energy politics. A particular focus is on organizations in the electricity system. Note that we consider these public submissions as actors' strategic activities and thus as reflecting internal organizational elements and processes, see Section 2.3. In Table 2 we provide an overview of the actors included in our analysis. Based on information about actors' system role, technology/resource base, and background information about actors and the German energy transition obtained from company website reading, interviews, secondary literature, and collective knowledge of the author group, we categorized actors as either incumbents or challengers (cf. Section 2.3). It is not always straightforward to categorize actors and the authors applied some measure of subjective judgement when making decisions. The incumbent category is used to indicate strong alignment between actors' resources, capabilities, identities, and mindsets with a centralized system architecture design and logic. Note that the system roles (generation, distribution, consumption) already offer some insights about diversity of incumbents.

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.

For each 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. With this coding scheme we went through each of the 22 submissions and coded every statement, typically entire sentences or paragraphs, where the dimensions were mentioned. Every coded statement was recorded as one entry in the respective category, i.e. if an actor mentioned three times that decentralized flexibility options are important, we counted all three instances. This is important for submissions that returned different values, e.g. some passages signalling importance while others could be interpreted as high importance, we calculated weighted average values. If a statement was between two categories, e.g. between important and very important, it was counted with a weight of 0.5 in both categories (See example in Appendix B).

Next to the coding 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. Figs. 3, 4 and 5), and asked for their interpretations. Interviews lasted about 1 h 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.

As a final step in our analysis, we combine our analysis of actor preferences with existing literature, expert interviews, our analytical approach, and contextual knowledge of the case, to make inferences about and discuss changes in actor preferences and strategies over time (Section 5.1).

4. Findings

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.

4.1. 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 Fig. 4.

Among the vivid supporters of grid expansion is the German association of energy and water industries (BDEW), the association of the

Table 2
Focal actors.

Actor (N = 22)	Description	System role	Resource base	Actor type	Comment
50Hertz	TSO	Grid	Transmission	Incumbent	Operate main established flexibility technology of the incumbent system
8KU	Association of 8 municipal utilities	Generation / Distribution	Generation/Distribution network	Challenger (Peripheral Incumbent)	Municipal utilities are peripheral incumbents because they have less influence, resources, capabilities, and market shares than core incumbents, and they are often locally-anchored and seeing new roles and opportunities in a more decentralized system.
Agora Energiewende	Energy transition think tank	Whole system	None	Challenger (Newcomer)	Develops strategies for the energy transition and as such challenges the incumbent system.
Amprion	TSO	Grid	Transmission	Incumbent	See 50Hertz
BDEW	German Association of Energy and Water Industries	Generation	All electricity and gas assets	Incumbent	Key association in the incumbent system. Membership is getting more diverse, but incumbents still play a key role.
BEE	Association for renewable energy producers	Generation	Mix of renewables	Challenger (Newcomer)	Advocates renewables as the new core technology, no interests related to the incumbent system.
BKWK	Association for CHP operators	Generation	CHP	Incumbent	CHP can be small-scale, but CHP has been an incumbent fossil technology.
BVES	German Energy Storage Association	Whole system	Storage technologies	Challenger (Newcomer)	Founded to promote storage for the energy transition
DENA	German Energy Agency	Whole system	None	Challenger	Was founded in 2000 to shape and implement the Federal Government's energy and climate policy goals on energy transition and climate protection.
DIHK	German Chamber of Commerce	Consumption	Consumption	Incumbent	Main focus on competitive and stable power supply, not on energy transition.
DUH	Environmental NGO	Whole system	None	Challenger (Newcomer)	Advocates the energy transition, no interests related to the incumbent system.
EnBW	Utility	Generation / Distribution	Conventional generation, renewables	Incumbent	Major company in the incumbent system
Eurosolar	Association	Generation	Renewables	Challenger (Newcomer)	Founded to replace the incumbent system, with a focus on PV
Greenpeace Energy	Green electricity and gas supplier	Generation	Renewables, Power-to-Gas	Challenger (Newcomer)	Main business around renewables, founded for the energy transition.
Next Kraftwerke	Aggregator, Operator of a virtual power plant	Generation	Virtual Power Plant, decentralized renewables	Challenger (Newcomer)	New business model, that was not there in the incumbent system
13 Oil & Gas actors	Sells oil and gas. Exonmobil, Equinor, Shell, Total, etc.	Adjacent system	Oil and gas resources	Challenger (Adjacent incumbent)	Incumbent in the gas system, but challenger in the electricity system
RWE	Utility	Generation	Conventional generation, renewables	Incumbent	See EnBW
Statkraft	Utility from Norway	Generation	Renewables (mainly hydro), gas plants	Incumbent	Relatively new entrant to the German market, but major company in the incumbent system
TenneT	TSO	Grid	Transmission	Incumbent	See 50Hertz
TransnetBW	TSO	Grid	Transmission	Incumbent	See 50Hertz
VCI	German Chemicals Industry Association	Consumption	Chemical plants	Incumbent	Major chemical plants require high voltage and stable power supply to avoid fluctuations and efficiency losses in production
Vzbv	The Federation of German Consumer Organisations	Consumption	Consumer interests / empowerment	Challenger (Peripheral Incumbent)	Has operated in centralized system for long but since consumers were ascribed passive roles, this actor was not influential or resourceful. Now they see new opportunities and roles for active consumers in decentralized system.

Table 3
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)

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. Their main argument is that transmission grid expansion is the most cost-efficient option to integrate renewables.

> *"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[5] 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." [Eurosolar]*

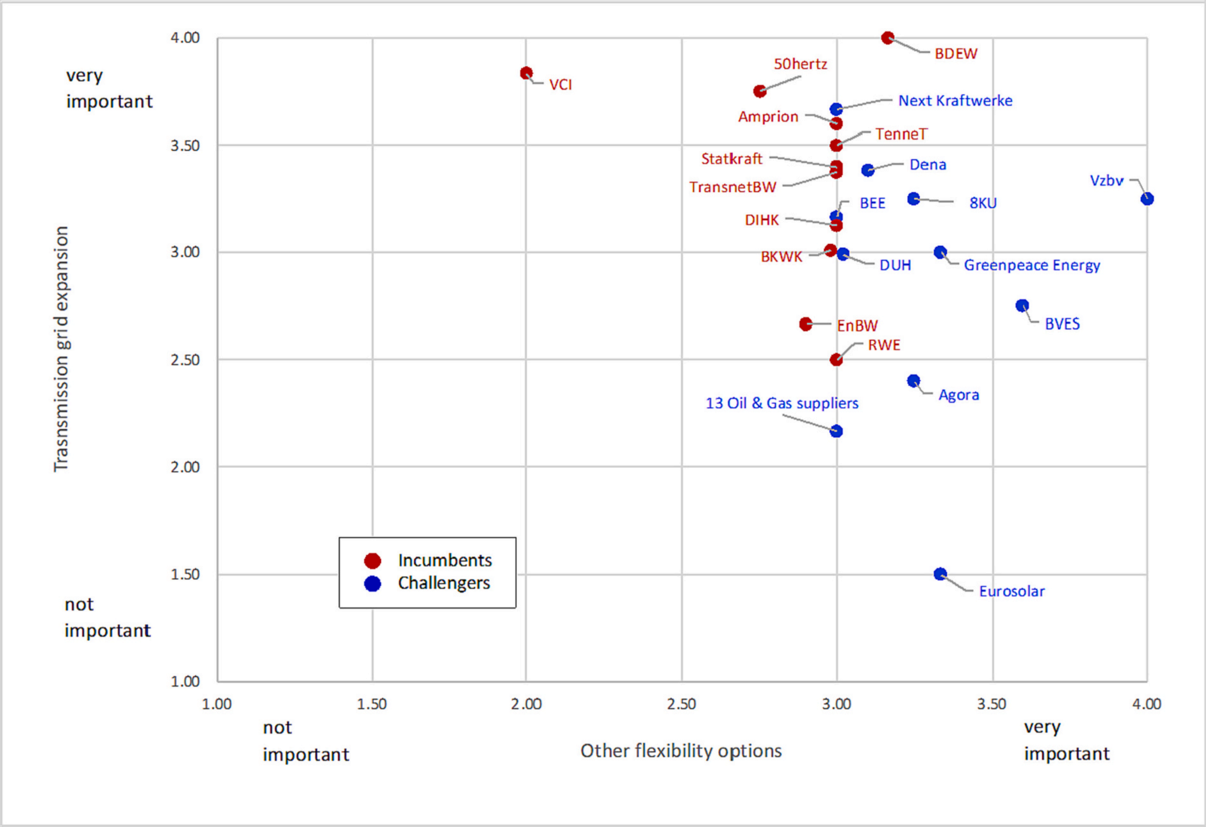


Fig. 4. Importance of transmission grid expansion vs. other flexibility options. Incumbents are marked in red and challengers in blue colour.

Interestingly, also oil and gas suppliers are hesitant towards 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*

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

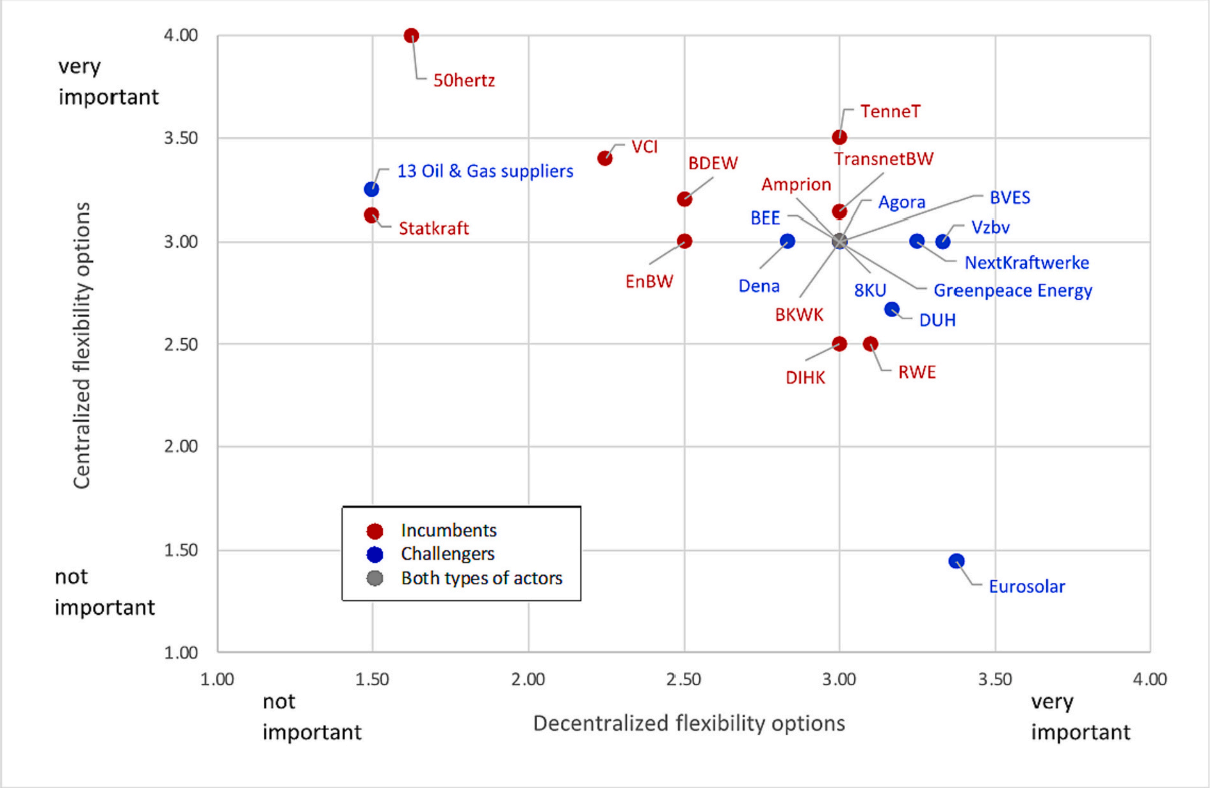

Fig. 5. Importance of centralized vs decentralized flexibility options. Incumbents are marked in red and challengers in blue colour, when both types of actors are in same place, we use grey markers.

> *the gas infrastructure needs to be used more [intensively]. … Gas infrastructure is energy transition infrastructure.… 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, that consider such flexibility options as complementary to the transmission grid for integrating intermittent renewable generation.

> *"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). They argue that grid expansion is not sufficient, and all options are needed for the energy transition. If there is too much focus on grid expansion, the necessary development of innovative options would be impeded.

> *"The German government is currently giving priority to grid expansion to promote the energy transition. 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]*

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 towards 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]*

4.2. 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 the 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]*

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. " [Statkraft]*

Eurosolar is the antipode to these positions. It clearly opposes transmission grid expansion and argues strongly in favour of decentralized flexibility which they see as the best fit for decentralized renewable generation.

"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.

4.3. Specific preferences for flexibility technologies

The actors in our study hold different positions regarding specific flexibility technologies. Fig. 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 Fig. 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 flexibility option (Fig. 4). However, they also acknowledge that transmission expansion is delayed due to public resistance. That is a main reason why they find non-grid flexibility options important.

For example, although Amprion endorses VRE flexibility (score 3 in Fig. 6), DSM (2,75) and battery storage (2) as flexibility options, the TSO states that network expansion is the fundamental condition for the energy transition.

> *"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. 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 states that grid expansion needs to be complemented by other options because grid expansion plans may not be fully implemented as a result of social resistance.

> *"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 highlights the fundamental role of grid expansion as well as its lack of acceptance.

> *"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)*

Some challengers, such as 8KU, however provide a different perspective by arguing that while transmission grid expansion is important a both misled and failed focus on transmission grid expansion as main source of flexibility has neglected other important options and 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)*

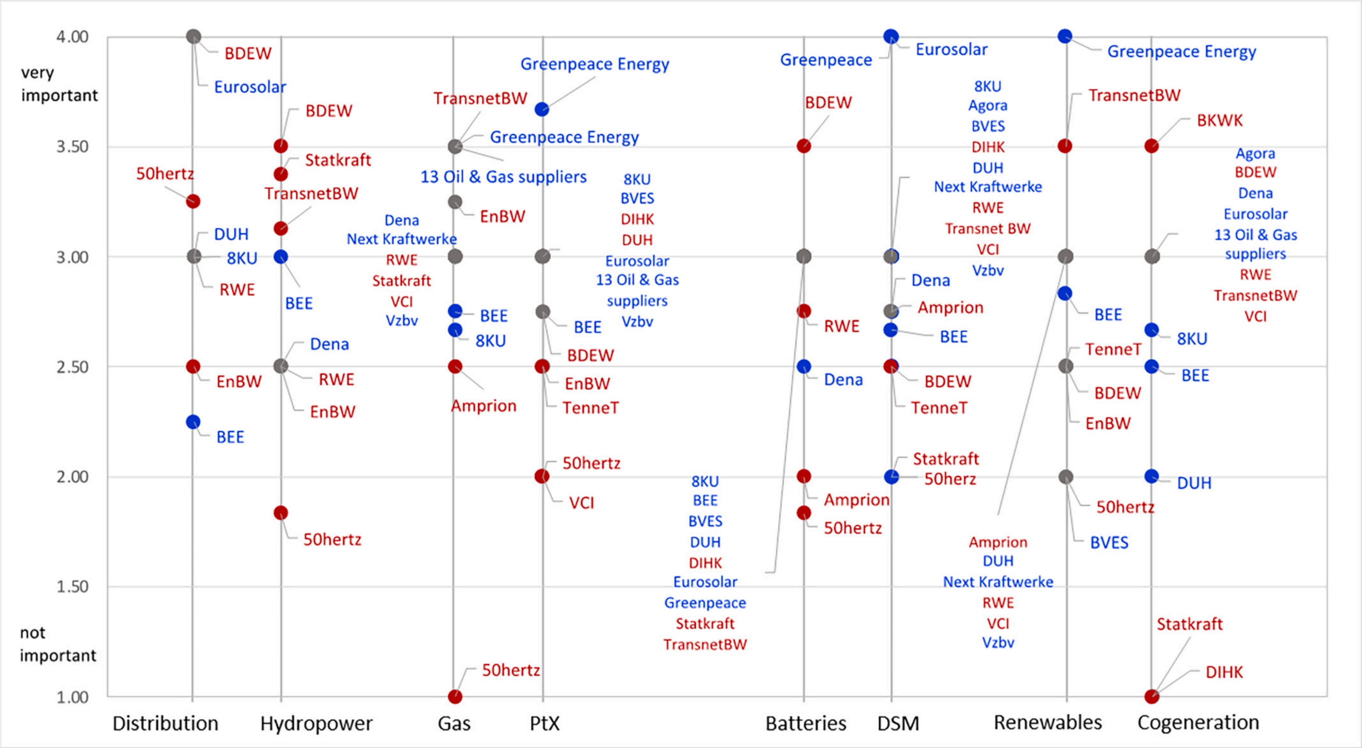

Fig. 6. Preferences for eight flexibility options, with more centralized ones on the left and more decentralized ones on the right part of the figure. Incumbents are marked in red and challengers in blue colour, when both types of actors are in same place, we use grey markers.

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 they will become more important in the future (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)*

At the same time, some challengers argue that the bias towards grid development must end and deployment of non-grid flexibility options start now (8KU, Eurosolar, BVES). Greenpeace Energy, suggests that many will be surprised by the speed of renewables expansion and supports experimentation and deployment of new non-grid flexibility options now to ensure that these technologies are available and well-functioning in a few years.

> *"Existing and new storage technologies will play an increasingly important role—including long-term storage. Here 'Impulse Paper Power 2030' states that these are only necessary when there is a very high proportion of renewable energies. Of course, these high shares of renewables will come much sooner than can be deduced from the current EEG. Moreover, the new long-term, storage systems are not 'plug and play'; they require development, market introduction, and installation in sufficient capacity. Only then will they be able to guarantee security of supply as soon as they become 'necessary'." (Greenpeace Energy)*

A third insight is that actors emphasize different types of institutional change. Several incumbents call for strengthening the rights and tools of grid actors to build with less delay (e.g., Amprion and TransnetBW above). Others oppose institutional changes that give support that is not technology neutral and distort markets (e.g., Statkraft). Meanwhile several challengers argue that new, decentralized flexibility technologies are both relatively immature and discriminated against by existing regulatory frameworks (e.g., BVES, DUH, DENA, BEE, Agora). Institutional changes that create a level playing field among diverse flexibility technologies is therefore needed (e.g., see BVES above and BEE below).

> *"There is no level playing-field for storage. This needs to be changed." (BEE)*

5. Discussion

The starting point for this paper is that transition studies need more empirical studies and conceptual development of the notion of architectural change in accelerating transitions, and especially the role of actors. In this section we summarize, discuss, and make sense of our empirical results in relation to our analytical framework and existing literature. We highlight two main issues: differences and convergence between actor groups, and value-added of the architectural technology concept. Subsequently, we discuss implications for transition policy and limitations of our study.

5.1. Architectural change and actor preferences

In this section we first discuss incumbents and thereafter challengers. Each part starts by summarizing our empirical results on observed actor preferences and in a second step moves to interpret and discuss results in relation to extant literature, interviews, and our theoretical approach.

5.1.1. Incumbents and architectural change

Regarding our expectation that incumbents in the German context would prefer mature, centralized flexibility technologies we found two issues.

First, we found heterogeneity among incumbents in terms of flexibility technology preferences. Many incumbents, as expected, have a strong preference for transmission. We also found, however, that many actors—both incumbents and challengers—prefer a mix of mature and immature, central and decentral flexibility options. This was also partly expected because flexibility technologies—new and old—can both compete and be complementary, cf. Section 3.2.2.

Second, we also found that many incumbents express preference for decentralized flexibility technologies mainly because transmission grid expansion is blocked by local, civic resistance against projects. In relative terms, incumbents thus express clear top priority for centralized solutions but due to circumstances accept and acknowledge a limited role for alternatives. Moreover, in terms of timing, several incumbents prefer that transmission grid expansion should be expanded first and that alternative flexibility technologies will only be relevant at a later stage. Lastly, in terms of institutional support for flexibility provision (innovation support versus level playing field), many incumbent actors emphasize that cost-efficiency and competition among flexibility technologies should be the guiding principle (e.g. 50 Hz 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 (e.g. TransnetBW and Amprion).

Our findings on incumbent actor preferences resonate with other studies that show that incumbent electric utilities were disrupted by VREs during the 2000s and gradually accepted that reorientation was necessary in the late 2000s [94,95]. In response, these actors engaged with new core technologies in the early 2010s—especially large-scale VREs such as offshore wind [3,96]—largely building on existing business models and capabilities for managing large-scale projects. They built new technological capabilities in VREs and changed strategies (Interview 2, [97,98]).

However, the majority of VREs deployed in the 2000s were small-scale and pushed by challengers. This new market with proactive and decentralized prosumers was quite different from what electric utility incumbents were used to. As diffusion of decentralized VREs accelerated during the 2010s, it started to influence the (social dimension of) system architecture in terms of new business models and customer interfaces towards decentralization [97,99]. Around 2015, incumbents started to respond by experimenting with new (decentralized) business models in form of research, development, and demonstration projects [3,95,96,100,101]. These attempts were challenging for incumbents due to capabilities and company culture rigged for the old system architecture with large-scale projects and passive consumers [97,98]. Similarly, TSOs started to realize that decentralized flexibility technologies could moderate public resistance against transmission projects (scaling them down or making them obsolete). Therefore, they explored decentralized flexibility options to make better use of the existing network (Interview 1 and 2; [102]). In addition, under critique from local grid companies, TSOs have worked to build capabilities in ICT and become the centralized controllers of distributed smart-meter data which is the basis for managing both central and decentral flexibility assets [103]. TSOs have thus started to reorient at the level of capabilities while still promoting a centralized architecture.

In 2016, the year for our data points, incumbents were thus largely supportive of a renewable energy transition, and electric utilities relatively successful in core technology changes with investments in large-scale VREs. Many incumbents were starting to experiment with solutions for a decentralized system architecture and flexibility technologies but still with strong uncertainty about how new, decentralized business models could look like. This context helps explain that incumbents in our results acknowledge that decentralization is part of the transition but also that they would prefer that system architecture remains as centralized as possible during the energy transition because within that architecture they have a clear role and proven business model.

When we interpret our results in terms of theory (cf. Section 2.3), we see that many incumbents already engaged with reorientation in routines, capabilities, and resources in 2016 by embracing a renewable energy transition and by adapting to new core technologies (modular substitution pathway). Yet, many incumbents subsequently started to experiment with reorientation in business models and company identity for a decentralized system architecture (radical transformative pathway). The latter was however very challenging. This aligns with the idea that deeper reorientation is more demanding, and that modular substitution is less challenging than radical transformative change [12,58].

Given that transition scholars have limited insight in actor strategies in the acceleration phase [104], our general framework that connects pathway types and the depth of incumbent actor reorientation can serve as a template for understanding the variety of strategies that proactive incumbents pursue in the acceleration phase of transitions including in different systems and places. One interesting example to study could be the diversity in how automotive incumbents engage with electric mobility (new core technology) and/or inter-modal shifts and shared mobility (architectural change) [105]. This avenue of research merits more attention from transitions researchers.

5.1.2. *Challengers and architectural change*

We also found heterogeneity among the preferences of challengers. We found that some challengers such as BVES and Eurosolar have strong preferences for decentralized flexibility technologies and are critical of transmission. Also, oil and gas suppliers do not support transmission (even though they prefer a centralized system architecture) because they see the gas system as a preferred source of flexibility. However, most challengers prefer a mix of decentralized and centralized solutions. This indicates that the challengers see value in centralized flexibility technologies because they can be important for the diffusion of more decentralized VREs (cf. complementarity between old and new flexibility technologies). For example, Greenpeace Energy, even though remaining sceptical, acknowledged the value of transmission networks for VRE integration (Interview 2). Moreover, challengers such as BEE (renewables association) and Next Kraftwerke (virtual power plants) partly depend on transmission to realize value of their assets.

However, challengers accept the value of centralized flexibility technologies only with several reservations. This manifests in three ways. First, in terms of the desired balance between flexibility technologies, some challengers strongly emphasize new flexibility options and want them to play a much more dominant role. 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 supportive institutions and innovation policies to help alternative architectural technologies mature via experimentation and learning, and subsequently diffuse (e.g. Greenpeace Energy, BVES, Eurosolar). Along with a few municipal utilities, they worry that grids will be overprioritised under current regulation leading to neglect of decentralized flexibility options which, in their view, leaves the system vulnerable (e.g. 8KU, Next Kraftwerke). Indeed, existing regulations in Germany favour transmission grids over new flexibility technologies [106,107].

In terms of theory, our findings suggest that challengers indeed push for architectural change and are vocal on the risks of being locked-in to the old system architecture. The fact that they acknowledge the value of old architectural technologies also indicate that challengers are interested in building a new system by combining old and new system elements via hybridization [47]. This differs from the general understanding in the literature of challengers as looking to overthrow the old system, which is often observed in earlier phases [47,108]. Interestingly, it also suggests that as transitions progress, challengers may shift perspective from promoting individual new core technologies to appreciate the transition challenge at the broader system level [109,110] such as considering the system cost of renewables integration. This is a novel aspect of challenger dynamics in transitions that merits more attention.

5.1.3. *Summary*

Overall, our analysis of actor preferences for system architecture shows that although there is heterogeneity within each actor group, there are also important differences across incumbents and challengers which indeed indicate important disagreements over the direction of the transition. This result is in line with our framework and expectations.

Our analysis also suggests that there have been movements within each actor group over time such that they in 2016 appear to share an understanding of the main problems including the importance of a renewable energy transition which also involves adding system flexibility via a mix of old and new flexibility technologies. Despite this convergence, they still have different views on which flexibility technologies to prioritise especially including i) how big a role is there for new, decentralized flexibility technologies, ii) when they are needed, and iii) which mechanisms should bring them about (innovation vs market policies). This result supports the understanding that in the acceleration phase the locus of innovation shifts from novel core technologies to renewables integration (architectural technologies) [111], and that the locus of actor disagreements shifts from 'whether to transition' towards 'how to transition' [7].

In conclusion, we observe gradual convergence but not agreement which is related to the scope of the challenges incumbents face when exploring architectural change and reorientation at the level of organizational identity and mindsets. Interestingly, we see reorientation signs among both incumbents and challengers suggesting that both actor groups attempt to change strategies over time as the transitions advances and new challenges occur.

5.2. *Architectural change in accelerating transitions*

In this paper we suggested a novel conceptualization of sociotechnical system architecture which advances our understanding both of system architectures as well as architectural change in transitions.

The notion of architectural technology allows us to describe and understand sociotechnical system architecture in new ways. For instance, we see how architectures can include different and partly overlapping combinations of architectural technologies. In that way, the architectural technology perspective opens a disaggregated and granular view on system architecture. This disaggregated view enables analysis of micro-level issues such as actor struggles, preferences, and strategies. In our analysis, it was, for example, useful for understanding variations in actor preferences at the level of specific architectural technologies. Compared to earlier studies, which showed more polarized conflicts around these issues [7,112], we were able to uncover and explain a higher degree of nuance. The approach also allows more fine-grained analysis of partial and/or ongoing architectural changes in some parts of the system although the old architecture remains dominant.

In terms of architectural change, our pathway typology based on varying degrees of change in core and architectural technologies illustrates the important point that transitions can accelerate with or without architectural change. It depends on whether (i) new core and architectural technologies are at all needed, and (ii) whether existing architectural technologies can accommodate diffusion of new core technologies. While transition scholars often assume that fundamental changes in systems such as architectural change is an integral part of accelerating transitions (radical transformative pathway) [4,16,24], others have shown that transitions can reach the acceleration phase with limited change in system architectures (modular substitution transition pathway) [8,17,18]. Our typology resolves this apparent anomaly.

Our pathway typology also draws attention to potential trade-offs between the speed and depth of system discontinuity and incumbent reorientation in accelerating transitions. Our pathways describe four types of system discontinuity and four types of reorientation challenges to incumbent actors of increasing depth. Since deeper reorientation is more challenging, it leads to higher levels of resistance [7]. From this we infer that the level of resistance from incumbents against transitions grows in the acceleration phase mainly if it involves major changes in system architecture. Given that high levels of resistance from powerful incumbent actors is likely to slow down transition processes [113], the acceleration phase of transitions may, if major changes to system architecture is involved, paradoxically, be very slow or even stagnate [104]. Our approach to architectural change provides an explanation for this apparent paradox. Following this logic, transition pathways without major architectural change are likely to be relatively faster because the resources and competences of incumbents are more easily mobilized to work for the transition rather than against [114,115]. Given both the obvious need for more rapid sustainability transitions to address global warming and our limited conceptual understanding of the pace of the acceleration phase of transitions, the latter is an important issue for further research. Moreover, our reflections here indicate that the term "acceleration phase" is misleading if it can also refer to slowing down transition processes. We therefore suggest that transition scholars apply other concepts for this part of the transition such as diffusion phase.

5.3. Implications for policy

Our study provides several tentative insights that policy-makers should be attentive to in the acceleration phase of transitions.

First, policymakers should be mindful that each phase of transitions come with a different set of challenges. Transitions can move from being concentrated around the development of a few core innovations to their diffusion that can create knock-on effects in the wider system. Believing that once transitions start to accelerate, self-reinforcing S-curve momentum and competitive markets will fix the rest, is misleading. There can for example still be need for policy attention to architectural technologies. Without such attention, these technologies are unlikely to appear in due time which can increase the cost of the transition or even delay or derail it.

Second, our paper also suggest that acceleration can look different across systems and even geographies. For example, the policy challenges related to acceleration in the modular substitution pathway differ from those in the radical transformative pathway. The former requires policy support around building capabilities for new core technologies while the latter requires exploring new configurations of system components [116]. Arguably, the latter requires learning from experimentation with whole systems rather than individual technologies. Concepts as 'innovation zones' or 'living labs' that provide real-time laboratories for combined experimentation with institutions, actors, and technologies seem useful for supporting architectural change [110,117].

Lastly, innovation policy research has in recent years focused more and more on transformative and mission-oriented innovation policy which aims to promote deep, structural, and disruptive change in sociotechnical systems [16,118]. Even so, research has arguably mostly focused on inclusion of new actors [119] or matching problems and solutions in socially robust ways [120] and thus paid limited attention to the set of challenges that come with implementation, widespread diffusion, and acceleration. Our approach and analysis provide a systematic way of thinking about whether transitions require deep social changes at all as well as how to understand the challenges actors face in bringing them about. The latter seems important for further advancing these new innovation policy approaches.

5.4. Limitations of study

Our study has several limitations. First, the electricity system is special. 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 architectural technologies for system performance may therefore be higher than in other settings. It is also a slowly changing system (e.g., due to long asset lifetimes), which is why reorientation of actors may be slower than elsewhere. Our study operationalized system architecture as degrees of (de)centralization. While this is meaningful for electricity, system architecture will certainly have to be operationalized differently in other systems.

Second, the application of our analytical framework is only partial. Although our theoretical account of the relationship between diverse transition pathways and the depth and challenges of incumbent reorientation is about actor routines, capabilities, and mindsets, we cannot trace these empirically with our data. Future studies might want to analyse intra-organizational processes related to architectural change in transitions.

Third, another issue related to our data is that consultation documents are written with the attempt to influence policymaking. So, what actors state in these documents (about what policy makers should do) might deviate from what they are willing to work with. For example, incumbents might appear more reluctant than they actually are. Future studies might want to compare actor preferences that are revealed in consultations or similar documents from preferences stated elsewhere, e.g. in interviews or at industry meetings.

Fourth, while our study focused on differences between incumbents and challengers, our results also showed that there is some diversity within each group. For example, the grid operator TransnetBW seems to be more open for a broad range of flexibility technologies than 50hertz or Amprion, while on the challengers' side Eurosolar and Greenpeace Energy embrace more flexibility options than the renewable energy association BEE. Future research could explore this aspect further.

Lastly, while our study is arguably technology-oriented, architectural change is also about institutions. Indeed, architectural change pathways that do not involve major changes in core technologies such as transitions to sharing economy, circular economy, or even a degrowth institutional logic merit more attention in the future.

6. Conclusions

This paper was motivated by limited conceptualization and empirical analysis of architectural change in accelerating transitions. We introduced the concept of architectural technology to transition studies to explore the specific role of technologies that underpin the interplay between core technologies under a particular system architecture. Architectural technologies are particularly important in the acceleration phase when architectural changes at the system level can occur. We illustrated the usefulness of the architectural technology concept for understanding and studying potentially disruptive architectural changes, and the preferences of different types of actors, in the German energy transition.

One main finding is that even though most incumbents support a renewable energy transition by shifting core technologies from fossil to renewable energies, they prefer to maintain existing system architecture and architectural technologies. However, because their preferred centralized architectural technologies are very difficult to expand, they reluctantly accept a minor role for novel decentralized architectural technologies. This illustrates that incumbents have embraced reorientation at the level of resources and capabilities and are experimenting with deeper reorientation in terms of business models and organizational mindsets in the acceleration phase. Another main finding is that many challengers also prefer a mix of old and new architectural technologies due to the realization that existing architectural technologies have a role to play in a future decentralized system. Challengers, however, remain sceptical to further expanding established architectural technologies and the current institutional setup that supports them. As both incumbents and challengers gradually change and adapt their businesses and interests, their preferences start to converge. Overall, we see that actor shifts are not the end of actor struggles, but rather a dynamic process that continues in the acceleration phase albeit in different form.

Our framework and analysis illustrate that transitions can accelerate with or without architectural change depending on technology characteristics and the system in question. The latter points to potential trade-offs between the speed and depth of reorientation in transitions opening for the paradoxical possibility that the rate of sociotechnical change may be slower rather than faster in the acceleration phase.

Declaration of competing interest

The authors have no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Flexibility technologies overview

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 [49].

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 [121]. 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 [122,123]. 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
I	Large-scale plants /	Wind	How well does the flex technology match large-scale (centralized) wind power
J	Centralized	Solar	How well does the flex technology match large-scale (centralized) solar PV
K	Small-scale plants /	Wind	How well does the flex technology match small-scale (distributed) wind power
L	Decentralized	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.[a] 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.
Large-scale plants /	Wind	Offshore wind deployment largely depends on building of new transmission capacity.
Centralized	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 /	Wind	More transmission capacity does indirectly improve conditions for decentralized renewables by increasing the export possibilities
Decentralized	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		[50,124,125]

[a] Grids are built up by different voltage levels, from Transmission (typically from 66 kV to 500 kV) to Distribution (below 66 kV). 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 centralized 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.
Large-scale plants / Centralized	Wind Solar	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
Small-scale plants / Decentralized	Wind Solar	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.
Key references		[126–128]

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 centralized system design. CCS will push this option even further in the centralized 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.
Large-scale plants / Centralized	Wind Solar	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.
Small-scale plants / Decentralized	Wind Solar	Same as above but are rarely deployed in decentralized systems, cf. above.
Key references		[129,130]

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.
Large-scale plants / Centralized	Wind Solar	Distribution grid expansion does not affect conditions for large-scale plants.
Small-scale plants / Decentralized	Wind Solar	Distribution grid expansion helps integrating small- to medium scale wind power and (aggregated) rooftop PV
Key references		[131,132]

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)
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 Solar	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
Key references		[133–135]

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
Large-scale plants / Centralized Small-scale plants / Decentralized	Wind Solar 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
Key references		[136–138]

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)
Large-scale plants / Centralized	Wind	Batteries are well suited to balance wind variations but even better with PV.
	Solar	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
Small-scale plants / Decentralized	Wind Solar	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.
Key references		[89,134,139]

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.
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		[140–142]

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
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		[143,144]

Appendix B. Coding example

Statkraft made 4 statements about the importance of centralized flexibility options, cf. Table 3. Three of these statements were assigned to category 3 (important), one was stronger than the other but not super strong. So we assigned 3.5 to category 3 and 0.5 to category 4, resulting in a weighted average of 3.125 (see Fig. 5). On the importance of decentralized flexibility options, we only found one statement in Statkraft’s submission which we classified in between category 1 (not important) and category 2 (somewhat important). So we ended up with a weighted average of 1.5 (see Fig. 5). Below you find the statements that we coded.

“Gerade vorhandene Pumpspeicher sollten eine tragende Rolle in einem flexiblen und von Erneuerbaren Energien dominerten Energiesystem der Zukunft haben.“[Especially existing pumped hydropower storage facilities should play a key role in a flexible future energy system dominated by renewable energies.] Centralized flexibility options important (C-3).

“Stattdessen sollten flexible Gaskraftwerke Bestandteil des Erzeugungsmixes sein und Speicher sowie Nachfrageoptionen eine größere Rolle spielen.“[Instead, flexible gas-fired power plants should be part of the generation mix and storage as well as demand side options should play a larger role.] C-3.

“Der weitere Ausbau von Interkonnektoren muss hier einen starken Beitrag leisten.“[The further expansion of interconnectors has to make an important contribution here.] C-3.

“Notwendig ist dabei auch, den grenzüberschreitenden Netzausbau, z.B. nach Norwegen, weiter voranzubringen. Die Wasserspeicher in Norwegen bieten eine riesige Menge an Flexibilität.“[It is also important to advance cross-border grid expansion, e.g. to Norway. Norwegian hydropower reservoirs offer a vast amount of flexibility.] C-3 / C-4.

“Eine separate Behandlung von Aggregatoren lehnt Statkraft ab! Sie führt zu Verzerrungen im Markt.“[Statkraft opposes a special treatment for aggregators! This would lead to market distortions.] Indirect indication that decentralized flexibility options, which typically depend on aggregators, are not regarded as important. C-1 / D-2.

Appendix C. Interviews

No.	Name	Merits and organization	When
1	Peter Ahmels	Worked many years with the German energy transition as Head of Energy and Climate Protection at the Environmental Action Germany (DUH). Since 2018 he works as Senior Adviser Energy & Climate Protection at DUH but focused on district heating	19/10–2020
2	Holger Loew	Works as Senior Manager in the secretariat supporting the Renewables Grid Initiative (RGI). His work focusses energy systems, sector coupling and systems integration across local and transnational levels	25/11–2020
3	Eva Schmid	Works as senior consultant at GermanWatch with a focus analysis of consistent transformation strategies for the German and European electricity system with particular interest infrastructure requirements	16/06–2021

References

[1] I. Stoddard, et al., Three decades of climate mitigation: why haven't we bent the global emissions curve? Annu. Rev. Environ. Resour. 46 (1) (2021) 653–689.

[2] IPCC, in: P.R. Shukla, et al. (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022.

[3] P. Johnstone, et al., Waves of disruption in clean energy transitions: sociotechnical dimensions of system disruption in Germany and the United Kingdom, Energy Res. Soc. Sci. 59 (2020), 101287.

[4] J. Markard, F.W. Geels, R. Raven, Challenges in the acceleration of sustainability transitions, Environ. Res. Lett. 15 (8) (2020), 081001.

[5] F.W. Geels, Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of american factory production (1850–1930), Technol. Soc. 28 (2006) 445–476.

[6] F.W. Geels, J. Schot, Typology of sociotechnical transition pathways, Res. Policy 36 (3) (2007) 399–417.

[7] M.B. Lindberg, J. Markard, A.D. Andersen, Policies, actors and sustainability transition pathways: a study of the EU's energy policy mix, Res. Policy 48 (10) (2019), 103668.

[8] A. McMeekin, F.W. Geels, M. Hodson, Mapping the winds of whole system reconfiguration: analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016), Res. Policy 48 (2019) 1216–1231.

[9] C.M. Christensen, R.S. Rosenbloom, Explaining the attacker's advantage: technological paradigms, organizational dynamics, and the value network, Res. Policy 24 (2) (1995) 233–257.

[10] R.M. Henderson, K.B. Clark, Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms, Adm. Sci. Q. 35 (1) (1990) 9–30.

[11] B. Turnheim, B.K. Sovacool, Forever stuck in old ways? Pluralising incumbencies in sustainability transitions, in: Environmental Innovation and Societal Transitions, 2020.

[12] F.W. Geels, Reconceptualising the co-evolution of firms-in-industries and their environments: developing an inter-disciplinary triple embeddedness framework, Res. Policy 43 (2) (2014) 261–277.

[13] C. Roberts, et al., The politics of accelerating low-carbon transitions: towards a new research agenda, Energy Res. Soc. Sci. 44 (2018) 304–311.

[14] J. Meadowcroft, Engaging with the politics of sustainability transitions, Environ. Innov. Soc. Trans. 1 (1) (2011) 70–75.

[15] J. Markard, The next phase of the energy transition and its implications for research and policy, Nat. Energy 3 (8) (2018) 628–633.

[16] J. Schot, W.E. Steinmueller, Three frames for innovation policy: R&D, systems of innovation and transformative change, Res. Policy 47 (2018) 1554–1567.

[17] C. Berggren, T. Magnusson, D. Sushandoyo, Transition pathways revisited: established firms as multi-level actors in the heavy vehicle industry, Res. Policy 44 (2015) 1017–1028.

[18] M.M. Bugge, A.D. Andersen, M. Steen, The role of regional innovation systems in mission-oriented innovation policy: exploring the problem-solution space in electrification of maritime transport, Eur. Plan. Stud. (2021) 1–22.

[19] P.A. David, J.A. Bunn, The economics of gateway technologies and network evolution: lessons from electricity supply history, Inf. Econ. Policy 3 (2) (1988) 165–202.

[20] M.L. Tushman, J.P. Murmann, Dominant designs, technology cycles and organizational outcomes, Res. Organ. Behav. 20 (1998) 231–266.

[21] J.P. Murmann, K. Frenken, Toward a systematic framework for research on dominant designs, technological innovations, and industrial change, Res. Policy 35 (7) (2006) 925–952.

[22] L. Bird, M. Milligan, D. Lew, Integrating Variable Renewable Energy: Challenges and Solutions, National Renewable Energy Laboratory, Golden, Colorado, 2013.

[23] IEA, Status of Power System Transformation 158, International Energy Agency, Paris, 2017.

[24] J. Köhler, et al., An agenda for sustainability transitions research: state of the art and future directions, Environ. Innov. Soc. Trans. 31 (2019) 1–32.

[25] A. Cherp, et al., Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework, Energy Res. Soc. Sci. 37 (2018) 175–190.

[26] M. Robinius, et al., Linking the power and transport sectors—part 1: the principle of sector coupling, Energies 10 (7) (2017) 956.

[27] B. Turnheim, B. Nykvist, Opening up the feasibility of sustainability transitions pathways (STPs): representations, potentials, and conditions, Res. Policy 48 (3) (2019) 775–788.

[28] F.W. Geels, F. Berkhout, D.P. van Vuuren, Bridging analytical approaches for low-carbon transitions, Nat. Clim. Chang. 6 (6) (2016) 576–583.

[29] F.W. Geels, Technological Transitions and System Innovations. A Co-evolutionary and Socio-Technical Analysis 328, Edward Elgar, 2005.

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

[31] G. Holtz, M. Brugnach, C. Pahl-Wostl, Specifying "regime" — a framework for defining and describing regimes in transition research, Technol. Forecast. Soc. Chang. 75 (5) (2008) 623–643.

[32] C.M. Christensen, Exploring the limits of the technology S-curve. Part II: architectural technologies, Prod. Oper. Manag. 1 (4) (1992) 358–366.

[33] M.L. Tushman, L. Rosenkopf, Organizational determinants of technological-change-toward a sociology of technological evolution, Res. Organ. Behav. 14 (1992) 311–347.

[34] J. Markard, V.H. Hoffmann, Analysis of complementarities: framework and examples from the energy transition, Technol. Forecast. Soc. Chang. 111 (2016) 63–75.

[35] L.J. Colfer, C.Y. Baldwin, The mirroring hypothesis: theory, evidence, and exceptions, Ind. Corp. Chang. 25 (5) (2016) 709–738.

[36] L. Fuenfschilling, B. Truffer, The structuration of socio-technical regimes—conceptual foundations from institutional theory, Res. Policy 43 (2014) 772–791.

[37] N. Fligstein, D. McAdam, Toward a general theory of strategic action fields, Sociological Theory 29 (1) (2011) 1–26.

[38] F.W. Geels, Micro-foundations of the multi-level perspective on socio-technical transitions: developing a multi-dimensional model of agency through crossovers between social constructivism, evolutionary economics and neo-institutional theory, Technol. Forecast. Soc. Chang. 152 (2020), 119894.

[39] P.J. DiMaggio, W.W. Powell, The iron cage revisited: institutional isomorphism and collective rationality in organizational fields, Am. Soc. Rev. 48 (2) (1983) 147–160.

[40] M.G. Jacobides, T. Knudsen, M. Augier, Benefiting from innovation: value creation, value appropriation and the role of industry architectures, Res. Policy 35 (8) (2006) 1200–1221.

[41] J. Rotmans, R. Kemp, M. van Asselt, More evolution than revolution: transition management in public policy, Foresight 3 (1) (2001) 15–31.

[42] A. Malhotra, T.S. Schmidt, Accelerating low-carbon innovation, Joule 4 (11) (2020) 2259–2267.

[43] D. Sahal, Technological guideposts and innovation avenues, Res. Policy 14 (2) (1985) 61–82.

[44] F.W. Geels, Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of american factory production (1850–1930), Technol. Soc. 28 (4) (2006) 445–476.

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

[46] A. Davies, The life cycle of a complex product, Int. J. Innov. Manag. 1 (1997) 229–256.

[47] R. Raven, Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: an assessment of differences and pitfalls, Energy Policy 35 (4) (2007) 2390–2400.

[48] P.A. David, Path dependence and the quest for historical economics: one more chorus of the ballad of QWERTY, in: Souls, 1997.

[49] S.R. Sinsel, J. Markard, V.H. Hoffmann, How deployment policies affect innovation in complementary technologies—evidence from the German energy transition, Technol. Forecast. Soc. Chang. 161 (2020), 120274.

[50] A.D. Andersen, J. Markard, Multi-technology interaction in socio-technical transitions: how recent dynamics in HVDC technology can inform transition theories, Technol. Forecast. Soc. Chang. (2020) 151.

[51] F.W. Geels, From leadership to followership: a suggestion for interdisciplinary theorising of mainstream actor reorientation in sustainability transitions, Environ. Innov. Soc. Trans. 41 (2021) 45–48.

[52] F.W. Geels, B. Turnheim, The Great Reconfiguration: A Socio-technical Analysis of Low-carbon Transitions in UK Electricity, Heat, and Mobility Systems, Cambridge University Press, 2022.
[53] G. Gavetti, J.W. Rivkin, On the origin of strategy: action and cognition over time, Organ. Sci. 18 (3) (2007) 420–439.
[54] M.L. Tushman, P. Anderson, Technological discontinuities and organizational environments, Adm. Sci. Q. 31 (3) (1986) 439–465.
[55] A. Smith, R. Raven, What is protective space? Reconsidering niches in transitions to sustainability, Res. Policy 41 (2012) 1025–1036.
[56] F.W. Geels, et al., 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), Res. Policy 45 (4) (2016) 896–913.
[57] C.M. Fiol, M.A. Lyles, Organizational learning, Acad. Manag. Rev. 10 (4) (1985) 803–813.
[58] M.L. Tushman, E. Romanelli, Organizational evolution: a metamorphosis model of convergence and reorientation, Res. Organ. Behav. 7 (1985) 171–222.
[59] C.C.R. Penna, F.W. Geels, Multi-dimensional struggles in the greening of industry: a dialectic issue lifecycle model and case study, Technol. Forecast. Soc. Chang. 79 (6) (2012) 999–1020.
[60] J.H. Wesseling, et al., Car manufacturers' changing political strategies on the ZEV mandate, Transp. Res. Part D: Transp. Environ. 33 (2014) 196–209.
[61] S. Jacobsson, V. Lauber, The politics and policy of energy system transformation - explaining the German diffusion of renewable energy technology, Energy Policy 34 (3) (2006) 256–276.
[62] M.M. Smink, M.P. Hekkert, S.O. Negro, Keeping sustainable innovation on a leash? Exploring incumbents' institutional strategies, Bus. Strateg. Environ. 24 (2015) 86–101.
[63] D.J. Hess, Sustainability transitions: a political coalition perspective, Res. Policy 43 (2) (2014) 278–283.
[64] F.T. Rothaermel, Complementary assets, strategic alliances, and the incumbent's advantage: an empirical study of industry and firm effects in the biopharmaceutical industry, Res. Policy 30 (8) (2001) 1235–1251.
[65] M. Steen, T. Weaver, Incumbents' diversification and cross-sectorial energy industry dynamics, Res. Policy 46 (6) (2017) 1071–1086.
[66] M. Kattirtzi, I. Ketsopoulou, J. Watson, Incumbents in transition? The role of the 'Big six' energy companies in the UK, Energy Policy 148 (2021), 111927.
[67] E.-L. Apajalahti, A. Temmes, T. Lempiälä, Incumbent organisations shaping emerging technological fields: cases of solar photovoltaic and electric vehicle charging, Tech. Anal. Strat. Manag. 30 (1) (2018) 44–57.
[68] A.D. Andersen, M. Gulbrandsen, The innovation and industry dynamics of technology phase-out in sustainability transitions: insights from diversifying petroleum technology suppliers in Norway, Energy Res. Soc. Sci. 64 (2020) (June).
[69] T. Magnusson, V. Werner, Conceptualisations of incumbent firms in sustainability transitions: Insights from organisation theory and a systematic literature review, Bus. Strateg. Environ. (2022) 1–17, n/a(n/a).
[70] A. van Mossel, F.J. van Rijnsoever, M.P. Hekkert, Navigators through the storm: A review of organization theories and the behavior of incumbent firms during transitions, Environ. Innov. Soc. Trans. 26 (2018) 44–63.
[71] J.M. Wittmayer, et al., Actor roles in transition: insights from sociological perspectives, Environ. Innov. Soc. Trans. 24 (2017) 45–56.
[72] A. Bergek, et al., Technological discontinuities and the challenge for incumbent firms: destruction, disruption or creative accumulation? Res. Policy 42 (2013) 1210–1224.
[73] C. Zietsma, T.B. Lawrence, Institutional work in the transformation of an organizational field: the interplay of boundary work and practice work, Adm. Sci. Q. 55 (2) (2010) 189–221.
[74] W. McDowall, Disruptive innovation and energy transitions: is Christensen's theory helpful? Energy Res. Soc. Sci. 37 (2018) 243–246.
[75] S. Erlinghagen, J. Markard, Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change, Energy Policy 51 (2012) 895–906.
[76] H. Leblebici, et al., Institutional Change and the Transformation of Interorganizational Fields: An Organizational History of the U.S. Radio Broadcasting Industry, Adm. Sci. Q. 36 (3) (1991) 333–363.
[77] K.M. Eisenhardt, Building theories from case study research, Acad. Manag. Rev. 14 (1989) 532–550.
[78] German Environment Agency, Renewable energies in figures [cited 2020 June]; Available from: https://www.umweltbundesamt.de/en/topics/climate-energy/renewable-energies/renewable-energies-in-figures, 2020.
[79] D. Bauknecht, et al., Demand flexibility and what it can contribute in Germany, in: F. Sioshansi (Ed.), Variable Generation: Flexible Demand, Academic Press, 2020.
[80] Bundetzagentur, Quartalsbericht Netz- und Systemsicherheit - Gesamtes Jahr 2019, 2019.
[81] V. Bertsch, et al., Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for Germany, Energy 114 (2016) 465–477.
[82] J.-H. Kamlage, et al., Fighting fruitfully? Participation and conflict in the context of electricity grid extension in Germany, Util. Policy 64 (2020), 101022.
[83] E. Schmid, et al., Imagine all these futures: on heterogeneous preferences and mental models in the German energy transition, Energy Res. Soc. Sci. 27 (2017) 45–56.
[84] F.-A. Prognos, in: Dezentralität und zellulare Optimierung – Auswirkungen auf den Netzausbaubedarf: Kurzfassung des Endberichts, Universität Erlangen-Nürnberg, Energie-Campus Nürnberg, N-ERGIE Aktiengesellschaft, Nürnberg, 2016, p. 10.
[85] ETIP SNET, Sector Coupling: Concepts, State-of-the-art and Perspectives. White Paper, ETIP Smart Networks for Energy Transition, 2020.
[86] OECD/IEA, Power of Transformation - Wind, Sun and the Economics of Flexible Power Systems, 2014.
[87] S. Funcke, D. Bauknecht, Typology of centralised and decentralised visions for electricity infrastructure, Util. Policy 40 (2016) 67–74.
[88] J. Lilliestam, S. Hangera, Shades of green: centralisation, decentralisation and controversy among European renewable electricity visions, Energy Res. Soc. Sci. 17 (2016) 20–29.
[89] IEA, World Energy Outlook 661, International Energy Agency, Paris, 2018.
[90] F. Robertson Munro, P. Cairney, A systematic review of energy systems: the role of policymaking in sustainable transitions, Renew. Sust. Energ. Rev. 119 (2020), 109598.
[91] M. Winskel, et al., Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates, Technol. Forecast. Soc. Chang. 81 (2014) 96–114.
[92] S.R. Sinsel, R.L. Riemke, V.H. Hoffmann, Challenges and solution technologies for the integration of variable renewable energy sources—a review, Renew. Energy 145 (2020) 2271–2285.
[93] M. Korpaas, A.T. Holen, R. Hildrum, Operation and sizing of energy storage for wind power plants in a market system, Int. J. Electr. Power Energy Syst. 25 (8) (2003) 599–606.
[94] E. Schmid, B. Knopf, A. Pechan, Putting an energy system transformation into practice: the case of the German Energiewende, Energy Res. Soc. Sci. 11 (2016) 263–275.
[95] G. Kungl, Stewards or sticklers for change? Incumbent energy providers and the politics of the German energy transition, Energy Res. Soc. Sci. 8 (2015) 13–23.
[96] Clean Energy Wire, Power production at sea re-emerges as Energiewende cornerstone, cited 2020; Available from: https://www.cleanenergywire.org/dossiers/offshore-wind-power-germany, 2018.
[97] J. Ossenbrink, J. Hoppmann, V.H. Hoffmann, Hybrid ambidexterity: how the environment shapes incumbents' use of structural and contextual approaches, Organ. Sci. 30 (6) (2019) 1319–1348.
[98] M. Richter, Business model innovation for sustainable energy: German utilities and renewable energy, Energy Policy 62 (2013) 1226–1237.
[99] G. Kungl, F.W. Geels, Sequence and alignment of external pressures in industry destabilisation: understanding the downfall of incumbent utilities in the German energy transition (1998–2015), Environ. Innov. Soc. Trans. 26 (2018) 78–100.
[100] Clean Energy Wire, Germany's largest utilities at a glance, cited 2020; Available from: https://www.cleanenergywire.org/factsheets/germanys-largest-utilities-glance, 2018.
[101] F. Frei, et al., Leaders or laggards? The evolution of electric utilities' business portfolios during the energy transition, Energy Policy 120 (2018) 655–665.
[102] A. Klitkou, A.M. Fevolden, A.D. Andersen, EU R&D funding for electricity grid technologies and the energy transition: centralised versus decentralised transition pathways, Energies 15 (3) (2022) 868.
[103] F. Rohde, S. Hielscher, Smart grids and institutional change: Emerging contestations between organisations over smart energy transitions, Energy Res. Soc. Sci. 74 (2021), 101974.
[104] M. Löhr, J. Mattes, Facing transition phase two: Analysing actor strategies in a stagnating acceleration phase, Technol. Forecast. Soc. Chang. 174 (2022), 121221.
[105] E. Costa, et al., The electric vehicle and renewable energy: changes in boundary conditions that enhance business model innovations, J. Clean. Prod. 333 (2022), 130034.
[106] M. Winfield, S. Shokrzadeh, A. Jones, Energy policy regime change and advanced energy storage: a comparative analysis, Energy Policy 115 (2018) 572–583.
[107] C. Kemfert, F. Kunz, J. Rosellón, A welfare analysis of electricity transmission planning in Germany, Energy Policy 94 (2016) 446–452.
[108] R. Kemp, J. Schot, R. Hoogma, Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management, Tech. Anal. Strat. Manag. 10 (1998) 175–198.
[109] F.W. Geels, Disruption and low-carbon system transformation: progress and new challenges in socio-technical transitions research and the multi-level perspective, Energy Res. Soc. Sci. 37 (2018) 224–231.
[110] D. Bauknecht, A.D. Andersen, K.T. Dunne, Challenges for electricity network governance in whole system change: insights from energy transition in Norway, Environ. Innov. Soc. Trans. 37 (2020) 318–331.
[111] L. Neij, G. Nemet, Accelerating the low-carbon transition will require policy to enhance local learning, Energy Policy 167 (2022), 113043.
[112] B. Turnheim, B.K. Sovacool, Socio-technical transitions and policy change - advocacy coalitions in Swiss energy policy, Environ. Innov. Soc. Trans. 18 (2016) 215–237.
[113] B. Pel, Transition 'backlash': Towards explanation, governance and critical understanding, Environ. Innov. Soc. Trans. 41 (2021) 32–34.
[114] P.J. Newell, F.W. Geels, B.K. Sovacool, Navigating tensions between rapid and just low-carbon transitions, Environ. Res. Lett. 17 (4) (2022), 041006.
[115] F.W. Geels, B. Turnheim, The Great Reconfiguration: A Socio-technical Analysis of Low-carbon Transitions in UK Electricity, Heat, and Mobility Systems, Cambridge University Press, Cambridge, 2022.
[116] K. Frenken, A complexity-theoretic perspective on innovation policy, Complex. Govern. Netw. (2017) 35–47.

[117] T. von Wirth, et al., Impacts of urban living labs on sustainability transitions: mechanisms and strategies for systemic change through experimentation, Eur. Plan. Stud. 27 (2) (2019) 229–257.
[118] M. Mazzucato, Mission-oriented innovation policies: challenges and opportunities, Ind. Corp. Chang. 27 (5) (2018) 803–815.
[119] W. Boon, J. Edler, Demand, challenges, and innovation. Making sense of new trends in innovation policy, Sci. Public Policy 45 (4) (2018) 435–447.
[120] I. Wanzenböck, et al., A framework for mission-oriented innovation policy: alternative pathways through the problem–solution space, Sci. Public Policy 47 (4) (2020) 474–489.
[121] C. Azar, B. Sandén, The elusive quest for technology-neutral policies, Environ. Innov. Soc. Trans. (2011) 135–139.
[122] E. Dahlgren, et al., Small Modular Infrastructure, Eng. Econ. 58 (4) (2013) 231–264.
[123] A. Lovins, Small Is Profitable. The Hidden Economic Benefits of Making Electrical Resources the Right Size, Rocky Mountain Institute, 2002.
[124] T. Ackermann, Wind Power in Power Systems, John Wiley & Sons, Ltd., 2005.
[125] B. Bayer, et al., The German experience with integrating photovoltaic systems into the low-voltage grids, Renew. Energy 119 (2018) 129–141.
[126] E.D. Castronuovo, J.A.P. Lopes, On the optimization of the daily operation of a wind-hydro power plant, IEEE Trans. Power Syst. 19 (3) (2004) 1599–1606.
[127] I. Graabak, et al., Balancing future variable wind and solar power production in central-west Europe with Norwegian hydropower, Energy 168 (2019) 870–882.
[128] K.B. Lindberg, et al., Large scale introduction of zero energy buildings in the Nordic power system, in: 2016 13th International Conference on the European Energy Market (EEM), 2016.
[129] R.M. Montañés, et al., Identifying operational requirements for flexible CCS power plant in future energy systems, Energy Procedia 86 (2016) 22–31.
[130] M.L. Kubik, P.J. Coker, C. Hunt, The role of conventional generation in managing variability, Energy Policy 50 (2012) 253–261.
[131] R. Seguin, et al., High-Penetration PV Integration. Handbook for Distribution Engineers, National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2016.
[132] J.O.G. Tande, Exploitation of wind-energy resources in proximity to weak electric grids, Appl. Energy 65 (1) (2000) 395–401.
[133] C. Wulf, J. Linssen, P. Zapp, Chapter 9 - power-to-gas—concepts, demonstration, and prospects, in: C. Azzaro-Pantel (Ed.), Hydrogen Supply Chains, Academic Press, 2018, pp. 309–345.
[134] M. Jafari, M. Korpås, A. Botterud, Power system decarbonization: Impacts of energy storage duration and interannual renewables variability, Renew. Energy 156 (2020) 1171–1185.
[135] A. Varone, M. Ferrari, Power to liquid and power to gas: an option for the German Energiewende, Renew. Sust. Energ. Rev. 45 (2015) 207–218.
[136] G. Streckienė, et al., Feasibility of CHP-plants with thermal stores in the German spot market, Appl. Energy 86 (11) (2009) 2308–2316.
[137] N. Szarka, et al., A novel role for bioenergy: a flexible, demand-oriented power supply, Energy 61 (2013) 18–26.
[138] J. Beiron, et al., Flexible operation of a combined cycle cogeneration plant – a techno-economic assessment, Appl. Energy 278 (2020), 115630.
[139] T. Sylvia, World's largest battery storage system now operational. PV Magazine [cited 2020 December]; Available from: https://www.pv-magazine.com/2020/08/20/worlds-largest-battery-storage-system-now-operational/, 2020.
[140] G. Strbac, Demand side management: benefits and challenges, Energy Policy 36 (12) (2008) 4419–4426.
[141] O. Wolfgang, G. Doorman, Evaluating demand side measures in simulation models for the power market, Electr. Power Syst. Res. 81 (3) (2011) 790–797.
[142] M. Stötzer, et al., Potential of demand side integration to maximize use of renewable energy sources in Germany, Appl. Energy 146 (2015) 344–352.
[143] D. Pudjianto, C. Ramsay, G. Strbac, Virtual power plant and system integration of distributed energy resources, IET Renew. Power Gener. 1 (2007) 10–16.
[144] F.V. Hulle, I. Pineda, P. Wilczek, Economic Grid Support Services by Wind and Solar PV. A Review of System Needs, Technology Options, Economic Benefits and Suitable Market Mechanisms, The European Wind Energy Association, 2014.