

Rogge, Karoline S.; Pfluger, Benjamin; Geels, Frank

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Transformative policy mixes in socio-technical scenarios: The case of the low-carbon transition of the German electricity system (2010-2050)

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Working Paper Sustainability and Innovation
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Karoline S. Rogge
Benjamin Pfluger
Frank Geels

Transformative policy mixes in socio-technical scenarios: the case of the low-carbon transition of the German electricity system (2010-2050)

Abstract

Global climate change represents one of the grand societal challenges which policy makers around the world have agreed to jointly tackle it under the Paris Agreement. Henceforth, much research and policy advice has focused on developing model-based scenarios to identify pathways towards achieving corresponding decarbonisation targets. In this paper, we complement such model-based analysis (based on IMAGE and Enertile) with insights from socio-technical transition analysis (MLP) to develop socio-technical storylines that plausibly show how low-carbon transitions can be implemented. We take the example of the transition of the German electricity system towards renewable energies, and elaborate two transition pathways which are assumed to achieve an 80% reduction in GHG emissions by 2050, but differ in terms of lead actors, depth of change and scope of change: the first pathway captures the *substitution of technological components (pathway A)* and assumes incumbents as lead actors and focuses on radical technological change while leaving other system elements intact; in contrast, *pathway B (broader system transformation)* postulates new entrants as lead actors, which rests on the assumption that transformative change occurs in the whole system, i.e. affecting the architecture of the system, technologies but also practises. For both pathways, we focus on how policy makers could govern such transition processes through transformative policy mixes, and compare the requirements of such policy mixes depending on the pathway pursued. We find that multi-dimensional socio-technical change going beyond technological substitution (pathway B) requires much greater emphasis on societal experimentation and a more proactive role for anticipatory deliberation processes from the outset. In contrast, shifting gear from a new entrant friendly past trajectory to an incumbent dominated pathway (pathway A) requires active agency from incumbents and is associated with what we have called regime stabilizing instruments which defend core principles of the old regime while simultaneously fulfilling decarbonisation as additional success criteria.

Keywords: socio-technical scenarios, transformative policy mix, German Energiewende, MLP, energy system modelling, transition pathways

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1 Introduction

Global climate change represents one of the grand societal challenges which policy makers around the world have agreed to jointly tackle it under the Paris Agreement. This agreement foresees the decarbonisation of the economy to limit global warming to at least 2°C. This ambitious policy objective requires major reductions in greenhouse gas (GHG) emissions, with the energy sector being one of the key contributors to such reductions. Henceforth, much research and policy advice has focused on developing model-based scenarios to identify pathways towards achieving such decarbonisation targets. However, implementing these scenarios has proven to be a major challenge due to economic, political and social bottlenecks. In this paper, we therefore complement such model-based analysis with insights from socio-technical transition analysis to develop socio-technical storylines that plausibly show how low-carbon transitions can be implemented (Turnheim et al., 2015; Geels et al., 2016a). In doing so, we focus on how transformative policy mixes can assist in overcoming transition bottlenecks, thereby paying greater attention to actors, struggles, strategies and resistance to change (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016; Schot and Steinmueller, 2016).

We take the example of the German energy transition which foresees ambitious decarbonisation targets, has already made significant progress towards these targets but is also facing major transition challenges (Strunz, 2014; Geels et al., 2016b; Quitzow et al., 2016; Matthes, 2017). For this research case we have applied the bridging methodology proposed by Geels et al (this issue) which enables us to develop storylines that indicate how bottlenecks can be overcome and transitions achieved. This forward-oriented analysis builds on the investigation of historical trajectories in terms of the momentum of green niche innovations (e.g. solar PV, on- and offshore wind), and the stability and tensions of incumbent socio-technical regimes in the electricity sector (with its sub-regimes of electricity supply, demand and grids). It furthermore uses model results from an integrated assessment model (IMAGE) and an energy system optimization model (Enertile). Based on this, we develop future transition pathways from a socio-technical perspective, and in doing so focus on how policy makers could govern such transition processes through transformative policy mixes.

The remainder of the paper is structured as follows. Section 2 summarizes the literature on socio-technical scenarios and outlines key aspects of transforma-

tive policy mixes for sustainability transitions. This is followed by an introduction to the research case and methodology in section 3. The findings are presented in three steps: section 4 presents the model results, while section 5 presents the findings of a qualitative socio-technical MLP analysis. Section 6 contrasts MLP and model outcomes and identifies the main transition challenges to be overcome. We then turn to describing two socio-technical scenarios in sections 7 and 8 in which we focus on the endogenous logic of transition pathways. In particular, we focus on the role of transformative policy mixes, i.e. explaining the underlying reasons for the developments based on choices, decisions, strategies, and beliefs of actors, all of which can be influenced by policy. The paper ends with concluding remarks in section 9.

2 Literature review on socio-technical scenarios and transformative policy mixes

2.1 Socio-technical scenarios

Socio-technical scenarios (STSc) were developed because model-based scenarios over-privilege techno-economic factors and “lack attention for actors, their decisions, interactions and learning processes, and the way these shape twisting transition paths” (Hofman et al., 2004, p. 349). Using the Multi-Level Perspective (MLP) on transitions, most STSc have two characteristics: first, they address the co-evolution of multiple dimensions (techno-economic and socio-political); and second, instead of deterministically relying on external macro-trends, they focus on the *endogenous enactment logic*, describing how “attitudes and behaviour of actors change in the course of new developments. (...) Thus, a transition path does not come out of the blue but it becomes clear *why* it develops” (Hofman and Elzen, 2010, p. 656).

To reduce the complexity and offer some guidance for actor-based scenarios, STSc often use the MLP, organizing the narrative scenario logic in terms of niche-innovations struggling against existing regimes (Elzen et al., 2004; Hofman et al., 2004). While early STSc were qualitative, scholars have subsequently developed STSc in which actor-based storylines are (partially) constrained by quantitative models (Foxon, 2013; McDowall, 2014). In line with Geels et al. (2017) our socio-technical storylines are normative and model-oriented, i.e. they aim to develop plausible actor-based transition pathways for the quantitative model-based scenarios that are assumed to reach the target of

2°C climate change. We thus aim for a *socio-technical qualification of model-based scenarios*. This approach helps shed light on problems with political feasibility and social acceptance that real-world transitions are currently encountering. We therefore focus our socio-technical scenarios on transition bottlenecks and how these may be overcome.

2.2 Transformative policy mixes for sustainability transitions

In recent years it has been increasingly acknowledged that sustainability transitions call for broader *policy mixes* (Rogge and Reichardt, 2016) to address various market and system failures (Weber and Rohracher, 2012). This implies that policy mixes for sustainability transitions should not only promote green niches but also include policies aimed at regime destabilization (Kivimaa and Kern, 2016). Importantly, it has been argued that such a broader perspective must also explicitly include the politics of transition processes (Meadowcroft, 2009; Stirling, 2014) as well as policy strategies and strategic capabilities of policy makers (Quitow, 2015; Rogge and Reichardt, 2016) as well as credibility and other characteristics (Reichardt and Rogge, 2016). Others have introduced *transformative innovation policy* as a third frame of innovation policy which supplements the earlier focus of innovation policy on R&D support and the promotion of innovation systems (Schot and Steinmueller, 2016).¹ The idea is that through processes of anticipatory deliberation transition possibilities can be outlined, that societal experimentation nurtures greater diversity and that new institutional arrangements and governance structures are needed to facilitate transition processes. The underlying innovation model assumes that “there is no single best pathway to sustainability, income equity and other socially desirable goals” and thus must be experimental as “at the outset, no pathway is known to be fit for purpose” (ibid, p. 18). Both the literature on policy mixes for sustainability transitions and the one on transformative innovation policy build on socio-technical transitions thinking, but have so far only very loosely been related to each other. However, we argue that in the context of developing socio-technical scenarios there is value in combining them to derive key aspects relevant for transformative policy mixes for sustainability transitions.

¹ In a similar vein, scholars have advocated for transformative environmental policy to complement more traditional approaches to environmental policy focusing on environmental protection and environmental policy integration Jacob et al. (2015).

For transformative policy mixes for sustainability transitions this combination implies, first, a need to address directionality failures and provide a clear direction of search for which the *policy strategy* with its policy objectives, often quantified in long-term targets, and principal plans for achieving them can play a key role (Rogge and Reichardt, 2016). The formulation of such a strategy should build on *anticipatory deliberation* processes to outline possibilities, identify different interests and ideas, consider political struggles and trade-offs, negotiate priorities and elaborate visions of a sustainable future (Schot and Steinmueller, 2016). For example, in the case of the low-carbon energy transitions multiple visions regarding the centralized and decentralized nature of the future energy system exist (Lilliestam and Hanger, 2016). It has been stressed that anticipatory deliberation should be inclusive by opening up space for public debate, for example by initiating transformative foresight processes with participation of multiple stakeholders (Da Costa et al., 2008; Kunseler et al., 2015; Carayannis et al., 2016). This requires enhanced strategic policy intelligence and strategic capabilities, e.g. regarding stakeholder engagement, vertical and horizontal policy coordination, or accountability mechanisms to avoid capture by powerful stakeholders (OECD, 2015; Quitzow, 2015). It also necessitates the development of bridging capabilities between social and technical sciences among policy makers, researchers and other stakeholders (Schot and Steinmueller, 2016). Similarly, but at an innovation system level, Lindner et al. (2016) have argued for self-reflection capacities, bridging and integration capacities and anticipation capacities to address directionality.

Second, transformative policy mixes for sustainability transitions need to combine traditional policy instruments to address both technology push and demand pull (Peters et al., 2012; Costantini et al., 2015) but also systemic concerns (Smits and Kuhlmann, 2004; Wieczorek and Hekkert, 2012). In addition, it has been argued that such policy mixes should pay attention to the 'creative destruction' and societal experimentation. Regarding the former it has been pointed out that in addition to policies supporting green niches (Raven et al., 2016) policy makers should also implement several destructive policies, such as control policies (e.g. carbon pricing), significant changes to regime rules (e.g. electricity market reform), reduced support for dominant regime technologies (e.g. reduction of subsidies for fossil fuels) and changes in social networks, for example by the replacement of key actors in stakeholder consultations or empowerment of new entrants in political debates (Kivimaa and Kern, 2016). However, policies for the protection of green niches (e.g. feed-in tariffs) may initially be easier to implement than policies destabilizing existing regimes, underlining that

inconsistencies within transformative policy mixes are highly likely in times of transitions (Quitow, 2015; Rogge and Reichardt, 2016).

Regarding the latter, *societal experimentation* can be seen as key transformative policy instrument (Berkhout et al., 2010; van den Bosch, 2010; Kivimaa et al., 2017) and as such features prominently in transformative policy mixes for sustainability transitions, but is also seen as essential capacity of innovation systems addressing the directionality of innovation (Lindner et al., 2016). As pointed out by Schot and Steinmueller (2016) it “is only through actual practice that experience and deep learning are generated and that the advantages and disadvantages of a particular innovation pathway can be identified and remedied by revision or by choosing a different development pathway.” (p. 19). It is important to note that transition experiments differ from demonstration projects by a number of aspects. Transition experiments take a societal challenge as starting point rather than a possible solution, by a focus on exploring, searching and learning vs. testing and demonstration, and by including multi-actor alliances across society rather than specialized R&D staff (van den Bosch, 2010). This implies that experimentation needs to include a wide range of societal actors, thereby also drawing on grassroots innovation with communities and civil society (Smith and Seyfang, 2013). In addition, such societal experimentation should facilitate and empower those involved in search, experimentation and learning, challenge dominant views and resistance to change from vested interests (Geels, 2014), nurture greater diversity and explicitly allow for failures which may require a different policy culture (Jacob et al., 2015; Schot and Steinmueller, 2016). Under such conditions, it is argued that deep learning can occur collectively and may ultimately lead to changes in cognitive frames and assumptions, implying second-order learning (Schot and Geels, 2008). Given its relevance, it is therefore no coincidence that policy learning and experimentation (Kemp et al., 2007; Frantzeskaki et al., 2012) has been singled out as important aspect of policy making within the policy mix literature (Rogge and Reichardt, 2016).

Third, the transformative innovation policy literature calls for establishing *new institutional arrangements and governance structures* which include governments, market actors and civil society and are tailored to achieving societal goals. This resonates well with the increasing attention in transition studies to focus on institutional change as key dimension of socio-technical change (Fuenfschilling and Truffer, 2014), as well as thinking on governing sustainability transitions (Smith et al., 2005; Laes et al., 2014). Institutions and governance aspects are also implicitly captured in the policy mix literature as they provide

the context of policy processes (Rogge and Reichardt, 2016). More specifically, with regard to the coherence of policy processes it is pointed out that structural and procedural mechanisms (e.g. strategic planning, coordinating structures and communication networks) are needed to enable more synergistic and systematic policy processes (OECD, 1996, 2001). In addition, policy coordination and policy integration are seen as tools of enhancing such coherence, with the former aiming at the alignment of the tasks and efforts of public sector organizations (Bouckaert et al., 2010; Magro et al., 2014) and the latter enabling more holistic processes and more holistic thinking across different policy sectors (OECD, 2003). However, as noted by Fuenfschilling and Truffer (2016) such changes in institutional arrangements and governance structures require institutional work and thus agency regarding the disruption of existing institutions (e.g. by questioning assumptions and beliefs), the creation of new ones (e.g. by advocacy, changing normative associations, and educating) and their later maintenance (e.g. through embedding and routinizing). Such agency is increasingly present in the case of low-carbon energy transitions and has been singled out as one of the key factors for accelerating such transitions (Kern and Rogge, 2016).

In conclusion, we argue that transformative policy mixes for sustainability transitions are (i) sensitive of conflict and power struggles present in policy making processes and establish an inclusive policy style which embraces policy and societal learning, including from failures; (ii) incorporate anticipatory deliberation to formulate societal visions then translated into policy strategies; (iii) include instrument mixes which promote societal experimentation in green niches while at the same time destabilizing unsustainable regimes; and (iv) change institutional arrangements and governance structures to facilitate sustainability transitions. In addition, transformative policy mixes for sustainability transitions pay greater attention to agency and differences between incumbents and new entrants, implying that policy makers must be well attuned to actor-differences arising from different transition pathways.

3 Research case and methodology

In this paper, we adopt the same methodological approach as described in Geels et al. (2017) and which we summarize in Table 1. That is, we have followed eight iterative steps to ensure a structured dialogue between modellers and transitions scholars, thereby bridging two analytical approaches (Turnheim et al., 2015). This was done within the PATHWAYS project, and intermediary

results were reported in the deliverables mentioned in Table 1 and available on the project website.² We have started by setting the boundary of our analysis (step 1), which in our case refers to the German electricity system with its sub-systems of generation, consumption and grids. We have chosen Germany as it has an ambitious climate and energy policy mix in place and has already made significant progress with increasing the share of electricity generated from renewable energy sources (BMW, 2015).

Table 1: List of methodological steps and corresponding PATHWAYS reports for the German electricity system

No.	Methodological step	Publication of results
1	Boundary setting (<i>here: German electricity system</i>)	
2	Determining conceptual logic for transition pathways (<i>here: technical component substitution (A) and broader system transformation (B)</i>)	D4.1
3	First set of quantitative scenarios (<i>here: models IMAGE and Enertile</i>)	D1.1
4	Qualitative MLP-based analysis of green niche innovations and their momentum (<i>here: solar PV, on- and offshore wind, bioenergy, and smart meters</i>), regimes and their stability and tensions (<i>here: electricity generation, network, and consumption</i>) and landscape factors	D2.1, D2.2 and D2.3
5	Feasibility assessment of quantitative future scenarios (step 3) based on qualitative assessments of contemporary developments (step 4), thereby identifying transition bottlenecks	D2.5
6	Second set of quantitative scenarios after adjustment of model assumptions and parameters resulting from step 5 (<i>here: IMAGE and Enertile</i>)	D1.3
7	Specifying transition challenges	D2.5
8	Development of qualitative socio-technical scenarios with plausible actor-based storylines for the quantitative pathways produced in step 6 (<i>here: particular focus on transformative policy mixes</i>)	D2.5

Source: Summarized and adapted from Geels et al. (2017)

In the second step we elaborated transition pathways (Smith et al., 2005; Geels and Schot, 2007) which have a strong climate policy mix in place and are assumed to achieve an 80% reduction in GHG emissions by 2050 compared to 1990 levels. However, the specifics of the transition pathways are quite differ-

² All deliverables listed in Table 1 are available under <http://www.pathways-project.eu/>.

ent. To simplify the analysis and allow for pointed comparisons of extreme cases, we defined two distinct transition pathways which differ in terms of lead actors, depth of change and scope of change (see Table 2). The first pathway captures the *substitution of technological components (pathway A)* and assumes incumbents (typically from industry and policy) as lead actors. This pathway further assumes radical technological change while leaving other system elements intact, thereby only changing technology and markets. In contrast, *pathway B (broader system transformation)* postulates new entrants as lead actors, thereby focusing on new firms, social movements, and civil society actors, which to some extent resembles the German Energiewende so far (Geels et al., 2016b). This second pathway rests on the assumption that transformative change occurs in the whole system, i.e. affecting the architecture of the system, technologies but also practises. This implies that change occurs on multiple dimensions, ranging from markets and technology to organisational, policy, social, cultural and consumer practises.

Table 2: Ideal-type transition pathways A and B, and their defining elements

	Pathway A: Technical component substitution	Pathway B: Broader regime transformation
Departure from existing system performance	Substantial	Substantial
Lead actors	Incumbent actors (often established industry and policy actors)	New entrants, including new firms , social movements, civil society actors.
Depth of change	Radical technical change (substitution), but leaving other system elements mostly intact	Radical transformative change in entire system (fundamentally new ways of doing, new system architectures, new technologies)
Scope of change	1-2 dimensions: technical component and/or market change, with socio-cultural and consumer practises unchanged	Multi-dimensional change (technical base, markets, organisational, policy, social, cultural, consumer preferences, user practices)

Source: D4.1 (available online at <http://www.pathways-project.eu/>)

In step 3, these ideal-type transition pathways have been implemented in the integrated assessment model IMAGE and the energy system model Enertile to generate a first set of quantitative scenarios. Both of these are based on the general assumptions that there are substantial energy efficiency improvements and learning rates in renewable electricity technologies (RETs) and that EU countries meet their RES targets for 2020 as defined in their National Renewa-

ble Energy Action Plans (NREAPs). Both models focus on the techno-economic aspects of the transition. The models have the objective of reaching levels of emission reductions and search for energy systems in line with these. However, the model formulation does not require explicit, detailed assumptions on the policies driving the transition. For example, the model results typically show increasing shares of renewable energies; the results do not include an explicit support policy, such as a feed-in tariff or a tender system.

In the parallel step 4 we conducted a qualitative MLP-analysis in which we assessed three dimensions of selected niches and three sub-regimes within the German electricity system in the last 5-10 years (techno-economic, socio-cognitive, policy) to assess their endogenous momentum (results are reported on the PATHWAYS website, see D2.1, D2.2. and D2.3). Based on our qualitative insights generated within step 5 we assessed the feasibility of the initial quantitative future scenarios, thereby identifying transition bottlenecks which were used in step 6 to adjust model assumptions and parameters.

In this paper, we mainly focus on steps 6-8 for which we report and discuss our findings. In step 6 we produced a second set of quantitative scenarios (see section 4). These scenarios were again contrasted with the qualitative socio-technical analysis of niche and regime developments in the German electricity system, based on which major transition challenges were identified in step 7 (see section 5). Finally, in step 8 we develop qualitative socio-technical scenarios which are guided by four main constraints. First, the socio-technical scenarios are guided by the MLP and the logic of *pathways A and B*. Second, the scenarios recognize *lock-in mechanisms and path dependencies in the present*, based on findings of the socio-technical analysis conducted under step 4. Third, the quantitative model outcomes provide the aggregate pathways for which we try to develop plausible endogenous storylines for how decarbonization can be reached. And finally, we focus on overcoming the *tensions* ('transition challenges') between future model scenarios and analysis of the present socio-technical system. That is, we develop an endogenous storyline for the German electricity system – written as '*history of the future*', i.e. in past tense – describing how interactions between various actors (and changes in technology, institutions, beliefs, social networks, etc.) can generate dynamics which overcome the 'transition challenges' (see sections 6 and 7). Since the storylines focus on the endogenous logic, we pay most attention to niche-innovations and existing regimes rather than relying on sudden exogenous landscape shocks, such as rapid technological advances. We extend the procedure proposed in Geels et al.

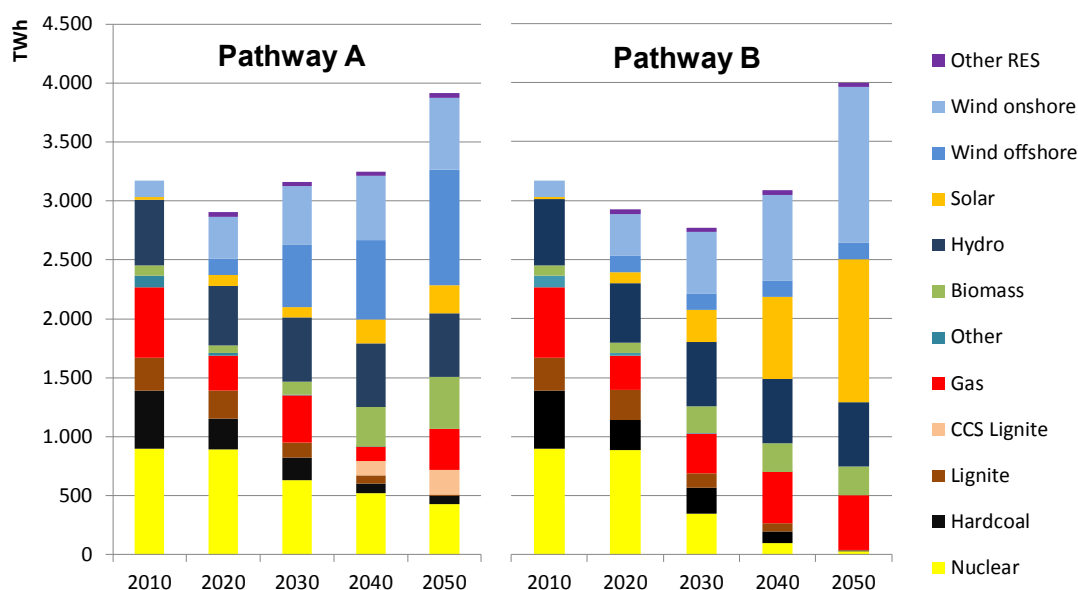
(this issue) by highlighting the role of transformative policy mixes in constructing such socio-technical scenarios driven by endogenous change, thereby concretizing the last methodological step. In particular, we draw on the key aspects of transformative policy mixes derived from the combination of the policy mix and transformative policy literature to arrive at plausible storylines, thereby aiming at providing valuable novel insights to policy makers interested in supporting sustainability transitions.

4 Quantitative model-based scenarios for German electricity generation

In this section we describe the revised set of quantitative scenarios for the German electricity system which have been developed using computer models and with input from the MLP analysis. It is important to stress that both pathways are explicitly designed to represent stylized, exaggerated developments of the underlying storylines. National preferences or strategies (besides nuclear phase-out policies) are not implemented in order to show the full impact of the Pathways.

Figure 1 shows the overall results for the European power sector, comparing both transformation Pathways. The model specifications are set to ensure that Pathway A is dominated by incumbent actors with a preference for large-scale technologies. This means high shares of onshore and offshore wind parks, free-field PV and a still substantial contribution from nuclear power in countries that – unlike Germany – do not have a phase-out policy in place. The land availability is used as an indicator to represent social and political acceptance of renewable electricity technologies, and is decreased by one third for solar PV, and increased by a half for on- and offshore wind. CCS is available in the the scenario, but is only utilized in power plants running on lignite (a very cheap fuel) or biomass (to generate negative emissions). Finally, the use of low-carbon vehicles is stimulated by subsidizing the upfront purchasing price of new vehicles in passenger transport, thereby significantly increasing demand for electric mobility and thus electricity after 2037.

Figure 1: Electricity generation in Europe in TWh (based on D1.3)

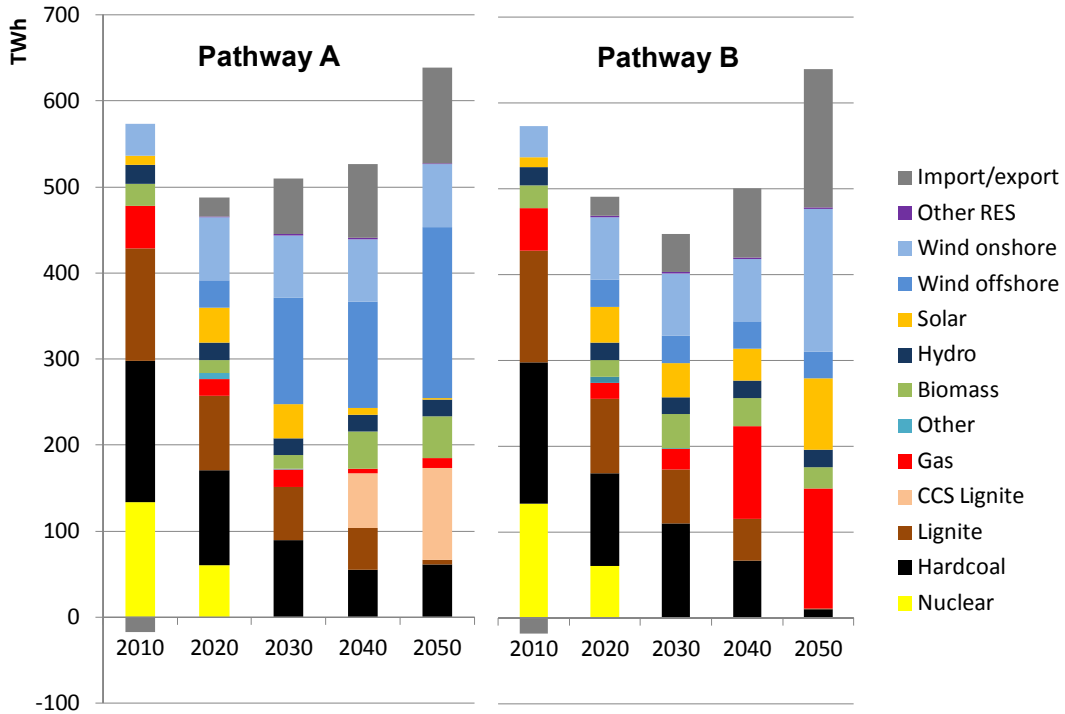


Source: own calculations with Enertile

In contrast, in Pathway B the electricity system is transformed more broadly through the involvement of new actors, changing preferences and different lifestyles. CCS is excluded in this scenario, because it faces social acceptance problems. Onshore wind is a very attractive renewable electricity technology due to its low costs, with the model performing a European optimization resulting in constructions where it is windiest (particularly in the UK). Solar-PV is privileged because its decentralized characteristics work well with new entrants, which is represented by assuming a higher utilization of land and a lower interest rate for roof-mounted PV modules. In addition, greater bottom-up participation is assumed. In addition, the use of low-carbon vehicles is stimulated by subsidizing the upfront purchasing price of new vehicles in passenger transport and people's increased preference for car-sharing, thereby significantly increasing demand for electric mobility and thus electricity already after 2035.

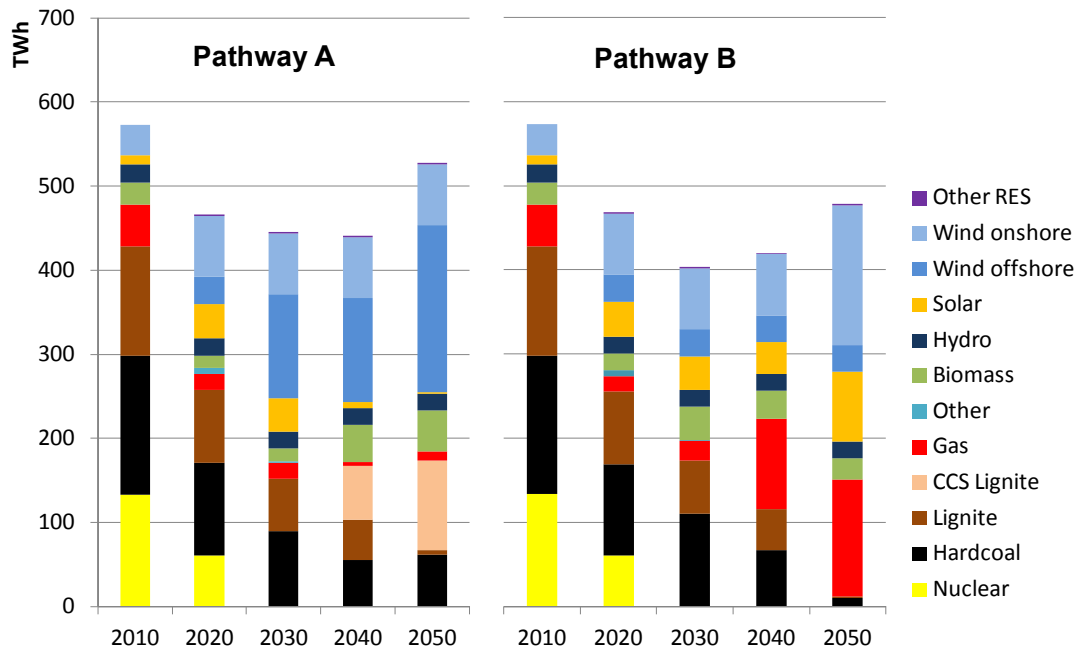
Figure 2 and Figure 3 show the quantitative Enertile model results for Germany for the two different transition pathways A and B, both in terms of capacity and actual electricity generation. In many aspects, the developments in Germany mirror the European ones.

Figure 2: Installed capacity in electricity generation in Germany (based on D1.3)



Source: own calculations with Enertile

Figure 3: Electricity generation in Germany in TWh (based on D1.3)



Source: own calculations with Enertile

Pathway A in Germany leads to an electricity generation system which by 2050 is dominated by offshore wind, lignite power plants equipped with CCS, as well as and gas turbines serving as back-up. Nuclear power is phased out by 2022, in line with the German nuclear phase-out strategy. Offshore wind experiences a steady and significant growth, turning into the dominant electricity supply technology by 2040. In contrast, onshore wind stagnates from 2020 onwards even experiencing a reduction in electricity generation capacities, as only the most productive sites are repowered. Together, by 2050 offshore and onshore wind generate roughly 60% of electricity in Germany, and make up 50% of the installed capacity. The high shares of offshore wind require significant expansions of the electricity grid, particularly long-distance transmission grids, offshore grids, and interconnectors to European countries. Perhaps most strikingly, solar-PV is being phased-out, with existing plants not being replaced, so that by 2050 the remaining share of German solar-PV is negligible. Unabated lignite is almost completely phased-out by 2050, but with CCS becoming available around 2040 there is a renaissance for the use of lignite. The use of hard coal declines significantly, but some capacity is still left by 2050, however it is not combined with CCS. Gas capacities remain at almost the same level with just a slight increase in 2050, but gas is only sparsely needed as back-up capacity for intermittent renewables, implying a significantly reduced share in overall electricity generation. Power from biomass expands after 2030, particularly in terms of its share in electricity generation, due to its ability to serve as back-up capacity and combined use with CCS as BECCS (Bio-Energy with Carbon Capture and Storage) to lead to negative emissions. Electricity consumption declines at first, driven mainly by improvements in energy efficiency. With the increased diffusion of electric vehicles electricity and the diffusion of heat pumps demands starts rising again in 2037. This development is reflected by the decrease in German generation capacities and electricity generation until 2040, and strong increase by 2050. Around 2040, Germany switches from exporting to importing electricity from the rest of Europe, and by 2050 imports 17 % of its domestic electricity demand.

In contrast, Pathway B leads to an electricity generation system which by 2050 is dominated by onshore wind, gas and solar PV, while as in pathway A, nuclear is phased-out by 2022. Unabated lignite is completely phased-out by 2050, as (in contrast to Pathway A) CCS is not available. While unabated hard coal follows a similar retirement pattern as within pathway A, in pathway B the remaining hard coal power plants run with lower load factors, leading to a much smaller share in electricity generation than in pathway A. Natural gas (without CCS)

declines until 2030 (similar as in Pathway A), but thereafter has a strong renaissance both in terms of capacity (which is almost doubled between 2040 and 2050) and generation. The model uses Germany as a “flexibility hub” by building gas power plants and using the enhanced transmission grid to transport electricity across Europe. Therefore, due to the European optimization Germany appears atypical for this scenario, with a relatively low share of renewable electricity. Solar-PV, in stark contrast to pathway A, maintains a high share in electricity generation capacities and more than doubles between 2040 and 2050 to become the largest share of overall capacities, followed by onshore wind and gas. However, load factors remain low, so that the overall share in electricity generation increases to roughly 15% by 2050. After 2023, onshore wind as cheapest renewable electricity technology increases much faster than in Pathway A, and becomes the central pillar of Germany’s electricity supply. In contrast, offshore wind does not increase beyond 2020, but only maintains 2020 levels up to 2050 (through repowering). Biomass remains fairly stable at current figures, and is slightly reduced between 2040 and 2050. Even earlier than in pathway A Germany becomes an importer of cost-efficient renewables, reaching a share of approximately 25% by 2050. The high shares of solar-PV and onshore wind require a strong expansion of the electricity grid, particularly long-distance transmission grids, interconnectors to European countries, and storage solutions. Electricity demand follows a similar pattern as in pathway A, but with more pronounced demand reductions. Also, demand increases caused by the surge of electric vehicles kick in slightly earlier than in pathway A (already around 2035).

To conclude, both pathways reach 80% reductions in CO₂ emissions by 2050, but represent substantial changes compared to the historical and contemporary trajectories in the German electricity system.

5 Socio-technical developments in the recent past and present (2000-2015)

5.1 Niche-innovations

Table 3 summarises the conclusions of the analysis of selected niches within the German electricity system which was conducted in 2014 and published 2015 in D2.1. In its assessments it covers three dimensions of niche-momentum: *techno-economic* (market share, price/performance improvements),

socio-cognitive (size of social networks, learning processes, coherence of future vision), and *governance* (degree of policy support). It also includes our interpretation of whether the niche fits better with Pathway A or B. With regard to electricity generation options, the results show a clear relative ranking and assessments of current momentum (as of 2014):

- Onshore wind: Very high (in 2014)
(but given recent policy changes this will be decreasing, in order to make room mainly for the more expensive offshore wind (but also for solar PV) while slowing down the expansion of renewable energies to stay within foreseen political expansion corridors)
- Solar PV: High (in 2014) (but further decreasing, as desired by policy changes)
- Offshore wind: Moderate (in 2014)
(but increasing and stabilizing at a high level, mainly due to favourable policy changes and solution of grid access bottlenecks)
- Bioenergy: Low (in 2014) (and continuing to remain low).

Table 3: Findings on momentum of German electricity niche-innovations

Niche-innovation	Assessment of Momentum (incl. ranking)	Pathway
Onshore wind	1 – very high Large techno-economic potential at lowest cost Currently still relatively high socio-cognitive acceptance Continuing deployment support, but attempt to limit rate of deployment and integrate into market	B
Energy saving lighting	2 (LED) – very high technological and economic advantages and fast progress (including total cost of ownership) 2 (CFL) – medium economic advantages (including total cost of ownership) technological disadvantage (e.g. containing mercury) technology has yet to overcome reluctance in social acceptance on the user side political support largely originating from the EU (ban of incandescent lamps in 2009)	A
Solar PV	3 – high high cost burdens for final customers due to EEG surcharge, but costs are expected to continue to decrease social acceptance for rooftop PV is still high up to 2013 very high momentum, but now reduced due to a deterioration of the policy mix (attempts to limit diffusion rate, large cutbacks in the level of support granted through feed-in tariffs)	B
Offshore wind	4 – medium continuing high costs and delays in grid connection industry actors remain firmly committed to this technology which by now is also attractive to large utilities long-term targets recently reduced, but instrument mix remains favorable with extensions of high levels of support	A
Bioenergy	5 – low high costs and little cost reduction potential, but technological advantage of being a non-fluctuating energy source wider sustainability concerns and competing uses of biomass for the decarbonization of other sectors policy commitment for further expansion limited (very low rate of diffusion foreseen)	B
Smart meters	6 – low high implementation costs with cost-benefit ratios rarely being positive for individual households socio-cognitive acceptance rather low due to the issue of data protection policy makers are yet hesitant to show significant commitment to an accelerated deployment	A (with potential for B)

Source: Own compilation based on D2.1 and D2.5

However, this ranking has recently changed, which points to the highly dynamic nature of these niches and the currently still very high dependence of their momentum on the policy mix. More precisely, the current government has recently implemented significant policy changes in order to limit the expansion of renewable energy within the foreseen, conservative expansion corridors, with offshore wind being the main winner – largely at the expense of onshore wind, despite its higher costs.

5.2 Electricity regime developments

Below we summarise some of the main findings about the degree of stability and lock-in of the German electricity regime, and the degree of tensions and cracks, which offer opportunities for wider change (see D2.2). In doing so, we distinguish the regime developments in three interrelated sub-systems: electricity generation, electricity transmission and electricity use.

Over the period from 1990 until today the **German electricity generation regime** has witnessed major landscape pressures – most importantly a strong anti-nuclear movement paired with concerns about climate change. Additional tensions have resulted from the increasing impacts of the emerging niches of wind, solar PV and bioenergy, which have expanded significantly and can now start to be viewed as new sub-regimes. The sheer size, different ownership structure and characteristics of these emerging green sub-regimes have meant fundamental changes along many dimensions of the German electricity regime. This regime is now transforming from one characterized by centralized, large-scale electricity generation dominated by large utilities to a much more decentralized, and smaller scale electricity generation regime based on renewable energies, with the ownership of generation capacities spread across a multitude of new entrants, including a high share of citizens, farmers and cooperatives. In addition, the established business models of the incumbent utilities are eroding. Indeed, while the large incumbents have undergone multiple changes in beliefs and are now investing in large-scale renewable energies, their long-term survival is still at stake because of their lack of business model capabilities to harness the chances and opportunities from the ongoing energy transition. In 2012 and 2013, however, the decarbonisation of the electricity generation system experienced a setback due to rising shares of lignite and hard coal in the generation mix – despite declining capacities. There have also been recent changes in the key policy instrument supporting the expansion of renewable energies, the EEG, which indicate a change in policy favouring larger investors. This is partly

due to pressures to advance the market integration of renewables, and partly due to political concerns about the ever-increasing EEG surcharge, which is largely borne by private electricity consumers because of the exemptions for energy-intensive industries. Hence, while nuclear phase-out and the transition towards renewable energies are not being questioned, there are ongoing disputes about what the future regime will look like (e.g. regarding the degree of decentralization) and who the winners and losers will be.

The **German electricity consumption and end-use regime** is evolving incrementally through the interplay of several dynamics which may have a reverse effect on the development of electricity consumption. Changes in the range and absolute number of electrical products and to production and employment in the industrial and service sectors have the predominant effect of increasing electricity consumption. These factors dampen the rise of electricity consumption only during periods of economic recession. Another growth-stimulating effect is the still ongoing trend to greater automation and widespread diffusion of new electrically powered applications and technologies (as e.g. information and communication technologies, electric vehicles and electric heat pumps). On the other hand, energy efficiency innovations have helped to suppress increases in electricity consumption. These manifested themselves in manufacturers' efforts to increase the energy efficiency of electric household appliances and cross-cutting technologies (e.g. electric motors, lighting, ICT) and the increasing market penetration of such technologies. This development was stimulated to a large extent by the EU's and national governments' policy measures. However, it is often unclear how behavioural and organisational changes impact the purchase and use of electric appliances and products in private households and companies. They can have a decreasing effect on electricity consumption, often stimulated by informational and advice programmes, but the opposite is also possible, e.g. through rebound effects. These patterns can be understood in the context of competing landscape pressures. On the one hand, concerns about climate change and energy security as well as the favourable side-effects of energy efficiency have exerted pressure on the consumption regime, generating the drive towards greater energy efficiency. On the other hand, the trend towards greater electrification of households and companies is an important stabilizing force on the regime. The following table summarizes the countervailing pressures exerted by the different actors in the electricity consumption regime.

Over the period from 1998 until 2015, the **German electricity network regime** has been experiencing major challenges to the traditional operating strategies of the power system. Major drivers were developments in the generation struc-

ture with the emerging niches of wind, solar PV and bioenergy as well as the nuclear phase-out driven by the anti-nuclear movement. Another major factor at landscape level was the push for liberalization and unbundling of the electricity sector initiated and pursued by the EU from 1996 to 2009 with three waves of liberalization directives. Changes in generation structure have challenged and are still challenging the system physically and require network expansions. However, since network expansion is not keeping pace with the changes, is plagued by acceptance issues and might not always be the most efficient solution, adaptations in network operation and management are also required. To some extent, this is taking place already with network operators engaging in redispatch and generation management. However, so far, this is mainly being managed centrally via the network operators and (nearly) limited to emergency situations. A wider use of flexibility options is being discussed, but the framework to implement this is still missing. This shifts the focus to the flexible management of generation and supply, optimization via smart grids using intelligent control and metering as well as storage solutions. It may therefore push the niche development of smart metering. Overall, the system is moving from centralized, top-down management towards a more decentralized, interactive system, but so far this is mainly happening on a physical level. This represents a challenge for the networks, some of which are approaching their limits already, but which cope mainly using existing measures. In the future, roles, responsibilities and regulations will have to be modified to be able to adapt operations to these changes. At the same time, transmission networks are also being enhanced by innovative technologies and it is not yet clear what the network regime of the future will look like and how it will combine smarter distribution and expanded and enhanced transmission (probably also long-distance, high-voltage transmission to connect with other countries). The network business as a centrally regulated activity is relatively stable per se, but is undergoing reconfiguration. Changes to regulation have been made to adapt it to the investment needs and quality demands which enable further changes in the future.

6 Specifying ‘transition challenges’

There are several tensions and in some cases even clear contradictions between the quantitative scenarios and qualitative socio-technical findings. These tensions form the ‘transition challenges’ between contemporary trends and developments, on the one hand, and the future changes that are needed to achieve the climate change goals. Table 4 describes these tensions for key low-

carbon innovations, disaggregated for Pathway A and B. The last column also qualifies the transition challenges in terms of different *kinds* of constraints, which shows that social acceptance is creating obstacles for all innovations, but many also raise concerns in terms of political commitment.

Table 4: Tensions between future model scenarios for German electricity generation and qualitative socio-technical analysis

Innovation	Pathway A	Pathway B	Constraint
Biomass	Pathway A assumes a moderate expansion of biomass in electricity use in 2040 and 2050, which contradicts with today's sustainability and cost concerns as well as competing uses of biomass use, which together have led to a downscaling of the further growth prospects of biomass in Germany.	Only intermediary upscaling, but by 2050 reduction to 2010 levels, therefore smaller and only temporary tensions.	Political commitment, social acceptance, environmental sustainability
CCS and BECCS (biomass energy with CCS)	The diffusion of CCS starts in 2030. In Germany, CCS comes into play for lignite power plants (see below) and for biomass plants in order to generate "negative emissions. 90% of all German/EU bioenergy use in the power sector by 2050 is combined with CCS. This creates two main tensions: 1) CCS and BECCS are not yet viable and not much is happening 'on-the-ground', making it risky to base future scenarios on something that hardly exists in the present. 2) CCS faces significant public resistance (see below).	No CCS in pathway B (and hence no BECCS) – therefore no tension.	Technology readiness, economic costs, political commitment, social acceptance
Lignite CCS	The roll-out of lignite CCS power plants starts between 2030 and 2040. The diffusion of CCS is in conflict with the lack of public acceptance for CO ₂ storage. Furthermore, this requires the continued use of Germany lignite reserves, which may address resistance against the phase-out of lignite (losses of income & jobs) but will also cause headwind from environmental groups.	No CCS. Therefore continuous phase out of lignite which is completed by 2050. This is in conflict with resistance from lignite regions, unions and incumbents opposing the phase-out of lignite.	Social and business acceptance, political commitment, economic development, jobs
Onshore wind	Generation slightly increases until 2020 and afterwards stabilizes at this level. This is in stark	Until 2040 onshore wind develops like pathway A, with	Social and business acceptance; industrial dynam-

Innovation	Pathway A	Pathway B	Constraint
	contrast to current high momentum of onshore wind as cheapest renewables option, despite the foreseen growth corridors being residual to offshore wind and PV. Tensions can be expected from onshore wind advocates (e.g. jobs, domestic industry decline) and cost-effectiveness concerns.	similar concerns. But thereafter it more than doubles its capacity and generation. This long-term jump raises questions of public acceptance (NIMBY, land-use) and is in conflict with continuous industry development.	ics; neglect of cost-minimization
Offshore wind	Offshore wind capacities and generation increase dramatically, particularly from 2020-2030 and 2040-2050, which due to the technologies higher total system costs is in conflict with Germany's shift towards cost-minimization. Resistance from excluded new entrants can also be expected, as well as technological risk due to missing long-term experience.	No further growth of offshore wind after 2020, thereby endangering economic development and jobs in Northern Germany which conflicts with strong offshore wind advocacy coalition.	Political, social and business acceptance, techno-economic costs and risks
Solar PV	Solar-PV is virtually phased-out by 2050, which is completely unthinkable from today's perspective, given the technologies legitimacy, financial benefits to investors (e.g. farmers, private households) and public acceptance as well as declining costs and tendencies towards prosuming and fit with envisaged smart home and mobility solutions.	No further growth of solar-PV between 2020 and 2040 (apart from repowering after 2030), with similar tensions as in A. Then doubling of capacities and generation between 2040 and 2050, with concerns regarding technology import and domestic industry rebuild.	Social, business and political acceptance, lack of technological diversity, industrial dynamics
Unabated hard coal	While no new coal power plants are built, existing ones are not completely phased out (nor complemented through CCS) by 2050. This is in conflict with climate policy ambitions and lack of public acceptance for a continuation of coal combustion.	Similar to Pathway A, but phase-out continues in 2050, with much lower load hours of the remaining coal capacities, and therefore smaller tensions.	Social acceptance, political credibility, climate policy concerns
Unabated gas	Stabilization of gas capacities with very low load hours, implying a challenge to the business model and necessitating policy	After initial decline of gas capacities and generation after 2030 gas capacities	Business model, social acceptance; political commitment,

Innovation	Pathway A	Pathway B	Constraint
	solution regarding much debated capacity mechanism.	grow, particularly after 2040, and generation reaches almost a third of German electricity, raising concerns about the achievement of renewable and decarbonisation targets.	energy security
Electricity grid expansion	The (at least economically) indicated strong grid expansion creates tensions with current grid trajectories where there is much inertia and local resistance to grid-projects. The transnational interconnector capacity has to be more than doubled until 2050, leading to the construction of new overhead lines at borders, but also within the countries.	Pathway B suggests even stronger grid expansion, more than tripling the transnational interconnector capacity due to the higher share of renewables. The higher share of PV also calls for a stronger expansion of the distribution grid, with associated NIMBY and cost concerns.	Social acceptance; political commitment; finance; organizational slack; regulatory conservatism
Import and export	Both pathways turn Germany from a net exporter of electricity to a net importer (in A ca. 110 TWh in 2050). This assumes a massive expansion of cheap renewables in other European countries, e.g. onshore wind in the UK (which currently faces serious barriers, see Geels et al. this issue) and requires the construction of new interconnectors. There may also be tensions regarding domestic efforts and energy security.	After 2040 import is significantly higher than in Pathway A (ca. 160 TWh in 2050), while up to 2040 it is lower, leading to similar but even intensified tensions as in pathway A.	Political and social acceptance; dependence on success of decarbonisation on developments abroad

Source: Own elaboration based on D2.5

The socio-technical scenarios described in the next section aim to offer plausible pathways for how these transition challenges can be overcome. The socio-technical scenarios do not represent forecasts, robust strategies or recommendations. They should be seen as thought experiments on the potential tensions and obstacles arising when a specific strategy is pursued. The approach relies on viewing the scenarios from the perspective of socio-technical interactions and endogenous changes. In particular, these endogenous storylines, which pay particular attention to actors and contexts, attempt to identify which role

transformative policy mixes could play in overcoming these tensions. We have divided both scenarios into three phases: the first one captures recent developments from 2015-2019 which are largely similar between pathways A and B, thereby reflecting lock-in and path dependencies inherent in socio-technical systems. In addition, by incorporating recent political developments and limiting policy changes to the end of the first phase, there is limited scope for differences in both scenarios, as most changes will only impact the next phases. Consequently, for this phase the scenarios resemble each other, and we therefore provide a description of joint developments and conclude with a discussion of differences between both pathways. For the second (2020-2034) and third phase (2035-2050), we then describe the further development of both scenarios in separate chapters to explain the various differences resulting from the logic of pathway A and B. Given that phase 3 is far into the future, we only sketch out the main developments, whereas we include a more elaborate explanation for phase 2 in which fundamental changes are starting to be prepared and kick-in.

7 Socio-technical scenario for pathway A for the German electricity system: decarbonising with off-shore wind and CCS-lignite

7.1 Phase 1 (2015-2019): switch to renewables auctions, continuation of nuclear phase-out and missing of 2020 climate targets

The nuclear phase-out was one of the key objective of energy policy in this period (Hermwille, 2016). In addition, in its Energy Concept from 2010 the German government had also committed itself to a reduction of its greenhouse gas emissions by 40% by 2020 (compared to 1990 levels), and to a reduction of 80-95% by 2050, as well as an expansion of renewables in final energy consumption by 60% and in electricity consumption of at least 80% by 2050 (BMW and BMU, 2010). These targets were reiterated at several occasions, including in the coalition agreement of Merkel's Grand Coalition government (2013-2017) and in the context of the Paris agreement from December 2015.

The core policy instrument at the time was the Renewable Energy Sources Act (EEG) for which policy makers had started to experiment with auctioning pilots as a potential substitute for feed-in tariffs, largely due to rising cost concerns and a desire to move to the next level of the energy transition with a more mar-

ket-based support policy. In contrast, at that time the core climate policy instrument – the EU emission trading system – did not set the proper decarbonisation incentives, nor were other sufficiently stringent instruments implemented to address the looming gap in achieving Germany's climate policy targets for 2020.

Old regime developments:

By 2015, the electricity *generation regime* in Germany was undergoing radical changes, given the rapid expansion of renewable energies. However, while no actor questioned anymore the transition towards renewable energies, there was a dispute about final regime dimensions. Resistance from regime actors focused on reducing losses (e.g. by law suits, asset sweating) and identifying new business models to ensure their survival in the new renewable-based regime (Richter, 2013a). There were major tensions and cracks in the electricity generation regime caused by socio-political responses to climate change and the anti-nuclear movement. The supportive policy mix, and in particular the EEG had enabled major investments in renewable energy infrastructure by new entrants, with only a negligible share owned by large incumbents. The merit-order effect of the electricity market led to a reduction of electricity market prices and thus decreased profitability of existing conventional plants, which forced large incumbents to rethink their beliefs, strategies and organisational structures (Strunz, 2014). A closer look at the different technological sub-regimes reveals the following developments:

- Germany's *nuclear* phase-out proceeded as planned, with a step-wise closing down of the remaining eight nuclear power plants, with plant closures in 2015 (Grafenrheinfeld), 2017 (Gundremmingen B) and 2019 (Philippsburg 2). These closures were welcomed across society and political parties. While three of the four affected plant operators sued the government for its abrupt phase-out decisions in the wake of the Fukushima disaster in Japan in 2011, this was not about reversing the decision but about who carries the costs of closing down the nuclear power plants prior to their retirement age. When the supreme court finally ruled against the incumbents, this was seen as another pointer for them to face the new realities. However, policy makers still struggled with identifying a suitable final deposit site for Germany's radioactive waste. While the corresponding expert commission worked hard they only managed to establish generic search criteria in 2016, which marked the beginning of a new, systematic search process.
- Regarding *coal and lignite* there were hardly any new plants being built, but existing plants reached very high load factors, exporting excess electricity abroad. The attractiveness of coal and lignite was largely based on low resource prices and low CO₂ prices, the latter resulting from the over-allocation

and built up surplus of allowances in the EU Emission Trading System (EU ETS). Particularly the nearly exhausted load hours of lignite power plants contributed to a rise in the CO₂ emissions of Germany's electricity system, which were coined as Paradoxon of the Energiewende, and led to criticisms from environmental NGOs and bad international publicity. Given trends in CO₂ emissions it became increasingly clear that a phase-out policy for lignite fired power plants was needed, but the initial proposal made by Minister Gabriel prior to COP21 in Paris in 2015, faced heavy political resistance from a coalition of incumbents, unions and federal states dependent on the income generated by the industry. Yet, given the gap in CO₂ target fulfilment and Germany's endangered international credibility several additional climate policy instruments were adopted, including financial compensation for the closure of the dirtiest lignite power plants. Also, Germany's climate protection plan for 2050 initiated an expert group addressing coal phase-out in 2018 ("Commission on Structural change, competitiveness and regional development"). After intensive public consultations in early 2019 this cumulated in the announcement of a long-term phase-out strategy for unabated lignite and coal with a time horizon of 2050, which included that the most inefficient lignite and coal fired power plants were going offline already in the end of 2019.

- Giving the strong resistance from incumbents to phase out coal and rising pressure to address the climate gap the government decided to revisit the *carbon capture and storage (CCS)* technology as potential solution. In negotiating the coal phase-out deal the government brokered a deal with incumbents which foresaw a competition for so-called CCS model regions for economically deprived regions. Mindful of strong public opposition to earlier storage sites this initiative was equipped with substantial public funds to support the economic development of the regions towards green technologies while at the same time implementing two CCS demonstration plants with CO₂ storage to go online in 2030. In the public, it was cynically accepted as the price to pay for the coal phase-out deal, with much initial scepticism across society.
- The existing capacities for *gas fired power generation* had to significantly reduce their load hours, thereby further endangering the business model for gas-fired power plants. Main reasons included the low CO₂-price which continued in the fourth trading phase of the EU ETS due to the large remaining surplus of EUAs, and the rising shares of intermittent renewables which lowered electricity costs. In order to keep operators from mothballing their gas fired power plants, even those with highest efficiencies, the government implemented a partial capacity mechanism, which kept existing gas plants as back-up capacity. However, it was not attractive enough to generate any interest in constructing new gas fired power plants, leaving operators to search for alternative investment options.

In contrast, the electricity *consumption regime* remained fairly locked-in, even though overall electricity consumption declined slightly due to incremental energy efficiency improvements. However, the trend towards greater electrification in some fields (ICT, heat pumps) and some rebound effects (e.g. in lighting) partly counteracted the efforts to reduce electricity consumption. Yet, particularly the increase of electricity demand from e-mobility remained limited, since the diffusion of electric vehicles had a very slow start, and only slightly accelerated after the government had introduced purchase subsidies for electric vehicles in 2016. Initially, several important actors remained reluctant to see energy efficiency as a top priority (esp. electricity utilities, retailers and wholesale trade) which undermined the efforts to increase efficiency and reduce electricity demand. Yet, given the initial problems of phasing out coal and lignite and the immense reputational pressure from the international community resting on Germany to achieve its 2020 target, a relatively broad consensus of affected groups emerged on the benefits of energy efficiency. As a consequence, energy efficiency saw some increased political attention, so that the government slowly started to shift its policy approach, which so far was largely based on voluntary policy measures (such as learning energy efficiency networks) and financial support for investments in energy efficiency improvements (e.g. through KfW funding), to a more ambitious market-based approach. A visible sign of this emerging shift was the new government's turnaround regarding the introduction of a white certificate trading scheme. However, implementing such a scheme on a mandatory basis faced some opposition from incumbents, so that the government was finally only able to roll out this new scheme in ten model regions in 2017. To ensure the buy-in of these model regions they benefited from generous financial support for the implementation, monitoring and evaluation of the scheme which became possible due to excess tax income. In addition, this support was meant to enable policy learning and provide evidence for a later national roll-out of the scheme.

Finally, the *network regime* initially remained fairly stable with moderate lock-in due to its long-lived asset structure and conservative mind-set and regulation. While some regulatory changes were implemented, such as targeted investment incentives to spur certain developments, their implementation was rather slow and did initially not result in radical changes but only gradual adaptations of the regulatory framework. However, given the ever increasing share of intermittent renewables both industry and policy pressures on the network regime grew, as they shared a keen interest on making the Energiewende an attractive business case and political success story. There was a common understanding

that the increase in decentralized and intermittent generation required adaptations to the network management and structure. Policy makers therefore implemented some changes to the regulatory framework allowing and encouraging network operators to make such adaptations. The changes also improved the incentives for network expansion, increased acceptance and streamlined administrative processes. Also, a strong consensus emerged among policy makers and industry that network expansion was needed at the transmission and distribution level, and that distribution networks needed to become more intelligent. However, the actual expansion of networks was delayed, given some strong resistance of locally affected populations and some Federal States to proposed network routes. While solutions were sought and identified through elaborated stakeholder engagement processes these often implied delays in construction and higher costs due to the increased use of underground cables. However, rather than implementing further changes to network regulation the government reacted to these delays by implementing policy changes which were meant to slow down the speed of the expansion of renewable energies (see below), thereby alleviating some pressures on the network regime.

Emerging new regimes and niches:

In 2016 and after long and difficult negotiations Merkel's Grand Coalition government introduced a paradigm change to the Renewable Energy Sources Act (EEG) – changing its main incentive component from feed-in-tariffs to auctions. The idea behind these auctions was to reduce the costs of the further expansion of renewable energies by allowing for competitive bidding. The government also hoped to be better able to control the rate of expansion of renewable energies to keep each technology's and overall renewables' growth within the foreseen expansion corridor (40-45% in 2025, and 55-60% in 2035). These changes were contested by many new entrants, such as cooperatives and renewable energy industry associations, but also by leading economists and the media as being short-sighted and unduly benefiting large incumbents. As a consequence, the government allowed some exemptions for small-scale investors and cooperatives, but the atmosphere in the renewables advocacy coalition towards the government seriously cooled down, and many players lost their belief in the government being a strong promoter of the *Energiewende*. However, the government defended the implemented policy change by stating that the nurturing phase was over, and that it was time for renewables to grow up. Later results initially supported these claims, as the early auctions indeed resulted in surprisingly low tariffs.

- *Onshore wind* experienced massive additional investments prior to the adoption of EEG 2016, because the industry and cooperatives wanted to benefit from the old feed-in tariff system and because onshore wind so far kept its role as cheapest renewable energy technology. However, this boom in onshore wind led to investments exceeding the foreseen expansion corridor. While the industry with its green advocacy coalition argued for an increase of these corridors, which was also supported by calculations of leading experts in light of reaching Germany's 2050 targets, the government eventually made some upwards adjustments in their yearly allowance for onshore wind auctions to address opposition from federal states: it was agreed that from 2017-19 the government would auction off 2.800 MW annually, and thereafter 2.900 MW. However, the government set these as gross figures, thereby incorporating the upcoming repowering of old wind farms. These policy changes led to reduced activities by cooperatives and farmers which had been the backbone of the *Energiewende's* take off phase – despite simplifications foreseen for them, and initial domination in first auction rounds. Yet, as many of them could not afford the risks associated with the tendering process – despite simplifications –, in later rounds the majority of the winning bids came from specialized wind energy project developers and the renewable subsidiaries of incumbents. This change in investors initiated a decline in public acceptance for onshore wind in local communities, and a general dissatisfaction of citizens with the *Energiewende* policy of their government.
- In the negotiations for the reform of the EEG the *offshore wind* advocacy coalition managed to strike an attractive deal with the government, securing sufficient room for the continued expansion for offshore wind despite it being more expensive than onshore wind (namely 6,5GW until 2020, and 15 GW until 2030). This included a preferential change in the cost structure by decoupling site development costs, enabling a new low cost narrative. One reason for the strength of the offshore wind advocacy coalition may have been its contribution to the economic development of deprived coastal regions. Also, after the bottle neck of grid access for offshore wind had been largely resolved in the beginning of the period (Reichardt et al., 2016), a number of new parks went online in 2015 which performed very well, even exceeding expectations regarding load hours. This further contributed to incumbents fully embracing the technology as large-scale renewable energy technology which worked well with their capabilities and provided them with an attractive business model in a time of fundamental change (Richter, 2013b). Some policy makers also argued that by allowing incumbents to invest in offshore wind, this could help their survival as they were increasingly seen as critical and essential to keep the lights on in the medium-term. Strategic bids of two offshore wind pioneers in the first offshore auction further strengthened the position of offshore wind, as three of the four winning bids did not ask for public support.

- *Solar PV* experienced a reduction of its momentum which had started with large cutbacks in the level of feed-in tariffs (Grau, 2014) and the introduction of a correcting mechanisms (a “breathing cap”) to avoid unsolicited future growth. However, the resulting industry consolidation and losses in PV jobs as well as rising levels of the EEG levy (mainly paid by households and SME) undermined previously high levels of legitimacy. By 2015 investments in decentralized small-scale rooftop PV systems had collapsed dramatically, although calculations had shown that if largely used for self-consumption the technology would be financially attractive even without feed-in tariffs. In 2016, the government decided to roll out auctioning more widely after having made positive experiences with a pilot schemes for large-scale PV auctions, leading to lower costs (but also lower investor diversity). Acknowledging the benefits of a diversified technology portfolio, the government foresaw yearly auctions of 600MW. However, given public opposition to the proposed policy change small-scale PV plants (up to 750kW) continued to receive feed-in tariffs, albeit reduced ones, in an attempt to accommodate concerns of private investors and environmental NGOs. Yet, due to lacking financial attractiveness private households became increasingly hesitant to invest in rooftop PV, so that further capacity additions were mainly driven by free-field PV.
- The government continued to limit the further expansion of *bioenergy* for a variety of reasons: high costs combined with limited cost reduction potential, wider sustainability concerns and competing uses of biomass for the decarbonisation of other sectors. Given its technological advantage of being a non-fluctuating renewable energy source the industry actively lobbied for a more supportive policy mix, but with very limited success: the amended EEG foresaw yearly auctions of 150MW in 2017-19 and 200MW in 2020-2022, which implied hardly any further growth. Ultimately, the actual use of existing bio-energy plants was very low, so that biomass could be put to more productive uses. By the end of phase 1, its consideration for electricity generation was sidelined.

Overall, by the end of 2019 all but 6 nuclear power had been phased-out. The expansion path foreseen for renewable energies was only marginally exceeded, the least efficient lignite and coal plants had been shut down, offshore wind had started to kick off, and auctions became the new normal in determining the level of support, thereby twisting the discourse more towards cost-effectiveness. In fact, by the end of the period cost-efficiency had been established as a prime motive within Germany’s renewables policy. However, the resulting policy changes (auctions within narrow expansion corridors) had started to exclude new entrant, as investors into renewable energies. As a result, new entrants became increasingly frustrated and citizens appeared to become somewhat disconnected from the *Energiewende*, seeing it increasingly as technological

transition project managed by the big guys, with many households eventually becoming less enthusiastic about the idea of producing and consuming their own energy. Finally, a major concern was that Germany's 2020 climate targets – despite several additional measures across various sectors and the expensive lignite phase-out deal – could not fully be met, which was seen by many as a wake-up call for a more ambitious climate policy mix.

7.2 Phase 2 (2020-2034): offshore wind rules as public acceptance for onshore wind declines, PV goes abroad CCS moves forward

With the embarrassing failure to meet the 2020 climate targets (-40% GHG emissions by 2020) the government initially only confirmed its climate policy target of a reduction of greenhouse gas emissions by 80% by 2050 under the pledge-and-review process agreed in Paris. However, given the negative image and press coverage it was keen on rebuilding its credibility as climate champion and therefore started to strongly lobby for strengthening the carbon price signal from the EU ETS. However, resistance from coal-based EU Member States remained high, as well as opposition from Germany's energy-intensive industries. Therefore, Germany joined "the EU low carbon club" of a handful of progressive EU Member States promoting stringent market-based climate policies, who agreed to buy out and surrender a certain number of EUAs between 2025 and 2035, a decision which was applauded by green groups and parts of industry, but heavily contested by others. Yet, over time this commitment of public money was able to fix the carbon price across Europe and was celebrated as major success. This previously unthinkable detour to fix European climate policy inertia established Germany as once again committed player in the decarbonisation of the economy, together with some other developments in niches and regimes, and helped strengthen the outcomes from international climate policy negotiations after 2025.

'New' renewables regimes and niches

In the beginning of phase 2 the auctioning scheme (adopted in 2016) started to bring in some decent cost reductions for *onshore wind*.. Given the cost-pressures and investment risks introduced by the auctioning scheme the winning bids tended towards large wind parks by large investors and increasingly fewer community energy projects which focused on repowering old sites. However, the winning large project developers and incumbents faced increasing public resistance from local communities. Leading to lengthy and challenging

stakeholder consultations, which often increased the implementation costs beyond the auctioning price. As a consequence by the beginning of the second phase these initiatives had significantly died down and investors started to heavily lobby for the opportunity to invest abroad. In response to these concerns and following its cost minimization principle increased the speed of their ongoing negotiations with neighbouring countries to set up a supranational auctioning scheme, but due to initial resistance fulfilling Germany's renewable targets abroad it was not until 2025 when implementation problems had increased that the voluntary auctioning scheme for onshore wind was piloted with its neighbouring countries Denmark and the Netherlands to contain local protest. This led to a rapid shift of the onshore wind investments of the internationally positioned incumbents to other countries, while leaving the repowering business to smaller players. Due to its success in reducing renewable expansion costs country membership grew, including the joining of the UK in 2028. As a result of these developments, onshore wind capacities in Germany declined, but lobbying for policy changes from the weakened new entrants' advocacy coalition remained unanswered, as the policy climate had by now fully swung to working with market-based instruments. .

A second response from incumbents resulting from the difficulties of implementing onshore wind was that they focused their attention on *offshore wind* whose role out proceeded with a high success rate. The expansion target of 15 GW by 2025 was easily met and load factors continued to be high, thereby leading to a significant increase in offshore wind's share in electricity generation. The positive impact on the economic development of previously deprived coastal regions was saluted by local policy makers, industry associations and unions. Importantly, costs had come down much faster and stronger than originally expected, based on technological learning, expected rises in electricity prices, reduced finance costs, state funding of site development costs and strategic bidding of incumbents. Based on these developments the major investors had established a positive image around offshore wind, e.g. by advertisement, social media and tourism offers. Therefore, the proposal of a powerful advocacy coalition of incumbents, regional and local policy makers, industry associations, and unions to extend the offshore wind expansion target for 2035 to 25 GW met little resistance. Hence, in 2024 the German government announced the issuance of another 10 GW of auctions up to 2035, which received positive media coverage portraying offshore wind as the green success story. And indeed, the industry kept its promises by quadrupling capacities between 2020 and 2030 alone,

reaching the 2035 target already ahead of time which further confirmed its positive image as green technology that delivers.

After the initially large interest in freefield *solar PV* public opposition increased towards large investors coming in without the community financially benefitting from their installations. At the same time, Southern countries had demonstrated their low costs due to higher sunshine hours and cheaper labour which left large-scale investors in solar PV eye investments within these countries, rather than forging deals with local communities. Therefore, incumbents advocated for a supranational auctioning scheme, mainly by arguing for a further reduction of the costs for renewable expansion and pointing to positive experiences made in the first years of the onshore wind supranational auctioning pilot scheme. The protests of local activists were largely unheard as the rising electricity prices and much better solar conditions in the South provided a strong economic rationale. Therefore, in 2030 the German government joined the “Solar South Scheme” as founding member, thereby introducing cross-country auctions. This agreement, breathing the spirit of cost-reductions led to massive solar PV deployment in Southern member countries such as Spain, Italy and Greece. Part of this deal was the abolishment of any remaining feed-in tariffs for small-scale rooftop PV as well as the requirement to pay full grid costs and taxes, including for self-consumed electricity. This led to a further decrease in private investment. Also, when reaching their twenty year life time many of the installed rooftop PV capacities were decommissioned through a novel cheap solar business model of incumbents, with only a few actors bothering to invest into repowering. Trying to make sense of these developments some argued that citizens had given up the idea of generating their own electricity and got used to the idea of large investors finishing the energy transition for them, while others saw this as silent protest of citizens who felt disempowered in influencing the path of the *Energiewende*.

As for *bioenergy*, there were rarely any changes in capacity nor generation. The little investment that took place was the replacement of existing plants, but much more was also not possible in the realm of the foreseen expansion corridor. However, biomass co-firing was experimented with in the two CCS+lignite demonstration regions which took shape towards the end of the period.

‘Old’ regimes

The further close down of the last remaining *nuclear* power plants occurred according to plan, with Grohnde, Brokdorf and Gundremmingen C ceasing opera-

tion in 2021 and Isar 2, Neckarwestheim 2, and Emsland in 2022. However, the determination of a final nuclear waste storage site remained heavily contested, despite progress made in analyzing potential locations.

Yet, given the high international and national pressure to reduce GHG emissions much of the government's attention focused on turning CCS into a viable option. Having thrown in a significant budget for the two *CCS+lignite* model regions, the government was able to nominate two volunteers in 2020. For these model regions, the government established a cross-departmental CCS task force which – in close cooperation with the affected regions and academics – designed a participatory visioning process. Over the period of three years this process brought together all affected parties to create a shared vision of the clean energy future of both regions which addressed not only lignite with CCS but also all other areas of economic, social and environmental development. After initial hesitance citizens, companies and universities got increasingly enthusiastic about the project, particularly when in the subsequent roadmapping exercise concrete steps for achieving the vision were jointly identified. In 2025, both regions proudly presented their visions and roadmaps to the chancellor. While the media and much of the general population were reacting very reserved to the announced plans and criticized the attached enormous budget, the regions and the task force themselves were highly motivated and very committed to implement them.

After the successful visioning phase the task force took on the job of a monitoring, evaluation and learning agency which facilitated exchanges between the regions, provided transparency through regular progress updates. When the carbon price started to steadily increase as a consequence of the EUA buy-out by the 'EU low-carbon club' and reached 25 Euros in 2027, lignite plant operators announced that they would accelerate their plans to construct the two CCS demonstration plants. Construction started in 2029 and 2030, respectively. Their opening ceremonies in 2034 and 2035, received a lot of media attention, reporting both about the economic attractiveness of the investment due to carbon prices having reached 33 Euros, but also about the associated transition of the model regions within the past ten years – including the relocation of CCS technology providers to the model regions, the green transformation of the region's universities with new interdisciplinary chairs and study programs, a green entrepreneurial boom, the reduction of unemployment rates and rejuvenation of the population due to attractive job offers, the improvement of key sustainability indicators, and multiple green initiatives proceeding with unusually high levels of citizen engagement. Given its large success, several other regions' contacted

the model regions and the task force to learn about its transition management process and started to lobby for a second round of CCS model regions. In addition, several parties suggested that a similar approach should be applied to the most promising nuclear waste location, and increasing revenues from EU ETS auctions were identified as potential source of funding.

As for *gas*, the situation remained largely unchanged – the implemented capacity mechanism ensured that the existing gas-fired power plants remained online as back-up capacity, but were increasingly less used as the expansion of the grid and interconnectors with neighbouring countries were largely able to balance demand and supply.

The ever increasing shares of intermittent renewables, which by 2035 covered exactly half of the electricity generated in Germany (with growth occurring for offshore wind only), necessitated an accelerated rate of change in the conservative *electricity network regime*. To facilitate the implementation of investment plans, in 2025 the government initiated an independent grid stakeholder consultation task force to negotiate the best possible routes for the construction of new transmission lines. However, the task force was making little progress given its limited power in making recommendations with budget implications, such as the construction of underground cabling, landscaping or compensatory measures for affected communities. Therefore, in 2027 the government equipped the task force with a significant budget – financed through the proceeds of EUA auctions which increased between 20125-2035 due to the intervention by the ‘EU low carbon club’ - thereby granting it greater flexibility and power in stakeholder consultations.

The government also made the further expansion of the offshore wind grid a high priority. For this, in 2026 it implemented several regulatory changes which provided a clear incentive structure for delivering grid expansion in time and respecting social and environmental criteria – but also penalties for delays and underperformance in terms of sustainability criteria. When evaluating the impact of these changes in 2030, an expert commission came to the conclusion that a similar incentive structure should be rolled out for the mainland grids as well. In 2031 this was taken up by a yearlong consultation process which resulted in the adoption of a revamped energy system law (EnWG) in 2032. This radical amendment led to the proper incentives for a faster low-carbon reorientation of the network regime. Among others, it included the introduction of ‘time-of-use tariffs’ to allow for dynamic pricing of electricity, which due to distributional and efficiency concerns was first rolled out for large users only.

Furthermore, in 2020 Germany became a net importer of cheap electricity and intensified its negotiation with neighbouring countries for the construction of additional interconnectors to create an emerging European super-grid. This Europeanization was seen by some as precondition for the supranational auctioning schemes for onshore wind (2025) and solar PV (2030). In 2023 an agreement was struck by several European countries to jointly finance these essential infrastructures and one of the first great successes was the opening of a new interconnector between the UK and continental Europe in 2030, which lay the foundation for an increased utilization of the vast onshore wind potential in the UK and had a dampening effect on electricity prices.

Finally, based on the experience gained from the ten pilot regions with white certificate schemes and in the spirit of increased use of market-based instruments, in 2026 the government managed to roll-out this white certificate scheme on a national level, taking on board some modifications based on the lessons learned from the pilot schemes. This scheme initiated some efficiency gains of large users, but the associated reductions in electricity demand were largely eaten up by the rebound effect and new users.

In conclusion, in the second phase offshore wind emerged as new regime, while onshore wind and solar PV experienced stagnation and even negative momentum, with much of the investment eventually being channelled to locations abroad with higher resource endowments. Efforts to integrate the increasing share of intermittent renewables were intensified by changing the rules of the game for the network regime (e.g. EnWG amendment). The CCS model regions were successful in creating local public acceptance for CCS and lignite by pursuing a holistic regional development strategy, while unabated coal and lignite were phased out according to plan. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. auction pilots onshore wind, EUA buy-out, interconnectors), a broader use of market-based policies and the overriding dominance of cost minimization (e.g. renewable auctions EU ETS, national white certificate scheme, dynamic pricing). In addition, the need for active stakeholder engagement through explicit government bodies with budgetary independence was fully recognized (e.g. grid stakeholder consultation task force, cross-departmental CCS task force). Together, these changes put Germany back on track for meeting its climate targets and helped re-establish its role as climate pioneer. However, with these changes in policy style civil society became further disconnected from the Energiewende and started to see this less as a societal project but something jointly managed by their government and industry players. Yet, since shares in renew-

ables continued to rise according to plan (mainly offshore wind in Germany, and solar PV and onshore wind abroad), this discontent with the pursued pathway was largely muted. Over time the general public started to accept their more passive role in the further expansion of renewable energies and many local activists shifted their attention to other decarbonisation priorities, particularly in decarbonising transport and heat.

7.3 Phase 3 (2035-2050): Germany within a European low-carbon flexible electricity system

In the beginning of the third phase changes continued along the line of the path set out in phase 2. Initially most investments into off- and onshore wind were mainly concerned with repowering existing sites. Smart grids and smart pricing had made significant advances, making the electricity system more flexible. Three major changes occurred in the first five years:

- (1) With the introduction of the supranational auctioning scheme for solar PV no more new investments went into Germany. Therefore, with many plants reaching the end of their lifetime, solar PV capacities and hence national PV generation shrank by a factor of 6 between 2030 and 2040. However, there was not a large outcry as incumbents had shown that they could deliver cheap electricity from renewables without the hassles of personal involvement and as private investors were preoccupied with electric vehicles which by this period were fully embraced and diffused massively.
- (2) Due to the globally necessity for negative emissions and the relatively successful introduction of BECCS power plants in the CCS+lignite model regions some new investments in biomass and co-firing plants were made.
- (3) By 2040, the nuclear storage commission had identified three suitable regions for the permanent storage of Germany's radioactive waste. As none of the regions was volunteering the government promised the provision of massive funds as compensation for hosting the storage facility, which ultimately led to the poorest of the three regions to strike a very attractive deal. A visioning and roadmap process was set up and a massive budget was set aside to turn the vision into reality, which eventually enabled the closure of this lengthy chapter of Germany's nuclear energy policy.

After 2040 electricity demand increased significantly due to the diffusion of electric vehicles kicking in, but also due to other new users, such as heat pumps. Also, carbon prices reached levels of above 40 Euros / t CO_{2e}, thereby providing incentives for CCS but also for new gas plants. Finally, international coal prices dropped quite significantly due to decreased demand on the world market, following developments around the world to phase out coal. As a conse-

quence of these developments, three main changes could be observed after 2040:

- (1) The 2050 expansion target for *offshore wind* was increased to 42 GW, leading to many new parks being built by incumbents between 2040 and 2050. However, given the relatively sudden spike in electricity consumption between 2040 and 2050, the usage of *coal* fired power plants was extended beyond 2050. This implied that by 2050 Germany was still generating 11% of its electricity based on coal (mostly in CHP and BECCS co-firing power plants), and still had one last unabated lignite power plant running.
- (2) For the first time in over 25 years the construction of new gas plants became a lucrative investment, based on the prospects of steadily increasing carbon prices, and the continued existence of a capacity mechanism. Actual generation, however, increased only slightly, and remained at a very low level since most balancing continued to occur through the import and export of electricity (with Germany remaining a net importer of electricity, covering a share of 17% of its electricity demand).
- (3) New CCS-lignite power plants with a capacity of 13 GW were built on the existing lignite sites. With extensive BECCS co-firing, these plants effectively turned into carbon sinks, helping to prove the large-scale feasibility of the concept of negative emissions. These CCS related investments were embedded in similar stakeholder visioning and roadmapping processes as in the original model regions, thereby securing local public acceptance for carbon storage. Also, Germany's success story received significant attention in other countries and started to be exported abroad. With CCS gaining momentum internationally, Germany benefited from increased exports of its CCS technological expertise, which was hailed as big success of the pilot regions and their industrial clusters.

In conclusion, phase 3 was characterized by the continued expansion of offshore wind and CCS+lignite (and export of these technologies), an increase in bioenergy and gas generation capacities as back-up of the system, and an almost complete discontinuation of solar PV located in Germany. Due to the sudden increase in electricity demand the coal phase-out was extended and the flexibility of demand increased further. At the end of phase 3, electricity generation capacities were fairly large-scale and mainly owned by a handful of incumbents, with citizens largely content with a fairly passive role in the energy transition project.

8 Socio-technical scenario for pathway B for the German electricity system: Solar PV and onshore wind with flexible gas back up for the rest of Europe

8.1 Phase 1 (2015-2019): similar developments as under pathway A, apart from inclusive deliberation process and resulting policy mix initiatives

The starting conditions and main developments for pathway B resemble those already described in pathway A, including Germany's climate and energy policy targets, the nuclear-phase out, the changes in the EEG as well as the successful expansion of renewable energies but problems in meeting the 2020 climate target. Also, as was the case in pathway A the policy mix led to major changes in existing regimes (nuclear, coal, lignite, gas, network) and a further upscaling of niche-innovations (particularly onshore wind and solar PV), i.e. differences are not yet becoming visible in terms of deployment. However, the desired speed of the Energiewende became one of the topics debated in the run up to the 2017 elections, with those parties opting for a faster expansion casting in additional votes. As one of the first responses the new government started to lobby much stronger on a European level for a clear carbon signal arising from the EU ETS, however with limited success. In addition, the newly elected government initiated a thorough policy evaluation which not only looked at costs but also included ownership structure, public acceptance and other sectors. Among others, evaluation results showed that experience with auctions was mixed: on the one hand, costs had gone down, but on the other hand winning bids had experienced implementation difficulties. Eager to counter these concerns, the government enacted a large consultation process on the revision of the EEG due in 2019 which, however, turned into a larger visioning process for the desired shape of the decarbonized future electricity system which challenged the cost-effectiveness discourse and denounced CCS. Also, the public discourse towards large incumbents became very unfavourable for continuing to exploiting their coal-fired power plants, arguing that as a penalty they should no longer be subsidized for their offshore wind activities.

After long and difficult political and societal debates which the Chancellery had channelled into a deliberate vision building process, in November 2019 right before the next COP it was decided that Germany would step up its efforts to address climate change and for its electricity supply focus on onshore wind and

solar PV. Concrete first steps of its proclaimed new entrant friendly policy style included: (1) the EEG would rejuvenate feed-in tariffs for small-scale projects of households, farmers and other small investors; (2) Germany would forge a supranational auctioning scheme for offshore wind (3) the white certificate scheme would be rolled out on a national level; and (4) an economy-wide carbon tax of initially 20 Euros/tCO₂ would be introduced whose proceeds were to be split in equal parts into (i) funding local experimentation with behavioral change regarding a range of activities, including in areas of reducing electricity consumption, changing mobility patterns (e.g. higher bike use), and adjusting nutritional habits (e.g. Veggie-Thursdays), (ii) supporting radical low-carbon innovation in industry, (iii) retiring EUA in an effort to increase the carbon price signal from the EU ETS, and (iv) financing the structural change in two model regions willing to phase-out lignite. These changes were generally applauded by citizens, environmental NGOs, renewable energy and energy efficiency representatives, and COP25 participants. In contrast, incumbents were disillusioned that their lobbying activities had failed to produce better results, and tried to make sense of the implications of these policy changes.

Nevertheless, Germany would miss its 2020 climate targets, and the impact of the proposed policy solutions would only become visible in official statistics in later periods. Yet, these announcements send strong signals across industry, society, finance and abroad that the German governments was seriously re-committed to the decarbonisation of the economy as a top level priority, and prepared to implement novel and previously unthinkable solutions which made Germans look optimistically into their low-carbon future. With hindsight, many managers later said that it was this unexpected sign of a strong political will to move forward in the fight against climate change which cemented their full-fledged strategic reorientations towards a carbon constrained world.

8.2 Phase 2 (2020-2034): clear carbon price signal, electricity demand reductions, repowering of wind and PV, termination of least efficient conventional plants, and lignite phase-out model regions

The second phase marked the implementation of the changes announced in 2019 to get back on track with Germany's climate targets. After an EU wide solution failed Germany initiated a club of progressive EU Member States which were equally frustrated in the political deadlock keeping EU ETS carbon price down. Just before COP26 in 2020 this 'EU low carbon club' announced its

pledge to buy out and surrender EUAs until the EU allowance price had reached 20 €/t CO₂ (which ultimately took until 2027). Over time this commitment reduced the huge surplus of EUAs which had accumulated over the first two trading phases of the EU ETS, thereby strengthening the carbon price signal across Europe, including in those MS which had resisted the strengthening of the scheme. However, to send out a clearer carbon price signal, Germany was keen on implementing an economy-wide carbon tax of 20 €/t CO₂, but faced significant opposition from lignite dependent regions, energy-intensive industries and others on such a national move. However, at the closing ceremony of the last nuclear power plant the government proudly announced its launch for 2023. This further intensified the search process for low-carbon solutions, with many of the more ambitious initiatives ending up applying for 'radical innovation grants' which the government had introduced alongside the introduction of the carbon tax. To facilitate knowledge exchange and learning across actors the government also launched a central 'Climate innovation platform' which provided information, held various conferences and workshops, and supported other networking activities.

'New' renewables regimes and niches

The second period was marked by a stabilization of most 'new' renewable regimes and niches, with solar PV and bioenergy seeing a slight expansion, offshore wind remaining stable at 2020 levels, and onshore wind also largely stable as much activity focused on repowering rather than constructing plants at new sites.

- While the EEG had returned to feed-in tariffs for small investors (but stuck to auctions for large investors), there was no immediate boom in *onshore wind*. One reason for this reluctance was that the internationally positioned incumbents were fed up with losing bids to cooperatives and dealing with public opposition, and therefore had decided to reorient their activities to other countries. Another reason was that many new entrants focused on the repowering of turbines at existing locations. Others decommissioned their plants and sought out other investment options. As a result of these rather slow developments, onshore wind capacities declined slightly, but given the technical improvements in the newest generation of wind turbines overall electricity generation remained fairly stable.
- In contrast, *offshore wind* came to a temporary halt since no more national auctions were being put forward, as negotiations had started for an European auctioning scheme. Large incumbents responded by forging strategic alliances with partners in EU Member States with high wind conditions, lower water depths and shorter distances from the shore. When in 2022 the first round of

the European auctioning scheme for offshore wind was launched, German incumbents were well represented in the winning bids, but for cost reasons none of these were located in Germany. Yet, with their good references German manufacturers, construction firms and service providers managed to tap into the newly opened European market and played a leading role. Towards the end of the second phase, a small number of German repowering projects won European bids, thereby keeping overall offshore wind capacities at the 6.5 GW which had been reached in 2020. This did not mean, however, that the government had abandoned their expansion target of 15GW by 2025, but rather that these capacities were built up at more profitable locations, thereby contributing to turning Germany into a net importer of electricity.

- Whereas much hope of the previous government had been put on free field *solar PV* due to its lower costs, by 2020 little interest had remained to invest in such free field PV plants. On the one hand, large incumbents were eyeing more profitable investment opportunities in Southern countries with higher sunshine hours and less public resistance. On the other hand, in the wake of the creative rethinking of the future energy system a societal consensus emerged for rooftop PV or integrated building solutions as part of smart home concepts. Therefore, start ups, housing cooperatives and others applied for funding from the experimentation scheme to test creative new solutions and smart prosuming. As a result, in the beginning of the period capacity additions remained small, but the search for new ideas for solar PV and integrated solutions boomed, with much learning taking place from successes and failures.

New integrative products and services were brought to the market starting in 2030. Initially, entrepreneurs mainly worked with those who owned rooftop solar PV which came to the end of its lifetime. Many of these solar PV owners signed on to contracts with specialized project developers or local municipalities who offered various business models which combined the repowering of solar PV plants with the installation of a smart meter, membership in user groups, and sometimes even integrated storage solutions. This created a significant market dynamic. For example, the development of novel “Smart Apps” boomed, and appliance manufactures started to jump onto the trend of smart electricity solutions. In addition to private households also hotels, schools, local businesses and other companies were equally eager to not only replace their solar PV rooftop solution, but to purchase an integrated solution for which EEG funding became available in 2030.

- Finally, bioenergy saw slight increases in generation capacities which was driven by carbon prices reaching levels of 20 Euros and more, but growth

was limited due to sustainability concerns and the ever increasing interest in alternative uses, including the emergence of biomaterials in the chemical industry, which drove up biomass prices.

‘Old’ regimes

In this period Germany was most occupied with supporting the structural change and associated social challenges resulting from the much needed closure of its lignite and coal fired power plants.

- While the carbon tax introduced in 2023 and the recovering EU ETS carbon price started to push the least efficient *coal and lignite* fired power plants out of the market, these policy changes had only been made possible by the government promising to provide financial support for the affected regions, particularly those with lignite deposits. The idea behind this was to govern the structural change associated with the gradual closure of the lignite industry, thereby alleviating concerns regarding the loss of jobs and regional income. Therefore, in 2020 the government issued a call for applications to become a “green transformation region” willing to commit to a lignite phase-out plan and redevelopment of the region. One year later the government selected two transformation regions for which it established a cross-departmental transformation task force operating similarly as the ‘CCS+lignite’ task force under Pathway A. That is, among others, it implemented a participatory visioning process which by 2024 produced a joint vision and roadmap of the transformation of the regions which received much applause from politicians, environmental NGOs and even the media. There was also increasing international interest in the model regions which at the end of the period, i.e. after ten years, had already come a long way – with new interdisciplinary chairs and study programs, a green entrepreneurial boom, a rejuvenation of the population due to attractive clean tech and ICT jobs, a reduction of unemployment rates, the improvement of key sustainability indicators, and multiple other initiatives. However, with the ongoing phase-out of lignite and coal (largely due to rising EUA prices) the conventional business units of former incumbents faced severe financial difficulties but ran their remaining most-efficient coal plants with higher load hours thanks to declining global coal prices which partly compensated rising CO₂ prices. In 2030, the two operators of lignite fired power plants merged, but consolidation continued. As a consequence several other regions’ started to lobby for a second round of transformation regions.
- As for *gas*, the increase of EU ETS carbon prices and introduction of the carbon tax initially was not sufficient to stop the closure of gas fired power plants. Therefore, in an act to enable the survival of incumbents and in foresight of a future increase of electricity demand governments around Europe got together and designed a European capacity mechanism for gas fired

power plants. This mechanism was implemented in 2030 and ensured that the remaining capacities of gas-fired power plants remained online as back-up capacity and that companies started to invest into new capacity. German companies were among the fastest and most successful in building these new gas fired power plants, which was argued to be the case because of their desperate search for a new role in the electricity system of the future.

- Germany's *nuclear* phase-out continued to proceed as planned, with the final plant closures in 2022 (Isar 2, Neckarwestheim 2, Emsland) being highly celebrated across society. However, similar as in pathway A there was only slow progress in a nuclear storage site. In 2022, the commission charged with the task of coordinating the scientific screening of suitable locations could only report intermediary results of the progress made so far. However, by 2030 three suitable regions for the permanent storage of Germany's radioactive waste had been identified. In lack of volunteers the government borrowed the idea of the transformation regions and supported the deliberation of visions and roadmaps, and by the end of the period one of the region had started to dream big in light of the chance of 'winning' a fully budgeted regional transformation.

Given the reduction in fossil generation by 2035 the share of wind and solar PV had increased to approximately half of the electricity generated in Germany which necessitated a much greater rate of change in the conservative *electricity network regime* than witnessed before. As in pathway A the government therefore started to put much more pressure on network operators to increase the speed of the further expansion of long-distance transmission grids and interconnectors. In 2023 an independent grid stakeholder consultation task force was set up and in 2025 equipped with a significant budget to negotiate the best possible route for the construction of new transmission lines and support compensation measures for affected communities. This budget was financed through part of the proceeds of EUA auctions which started to increase significantly in the period between 2025 and 2035, resulting from the interventions of the EU low carbon club. In 2026, the government also implemented several regulatory changes with the adoption of a revamped energy system law (EnWG) up to address recent developments in digitization, technological innovation and sector integration. This EnWG 4.0 also enabled the formation of regional clusters for distribution grids and introduced 'time-of-use tariffs' to allow for dynamic pricing of electricity. Eagerly, several new entrants developed innovative projects which they tested out in the context of Germany's experimentation scheme. Some failed, but others were promising and were developed further. However, their time was yet to come in the third period.

Finally, Germany intensified its collaboration with neighbouring countries for the continued construction of interconnectors to create an emerging European super-grid. While up to 2019 Germany had been a net exporter of electricity, by 2020 it had turned into a net importer of electricity. However, promising radical innovations and integrated solutions were underway for future storage solutions, and a prospering smart energy industry had built up in Germany. However, it was clear that a European super-grid would also be needed, so Germany was actively pushing for an agreement to jointly finance these essential infrastructures which was eventually struck in 2024 among the “Climate Coalition”. One of the first great successes was when in 2029 a new interconnector between the UK and continental Europe was opened.

The perhaps most wide-reaching changes, however, occurred in the electricity *consumption regime*, which saw a remarkable reduction of electricity demand and flexibilisation of consumption patterns. These changes were mainly achieved by a combination of price incentives and a culture of open experimentation, which together ushered in an era of behavioural changes. The price incentives were largely originating from the national roll-out of a white certification scheme in 2021 whose design had benefited significantly from the experience gained from the ten pilot regions.

However, while substantial improvements in energy efficiency could be attributed to the former, the observed change in thinking about electricity demand was largely driven by the creative spirit introduced by the experimentation schemes. Funding for the first round of projects in 2020 was made available from the climate and energy innovation fund already, to cover the gap until carbon tax revenues came in. When it became clear that the government did not lose any time in implementing their announced plans and even put aside additional funding, this sparked a search for innovative ideas bubbling up from a variety of actors, including local communities, schools, universities, sport clubs, environmental NGOs, businesses and even public administrations. The combination of these two new policy instruments – together with an active and increasing usage of smart meters – led to absolute reductions in electricity demand, despite new users (e.g. ICT, electric vehicles) and increased consumption elsewhere (through the rebound effect). As a consequence of these initiatives and other novel policy instruments, over the period from 2020 to 2035 Germany’s electricity consumption and CO₂ emissions decreased significantly.

Overall, the whole period was marked by a blossoming of decarbonization activities across sectors and actors at a level previously unthinkable. It seemed like

an increasing number of citizen and businesses wanted to be on board. Industry associations and social media became a key means in distributing knowledge about the next cool thing being done to reduce CO₂ emissions, reduce energy consumption or change mobility patterns. The topic was even picked up in soap-operas, movies, and festivals. Also, sport and movie stars were starting their own initiatives or were recruited for serving as glamorous spokesperson of existing or new climate initiatives. This led to tabloids starting to report about the many initiatives being developed and implemented, thereby leading to a further spreading of the new thinking about climate change action. Together, these activities resulted in a change in attitudes and way of thinking about decarbonising Germany which was described as “Let a thousand flowers bloom” and “We can do it!” atmosphere.

All this progress and enthusiasm made Germany confident to be able to reach its commitment under the Paris Agreement to reduce its greenhouse gas emissions by 80% in 2050. In order to motivate others to step up their aspirations, Germany put extra efforts into actively sharing its experiences with transitioning to a low carbon economy. When in 2028 Germany ceased to buy and retire EUAs from parts of its proceeds from the carbon tax, it announced at COP34 that it would earmark the freed-up carbon-tax revenues to fund low-carbon experimentation programs in interested developing countries. After several successful trials in a handful of countries these were included in the NDCs of several partnering countries. Also, by the end of phase 2, Germany, China, the US, India and other countries had all tightened up their commitments under the Paris pledge-and-review process, thereby bringing life to the Paris Agreement.

In conclusion, in the second phase Germany saw many actors getting enthusiastically involved in experiments aiming at novel ways of smart and clean electricity generation and use. At the same time, growth of offshore wind, onshore wind, bioenergy and solar PV more or less came to a halt, while conventional capacities were being reduced across the board. The two green transformation regions in former lignite-dependent areas witnessed great success in pursuing a holistic and inclusive regional development strategy. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. EUA buy-out, interconnectors), a strengthening of market-based policies (e.g. EU ETS, European auctioning for offshore wind, national roll out of a white certificate scheme), and a recognition of the need for active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental lignite model region task force), as well as new regulatory institutions (e.g. dynamic pricing,

European wide capacity mechanism for gas). Together, these changes enabled Germany to meet both its renewable and energy efficiency targets as well as its climate targets. Overall, Germany's climate actions caught plenty of international attention, particularly due to the country's success with lifestyle changes and electricity demand reductions, as well as its transformation regions.

8.3 Phase 3 (2035-2050): Doubling of onshore wind, solar PV and gas for the electricity-mobility revolution

The beginning of the third phase was marked by the take off of electric vehicles. After two decades of a reduction of electricity demand this wide diffusion implied a steady increase of electricity demand. These developments almost led to a doubling of onshore wind and solar PV capacities. As the diffusion of e-vehicles continued and new models came on the market, car manufactures linked up with project developers specialized in PV in order to provide buyers with their own low-carbon PV charging infrastructure. These combined deals became highly popular and by 2040 almost each electric car sold to a private household was purchased together with a freely-installed solar PV rooftop solution and smart charging interface. Similarly, car sharing companies and company car fleets started to cooperate with project developers to develop smart charging solutions connected to wind parks and solar PV on their premises, as well as integrated solutions in new builds.

As a response to these developments, the government tightened the stringency of the white certificate trading scheme and increased the carbon tax to 50€/tCO₂. In exchange, it earmarked half of its revenues to a newly established "Green Transformation Agency" which was charged with the task of providing assistance in participatory visioning and roadmapping processes of all regions affected by the ongoing energy transition and decarbonization of the economy. This had been a result of the successful work done by the lignite model region task force, and increasing calls by other regions for similar support in the structural change they are faced with through the breaking away of lignite and coal as foundation of their regional economy. The GTA was equipped with an independent status and financial flows arising from the carbon tax. Given the great interest in its demands, the Transformation Agency rapidly grew and opened regional subsidiaries and its budget was supplemented by part of the proceeds from the auction of EUAs.

Given the great increases in fluctuating renewables, flexible back-up capacity together with a further expansion of the European super grid was needed. The

former was incentivized by the previously negotiated European capacity mechanism but also benefited from a combined carbon price of over 80 €/tCO₂. Therefore, the spike in investment in *gas* fired electricity generation plants continued, with a significant share of the needed capacities being built in Germany, providing a new business model for the remaining incumbents. As a result, within fifteen years Germany had almost tripled its gas capacities and became the European hub for flexible back-up and balancing. Although this increased Germany's emissions, over the past decade carbon accounting had already shifted from a national perspective to a European one. However, as electricity demand was that high a small number of *coal* fired power plants remained online, as high carbon prices were partly compensated by low coal prices, much to the dismay of environmental NGOs. However, when more and more of the new gas plants came online after 2040 the full load hours of these remaining coal plants reduced significantly. Yet, despite the overall spike in generation capacity Germany remained a net importer of electricity from countries with sites with better wind and sunshine conditions, with the net import share reaching over 25% in 2050.

These developments went along with the further expansion and flexible utilization of smart grids. In addition, smart pricing which varied according to time of use made significant advances and became business as usual for industry and households. Also, households and industry continued their quest for identifying options to reduce electricity demand, which helped to somewhat contain the increasing electricity demand from electric vehicles. Taken together, these changes made the electricity system highly flexible in its response to intermittent demand. Finally, in 2045 the nuclear waste commission announced the location of Germany's permanent storage site after which a green transformation task force took on the redevelopment of the region and construction teams started the establishment of the storage site.

In conclusion, phase 3 was characterized by the doubling of capacities and generation from onshore wind, solar PV and gas. This was driven by the massive deployment of electric vehicles which increased electricity demand. At the end of phase 3, electricity generation capacities were largely small scale, and the ownership structure was diversified among citizens, cooperatives, project developers, industry and incumbents. Given Germany's role as flexible European back-up hub a full decarbonisation was only achieved with the new European nature of carbon accounting.

9 Discussion and concluding comments

9.1 Synopsis

In this paper, we have developed two socio-technical scenarios that explain in more detail how the decarbonisation of the electricity system as calculated by optimization models can actually be implemented and enacted through endogenous dynamics. The main emphasis in writing these fictional histories of the future was to develop plausible narratives of how the model results could be achieved through internal change rather than external drivers or shocks. In particular, we have explored how transformative policy mixes could contribute to overcoming major tensions between model outcomes and real-world developments through instigating endogenous changes in the German electricity system. This required an actor-based perspective and the utilization of insights arising from a socio-technical analysis of niches, regimes and landscape factors. By bridging modelling and MLP approaches we constructed two archetypes of socio-technical scenarios which would both reach 80% reduction in GHG emissions by 2050. The first scenario (pathway A) provides a socio-technical storyline which is dominated by large-scale low-carbon technologies, in particular offshore wind and CCS+lignite. Incumbent actors are the dominant actors, and the core logic is that governments change the policy mix and institutions to facilitate the low-carbon reorientation of large firms. These changes do, however, need to be underpinned by societal legitimacy and support coalitions. In contrast, the second scenario (pathway B) focuses on a wider set of changes across several system dimensions. New entrants play a large role in electricity generation based on the growth and stabilization of new regimes, in particular onshore wind and solar-PV, backed up by gas. In this scenario, wider shifts in cultural discourses and social legitimacy develop, which is encouraged by a more inclusive, experimental, new entrant friendly governance approach going beyond large firms and technologies. In both scenarios public acceptance is a crucial success factor for the decarbonisation of the German electricity system, because it affects the massive roll-out of onshore wind, phase-out of solar-PV, introduction of CCS, and grid enhancement.

9.2 Comparison of transformative policy mixes across pathways

From our development of two distinct socio-technical scenarios, we find a number of *similarities* for the required transformative policy mixes. First, in both

pathways policymakers need to address political struggles and conflict through creative and costly policy solutions. The prime example is how policy makers overcome resistance to increase the stringency of the EU ETS by forming a coalition with progressive EU MS EU (low carbon club). Another example is the transfer of funds to compensate losers and/or buy policy support for decarbonisation projects (e.g. budgets for model regions, such as in the model regions), and both pathways rely on increasing revenues from EUA auctions for funding these decarbonisation initiatives. Yet another strategy to address conflict is the introduction of new policy instruments in pilots, before rolling them out more widely (e.g. white certificate trading scheme). This implies an increased utilization of 'destruction instruments' and greater role for policy learning and adjustment regardless of the scenario. Second, both pathways make use of societal vision building and road-mapping processes in their model regions, with the only difference being that one includes CCS demonstration plants whereas the other does not. Third, both decarbonisation pathways foresee Europeanization of some of the elements of policy mixes (e.g. in terms of a European grid), but with some differences in actual technologies (e.g. European onshore wind and solar-PV schemes in pathway A, and European offshore wind schemes), a trend which is partly predetermined by the European nature of the model results. Finally, both pathways rely on changes in institutional arrangement and governance structures. A key example is the implementation of task forces, increased cooperation and enhanced stakeholder consultation to drive forward those changes which the government deems important (e.g. cross-departmental model region task force, independent grid stakeholder consultation task force). Another example is the radical redesign of the regulatory framework conditions for the electricity sector laid out in the Energy Economy Law (EnWG 4.0), introducing, for example, dynamic pricing.

The pathways also *differ* in a number of aspects. On the one hand, *pathway A* does not purposefully and instantly change towards an incumbent-friendly, large-scale solution-oriented trajectory, but rather drifts there over time. This needs to be understood in the context of the starting conditions in which Germany followed a 'new entrant friendly' trajectory similar to pathway B (Geels et al., 2016b). We argue that the lack of establishing early on a societal vision about desirable properties of the future energy system through deliberate anticipation provides an entry point for active agency of incumbents. Over time, incumbents are able to tilt the trajectory more towards offshore wind and CCS, which is supported by the implementation of 'regime stabilizing policies' and reorientation (or even termination) of green niche promoting ones (e.g. capacity

mechanism, abolishment of feed-in tariffs, Europeanization of renewable support schemes for onshore wind and solar-PV, extension of coal-phase out, increase of offshore wind targets). The policy mix thus gradually integrates elements of stabilization resulting from the regime trying to maintain itself, e.g. by excluding new actors and securing support for regime-improvement technologies, such as CCS.

On the other hand, *pathway B* starts with a broad societal vision building process towards the end of phase 1, based on which a policy roadmap is developed which consists of key building stones that enable a different trajectory. Besides this implicit use of deliberate anticipation from the start, two further key differences are apparent. First, in pathway B policy makers agree to establish a societal experimentation scheme which provides the seeds for a societal and business culture of trying, diversifying and empowering which harnesses creative solutions, facilitates broad participation, and allows for learning from failure. Second, policy makers show a greater commitment to decarbonising all sectors of the economy rather than the electricity sector first by introducing early on a national CO₂-tax which provides clear guidance for the direction of travel and simultaneously provides funds for the experimentation scheme.

We conclude that overcoming ‘transition challenges’ requires transformative policy mixes for sustainability transitions. While we have seen subtle differences in how these are shaped, in both pathways all five key aspects have played a role one way or another. Yet, it should be noted that multi-dimensional socio-technical change going beyond technological substitution requires much greater emphasis on societal experimentation and a more proactive role for anticipatory deliberation processes from the outset. In contrast, shifting gear from a new entrant friendly past trajectory to an incumbent dominated pathway requires active agency from incumbents and is associated with what we have called regime stabilizing instruments which defend core principles of the old regime (e.g. incumbents as actors, large scale solutions) while simultaneously fulfilling decarbonisation as additional success criteria.

9.3 Policy implications

There are several policy risks – mostly concerning political and social acceptance issues – which potentially threaten the realization of the decarbonization pathways. These include:

- *Political commitment to fixing weak carbon signal of EU ETS:* There is a risk that the German government will not take unilateral or bilateral action to ad-

dress the oversupply of EU allowances and thereby contribute to a strengthening of the CO₂ price. This risk could be addressed by Germany attempting to strike a European deal for reforming the EU ETS, or by using alternative measures, which, however, would likely lead to an increase in decarbonisation costs and less clearer carbon signals.

- *Political commitment to significantly improve energy efficiency:* While energy efficiency has been recently tried to be established as second pillar of the energy transition, there is a real risk that policy makers will not show the needed commitment to penalize electricity consumption in order to incentivize improvements in efficiency and reductions in electricity demand. There are currently no indications that Germany would change from a voluntary policy approach with the provision of financial support to a policy paradigm which pushes for radical improvements in energy efficiency rather than just incremental improvements.
- *Maintaining acceptance for massive role of wind:* while for offshore wind this risk is mainly associated with expected cost-reductions which might not materialize as well as concerns about incumbents becoming the main investors and beneficiaries of the Energiewende (Pathway A), for onshore wind the main risk is linked to increasing land-use, visibility and noise concerns at an ever greater roll-out of onshore wind parks. While in Pathway A it is mainly in the interest of the offshore wind advocacy coalition to reduce costs in order to expand its role in the German Energiewende, in Pathway B this risk is mitigated by stakeholders and communities benefiting from the construction of onshore wind parks, either directly through energy cooperatives or indirectly through new business models.
- *Grid access and expansion delays:* grid improvements and pan-European interconnectors might be made too late, which could limit the system's ability to deal with increasing amounts of intermittent renewables. To overcome this risk resulting from a conservative network regime the government is assumed to introduce major changes to the regulatory institutions governing the network regime, as well as negotiate European investments into the construction of a European smart grid.
- *Public acceptance for an Europeanization of renewables policy and decarbonisation targets:* The high reliance on import of renewable electricity implies a great dependence of the decarbonisation of Germany's electricity system from developments abroad, including policy commitment and social acceptance. While this might be ensured through the Europeanization of funding schemes for renewable electricity, by no mean it is clear that countries would agree to such a scheme and that German civil society would accept such a move of investing renewable abroad, as it would imply transferring public funds to other European Member States, with most of the associated co-benefits (such as local jobs) occurring there as well. Also, it is by no

means certain that there would be public acceptance for the German energy mix of 2050 not being fully decarbonized due to remaining levels of coal and – in pathway B – high levels of gas. These developments imply a change in thinking about where renewable and decarbonisation targets need to be met – at the nation state level or at the European level. Therefore, policy makers may want to start a debate on the desirability of a future electricity system which is decarbonized within each nation state or only at a European level, as well as a discussion of European vs national renewable targets, with the EU's 2030 target making a first step in that direction.

- *Energy security concerns:* Closely associated with the former policy risk another one concerns energy security concerns which may arise from an over-reliance on offshore wind in pathway A (arising from technological risk) and on gas in pathway B (arising from geopolitical risks). Both risks call for a more diversified portfolio, but the question arises again whether this needs to be accomplished on a national vs European level. In the latter case new institutional EU arrangements could address this risk.
- *Achievement of 2020 climate policy target:* Both scenarios suggest that it may be quite difficult for Germany to achieve its GHG emission reduction targets for 2020, mainly due to the lack of a clear policy phasing-out unabated coal and lignite as well as limited action in other sectors, including transport, buildings and agriculture. However, a failure to meet Germany's climate policy targets would declassify Germany's commitment to the decarbonisation of the economy and society, and would shed some light on the Energiewende. This implies an urgent need to step up policy commitment in decarbonising other sectors and addressing unabated coal and lignite.

In addition, both decarbonisation scenarios are very demanding and require major reorientations in the energy system and therefore necessitate strong political commitment and the prompt implementation of transformative policy mixes which guide and accelerate the low-carbon transition. For this, we want to stress four main points.

First, anticipatory deliberation processes to generate joint societal visions of the future energy system and their implementation into policy strategies should constitute a crucial part of any transformative policy mix to guide future policy making but also business and societal activities. As such, German policymakers are recommended to keep and further strengthen their participatory and inclusive policy making style.

Second, policy makers need to find novel ways to deal with conflicts and power struggles which are unavoidable in any transition process. This implies the need for coalition building, step-wise tightening and roll-out of policy instruments and

taking previously unthinkable steps to overcome resistance to change. Also, climate policy will need to move towards proactively governing structural change and regional development, for example when it comes to phasing out coal.

Third, existing instrument mixes need to be complemented in two ways: by paying greater attention to the destabilization of carbon-intensive activities and by establishing a culture of societal experimentation which stimulates the creative energy of individuals and organizations for identifying and testing low carbon solutions. This includes the provision of financial and other support, an acceptance of failure, and a greater emphasis on societal and policy learning. The latter incorporates close monitoring of policy effects, their evaluation and subsequent adjustments which is essential given the uncertainties and multiple challenges associated with the energy transition.

Finally, transformative policy mixes for sustainability transitions require changes in institutional arrangements and governance structures, such as independent and financially well-equipped cross-departmental task forces or transformation agencies, and low-carbon clubs of actors willing to accelerate the low-carbon transition.

9.4 Methodological reflections

Given the peculiarities and stylized nature of the model results, explaining the evolution of the electricity system in a plausible way presented a major challenge – for both pathways. For example, for Pathway A it was particularly challenging to explain the complete decommissioning of solar rooftop PV, which has become a common sight in Germany. It was also very difficult to write a history of the future which saw CCS happen despite major resistance in the population. Similar challenges arose for Pathway B, with one example being how to explain the stagnation of offshore wind, despite the current strength of its advocacy coalition. Equally challenging was to explain the changes in behaviour or the acceptance of as high levels of imported electricity as up to 25%.

However, this exercise has sharpened our analysis and interpretation of the plausibility of model results and inspired several ideas for a more realistic pathway which takes on board the insights from the MLP analysis conducted within the PATHWAYS project (and documented throughout D2.1 until D2.4). Therefore, while it may be an unusual exercise for the modelling community, we would like to recommend a similar approach in writing plausible, endogenously

driven histories of the future to heighten our insights in model results and allow for model modifications.

As a final disclaimer we would like to state that none of these scenarios should be interpreted as prediction of the future – rather, they should be read as thought experiment intended to stimulate a deeper and more critical engagement with model results. Ultimately, we expect such socio-technical scenarios to provide illuminating insights into long-term thinking about energy transitions which also allow the derivation of relevant implications for policy makers, researchers and other interested stakeholders.

9.5 Conclusion

This paper contributes to the literature in two ways: First, we combined the literatures on policy mixes for sustainability transitions and transformative innovation policy to derive five key aspects of transformative policy mixes for sustainability transitions. Second, we provide the first socio-technical scenario for the German electricity transition which bridges modelling with MLP analysis.

However, as a disclaimer we want to emphasize that our two pathways are stylized archetypes. One scenario is dominated by technological change only (pathway A), the other characterized by broader changes to the electricity regime (pathway B). Both are designed as extreme cases to facilitate the exploration of the usefulness of the methodological approach, as well as to sharpen insights on general requirements of transformative policy mixes. That is, neither scenario presents a pathway that we expect to materialize in its extreme form. We have also not been able to cover all intricate details of policy mixes and endogenous mechanisms driving socio-technical change, but focused on overcoming transition challenges. That is, none of these scenarios should be interpreted as predictions of the future – rather, they should be read as thought experiment intended to stimulate a deeper and more critical engagement with model results. Ultimately, we expect such socio-technical scenarios and thus the combination of quantitative model analysis with qualitative MLP analysis to provide illuminating insights into long-term thinking about energy transitions and an enhanced basis for policy recommendations.

We envisage that these limitations can be addressed by future research. In particular, as a next step we would recommend the development of more realistic pathways which build on societal visions for the energy system. Based on their model results, a promising way forward could be to use transformative foresight

methods to engage stakeholders in constructing the corresponding socio-technical scenarios.

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Authors' affiliations

Karoline S. Rogge

Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany
University of Sussex SPRU – Science Policy Research Unit, Brighton, UK

Benjamin Pfluger

Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany

Frank Geels

University of Manchester, Sustainable Consumption Institute (SCI), Manchester,
UK

Contact: Brigitte Mastel

Fraunhofer Institute for Systems
and Innovation Research (Fraunhofer ISI)
Breslauer Strasse 48
76139 Karlsruhe
Germany
Phone: +49 721 6809-221
Fax: +49 721 6891-52
E-Mail: brigitte.mastel@isi.fraunhofer.de
www.isi.fraunhofer.de

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