ARTICLE IN PRESS

Technological Forecasting & Social Change xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

# 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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ARTICLE INFO

*Keywords:*
Socio-technical scenarios
Transformative policy mix
German Energiewende
MLP
Energy system modelling
Transition pathways

ABSTRACT

Much research and policy advice for addressing climate change has focused on developing model-based scenarios to identify pathways towards achieving decarbonisation targets. The paper's first aim is to complement such model-based analysis with insights from socio-technical transition analysis to develop socio-technical storylines that show how low-carbon transitions can be implemented. Our second aim is to explore how policymakers could govern such transition processes through transformative policy mixes. 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 greenhouse gas emissions by 2050, but differ in terms of lead actors, depth and scope of change: the first pathway captures the substitution of technological components (pathway A), while the second aims at broader system transformation (pathway B). We find that multi-dimensional socio-technical change (pathway B) requires 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 agency from incumbents and is associated with regime stabilizing instruments defending the old regime while simultaneously fulfilling decarbonisation as additional success criteria.

## 1. Introduction

Policy makers around the world have agreed to jointly tackle the climate change challenge under the Paris Agreement, which aims at keeping the average temperature increase well below 2C (UN, 2015). This ambitious policy objective requires major reductions in greenhouse gas (GHG) emissions, with the electricity sector being one of the key contributors to current emissions and potential reductions.

Much research has focused on developing model-based scenarios to identify pathways towards achieving such decarbonisation targets (European Commission, 2011; Greenpeace, 2015; IEA, 2016). However, implementing policies to achieve these scenarios has proven to be a major challenge due to economic, political and social bottlenecks. To address this problem and improve the social realism of long-term explorations, scholars started developing socio-technical scenarios (STSc). The rationale for developing STSc was that model-based scenarios overprivilege 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). STSc therefore address the co-evolution of multiple dimensions (techno-economic and socio-political) and use an *endogenous enactment logic* that describes 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). The endogenous enactment logic thus forms a complementary way of thinking about how future transition pathways unfold.

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). We aim to contribute to this emerging research stream, which develops STSc by combining insights from between quantitative computer models and qualitative socio-technical transitions research (Geels et al., 2016a; Turnheim et al., 2015). We use the methodological procedure developed by Geels et al. (2018) to first identify 'transition bottlenecks'. These refer to tensions between model-generated *future* pathways that could lead to desired goals and *present* developments that are interpreted with the Multi-Level Perspective (MLP) which analyses how niche-innovations struggle against existing regimes in the context of

☆ Paper for special issue "Understanding transition pathways. Insights from bridging modelling and transition-science based studies", Technological Forecasting and Social Change.

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https://doi.org/10.1016/j.techfore.2018.04.002
Received 4 October 2017; Received in revised form 8 March 2018; Accepted 2 April 2018
0040-1625/ 

Please cite this article as: Rogge, K.S., Technological Forecasting & Social Change (2018), https://doi.org/10.1016/j.techfore.2018.04.002

gradually changing 'landscape' trends (Geels, 2002; Geels and Schot, 2007). We then develop *socio-technical storylines* that show how the bottlenecks could be overcome through social interactions, learning processes and coalitions, leading to the realisation of low-carbon transitions. Using the MLP, these socio-technical storylines are normative and model-oriented, i.e. they aim to develop endogenously enacted actor-based transition pathways for the quantitative model-based scenarios in line with the 2 °C target. We thus aim for a *socio-technical qualification of model-generated scenarios*. This approach helps shed light on problems with political feasibility and social acceptance that real-world transitions are currently encountering.

Our second, more specific, contribution is to show how transformative policy mixes can assist in overcoming transition bottlenecks associated with a fundamental transformation towards more sustainable modes of production and consumption. The rationale for such policy mixes for sustainability transitions lies in the existence of various market, structural and transformational system failures, as for example evidenced in the transition to low-carbon electricity systems (Markard et al., 2012; Rogge and Reichardt, 2016; Weber and Rohracher, 2012). To address the transformational challenges associated with such transition processes transformative innovation policy has been suggested as a third frame of innovation policy (Schot and Steinmueller, 2016). In this paper, we combine the literatures on policy mixes and on transformative innovation policy to derive key aspects of *transformative policy mixes* which arguably may be of value for developing socio-technical scenarios for achieving a decarbonised electricity system or other transitions towards sustainability. These include (i) greater attention paid to strategic long-term policy making providing clear direction for transitions processes, including through inclusive anticipatory deliberation; (ii) the utilization of instrument mixes which pay attention to the creation and destruction side of transition processes, including through a greater openness to societal experimentation; and (iii) the establishment of new or adjustment of existing institutional arrangements and governance structures to support transitions towards sustainability.

We take the example of the German *Energiewende* and focus on its electricity transition. While ambitious long-term climate targets are in place for 2050 (e.g. reduction of its greenhouse gas emissions by 80–95%)[1] and significant progress has already been made in increasing the contribution from renewable energy Germany is also facing major transition challenges, as evidenced by problems in meeting its greenhouse gas emission reduction target for 2020 (Geels et al., 2016b; Matthes, 2017; Quitzow et al., 2016; Strunz, 2014). For this research case we have applied the bridging methodology proposed by Geels et al. (2018) which enables us to develop storylines indicating how potential 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 also uses combined model results from an integrated assessment model (IMAGE) and an electricity system optimization model (Enertile). Based on this, we develop future transition pathways from a socio-technical perspective, and focus on how policy makers could govern such transition processes through transformative policy mixes.

The remainder of the paper is structured as follows. Section 1 derives key aspects of transformative policy mixes for sustainability transitions. This is followed by an introduction of the methodology in Section 3. Section 4 presents the model results, while Section 5 identifies the main transition challenges to be overcome. We then turn to describing two socio-technical scenarios in Sections 6 and 7 in which we focus on the role of transformative policy mixes for the endogenous logic of transition pathways. The paper ends with concluding remarks in Section 8.

## 2. Key aspects of transformative policy mixes for sustainability transitions

In recent years it has been increasingly acknowledged that sustainability transitions call for broader *policy mixes* to address various market and system failures (Rogge and Reichardt, 2016; Weber and Rohracher, 2012), particularly with regard to energy transitions (Rogge et al., 2017). In addition, *transformative innovation policy* has been suggested 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). While both literatures build on socio-technical transitions thinking, they have so far been only loosely related to each other. However, combining them more explicitly makes it possible to derive key aspects of *transformative policy mixes* which can be utilized for developing socio-technical scenarios for achieving a decarbonised energy system or other transitions to sustainability.

First, governing sustainability transitions requires addressing *directionality* as one of the transformational system failures identified by Weber and Rohracher (2012). In the policy mix literature it has been argued that a clear direction of search can be provided by the *policy strategy* with its policy objectives, often quantified in long-term targets, and principal plans for achieving them (Rogge and Reichardt, 2016). The formulation of such a strategy can 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 (Carayannis et al., 2016; Da Costa et al., 2008; Kunseler et al., 2015). Among others, 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).[2]

Second, transformative policy mixes for sustainability transitions need to combine different instruments addressing multiple market and system failures by fulfilling different purposes, such as technology push and demand pull (Costantini et al., 2015; Peters et al., 2012) but also systemic concerns (Smits and Kuhlmann, 2004; Wieczorek and Hekkert, 2012). For this, a combination of different types of instruments need to be orchestrated in synergetic *instrument mixes* consistent with long-term targets and well aligned across different policy fields and governance levels (Borrás and Edquist, 2013; Flanagan et al., 2011; OECD/IEA/NEA/ITF, 2015; Rogge and Reichardt, 2016). In addition, transformative policy mixes should pay attention to 'creative destruction' and societal experimentation.

Regarding the former it has been pointed out that policies should not only support green niches (Raven et al., 2016) but also target the destruction of the regime (Kivimaa and Kern, 2016). Such *destruction policies* include control policies (e.g. carbon pricing or regulatory

[1] In the following, in line with the PATHWAYS project we develop scenarios which meet the lower bound of Germany's decarbonisation target of 80 − 95% by 2050.

[2] Similarly, but at an innovation system level, Lindner et al. (2016) argue for self-reflection, bridging and integration as well as anticipation capacities to address directionality.

restrictions), 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). In addition, policies can also support the destruction side of transitions by enabling changes in the organisational and institutional practices of policy making processes (Kivimaa et al., 2017b). However, implementing such destabilization policies requires overcoming resistance from powerful vested interests and may thus be more difficult to be adopted than instruments promoting green niches, underlining that inconsistencies within transformative policy mixes are highly likely in times of transitions (Quitzow, 2015; Rogge and Reichardt, 2016).

Regarding the latter, *societal experimentation* can act as promising transformative policy instrument particularly in early phases of transitions (Berkhout et al., 2010; Kivimaa et al., 2017a; van den Bosch, 2010). Transition experiments differ from demonstration projects by taking a societal challenge as starting point (rather than a possible solution), by focusing 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, it 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 (Jacob et al., 2015; Schot and Steinmueller, 2016). This may require a different policy culture, but could enable deep and collective learning which may ultimately lead to changes in cognitive frames and assumptions (Frantzeskaki et al., 2012; Kemp et al., 2007; Schot and Geels, 2008). However, experimentation is no magic bullet but rather one additional policy instrument complementing traditional ones.

Third, the transformative innovation policy literature calls for establishing *new institutional arrangements and governance structures* tailored to achieving societal goals and including governments, market actors and civil society. 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 (Laes et al., 2014; Smith et al., 2005). 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). 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).

While we have discussed these key aspects of transformative policy mixes separately, we would like to stress that in reality they are closely interrelated. We take these key aspects and their interrelated nature into consideration when elaborating the role of transformative policy mixes for implementing the socio-technical storylines developed in this paper for the case of the low-carbon electricity transition in Germany.

## 3. Methodology

McDowall (2014) distinguishes three approaches to combining quantitative models with qualitative storylines: A first approach is qualitative (macro)-storylines which remain exogenous to computer models, but provide contextual inputs (e.g. with regard to demographic change, social and economic development, and broad technological developments). This approach informs the IPCC Special Report on Emission Scenarios (Nakićenović et al., 2000) and recent work on Shared Socioeconomic Pathways (O'Neill et al., 2017); 2). A second approach concerns the detailed quantification of narrative scenarios to ensure that they are technically feasible and consistent (Fortes et al., 2015). A third approach focuses on dialogue between models and qualitative approaches to compare and contrast insights, which leads to deeper, multi-faceted understanding of specific transition pathways (Foxon, 2013; McDowall, 2014). The development of our socio-technical scenarios (STSc) follows this third 'bridging' approach by developing endogenous storylines (i.e. generated by actors and social interactions) for model-generated scenarios, which suggest ways for overcoming transition bottlenecks. Our STSc use the Multi-Level Perspective to organize the storyline logic in terms of niche-innovations and associated actors struggling against existing regimes and incumbent actors (Geels, 2002; Geels and Schot, 2007).

We have followed the same methodological approach as described in detail in Geels et al. (2018) and applied to the UK electricity system. Therefore, in the following we only present a brief overview of this approach which we extend by paying dedicated attention to the role of transformative policy mixes within socio-technical scenarios.

Since socio-technical scenarios focus on actors and social interactions, a key starting point was a conceptualization of transition pathways that goes beyond the techno-economic variables that dominate model-based scenarios. We used the Multi-Level Perspective to distinguish two distinct transition pathways (Geels and Schot, 2007; Smith et al., 2005) that differ in terms of lead actors, depth and scope of

**Table 1**
Ideal-type transition pathways A and B, and their defining elements.

| | Pathway A: Technological 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 practices unchanged | Multi-dimensional change (technical base, markets, organisational, policy, social, cultural, consumer preferences, user practices) |

*Source*: PATHWAYS deliverable *D4.1* (*available at* http://www.pathways-project.eu/).

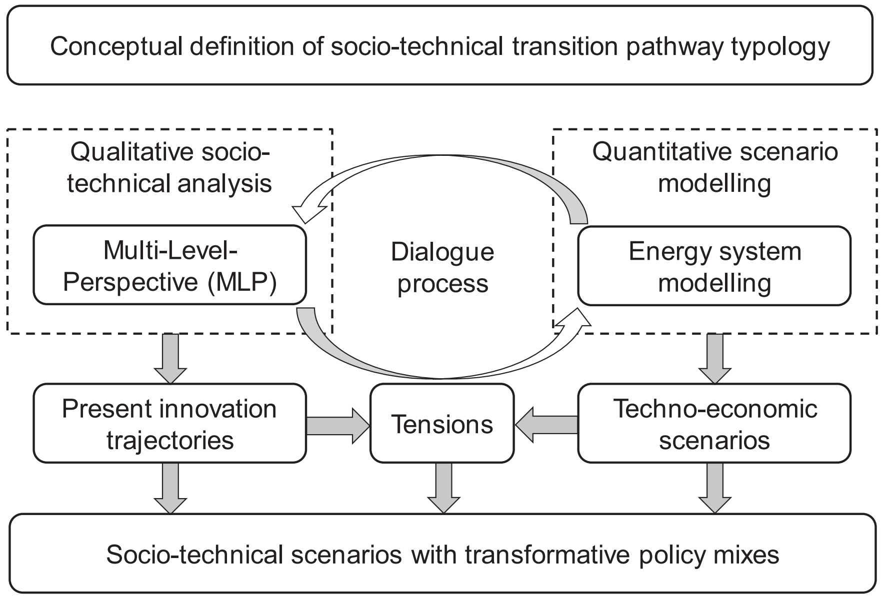


**Fig. 1.** Schematic overview of methodological approach.

change (see Table 1). The first pathway captures a "*Technological substitution*" (*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 regime 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 affects the system architecture not just in terms of technologies, but also in terms of user practises, cultural meanings and institutions.

The underlying feature of our bridging approach was the facilitation of a structured dialogue between two main analytical approaches (Turnheim et al., 2015). This ongoing dialogue led to iterative interactions between transition scholars who conducted a qualitative socio-technical analysis of the German electricity system on the one hand and modellers who performed the quantitative scenario modelling on the other hand (see Fig. 1).

For the socio-technical analysis we drew on the Multi-Level Perspective (MLP) to analyse the technologies, actors and institutions of the German electricity system, with its sub-systems of generation, consumption and networks. For this, we started by analyzing multiple dimensions of selected *niches* within the German electricity system in the last 5–10 years (techno-economic, socio-cognitive, policy) to assess their endogenous momentum (deliverable D2.1).[3] For the niche analysis we focused on solar PV, on- and offshore wind, bioenergy, and smart meters. We also assessed the stability and tensions in the electricity *regime* in light of landscape factors, and in doing so differentiated between the three sub-regimes for electricity generation, network, and consumption (deliverable D2.2). Overall, of all the transition processes studied within the PATHWAYS project, the German electricity system has seen some of the most pronounced transformative changes driven by a high momentum in several niches (most predominantly onshore wind and solar PV) paired with a strong tensions within the regime resulting from significant landscape pressures and policies (deliverable D2.3).

Simultaneously, we developed and refined quantitative scenarios. For this, we combined the Integrated Assessment Models (IAM) *IMAGE* and *WITCH*, which apply a global perspective on energy, with the power sector model *Enertile*, which has a detailed European coverage.[4] More specifically, the IAMs provided boundary conditions for energy demand, global developments like fuel prices and biomass trade and the maximum emissions in line with the 2 °C target. Within these boundary conditions, we used Enertile, a detailed power-system model with country-specific resolution and data for Europe, to develop two distinct pathways reaching the 2 °C target which mimick the ideal-type transition pathways A and B discussed above. For example, in Pathway A the model utilizes more technologies associated with incumbent actors, such as nuclear energy, while in Pathway B the model relies more on small-scale technologies like photovoltaics. The results of these techno-economic scenarios are discussed in Section 4 (deliverables D.1.1 and D.1.3).[5]

We then contrasted these two model scenarios with the qualitative socio-technical analysis of niche and regime developments in the German electricity system, which led to the identification of major tensions (presented in Section 5, and in deliverable D2.5). 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 policy goals. If current trends point in a completely different direction, this means that the transition challenge is large, which implies that drastic policies would be required to bend trends in the right direction. If current trends are already moving in the right direction, the transition challenge is less drastic, and mainly requires acceleration of ongoing dynamics. We find that social acceptance is creating obstacles for all innovations, but many also raise concerns in terms of political commitment.

In this paper, we focus on the development of qualitative socio-technical scenarios based on desktop research and guided by four main constraints. First, the socio-technical scenarios are guided by the MLP

[3] All project deliverables are available at http://www.pathways-project.eu/.

[4] For documentation, please see: www.enertile.eu.

[5] Note that the model formulation involves few detailed assumptions on the policies driving the transition; for example, we define certain shares for nuclear energy, but the models do not need or produce the actual policies behind the development.

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. Third, the quantitative model outcomes provide the aggregate pathways for which we try to develop endogenous enactment storylines for how decarbonisation can be reached. And finally, we focus on overcoming the 'transition challenges' (i.e. the tensions between future model scenarios and analysis of the present socio-technical system). We thus aim to develop an endogenously enacted storyline for low-carbon transitions in 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' (described below in Sections 6 and 7). Since the storylines focus on the endogenous enactment 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. (2018) by highlighting the role of transformative policy mixes in constructing such socio-technical scenarios driven by endogenous enactment. In particular, we draw on the identified key aspects of transformative policy mixes derived from the combination of the policy mix and transformative innovation policy literature to inform the governance of endogenously enacted storylines, thereby aiming to provide valuable novel insights to policy makers interested in supporting sustainability transitions.

## 4. Quantitative model-based scenarios for German electricity generation

In this section we briefly describe the quantitative scenarios for the German electricity system as output the iterative process between the MPL and the quantitative energy system models.

For Pathway A, we assume a preference for large-scale, centralized options like CCS, offshore wind and nuclear power plants, typically enacted through incumbent actors. CCS is favored in Pathway A through optimistic but plausible cost assumptions which in Germany render especially lignite-based CCS power plants economically attractive. We also assume that incumbent actors in Pathway A prefer offshore wind, which is realized in the model via subsidies reducing offshore wind costs to the levels of its onshore counterpart. Compared to the neutral model setting, we also lowered the spatial potential for wind onshore sites, which represents lower social acceptance. Finally, while in Germany the nuclear phase-out was kept in place, other countries still are allowed to rely on this technology in Pathway A.

For Pathway B, we made the following adjustments: Electricity demand decreases faster until 2030 because it is assumed that consumers increase their participation in energy efficiency measures (resulting from the IMAGE model). After 2030, electricity demand increases, as more electric vehicles are deployed and more houses use electric heat pumps compared to Pathway A. It is also assumed that CCS is not implemented in Pathway B, due to lack of social acceptance. Additionally, solar PV as a small scale electricity generation technology is subsidized in two ways. Firstly, a lowered interest rate of 1% reflects a greater tendency of consumers to buy rooftop PV systems. Secondly, the spatial potential for free-field sites was increased compared to the usual setting, representing for example a higher willingness of public bodies to provide building permits.

Based on these assumptions and parameter changes, the models were run to produce two scenarios for low-carbon electricity transition Pathways A and B. Fig. 2 and Fig. 3 show the quantitative Enertile model results for Germany for the two different transition pathways A and B, both in terms of capacity and electricity generation.[6]

The pathways represent substantial changes compared to current trajectories in the German electricity system.[7] Pathway A leads to an electricity generation system which by 2050 is dominated by offshore wind, lignite and biomass power plants equipped with CCS, as well as gas turbines serving as back-up. Nuclear power is phased out by 2022, in line with current legislation. 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. Electricity consumption declines at first, driven mainly by improvements in energy efficiency. But electricity demand increases again in the mid-2030s because of increased diffusion of electric vehicles and heat pumps. This development is accompanied by decreasing generation capacities and electricity generation until 2040, and strong increases by 2050. Around 2020, Germany switches from exporting to importing electricity from the rest of Europe, and by 2050 imports 20% of its domestic electricity demand.

In contrast, Pathway B by 2050 leads to an electricity generation system dominated by onshore wind, gas and solar PV. Unabated coal is phased-out by 2050, as CCS is not available. Natural gas plays a significant role as Germany in this scenario acts as a "flexibility hub" for central Europe. Therefore, Germany ends up with a relatively low share of renewable electricity when compared to the rest of Europe. Even earlier than in pathway A Germany becomes an importer of cost-efficient renewable electricity, reaching a share of approximately 34% by 2050. The higher shares of fluctuating renewables in this scenario require an even stronger expansion of the electricity grid than in Pathway A. Electricity demand follows a similar pattern as in pathway A, but with more pronounced demand reductions in the first decades.

## 5. Transition challenges as tensions between model scenarios and socio-technical analysis

There are several tensions, and in some cases even clear contradictions, between the quantitative scenarios and qualitative socio-technical findings for the recent past and present (2000–2015). These tensions form the 'transition challenges' between contemporary developments and the future changes that are needed to achieve the climate policy objectives. Table 2 summarizes these tensions for key niche and regime technologies, disaggregated for Pathway A and B. It is these tensions which need to be addressed in developing the socio-technical scenarios.

The socio-technical scenarios described in the next section aim to develop pathways for how these transition challenges can be overcome, and which role transformative policy mixes can play in addressing these tensions. Note that the socio-technical scenarios do not represent forecasts, robust strategies or recommendations, but rather should be seen as *thought experiments*.

We have divided both scenarios into three phases. The first one captures recent developments from 2015 to 2019 which are largely similar between pathways A and B, thereby reflecting path dependencies inherent in socio-technical systems. In addition, as policy changes are limited to the end of the first phase, their impact only becomes visible in the next phases. Therefore, we provide details of these developments in pathway A only and in pathway B instead focus on highlighting the few differences that do exist between A and B until 2019. For the second phase (2020–2034) fundamental policy changes are starting to be prepared and various differences in system developments can be observed. Finally, given that the third phase (2035–2050) is far into the future, we only

[6] Note that national preferences or strategies (besides nuclear phase-out policies) are not implemented in order to show the full impact of the pathways.

[7] They also differ from national decarbonisation scenarios due to their intentionally stylized and extreme nature.

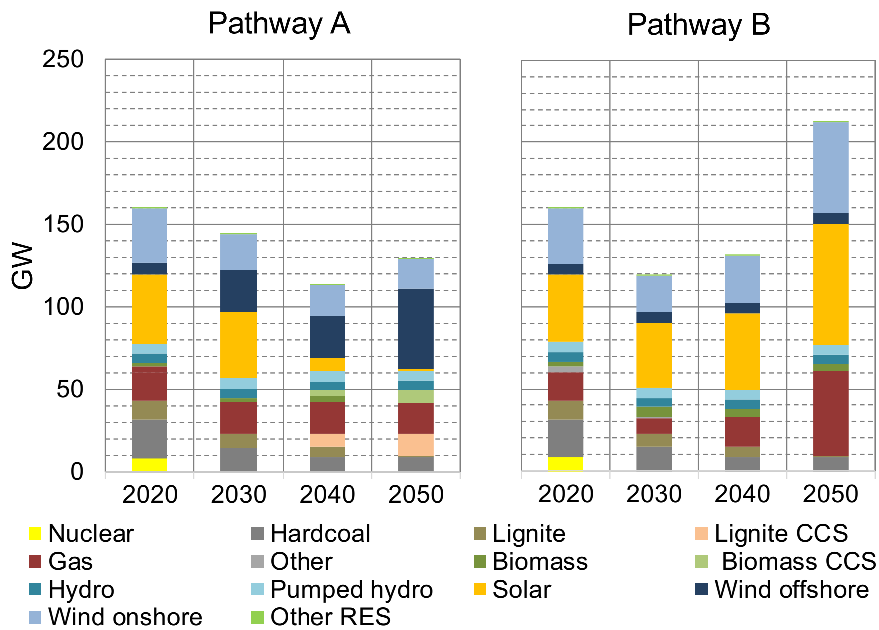


**Fig. 2.** Installed generation capacity in Germany for both pathways (2020–2050).
Source: Own calculations with Enertile.

briefly sketch out the main developments which differ significantly between both pathways.

## 6. Socio-technical scenario for pathway A for the German electricity system: decarbonising with offshore wind and CCS-lignite

### *6.1. Phase 1 (2015–2019): Continuation of nuclear phase-out, switch to renewables auctions, and missing of 2020 climate targets*

In its 2010 Energy Concept the German government committed itself to a nuclear phase-out by 2022, a reduction of greenhouse gas (GHG) emissions by 40% by 2020 (compared to 1990 levels) and 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 (BMWi and BMU, 2010). For renewables, the core policy instrument was the highly effective feed-in premium system of the Renewable Energy Sources Act (EEG) for which policy makers had started to experiment with auctioning as a potential market-based alternative to determining the level of support, largely due to rising cost concerns. In contrast, the core instrument for its climate target– the EU emission trading system – was suffering from accumulated surplus allowances and thus low carbon prices, nor were other sufficiently stringent instruments implemented to address the looming gap in achieving Germany's 2020 GHG target.

#### *6.1.1. Old regime developments*

By 2015, the electricity *generation regime* was undergoing radical

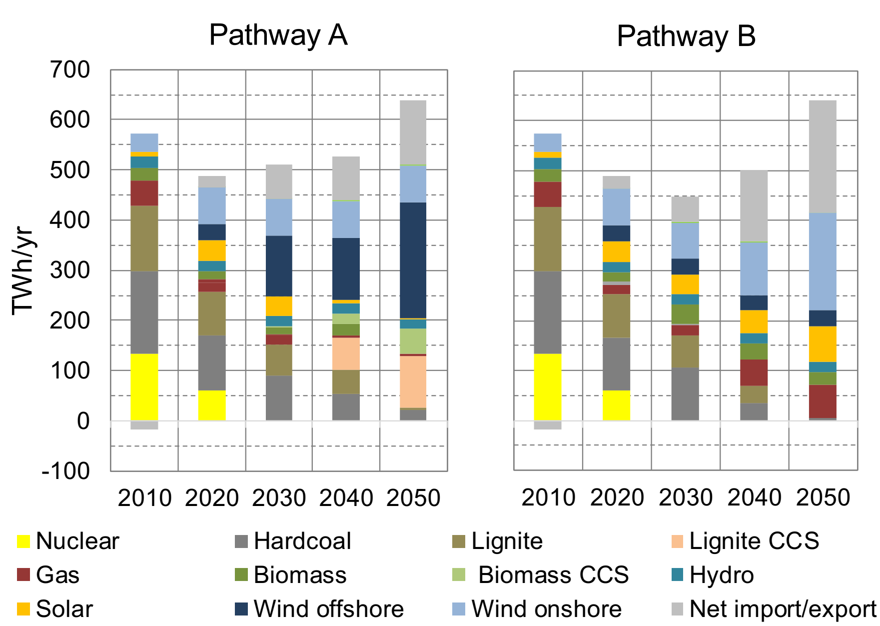


**Fig. 3.** Electricity generation in Germany in TWh for both pathways (2020–2050).
Source: Own calculations with Enertile.

**Table 2**
Tensions between future model scenarios and qualitative socio-technical analysis.

| Innovation | Pathway A | Pathway B |
|---|---|---|
| Biomass | Today's sustainability and cost concerns as well as competing uses of biomass use. | Similar, but smaller and only temporary tensions. |
| BECCS (bio-mass energy with CCS) | CCS and BECCS are not yet viable and not much is happening 'on-the-ground'. CCS faces significant public resistance. | – |
| Lignite CCS | Lack of public acceptance for $CO_2$ storage. Continued use of lignite may limit resistance against its phase-out (losses of income & jobs) but may also cause protests from environmental groups. | In conflict with resistance from lignite advocacy coalition consisting of regions, unions and incumbents opposing the phase-out of lignite. |
| Onshore wind | Decreased diffusion speed contrasts with current high momentum of the cheapest renewables option. Tensions can be expected from onshore wind advocates (e.g. jobs, domestic industry). | Until 2040 similar concerns as Pathway A. Only in the last decade the scenario shows a strong growth in onshore wind. In this phase of rapid growth, questions of public acceptance (NIMBY, land-use) and lack of continuous industry development (capacities, jobs) are likely to arise. |
| Offshore wind | Initially appeared to be not in line with Germany's shift towards cost-minimization. Resistance from excluded new entrants as well as technological risk due to missing long-term experience. | Endangers economic development and jobs in Northern Germany which conflicts with offshore wind advocacy coalition. |
| Solar PV | Declining role of solar PV is at odds with the technology's legitimacy, financial benefits to investors (e.g. farmers, private households) and public acceptance as well as declining costs and tendencies towards prosuming and smart homes. | Between today and 2030 very little additional PV capacities. Aftwards, the pace picks up substantially, which might, as in the past, lead to concerns regarding technology import and domestic industry rebuild. |
| Unabated hard coal | In conflict with climate policy ambitions and public opposition to coal. | Similar to Pathway A, but smaller tensions due to more rapid reduction. |
| Unabated gas | Necessitating policy solution regarding much debated capacity mechanism. | Concerns about the achievement of renewable and decarbonisation targets. |
| Electricity grid expansion | Tensions with current grid trajectories with much inertia and local resistance to grid-projects and transnational coordination challenges for interconnector capacity. | Even stronger tensions than in A, including NIMBY and cost concerns also for distribution grids. |
| Import and export | Net import assumes 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. 2018). Further tensions regarding domestic efforts and energy security. | Similar but even intensified tensions as in pathway A. |

Source: Own elaboration based on D2.5.

changes, given the rapid expansion of renewable energies caused by socio-political responses to climate change and the anti-nuclear movement (Geels et al., 2016b). The supportive policy mix, particularly the EEG, had enabled major investments in renewables 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, business models and organisational structures (Kungl and Geels, 2018; Richter, 2013; Strunz, 2014). Resistance from regime actors focused on reducing losses (e.g. by law suits) and shaping the new renewable-based regime to ensure their survival. 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. Three of the four affected plant operators sued the government for its abrupt phase-out decisions in the wake of the 2011 Fukushima accident, but lost. An expert commission was charged with identifying a suitable final deposit site for Germany's radioactive waste, and their announcement of generic search criteria marked the beginning of a new, systematic search process.
- Few new *coal and lignite* plants were built, but existing ones reached high load-factors due to low resource and $CO_2$-prices, the latter resulting from the built-up surplus of allowances in the EU Emission Trading System (EU ETS). This contributed to a rise in the $CO_2$ emissions of Germany's electricity system (coined 'Paradoxon of the Energiewende'), which endangered Germany's international credibility. An initial phase-out proposal formulated prior to 2015 Paris negotiations faced heavy political resistance from a coalition of incumbents, unions and federal states dependent on the income generated by the industry. Instead, financial compensation for the closure of the dirtiest lignite power plants was adopted, together with other additional climate policy instruments to address the gap in $CO_2$-target fulfilment. In 2018, Germany's climate protection plan for 2050 initiated an expert group addressing coal phase-out, which in 2019 announced a long-term phase-out strategy for unabated lignite and coal, including shut-down of the most inefficient plants already by the end of 2019.
- Giving the resistance to coal phase-out and rising pressure to address the climate gap, *carbon capture and storage* (*CCS*) resurfaced as potential solution. In negotiating the coal phase-out agreement, the government brokered a deal that foresaw so-called 'CCS model regions'. Mindful of strong public opposition to earlier storage sites, this initiative was equipped with substantial public funds to support the greening of the economy in affected regions while at the same time implementing two CCS demonstration plants with $CO_2$ storage to go online in 2030.
- The existing capacities for *gas-fired power generation* had to significantly reduce their load hours. In order to keep operators from mothballing their plants, the government implemented a partial capacity mechanism which, however, was not attractive enough for stimulating investments in new plants.

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 (ICT, heat pumps, but limited e-mobility) and rebound effects partly counteracted these reductions. Despite the reluctance of several important actors, the benefits of energy efficiency and shortcomings of Germany's existing policy approach, which was largely based on voluntary policy measures and financial support for energy efficiency investments (e.g. through KfW funding by the *Kreditanstalt für Wiederaufbau*), were increasingly recognized. The introduction of a white certificate-trading scheme aiming at improvements in energy efficiency signalled a shift towards a more ambitious approach. However, due to opposition to a mandatory national scheme, it was piloted in ten model regions to enable policy learning for a later national roll-out.

Finally, the *network regime* initially remained fairly stable with moderate lock-in due to its long-lived asset structure and conservative regulation. However, given the increasing share of fluctuating renewable energy, pressures on the network regime grew. A consensus emerged that faster network expansions were needed and that distribution networks needed to become more reactive. Gradual adaptations of the regulatory framework streamlined administrative processes and improved incentives for network expansion. However, proposed network routes still encountered local and regional resistance, which delayed construction and increased costs (e.g. for underground cables). These bottlenecks slowed down the integration of renewable energies.

#### 6.1.2. Emerging new regimes and niches

In 2016 the EEG saw a paradigm change from feed-in-tariffs to auctions to reduce the costs of further renewable energies by allowing for competitive bidding. In addition, expansion corridors (40–45% in 2025, and 55–60% in 2035) were set to better control the rate of expansion of renewable energies. Although the government allowed some exemptions for small-scale investors and cooperatives, these changes were contested by new entrants, such as cooperatives and renewable energy industry associations, but also by leading economists. Consequently, the 'atmosphere' in the renewables advocacy coalition seriously cooled down and citizens became increasingly disconnected from the Energiewende. But the government insisted that the nurturing phase was over, and that it was time for renewables to 'grow up'.

- *Onshore wind* – as cheapest renewable energy technology – experienced major additional investments exceeding the foreseen expansion corridor. While the renewables industry and affected federal states argued for an increase of these corridors, the government only made moderate adjustments in their yearly allowance for onshore wind auctions to 2.800 MW annually (2017–19), and thereafter 2.900 MW (gross figures incorporating repowering). Although new entrants were over-represented in first auction rounds, subsequent policy changes gradually reduced activities by cooperatives and farmers which had previously been the backbone of the Energiewende. Consequently, in later rounds, the majority of winning bids came from specialized wind energy project developers and the renewable subsidiaries of incumbents, which led to declining public acceptance for onshore wind in local communities.
- After the bottleneck of grid-access for *offshore wind* had been addressed (Reichardt et al., 2016), several parks went online in 2015. With load hours exceeding expectations and costs going down, incumbents fully embraced this large-scale technology. With offshore wind also contributing to the economic development of coastal regions, its advocacy coalition managed to secure room for continued expansion (6.5 GW until 2020 and 15 GW until 2030), despite offshore being more expensive than onshore wind. Strategic bids by two offshore wind pioneers in the first auction further strengthened the technology's position, with three of the four winning bids not asking for public subsidies. This enabled a new low-cost narrative, which was further supported by a policy change that excluded site-development costs from bids.
- *Solar PV* reduced its momentum after cutbacks in feed-in tariffs and the introduction of a correction mechanism (a "breathing cap"). Industry consolidation, PV job losses, and rising levels of the EEG levy (mainly paid by households and SMEs) undermined previously high levels of legitimacy. By 2015, investments in rooftop PV had collapsed dramatically, whereas cost-reductions for large-scale PV experienced in pilot auctions led to a broader roll-out of auctioning in 2016 (600 MW annually). While small-scale PV plants (up to 750 kW) continued to receive (reduced) feed-in tariffs, private households reduced investments in rooftop PV due to lacking financial attractiveness, which also made them less enthusiastic about the idea of producing and consuming their own energy.
- The government continued to limit the further expansion of *bioenergy* due to sustainability concerns, competing uses of biomass for the decarbonisation of other sectors and cost concerns. Despite industry opposition, the amended EEG included yearly auctions of only 150 MW in 2017–19 and 200 MW in 2020–2022, which allowed limited expansion.

### 6.2. Phase 2 (2020–2034): Offshore wind dominates as public acceptance for onshore declines, PV goes abroad and CCS moves forward

Despite the embarrassing failure to meet the 2020 climate targets of −40% GHG emissions by 2020, the government confirmed its GHG reduction target of 80% by 2050 under the pledge-and-review process agreed in Paris. However, given the negative image and press coverage, Germany was keen on rebuilding its credibility as climate champion and therefore started to lobby for strengthening the EU ETS carbon price signal. Resistance from coal-based EU Member States and Germany's energy-intensive industries remained high. Together with other progressive EU Member States, Germany founded "the EU low-carbon club" which aimed at surrendering a certain number of EU allowances (EUAs) between 2025 and 2035 to increase the EU ETS stringency. Over time this commitment of public money was able to fix the carbon price across Europe. This previously unthinkable detour to overcome European climate policy inertia together with other policy changes re-established Germany as committed player and positively impacted international climate policy negotiations after 2025.

#### 6.2.1. 'New' renewables regimes and niches

Cost pressures from the auctioning scheme enabled a reduction of support levels for *onshore wind*, with winning bids tending towards larger wind parks and the repowering of old sites. However, the winning large project developers and incumbents were faced with lengthy stakeholder consultations with locals, often increasing implementation costs beyond the auctioning price. As a consequence, incumbents lobbied for the opportunity to invest abroad, which accelerated negotiations with neighbouring countries to set up a supranational auctioning scheme aimed at cost minimization. However, due to initial resistance, fulfilling Germany's renewable targets abroad was not allowed until 2025 when implementation problems had increased so much that a voluntary auctioning scheme for onshore wind was piloted with neighbouring countries Denmark and the Netherlands. The internationally positioned incumbents consequently shifted their investments to these countries, while leaving the German repowering business to smaller players. Due to its success in reducing costs, other countries joined the supranational auctions, including the UK. Although German onshore wind capacities declined, criticism was muted by arguments for the cost-efficiency of supranational market-based instruments.

The roll-out of *offshore wind* by incumbents proceeded quickly. The target of 15 GW by 2025 was easily met, which established a positive image. High load factors led to increasing electricity generation from offshore wind. Technological learning, reduced finance costs, state funding of site development costs and strategic bidding of incumbents drove down costs much faster than originally expected. Therefore, the proposal of a powerful advocacy coalition of incumbents, regional and local policy makers, industry associations, and unions to extend the target for 2035 to 25 GW met little resistance. In 2024, the German government announced the issuance of another 10 GW of auctions, enabling the quadrupling of capacities between 2020 and 2030. When the 2035 target was accomplished ahead of time, offshore wind was hailed as 'green technology that delivers'.

*Solar PV* declined because free-field PV suffered from increasing public opposition towards external large investors. Rather than forging deals with local communities, incumbents advocated for a supranational auctioning scheme including Southern countries with higher sunshine hours. Because of rising electricity prices and positive experiences with a comparable pilot for onshore wind, in 2030 the German government joined the "Solar South Scheme", which introduced cross-country auctions and abolished feed-in tariffs and further exemptions for small-scale rooftop PV. This agreement led to massive solar PV deployment in Southern countries such as Spain, Italy and Greece. Many old German rooftop-PV capacities were decommissioned instead of repowered, thanks to a novel 'cheap solar abroad' business model offered by incumbents. While many citizens initially felt disempowered, over time they accepted the idea that incumbents would lead the energy transition.

There were limited changes in *bioenergy* generation or capacity, with only some replacement of older plants. In addition, towards the end of the period, the CCS + lignite demonstration regions started experimenting with biomass co-firing.

#### 6.2.2. 'Old' regimes

The remaining *nuclear* power plants were closed according to plan, but the determination of a nuclear waste storage site remained heavily contested, despite progress in analyzing potential locations.

Much of the government's attention focused on the two *CCS + lignite* 'model regions' selected in 2020. For these, the government established a cross-departmental CCS Taskforce which facilitated a participatory visioning process, bringing together parties to create a shared vision for each region, which addressed not only lignite-with-CCS but also other areas of socio-economic and environmental development. After initial hesitations, citizens, companies and universities became increasingly enthusiastic, particularly when the subsequent road-mapping exercise identified concrete steps and funding sources for achieving the vision. In 2025, both regions proudly presented their visions and roadmaps to the chancellor, and were highly motivated to implement them. When the carbon price reached 35 Euros towards the end of the 2030ies, lignite plant operators accelerated the construction of the two CCS-demonstration plants. Their opening ceremonies towards the end of the phase received surprisingly positive media attention: It emphasized the importance of negative emissions and the associated transitions in the model regions. The model regions the past ten years had witnessed the reduction of unemployment rates, the rejuvenation of the population, the improvement of key sustainability indicators, and multiple green initiatives with high levels of citizen engagement. Their success led to calls for a second round of CCS model regions, with increasing revenues from EU ETS auctions identified as funding source. A similar approach was suggested for creating buy-in for nuclear waste locations.

As for *gas*, the implemented capacity mechanism ensured that the existing gas-fired power plants remained online as back-up capacity, but were rarely needed to balance demand and supply.

The rate of change accelerated in the e*lectricity network regime* to cope with rising shares of renewable energies. To facilitate implementation plans, in 2025 the government initiated an independent Grid Stakeholder Consultation Task Force to negotiate the best possible routes for new transmission lines. When progressed stalled due to its limited negotiating power, the Taskforce was given a significant budget for financing negotiated solutions, such as underground cabling or compensations for affected communities. The government also implemented regulatory changes providing a clear incentive structure for delivering offshore wind grid expansion in time while respecting social and environmental criteria – but also penalties for underperformance. When evaluating the impact of these changes, an expert commission recommended adoption of a similar incentive structure for the mainland grids. In the early 2030s, this resulted in a radically revamped energy system law, aimed at the low-carbon reorientation of the network regime (e.g. introduction of 'time-of-use tariffs', initially for large users only). Furthermore, Germany gradually became a net importer of electricity and promoted the construction of additional interconnectors to create a European super-grid. In the early 2020s several European countries agreed to jointly finance these infrastructures, with one of the first successes being a new interconnector between the UK and continental Europe.

The main change in the electricity consumption regime was the national roll-out of the White Certificate Scheme in the mid 2020ies, taking on board some modifications based lessons learned from the ten pilot schemes. This market-based instrument initiated some efficiency gains of large users, but the associated reductions in electricity demand were largely negated by rebound effect and new users.

Together, these changes put Germany back on track for meeting its climate targets. But apart from the 'model regions' this new policy style disconnected civil society from the Energiewende, making them see it less as a societal project and more as a techno-economic undertaking managed by government and industry.

### 6.3. Phase 3 (2035–2050): Decarbonisation with offshore wind, lignite-and-BECCS and back-up gas within a European low-carbon electricity system

Continuing along ongoing trajectories most initial investments in offshore and onshore wind focused on repowering existing sites. Smart grids and smart pricing had made significant advances, making the electricity system more flexible and carbon-accounting was done at a European level. Three major changes occurred in the first five years:

(1) Because of supranational auctioning and decommissioning, *solar PV* capacities and generation decreased by a factor of 6 between 2030 and 2040. Incumbents delivered cheap electricity from renewables (increasingly combined with e-mobility solutions) without much consumer involvement.
(2) *Bioenergy-and-CCS plants* (BECCS) expanded because of the need for negative emissions and the success of CCS model regions.
(3) The *permanent storage of radioactive waste* was implemented at the most suitable region, with a massive budget being made available to compensate the selected region.

After 2040, *electricity demand* increased significantly, mainly due to rapid diffusion of electric vehicles. Carbon prices reached levels of above 60 Euros/t$CO_2$e, thereby providing incentives for CCS and new gas plants, while simultaneously global coal prices dropped due to decreased demand. As a consequence, three main changes occurred:

(1) The 2050 target for *offshore wind* was increased to 50 GW, leading to many new parks built by incumbents. In addition, the spike in electricity consumption led to extended *coal* usage beyond 2050, with most generation in CHP and BECCS co-firing plants.
(2) New *gas* plants became a lucrative investment due to steadily increasing carbon prices and a capacity mechanism. Actual generation, however, increased only slightly, as most balancing occurred through the import and export of electricity (with net imports reaching 20% of Germany's electricity demand).
(3) New *CCS-lignite* power plants with a capacity of 14 GW and extensive BECCS co-firing proved the large-scale feasibility of negative emissions. These investments were embedded in well-established visioning and road-mapping processes and supported through large budgets, thereby securing local acceptance. With CCS gaining momentum internationally, Germany benefited from increased exports of its CCS expertise built up in the pilot regions and their industrial clusters.

## 7. 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

### 7.1. Phase 1 (2015–2019): similar developments as under pathway A, apart from inclusive deliberation process and resulting policy initiatives

Early developments for pathway B resemble those in pathway A, including Germany's climate and energy policy targets, the nuclear phase-out and EEG-changes. As in pathway A, the policy mix led to major regime changes and a further upscaling of niche-innovations (particularly onshore wind and solar PV), but also a looming 2020 climate gap. The newly elected government initiated a critical stock-taking of the existing policy mix and intensified the deliberate societal and cross-sectoral vision-building process initiated for Germany's Climate Protection Plan 2050 for the desired shape of the decarbonisation of Germany. After protracted debates with much emphasis on the so far largely neglected mobility transition (heated up by Dieselgate and increasing international competition for electric vehicles) in 2019 the new coalition government agreed to increase its efforts to address climate change across sectors by combining a market-based with a new-entrant-friendly policy style, aimed at balancing cost-effectiveness, innovation incentives and societal inclusion. The proposed policy initiatives of greatest immediate relevance for the electricity sector included:

(1) an economy-wide carbon tax of initially 20 Euros/t$CO_2$, agreed upon after another failed attempt to fix the EU ETS;
(2) a national roll-out of the White Certificate Scheme, which build on earlier promising pilots;
(3) a supranational auctioning scheme for large-scale offshore wind projects, which alleviated concerns from incumbent actors, while
(4) the EEG would rejuvenate feed-in tariffs for small-scale projects of households, farmers and other small investors.

This was combined with an investment and experimentation strategy financed through the proceeds of the carbon tax, which was to be split in equal parts to

(i) finance the structural change in two model regions willing to phase-out lignite;
(ii) retire EUAs in an effort to increase the EU ETS carbon price-signal;
(iii) support breakthrough low-carbon innovation in industry through 'radical innovation grants' and
(iv) fund local projects experimenting with behavioral change through 'experimentation vouchers'.

While these policy initiatives came too late to avoid Germany missing its 2020 climate targets, they sent a clear signal that the German government was seriously recommitted to decarbonisation as a top-level priority, and prepared to implement novel and previously unthinkable policies. With hindsight, many managers later said that it was this unexpected sign of a strong political will that cemented their full-fledged strategic reorientations towards a carbon-constrained world.

### *7.2. Phase 2 (2020–2034): clear carbon price signal, electricity demand reductions, repowering of wind and PV, termination of inefficient conventional plants, and lignite phase-out model regions*

The second phase marked the implementation of the policies announced in 2019. Together with France Germany initiated a club of progressive EU Member States ('EU low-carbon club') which just before COP26 in 2020 announced its pledge to buy-out and surrender EUAs until the EU allowance price had reached 25 €/t$CO_2$. By the mid-2020s this commitment reduced the surplus of EUAs, thereby strengthening the carbon price signal across Europe. In contrast, the launch of an economy-wide carbon tax of 20 €/t$CO_2$ was initially delayed due to significant opposition, but eventually announced at the closing ceremony of the last nuclear power plant in 2022. Together with the national White Certificate Trading Scheme, this instrument mix intensified the low-carbon transition process. Increasingly more industry initiatives applied for 'radical innovation grants' and societal ideas for 'experimentation vouchers'. In addition, to facilitate knowledge exchange and learning about the diverse options, the government launched a central 'Climate Innovation Platform'.

#### *7.2.1. 'New' renewables regimes and niches*

The second period was marked by stabilization of most 'new' renewable regimes and niches, with only solar PV and bioenergy seeing slight expansion.

- While the EEG returned to feed-in tariffs for small investors (and maintained auctions for large ones), there was no immediate boom in *onshore wind*. One reason was internationally positioned incumbents reoriented towards more profitable countries with less public opposition. Another reason was the focus of many new entrants on repowering at existing locations.
- In contrast, *offshore wind* came to a temporary halt since no more national auctions were advanced during the negotiations for a European auctioning scheme. When the first supranational auction was launched in 2022, German incumbents and manufactures were well represented in the winning bids, albeit with locations outside of Germany. However, these offshore wind parks contributed to achieving the 15 GW target for 2030 as the target was reinterpreted as a European one. German offshore capacities remained at 6.5 GW.
- By 2020 little interest remained for investment in free-field *solar PV*. On the one hand, incumbents were eying more profitable investment opportunities in Southern countries with more sunshine and less public resistance. On the other hand, a societal consensus emerged for rooftop-PV and integrated building solutions as part of smart-home concepts, which were developed by start-ups and other actors supported by the 'experimentation scheme'. While PV capacity additions initially remained small, the search for new ideas increased, leading to much learning from successes and failures. This groundswell of experiments led to many new integrative products and services that started flooding the market around 2030. Project developers, municipal utilities and others focused on new business models for repowering privately-owned rooftop solar PV at the end of its lifetime, which created significant market dynamics. Novel "Smart Apps" boomed and appliance manufactures jumped on the trend of smart electricity solutions. Besides private households, hotels, schools, local businesses and other companies also started repowering through integrated solutions for which EEG funding became available towards the end of the period.
- *Bioenergy* slightly increased generation capacities driven by rising carbon prices, but growth was limited due to sustainability concerns and increasing interest in alternative uses (e.g. biomaterials) driving up biomass prices.

#### *7.2.2. 'Old' regimes*

Germany was occupied with managing the structural change and associated social challenges resulting from the closure of inefficient lignite and coal-fired power plants.

- While the carbon tax and the recovering EU ETS carbon price started to push the least-efficient *coal- and lignite*-fired power plants from the market, this improved internalization of external costs of $CO_2$ emissions had only been politically feasible because financial support was promised to affected regions. Socio-economic concerns (e.g. job losses) were alleviated by piloting two 'Green Transformation Regions' willing to commit to plans for lignite phase-out and low-carbon redevelopment. As in pathway A, a cross-departmental Transformation Taskforce was established which implemented a participatory societal visioning process which by 2024 produced a joint vision and roadmap for regional transformation backed up by significant budget. The subsequent success of these model regions received much national and international attention, praising its green entrepreneurial boom, attractive clean teach and ICT jobs, sustainability education and research at the region's universities, and improvement of key sustainability indicators. However, the conventional business units of former incumbents faced severe financial difficulties while also losing public acceptance of their remaining coal plants which were ran with high load factors. Towards the end of the period, the two operators of lignite-fired power plants merged, without large public outcries. Several other regions started lobbying for a second round of transformation regions to address the ongoing consolidation of the coal and lignite industry in a forward-looking manner.

- As for *gas*-fired power plants, the increasing carbon price was initially insufficient to stop their closure. EU Member States therefore implemented a European capacity mechanism to ensure sufficient back-up capacity. German companies were among the fastest and most successful in building these new gas-fired power plants showcasing their desperate search for a new role in the future electricity system.
- Germany's *nuclear* phase-out proceeded as planned, with final plant closures in 2022. But finding a nuclear storage site remained difficult, with three suitable regions finally identified by the end of 2030. Borrowing the idea of 'transformation regions', the government persuaded one of the regions to store the waste in exchange for a fully-budgeted regional transformation.

The rising shares of wind and solar PV (reaching approx. 50% of electricity generation in 2035) created increasing pressures on the conservative e*lectricity network regime* and called for more radical changes. Similarly as in pathway A, the government therefore initiated an independent Grid Stakeholder Consultation Taskforce to negotiate the best possible routes for new transmission lines. When progress stalled the Taskforce was given a significant budget to finance negotiated solutions (recycling increasing EU ETS auction revenues), such as underground cabling or compensations for affected communities. In addition, in the mid-2020s the government adopted a radically revamped energy system law to address recent developments in digitization, technological innovation and sector integration – enabling, for example, regional clusters for distribution grids and 'time-of-use tariffs'. Several new entrants eagerly experimented with innovative projects and future storage solutions, with the more promising ones being developed further by the prospering smart energy industry. Yet, as Germany had already become a net importer of electricity in 2020, it also promoted the construction of additional interconnectors to create a European super-grid which several European countries agreed to jointly finance (e.g. between the UK and continental Europe).

The perhaps most wide-reaching changes occurred in the electricity *consumption regime*, which saw a remarkable reduction of electricity demand and flexibilisation of consumption. These changes were mainly achieved by a combination of price incentives from the White Certificate Trading Scheme (rolled-out in the early 2020s) and an era of creative experimentation and behavioral change (stimulated by the 'experimentation scheme', such as smart home concepts and neighbourhood nudging), which together ushered in a change in thinking about electricity demand. The government showed commitment to the experimentation scheme by rolling it out more widely, despite a delay in carbon tax revenues which was overcome by putting aside additional funding. This sparked a search for innovative ideas by a variety of actors and led to absolute reductions in electricity demand, despite new uses (e.g. ICT, electric vehicles) and increased consumption elsewhere (rebound-effect).

Decarbonisation activities blossomed across sectors and actors at levels previously unthinkable. Increasing numbers of actors wanted to join the bandwagon. Industry associations and social media disseminated knowledge about the next 'cool' low-carbon initiative. Decarbonisation was even picked up in soap-operas, movies, and festivals. Celebrities started their own initiatives or were recruited to serve as glamorous spokespersons, which in turn led tabloids to start reporting about climate initiatives, thereby further spreading the new thinking. Together, these activities resulted in a different mind-set which was described as a "#decarbonizeit!" atmosphere (time to decarbonise it).

This progress and enthusiasm convinced Germany that it could reach its Paris Agreement commitments. To motivate others to increase their aspirations, Germany put extra efforts into sharing its experiences with transitioning to a low-carbon society. When the 'EU low carbon Club' ceased buying and retiring EUAs Germany announced that it would earmark the freed-up carbon-tax revenues to fund low-carbon experimentation programs in interested developing countries. After successful trials in several countries these were included in the NDCs of partnering countries, and ultimately contributed to tightening commitments under the Paris pledge-and-review process.

### *7.3. Phase 3 (2035–2050): Doubling of onshore wind, solar PV and gas for the electricity-mobility revolution*

The take-off of electric vehicles increased electricity demand, but negative implications were countered by a doubling of onshore wind and solar PV capacities. Car manufactures increasingly cooperated with project-developers specialized in PV to offer combined deals. Consequently, by 2040 many electric cars were purchased together with freely-installed solar PV smart-charging interface. Similarly, car-sharing companies and company car-fleets intensified their cooperation 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 buildings.

In response to these developments, the government tightened the stringency of the White Certificate Trading Scheme and increased the carbon tax to 50€/$tCO_2$. In tandem, the Transformation Task Force, which had successfully governed the structural change in the former lignite regions, was institutionalized into a "Green Transformation Agency" (GTA) that provided assistance in participatory visioning and road-mapping processes to regions affected by structural changes due to the decarbonisation of the economy. The GTA was independent and had a substantial budget for regional redevelopment (half of the revenues from the carbon tax). The GTA grew rapidly and opened regional subsidiaries, for which its budget was supplemented with proceeds from EUA auctions.

The increase of fluctuating renewables was increasingly complemented by *flexible back-up capacity and expansion of the European super grid*. The former was ensured by a European capacity mechanism and a carbon price of over 90 €/$tCO_2$ (which by then was incorporated in a green tax reform significantly reducing labor and company taxes by taxing GHG emissions). The remaining incumbents therefore continued to invest in *gas*-fired electricity generation plants, effectively turning Germany in a European hub for flexible back-up and balancing. Although this increased Germany's $CO_2$ emissions, this was unproblematic for meeting climate targets because carbon-accounting was changed from a national perspective to a European one. While *lignite* was completely phased-out, a small number of *coal*-fired power plants initially remained online due to low global coal prices. The new gas turbines starting operation after 2040 were used predominantly as back-up. As for *nuclear* waste, a permanent storage site was announced and the GTA assisted the redevelopment of the selected region which received substantive financial compensation.

These developments occurred in tandem with further expansion and flexible utilization of smart grids. The net import share of electricity reached almost 35% in 2050, with Germany importing from countries with better wind and sunshine conditions. Dynamic pricing made significant advances and households and industry continued their quest for identifying options to reduce electricity demand, which somewhat contained the increasing demand from electric vehicles. These changes made the new low-carbon electricity system highly flexible and European in nature, while at the same time ensuring the international competitiveness of the decarbonised German economy and continued high public support for climate change action.

**Table 3**
Overview of key developments in the two socio-technical scenarios in Germany (2010–2050).

| Pathway | Phase 1: 2015–201 | Phase 2: 2020–2034 | Phase 3: 2035–2050 |
|---|---|---|---|
| A. Technological substitution | *Continuation of nuclear phase-out, switch to renewables auctions, and missing of 2020 climate targets* | *Offshore wind dominates as public acceptance for onshore declines, PV goes abroad and CCS moves forward* | *Decarbonisation with offshore wind, lignite + BECCS and back-up gas within a European low-carbon electricity system* |
| *Decarbonising with offshore wind and CCS-lignite* | By the end of 2019 all but 6 nuclear power plants were phased-out, the least efficient lignite and coal plants were shut down, offshore wind started to kick off, and the expansion path foreseen for renewable energies was only marginally exceeded. Cost-efficiency was established as prime motive within Germany's renewables policy, but the resulting policy changes (auctions within narrow expansion corridors) started to exclude new entrants as investors into renewable energies. As a result, citizens increasingly saw the Energiewende rather as a technological transition project managed by the big guys and became less enthusiastic about prosuming. Yet, the overriding concern was that Germany's 2020 climate target – despite several additional policies across various sectors – was not met. This was seen as a wake-up call for more ambitious climate policy, with the phase out of unabated coal and lignite and the introduction of CCS model regions being a first step in this direction. | Offshore wind emerged as new regime, while much of the investment in onshore wind and PV was channelled to locations abroad. The two CCS model regions were successful in creating local acceptance by pursuing an 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, onshore wind and PV auctions, interconnectors), radical changes to network regulation (e.g. EnWG amendment, dynamic pricing), a broader use of market-based policies (e.g. EU ETS, white certificates) and an overriding dominance of cost minimization. Stakeholder engagement was facilitated through new government bodies with budgetary power (e.g. grid stakeholder consultation task force, cross-departmental CCS task force). While these changes put Germany back on track for meeting its climate target, they also led to a more passive role of civil society, apart from the model regions. | Phase 3 was characterized by the continued expansion of offshore wind and CCS + lignite plus BECCS (and export of these technologies), an increase in gas generation capacities as EU system back-up, and an almost complete discontinuation of solar PV in Germany. Smart grids and dynamic pricing led to flexible demand and net imports had grown to almost 20%, but a sudden increase in the 2040ies (e-mobility) led to postponing the coal phase-out. At last, a nuclear storage site was found, with the region receiving substantial financial compensation. The policy mix combined (European) market-based instruments with a further diffusion of participatory visioning processes combined with substantial transition budgets. By 2050, electricity generation capacities in Germany were fairly large-scale, largely decarbonised and mainly owned by a handful of incumbents, with citizens playing a fairly passive role in the energy transition. Germany's success in meeting its targets received considerate international attention. |
| B. Broader regime transformation | *Similar developments as under pathway A, apart from inclusive deliberation process and resulting policy initiatives* | *Clear carbon price signal, electricity demand reductions, repowering of wind and PV, termination of inefficient conventional plants, and lignite phase-out model regions* | *Doubling of onshore wind, solar PV and gas for the electricity-mobility revolution* |
| *Solar-PV and onshore wind with flexible gas back up for the rest of Europe* | While the nuclear phase-out and expansion of renewables continued as planned, too little progress was made with $CO_2$ emissions and reducing electricity demand. After a critical stocktaking and deliberate societal vision building process in 2019 it was decided that Germany would step up its efforts to address climate change, combining a market-based and at the same time new entrant friendly policy style, proposing several key policy initiative: (1) an economy-wide carbon tax of initially 20 Euros/t$CO_2$; (2) the national roll-out of the white certificate trading scheme; (3) a supranational auctioning scheme for large-scale offshore wind projects while (4) the EEG would rejuvenate feed-in tariffs for small-scale projects. This was combined with an investment and experimentation strategy financed through the proceeds of the carbon tax which would be split up in equal parts into (i) financing the structural change in two model regions willing to phase-out lignite; (ii) retiring EUAs in an effort to increase the carbon price signal from the EU ETS; (iii) supporting break-through low-carbon innovation in industry through 'radical innovation grants' and (iv) funding local projects experimenting with behavioral change through 'experimentation vouchers'. While too late for avoiding Germany to miss its 2020 climate targets, the adoption of these policy initiatives sent a clear signal to investors and abroad. | 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. The associated demand reductions enabled the closure of conventional capacities, while the growth of renewables came largely to a halt. The two green transformation regions in former lignite-dependent areas witnessed the societal deliberation of an inclusive regional development strategy which started to bear social, economic and environmental fruits. Policy initiatives were characterized by greater supranational initiatives of proactive countries (e.g. EUA buy-out, interconnectors), a strengthening of market-based policies (e.g. EU ETS, EU auctioning for offshore wind, national white certificate scheme), and active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental 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, climate and efficiency targets. Germany's climate actions received international attention (e.g. lifestyle changes, electricity demand reductions, green transformation regions). | Phase 3 was characterized by the doubling of capacities and generation from onshore wind and solar PV as well as gas, and an expansion of smart grids, flexibility of demand and integrated solutions. This was driven by the massive deployment of electric vehicles increasing electricity demand, and innovations in prosuming business models. Germany employed a policy mix which combined market based instruments (e.g. carbon pricing) with explicit institutional and financial long-term support for regions affected by the structural changes arising from the energy transition (Green Transformation Agency and its regional subsidiaries). It also continued with stimulating an experimental and innovative mindset (e.g. experimentation vouchers). 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 and net importer decarbonisation was achieved through the new European nature of carbon accounting. Overall, Germany's national, European and international policy engagement gained it a positive image as climate champion, with some of its policy and institutional innovations diffusing to other countries. |

## 8. Discussion and concluding comments

### 8.1. Synopsis

We have developed two socio-technical scenarios to explore how the decarbonisation of the electricity system as calculated by optimization models could materialize through endogenous enactment dynamics rather than external drivers or shocks. In particular, within these fictional histories of the future we have explored how transformative policy mixes may contribute to overcoming tensions between model outcomes and real-world developments ('transition challenges').

By bridging modelling and MLP approaches we constructed two archetypes of socio-technical scenarios reaching 80% reduction in GHG emissions by 2050 (for an overview, see Table 3). The first scenario (pathway A) provides an endogenously enacted storyline that is dominated by large-scale low-carbon technologies, in particular offshore wind and CCS-and-lignite power plants with biomass co-firing. Incumbents 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. 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 tandem with the expansion of smaller-scale, decentralized options like onshore wind and solar PV. This scenario includes wider shifts in cultural discourses and social legitimacy, which are encouraged by a more inclusive, experimental, new-entrant-friendly policy style going beyond large firms and technologies. Both scenarios increase the use of market-based instruments whose stringency is increased over time, with various mechanisms of revenue recycling supporting further decarbonisation activities. Public acceptance is crucial in both scenarios, requiring novel and financially well-equipped transformational institutions.

### 8.2. Comparison of transformative policy mixes across pathways

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. Both pathways include multiple aspects of transformative policy mixes, but there are similarities and differences in how these are shaped and implemented. In addition, the scenarios reveal that successful transformations require the full spectrum of policy instruments, with stringent market based instruments and substantial financial compensation mechanisms playing a fundamental role for the wide diffusion and acceptance of low carbon solutions.

#### 8.2.1. Similarities

First, in both pathways policymakers need to address political struggles and conflict through creative and often costly policy instruments. One example is how policy makers overcame resistance to increase the stringency of the EU ETS by forming a coalition with progressive EU member states. Another example is the transfer of funds to compensate losers and/or buy policy support for decarbonisation projects (e.g. budgets for 'model regions'). Another common conflict resolution strategy is the use of pilots for new policy instruments, before rolling them out more widely (e.g. White Certificate Trading scheme). Another similarity is the utilization of 'destruction instruments' and role for policy learning and adjustment in both scenarios.

Second, both pathways use societal vision building and road-mapping processes in their model regions, with the major difference being that one includes CCS demonstration plants whereas the other does not. Yet, in both cases these procedural policy instruments are used for overcoming public acceptance concerns and resistance to change, as well as establishing shared visions of the future, thereby guiding future developments in a jointly agreed direction.

Third, both decarbonisation pathways foresee Europeanization of some of the elements of policy mixes (e.g. in terms of European grid coordination and auctions), but with some differences in the applied technologies. This similarity may be partly shaped by the European nature of the model results. However, long-term decarbonisation strategies not based on an increasing Europeanization (e.g. autarchy approaches) may face substantial technological and economic obstacles.

Finally, both pathways include changes in institutional arrangements and governance structures, such as task forces and enhanced stakeholder consultation to drive forward those changes which are deemed important (e.g. cross-departmental Model Region Taskforce, independent Grid Stakeholder Consultation Taskforce). Another example is the radical redesign of the regulatory framework conditions for the electricity sector. That is, policy change is accompanied by institutional change which is enacted by policy makers in the pursuit of transition objectives.

#### 8.2.2. Differences

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 current trajectory in which Germany has been following a 'new-entrant-friendly' pattern similar to pathway B (Geels et al., 2016b). We argue that uncertainties in the societal vision about desirable properties of the future energy system provides an entry point for strategic agency of incumbents, who, over time, are able to tilt the trajectory towards offshore wind and CCS through the implementation of what we call '*regime stabilizing policies*' (e.g. Europeanization of renewable support schemes for onshore wind and solar PV, extension of coal phase-out, increasing offshore wind targets, capacity mechanism). In addition, the trajectory in pathway A tilts because several policy instruments promoting green niches are redesigned or terminated, such as the abolishment of feed-in premiums. The policy mix thus gradually integrates elements of stabilization of the old but decarbonising regime, 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 and critical policy stocktaking process that results in a policy roadmap with key building blocks 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* and *radical innovation grants* for industry, which provide the seeds for establishing a societal and business culture of trying, diversifying and empowering, thereby generating creative solutions, facilitating broad participation, and also allowing for learning from failure. Second, policy makers show a *greater commitment to decarbonising all sectors* of the economy rather than a continued predominant focus on the electricity sector, among others by introducing a national $CO_2$-tax early on to provide clear guidance for the direction of travel and simultaneously funds for the experimentation scheme.

### 8.3. Role of political commitment and social acceptance

The implementation of both decarbonisation pathways is faced with a number of massive obstacles, which are mostly related to political commitment and social acceptance issues.

Political commitment is a key success factor for implementing transformative policy mixes. Yet, as both scenarios show Germany is facing difficulties in achieving its GHG emission reduction targets for 2020, mainly due to the lack of an ambitious policy phasing-out unabated coal and lignite as well as limited action in other sectors, including transport, buildings and agriculture. This implies an urgent need to step up policy commitment in addressing unabated coal and lignite and decarbonising other sectors. Similarly, it remains unclear if the German government is committed to more ambitious carbon pricing. For example, policy makers might be reluctant to take unilateral or bilateral action to address the oversupply of EU allowances in the EU ETS to contribute to a further strengthening of $CO_2$ prices. In addition, while energy efficiency has been recently tried to be established as second pillar of the energy transition, there are limited indications that Germany would change from a voluntary policy approach with the provision of financial support to a policy paradigm that pushes for radical improvements in energy efficiency rather than just incremental ones.

Social acceptance is another important aspect for the success of either decarbonisation pathway in Germany. For example, maintaining acceptance for onshore wind may become problematic due to increasing land-use, visibility and noise concerns at an ever greater roll-out of onshore wind parks. Henceforth, much attention may need to be given to ensuring that stakeholders and communities benefit from the construction of onshore wind parks, either directly through energy cooperatives or indirectly through new business models. Another example concerns the foreseen high reliance on the import of renewable electricity as it implies a great dependence of the decarbonisation of Germany's electricity system from developments abroad, including policy commitment and social acceptance. Also, by no mean it is clear that civil society would accept a move to European funding schemes enabling investments in renewables abroad, as this 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. Additionally, a debate could unfold about the desirability of a future electricity system which is decarbonised within Germany vs at a European level only.

### *8.4. Conclusion*

This paper contributes to the literature in two ways. First, we combine the literatures on policy mixes for sustainability transitions and transformative innovation policy to derive four key aspects of transformative policy mixes. Second, we provide the first socio-technical scenarios for the German electricity transition which bridges modelling and MLP-analysis. We conclude that multi-dimensional socio-technical change going beyond technological substitution requires greater emphasis on societal experimentation and a more proactive role for anticipatory deliberation processes from the outset. In contrast, shifting gear from the present new-entrant-friendly trajectory to an incumbent-dominated pathway requires active agency from incumbents and is associated with regime-stabilizing instruments that strengthen core principles of the old regime (e.g. incumbents as crucial actors, large-scale solutions) while simultaneously fulfilling decarbonisation as additional success criteria.

Given the peculiarities and stylized nature of the model results, explaining them in an endogenously enacted 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, or to write a conceivable trajectory in which CCS happens despite major public resistance. Similar challenges arose for Pathway B, with one example being how to explain the stagnation of offshore wind despite its current strength, changes in behaviour or the acceptance of high levels of imported electricity.

One limitation of our work is that our two pathways are stylized archetypes representing intentionally extreme cases to sharpen insights on general requirements of transformative policy mixes. These scenarios should therefore not be seen as predictions of the future, but as thought experiment to stimulate a deeper and more critical engagement with model results. Ultimately, we expect such socio-technical scenarios to provide enhanced insights into the dynamics of energy transitions thereby enabling the articulation of improved and more nuanced policy implications.

We suggest that the development of socio-technical, endogenously-enacted histories of the future represents promising future research and engagement opportunities. In particular, as a next step, we recommend the articulation of more realistic pathways, which build on societal visions for the energy system. Based on model results, a particularly promising way forward would be to use transformative foresight methods to engage stakeholders in constructing the corresponding socio-technical scenarios. That is, we argue for a two-fold extension of the manifold modelling studies conducted in the context of the German energy transition: by extending their scope to developing socio-technical scenarios implementing the model results, and by integrating stakeholders in the development of these.

## Acknowledgements

The authors gratefully acknowledge support from the European Union's Seventh Framework Programme (FP7) under grant agreement no. 603942 (PATHWAYS). We would also like to thank two anonymous reviewers for their thoughtful comments and the guest editors for their editorial work.

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