PATHWAYS project

Exploring transition pathways to sustainable, low carbon societies

Grant Agreement number 603942

Deliverable D2.5: ‘Forward-looking analysis of transition pathways with socio-technical scenarios’

Country report 1: German electricity system

Karoline S. Rogge and Benjamin Pfluger

Fraunhofer Institute Systems and Innovation Research
(Fraunhofer ISI)

Karlsruhe, Germany, July 22, 2016

Preface

This report is produced in the context of work package 2 ('Dynamics of transition pathways') of the FP-7 funded PATHWAYS project ('Exploring transition pathways to sustainable, low carbon societies'). More precisely, this report provides the German country study of the electricity regime for deliverable 2.5 'Forward-looking analysis of transition pathways'.

The analysis in this report is based on a research template developed by Frank Geels and shared between the different contributors to WP 2 to enable comparative analysis of findings between countries (UK, Netherlands, Sweden, Portugal, Germany) and empirical domains (electricity, heat, mobility, agro-food and land-use). This deliverable draws its generic text from the UK country report (#2), and therefore its original contribution lies in the analysis being conducted for the German electricity system.

Contents

Executive summary

This report reports two socio-technical scenarios for the German electricity systems. These scenarios develop endogenous qualitative storylines for the quantitative pathways A and B, which have been described in the PATHWAYS deliverable 1.3 (Figure A and B). The socio-technical scenarios build on the findings from PATHWAYS deliverables 2.1 and 2.2, which assessed the contemporary momentum of green niche-innovations in the German electricity system (2.1) and the degree of stability of the existing electricity regime (2.2).

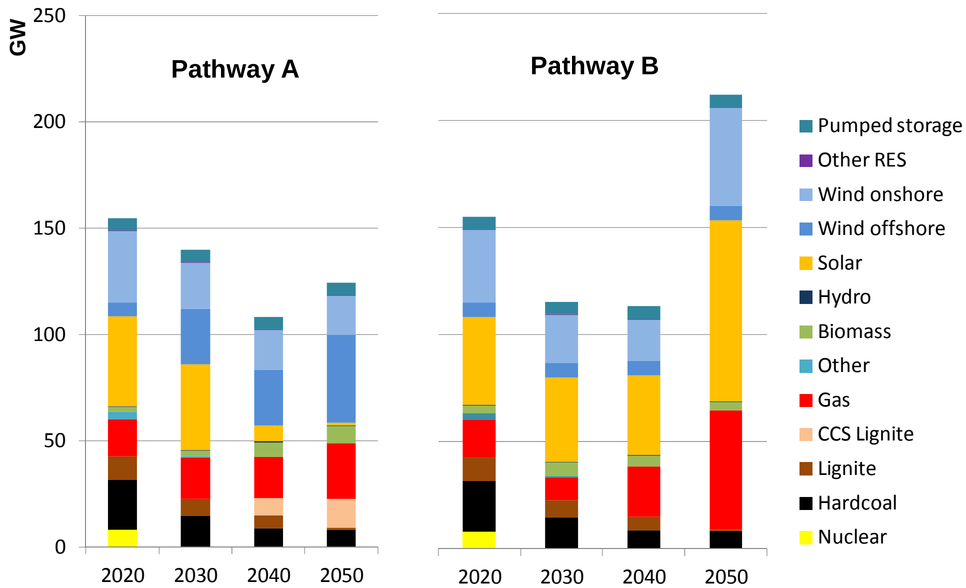

Figure A: Installed capacity in electricity generation in Germany (based on D1.3)

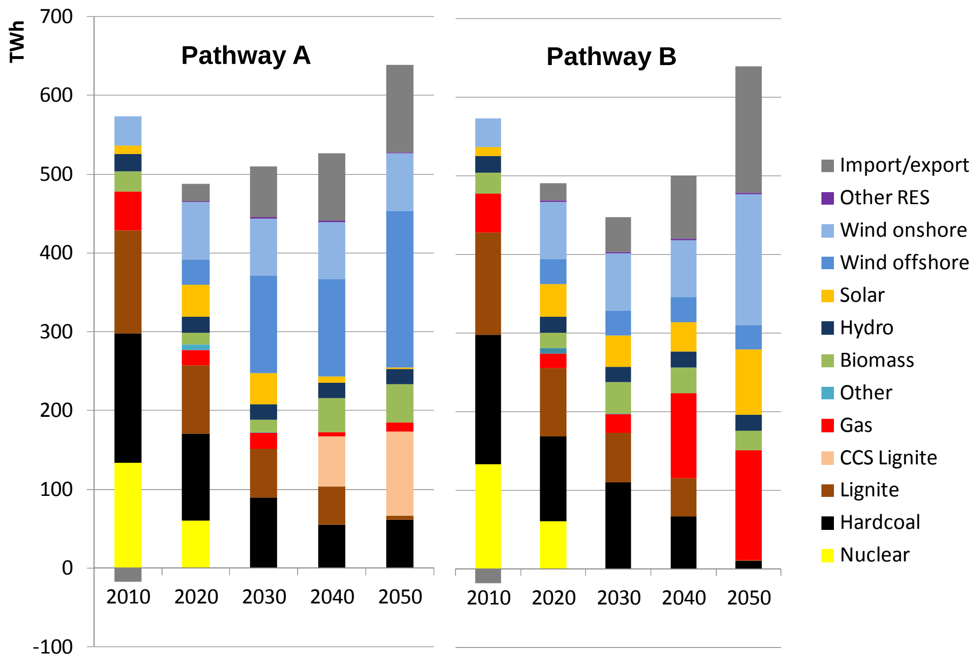

Figure B: Electricity generation in Germany in TWh (based on D1.3)

As an intermediate step, the report identifies and outlines several ‘transition challenges’, i.e. tensions between contemporary trends (documented in D2.1 and D2.2) and future model outcomes from PowerACE (Figure A and B). In this report, we develop socio-technical scenarios with endogenous storylines for how these ‘transition challenges’, which vary between both Pathways and which are summarized in Table C, can be overcome. Given the various constraints identified in our analysis of transition challenges, particularly those regarding public acceptance and political will, it is important to develop these more sociologically sensitive scenarios to address these obstacles for the diffusion of various low-carbon innovations in Figures A and B.

Table C: Tensions between future model scenarios for electricity generation in Germany and WP2 findings of niche-momentum and path dependencies

Innovation	**Pathway A**	**Pathway B**	**Constraint**
Biomass	Pathway A assumes a moderate expansion of biomass in electricity use in 2040 and 2050, which contradicts with today’s sustainability and cost concerns as well as competing uses of biomass use, which together have led to a downscaling of the further growth prospects of biomass within the German EEG.	Only intermediary upscaling, but by 2050 reduction to 2010 levels, therefore smaller and only temporary tensions.	Political commitment, social acceptance, environmental sustainability
BECCS (biomass energy with CCS)	BECCS plays a large role in European scenarios (especially after 2050 to generate ‘negative emissions’). BECCS is introduced in 2030 and reaches a 90% share of all German/EU bioenergy use by 2050. This creates two main tensions: 1) BECCS is not yet viable and not much is happening ‘on-the-ground’, making it risky to base future scenarios on something that hardly exists in the present. 2) CCS faces significant public resistance (see below).	No CCS in pathway B (and no BECCS).	Technology readiness, economic costs, political commitment, social acceptance
Onshore wind	Onshore wind capacities are assumed to decrease and remain stable from 2030 onwards (through repowering); generation is assumed to slightly increase until 2020, and thereafter is expected to stabilize at this level. This is in stark contrast to the currently very high momentum of onshore wind, which can be traced back to it being the most	Until 2040 onshore wind develops like pathway A, with similar concerns. But thereafter it more than doubles its capacity and generation. This long-term jump is in conflict with the need for continuous industry build, and	Social and business acceptance; industrial dynamics; neglect of cost-minimization

Innovation	Pathway A	Pathway B	Constraint
	cost-effective renewables option and favourable past policy support. The pending policy changes partly support the model outcomes, with only residual growth corridors for onshore wind foreseen in the short term (after offshore and PV), which has raised protests from onshore wind advocates and cost-effectiveness concerns.	raises questions of public acceptance due to conflicting land-uses and NIMBY effects (depending on its implementation).	
Offshore wind	Offshore wind capacities and generation increase dramatically, particularly from 2020-2030 and 2040-2050, which due to the technologies high costs is in conflict with Germany's new focus on cost-minimization. Resistance from excluded new entrants can also be expected. Technological risk due to missing long-term experience.	No further growth of offshore wind after 2020, thereby endangering economic development and jobs in Northern Germany.	Political and social acceptance, techno-economic costs and risks
Solar PV	Solar PV is phased out by 2050, which is completely unthinkable from today's perspective, given the technologies declining costs, legitimacy and public acceptance.	No further growth of solar PV between 2020 and 2040 (apart from repowering after 2030), and then doubling of capacities & generation between 2040 and 2050.	Social, business and political acceptance, lack of technological diversity, industrial dynamics
5. CCS + lignite	CCS roll-out starts around 2040 and is implemented for lignite only. CCS is in conflict with the lack of public acceptance for CO_2 storage and would require renewed policy commitment. It enables a growth of lignite use, which may address resistance against the phase-out of lignite (losses of income & jobs) but also cause turmoil of environmental groups.	No CCS. Therefore continuous phase out of lignite which is completed by 2050. This is in conflict with resistance from lignite regions, unions and incumbents opposing the phase-out of lignite.	Social acceptance, political commitment, economic development, jobs
Unabated hard coal	While the share of coal based capacities and generation declines until 2040 it does not shrink further, implying that coal is not completely phased out (nor complemented through CCS) by 2050. This is in conflict with	Similar to Pathway A, but phase-out continues in 2050, with much lower load hours of the remaining coal capacities, and therefore smaller	Public acceptance, political credibility, climate policy concerns

Innovation	Pathway A	Pathway B	Constraint
	climate policy ambitions and lack of public acceptance for a continuation of coal.	tensions.	
Unabated gas	Stabilization of gas capacities with very low load hours, implying a challenge to the business model and necessitating much debated capacity mechanism.	After initial decline of gas capacities and generation after 2030 gas capacities grow, particularly after 2040, and generation reaches almost a third of German electricity, raising concerns about the achievement of renewable and decarbonisation targets.	Business model, social acceptance; political commitment, energy security
Electricity grid expansion	The (at least economically) indicated strong grid expansion creates tensions with current grid trajectories where there is much inertia and local resistance to grid-projects. The transnational interconnector capacity has to be more than doubled until 2050, leading to the construction of new overhead lines at borders, but also within the countries.	Pathway B suggests even stronger grid expansion, more than tripling the transnational interconnector capacity due to the higher share of renewables. The higher share of PV also calls for a stronger expansion of the distribution grid, with associated NIMBY and cost concerns.	Social acceptance; political commitment; finance; organizational slack; regulatory conservatism
Import and export	Both pathways turn Germany from a net exporter of electricity to a net importer (in A ca. 110 TWh in 2050). This assumes a massive expansion of cheap renewables in other European countries, e.g. onshore wind in the UK (which currently faces serious barriers, see UK study) and requires the construction of new interconnectors.	After 2040 import is significantly higher than in Pathway A (ca. 160 TWh in 2050), while up to 2040 it is lower, leading to similar tensions – but energy security concerns may be significantly larger in B in 2050.	Political and social acceptance; dependence on success of decarbonisation on developments abroad; finance

Please note that in contrast to the UK case, in Germany nuclear power is discontinued both in pathway A and B, following the government's credible phase out strategy until 2022 (backed by cross-party consensus). Therefore, there are no tensions between model results and regime analysis regarding nuclear energy in Germany.

In the following, a short summary of both socio-technical scenarios representing pathway A and B is presented below. Underlying argumentation and lessons can be found in the chapter 5 and 6 of the report.

Scenario 1 (Pathway A): The renaissance of large-scale electricity generation based on offshore wind and CCS for lignite

Phase 1 (2015-2022): first experiences with renewables auctions and completion of nuclear phase-out

By the end of 2022 all nuclear power had been phased-out which was enthusiastically celebrated by policy makers and society alike. The expansion path foreseen for renewable energies was only marginally exceeded, the least efficient lignite and coal plants had been shut down, offshore wind had started to kick off, and auctions became the new normal in determining the level of support, thereby twisting the discourse more towards cost-effectiveness. The emerging exclusion of new entrants, such as cooperatives, farmers or private households as investors into renewable energies started to lead to some frustration and signs of citizen disconnection from the Energiewende vision. This also fed back to limited enthusiasm for smart meters, as the Energiewende was increasingly seen as technological transition project managed by the big guys, with many households becoming less enthusiastic about the idea of producing and consuming their own energy. However, climate targets could not fully be met, despite several additional measures across all sectors.

Phase 2 (2023-2035): offshore wind rules as public acceptance for onshore wind declines, CCS moves forward, and PV goes abroad

In the second phase offshore wind emerged as winning new regime, while onshore wind and solar PV experienced stagnation and even negative momentum, with much of the investment eventually being channelled to locations abroad with higher resource endowments. The CCS model regions witnessed great success in creating public acceptance for CCS and lignite, by pursuing a holistic regional development strategy, with the first plant going online in 2034. As for unabated coal and lignite, their phase out was occurring to plan. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. auction pilots onshore wind, EUA buy-out, interconnectors), a continuation of market-based policies (e.g. auctioning for renewable, EU ETS, roll out of white certificate scheme), and a recognition of the need for active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental CCS task force), and new regulatory institutions (e.g. dynamic pricing). Together, these changes enabled Germany to meet both its renewable and energy efficiency targets as well as its climate targets, and put it on track for an electricity system dominated by offshore wind and lignite+CCS.

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

Phase 3 was characterized by the continued expansion of offshore wind and CCS+lignite (and export of these technologies), further increases in the flexibility of demand, an almost complete discontinuation of solar PV located in Germany, an increase in bioenergy and gas generation capacities as back-up of the system, and an increase in electricity demand which led to an extension of the coal phase-out to secure cost-effective and secure electricity supply. At the end of phase 3, electricity generation capacities were once again fairly large-scale and mainly owned by a handful of incumbents. That is, while Germany's transition pathway up to 2015 was based on investments in decentralized capacities by new entrants which had led to high socio-political legitimacy for the transition, over time it has changed to a technology driven transition carried forward by incumbents.

Scenario 2 (Pathway B): Solar PV and onshore wind with flexible gas back up for the rest of Europe

Phase 1 (2015-2019): first experiences with renewables auctions alongside nuclear phase-out and experimentation with energy efficiency

In the first phase, the expansion path foreseen for renewable energies was only marginally exceeded, the least efficient lignite and coal plants had been shut down, offshore wind reached its 2020 target of 6.5GW, and climate targets could be met, but only barely, with several additional measures across all sectors. However, evaluation results showed that experience with auctions was mixed: on the one hand, costs had gone down, but on the other hand winning bids had experienced implementation difficulties due to massive public acceptance concerns. Also, the cost-effectiveness discourse was challenged, arguing that offshore wind should not be expanded any further due to its high costs and corresponding impact on the EEG surcharge. Also, the public discourse towards large incumbents became very unfavourable, arguing that they should be no longer subsidized for their offshore wind adventure. This incumbent bashing was further fueled by evaluation results which had clearly revealed the exclusion of new entrants, such as cooperatives, farmers or private households, as investors into renewable energies. The government was very anxious to counteract this development, to avoid further frustration of new entrants, and enacted a large consultation process on the revision of the EEG due in 2019 which turned into a larger visioning process for the desired shape of the decarbonized electricity system.

After long and difficult debates, in the summer of 2019 it was decided that (1) the EEG would return to feed-in premiums for all technologies but offshore wind, (2) Germany would forge a supranational auctioning scheme for offshore wind, ideally on a European level, (3) the white certificate scheme would be rolled out on a national level, and (4) a economy-wide carbon tax of initially 20 Euros/tCO_2 would be introduced whose proceeds were to be split in equal parts into (i) funding local experimentation with behavioral change regarding a range of activities, including in areas of reducing electricity consumption (e.g. lower room temperatures), changing mobility patterns (e.g. higher bike use), and adjusting nutritional habits (e.g. Veggie-Thursday in cafeterias and restaurants), (ii) supporting radical low-carbon and low-energy innovation in industry, (iii) retiring EUA in an effort to increase the carbon price signal from the EU ETS, and (iv) financing the structural change in two model regions willing to phase-out lignite. These changes were applauded by citizens, environmental NGOs, renewable energy and energy efficiency representatives, and COP25 participants. In contrast, incumbents and industry went fairly silent, trying to make sense of the implications of these radical changes for their survival strategies. These announcements sent strong signals across industry and the financial sector that the German governments was seriously committed to the decarbonisation of the economy, and even prepared to take creative and previously unthinkable detours to fix European climate policy inertia. It became clear that if implemented these moves would put Germany again in the position of a European climate champion – and many equally progressive European Member States announced they would join Germany's efforts to fix the EU ETS and support the introduction of a European auctioning scheme for offshore wind.

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

In the second phase Germany witnessed a great dynamic which became largely visible in electricity demand reductions and many actors getting enthusiastically involved in experiments aiming at novel ways of smart electricity generation and use. At the same time, growth of offshore wind, onshore wind, bioenergy and solar PV more or less came to a halt, while conventional capacities were being reduced across the board. Lignite model regions witnessed great success in pursuing a holistic regional development strategy. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. EUA buy-out, interconnectors), a strengthening of market-based policies (e.g. EU ETS, European auctioning for offshore wind, national roll out of a white certificate scheme), and a recognition of the need for active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental green transformation regional 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 its climate and energy efficiency targets (although renewables targets are only reached at a European level), and put it on track for an electricity system which was set to be dominated by solar PV, onshore wind and gas, while at the same time keeping a check on overall electricity demand. Overall, Germany's climate actions caught a lot of international attention due to the country's success with lifestyle changes and electricity demand reductions. However, Germany's electricity transition model was also criticized for too high a reliance on electricity imports rather than higher levels of domestic generation of renewable electricity.

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

Phase 3 was characterized by the doubling of capacities and generation from onshore wind, solar PV and gas. This was driven by the massive deployment of electric vehicles which increased electricity demand. At the end of phase 3, electricity generation capacities were largely small scale, and the ownership structure was diversified among citizens, cooperatives, project developers, industry and incumbents. Given Germany's role as flexible European back-up hub a full decarbonisation was, however, not achieved, which made some argue for a second look at CCS and others point to the European nature of carbon accounting.

.

Conclusion

Based on our analysis we derive a number of broader policy implications. First, both decarbonisation scenarios are very demanding and require major reorientations within the next 5-10 years, but also a continued need to adjust the policy mix to unexpected circumstances. Therefore, both scenarios convey a high degree of urgency to strengthen policy commitments while at the same time remaining flexible to adjust the policy mix as the transition unfolds and new insights become available.

Second, German policymakers are recommended to keep and further strengthen their participatory and reflective policy making style, which incorporates close monitoring of policy effects, their evaluation and subsequent adjustment of policy instruments. Such a focus on inclusive policy making and policy learning is essential given the uncertainties and multiple challenges associated with the energy transition. Also, given recent changes in Germany's renewable energy policy paradigm – away from a close focus on risk reduction to enable investments of new entrants to a greater attention to cost-efficiency typically associated with larger players, including incumbents – policy makers should pay particular attention to the impact of this policy paradigm shift. For example, monitoring should include changes in the ownership structure and associated changes in the public acceptance of the Energiewende.

Third, social acceptance will be a crucial success factor – if not the main success factor – for the decarbonisation of the German electricity system (e.g. massive role-out of onshore wind by incumbents, phasing out of solar PV, introduction of CCS, grid enhancement). Therefore, public acceptance should continue to receive close attention in designing policies for the Energiewende, rather than just focusing on cost-efficiency concerns.

Fourth, resistance from incumbents is a major challenge of the success of the German electricity transition. Therefore, policy makers should explore creative and novel policy approaches, such as green model regions, or a partial role-out of new instruments, such as pilot schemes. Such novel approaches will be needed to manage and overcome resistance to change, as, for example, being the case for the difficult phase-out of lignite.

1. Introduction

According to the D2.5 research protocol developed by Frank Geels this report aims to develop qualitative storylines that describe plausible socio-technical transition pathways for the revised quantitative scenarios that have been developed in WP1 in the context of D1.3. So, we take the revised WP1-scenarios as starting point and ask what needs to change (in a socio-technical sense) to make those scenarios happen. The problems we address are the huge "transition challenges" arising from D1.3 model results, and the limit attention paid to actors, struggles, strategies and resistance for change.

Against this background, the task for D2.5 is to develop more nuanced storylines that indicate and explain how turn-arounds and transitions can be made in the German electricity domain. In terms of the internal logic of WP2, this means that D2.5 is a forward-oriented analysis, which builds on the previous deliverables that investigated historical trajectories from ten years ago to the present:

- D2.1 analysed green niche-innovations and their momentum.
- D2.2 analyses stability and tensions of incumbent socio-technical regimes.
- D2.3 integrated findings from D2.1 and D2.2 to assess feasibility of different transition pathways.
- D2.4 made a comparative country analysis of contemporary transition pathways in different domains.

D2.5 makes the step from the recent past towards future transition pathways. To develop future transition pathways from a socio-technical perspective, D2.5 uses a relatively new methodology: socio-technical scenarios.

The key characteristics of socio-technical scenarios include (Geels, 2002; Elzen *et al.*, 2004; Hofman *et al*., 2004; Hofman and Elzen, 2010; Verbong and Geels, 2010; Marletto, 2014; Nilsson and Nykvist, 2016):

1. Description of the ***co-evolution of technology and its societal embedding***, i.e. attention is paid not only to technological development – the focus of PATHWAY A – but also to institutional change, different types of actors, their strategies and resources, among other broader changes in socio-technical system – predominantly covered in PATHWAY B.
2. Guidance of storylines by ***socio-technical theories***, i.e. discussing interactions between niche-innovations, incumbent regimes and broader 'landscape' dynamics (e.g. learning processes and niche dynamics, interaction between niches, niche niche-cumulation).
3. Focus on the ***endogenous logic*** of transition pathways, i.e. explaining the underlying reasons for its development based on choices, decisions, strategies, and beliefs of actors, all of which are shaped by changing micro- and meso-logics as well as external macro-developments.

The socio-technical scenarios in the PATHWAYS project are guided by the following ***constraints:***

- Guidance by MLP and by the logic of *pathways A and B*, with incumbent actors being the main actors in pathway A and new entrants in pathway B.
- Recognition of *lock-in mechanisms and path dependencies in the present*, based on WP2 findings.

- Quantitative model outcomes (and turning points) from WP1 as basis to develop plausible endogenous storylines for how the end goals can be reached.
- Focus on overcoming the *tensions* ('transition challenges') between WP1 future (quantitative) scenarios and present WP2-findings.

That is, this deliverable aims to develop an endogenous storyline for the German electricity system – written as 'history of the future', i.e. in past tense – describing how interactions between various actors (and changes in technology, institutions, beliefs, social networks, etc) can generate – either Pathway A or pathway B – dynamics which overcome the 'transition challenges'. While the two socio-technical scenarios developed here describe one trajectory each, at times we mention 'forks in the road' (branching points) and how/why actors decided to go down one road instead of the other, including controversies, setbacks and power struggles. Since the storylines focus on the endogenous logic (i.e. interactions between actors), we pay most attention to niche-innovations and existing regimes rather than sudden exogenous landscape shocks.

The report is structured as follows. Chapter 2 provides a summary of the quantitative scenarios for Pathway A and B which lead to the EU's climate change targets for 2050 and were calculated by the PowerACE model (a more detail description can be found in the PATHWAYS deliverable D1.3). Chapter 3 describes the empirical findings of a socio-technical analysis about contemporary developments in green-niche innovations and existing regimes in the German electricity system. As an intermediate step, chapter 4 articulates the 'transition challenges' by comparing outcomes from modelling (chapter 2) and the socio-technical analysis (chapter 3). These transition challenges offer specific guidance for the socio-technical scenarios which need to develop endogenous storylines for how the challenges can be overcome. Chapter 5 and 6 represent the core of the deliverable, as they describe two socio-technical scenarios for pathway A and B for the German electricity system. These scenarios, by paying particular attention to actors and contexts, aim to offer a socio-technical explanation for the quantitative developments from D1.3 (described in Chapter 2). The report ends with concluding remarks in chapter 7.

2. Quantitative scenarios from D1.3

2.1. Model assumptions

This chapter describes the quantitative scenarios for the German electricity system which have been developed in D1.3, using computer models – in particular the model PowerACE. In the context of the development of socio-technical scenarios which help explain how to achieve mitigation pathways which achieve the ambitious climate targets, here we focus on the differences and similarities between the two pathways A and B, which are based on different assumptions, as depicted in Table 1.

On the one hand, both Pathways A and B have strong climate policies in place and are assumed to reach an 80% reduction in GHG emissions in 2050 compared to 1990 levels. On the other hand, the specifics of the transition pathways are quite different, because they represent different analytical ideal-types, which differ both in terms of lead actors, depth of change and scope of change (Table 1). The main policy driver in both Pathways is an assumed high CO2 price or carbon cap, which improves the economic competitiveness of low-carbon options (like nuclear, CCS or renewables).

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

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

As already outlined in the UK electricity domain report Pathways A and B are based on several general assumptions:

- Autonomous energy efficiency improvements and learning rates in renewable electricity technologies (RETs).
- Policymakers introduce price-based policies and/or carbon caps (with the carbon price in pathway B being higher than in pathway A) which lead to price-based energy efficiency improvements throughout the economy (driving overall demand reduction) but also incentives for switching to electric vehicles.
- It is assumed that EU countries meet their RES targets for 2020 as defined in their National Renewable Energy Action Plans (NREAPs).

Pathway A further includes the following specific assumptions:

- Pathway A is dominated by incumbent actors with a preference for large-scale technologies (onshore and offshore wind parks, freefield PV, but no nuclear power due to the nuclear phase out policy in Germany).
- Offshore wind is stimulated with policies (e.g. subsidies, state-aided loans) so that the effective price becomes similar to the costs of onshore wind, making offshore wind highly attractive for investors.
- The land availability is used as an indicator to represent social and political acceptance of renewable electricity technologies: compared to a pathway without climate policy the parameter is decreased by one third for solar PV (to represent tensions of this option with the large-scale assumptions in pathway A), and increased by a half for on- and offshore wind (to represent higher acceptance).
- The use of low-carbon vehicles is stimulated by subsidizing the upfront purchasing price of new vehicles in passenger transport, thereby significantly increasing demand for electric mobility and thus electricity after 2037.
- Germany switches from being a net exporter of electricity to a net importer, with net imports reaching approximately 15% of Germany's electricity use in 2050.

Pathway B is based on the following specific assumptions:

- Electricity systems are transformed more broadly through the involvement of new actors, changing preferences and different lifestyles.
- CCS is excluded in this scenario, because it faces social acceptance problems (among others, due to its perceived risks, particularly regarding storage).
- Onshore wind is in general a very attractive renewable electricity technology due to its low costs; however, as PowerACE is a European optimization model onshore wind is largely build outside of Germany, e.g. in the UK as the windiest country in Europe.
- Solar PV is privileged in this scenario because its decentralized characteristics work well with new entrants (such as citizens, local communities, farmers, schools). This privileging is represented in the quantitative models by allowing a higher utilisation of land, representing a higher acceptance of PV field power plants. Furthermore, a lower interest rate is assumed especially for roof-mounted PV modules, representing a situation in which house owners are willing to accept lower (or no) profits compared to other investment opportunities, but actively want become involved in the power system.
- Greater bottom-up participation is assumed, which is reflected in several changes in lifestyle: the general public accepts a more local lifestyle, moves away from private vehicle use (e.g. favouring mass transit or car sharing), people accept a lowered level of comfort at home (via a lower temperature setting), they use their appliances smarter and refuse excessive electric appliances (clothes dryer).
- The use of low-carbon vehicles is stimulated by subsidizing the upfront purchasing price of new vehicles in passenger transport and further supported by a higher CO_2 price and people's increased preference for carsharing, thereby significantly increasing demand for electric mobility and thus electricity already after 2035.
- The model uses Germany as a flexibility source in this scenario, especially by building gas power plants. The model then uses the enhanced transmission grid to transport electricity both to Germany and its neighbours. Overall, Germany imports even more electricity in this scenario (about 25%). Therefore, Germany is atypical for this scenario, with a relatively low share of renewable electricity.

2.2. Quantitative scenarios for the German electricity system

Figure 2 and 3 show the quantitative PowerACE model results for the two different transition pathways A and B, both in terms of capacity and actual electricity generation. The difference between both indicators may be especially large for solar PV as intermittent renewables with a relatively low load factor, given fairly moderate sunshine hours in Germany. Given the increasing share of intermittent renewables (apart from PV mainly wind energy) both pathways require significant amounts of back-up capacity (e.g. gas-fired power stations) that can be flexibly switched on when there is limited wind or sunshine. Below, we describe the model outcomes of each scenario in greater detail, drawing on findings from D1.3.

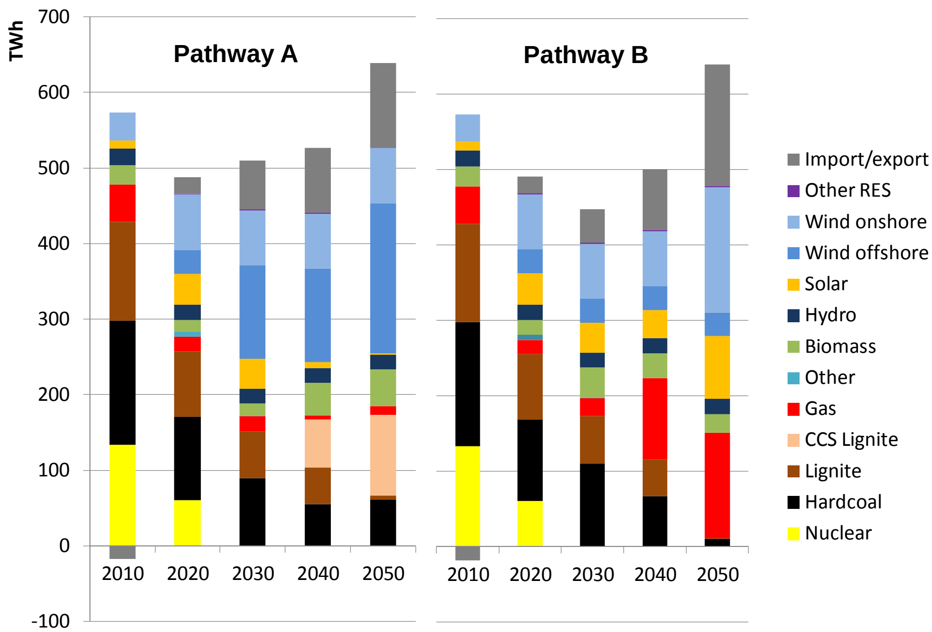

Figure 2: Installed capacity in electricity generation in Germany (based on D1.3)

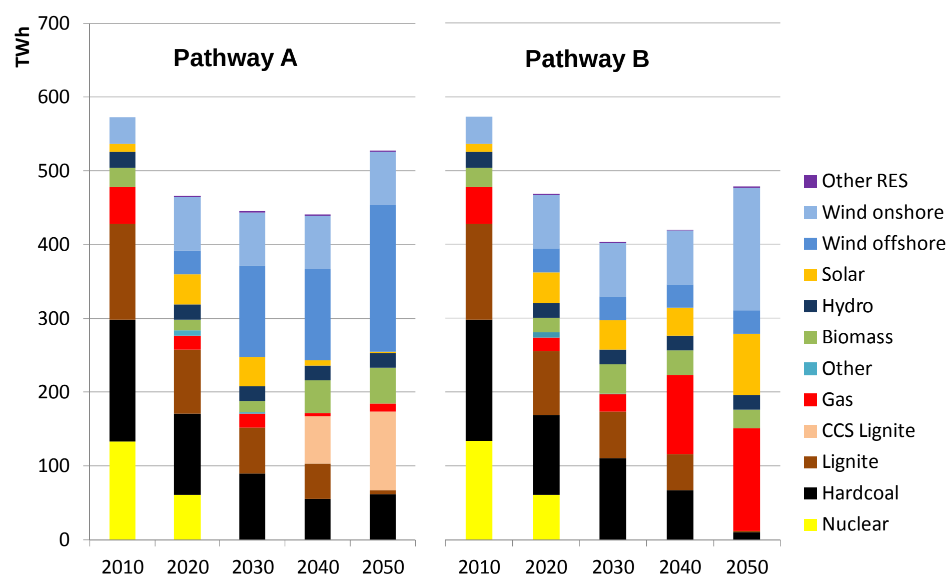

Figure 3: Electricity generation in Germany in TWh (based on D1.3)

Pathway A in the German electricity system

Pathway A in Germany leads to an electricity generation system which by 2050 is dominated by offshore wind, lignite+CCS, and gas as back-up:

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

Pathway B in German electricity

Pathway B in Germany leads to an electricity generation system which by 2050 is dominated by onshore wind, gas and solar PV:

- As in pathway A, nuclear is phased out by 2022, in line with the German nuclear phase-out strategy.
- In contrast to pathway A, unabated lignite is completely phased-out by 2050, showing the critical relevance of CCS for a continued future of lignite based electricity generation.
- While unabated hard coal follows a similar retirement pattern as within pathway A, in pathway B the remaining hard coal power plants run with lower load factors, leading to a much smaller share in electricity generation than in pathway A.
- Natural gas (without CCS) declines until 2030 (similar as in Pathway A), but thereafter has a strong renaissance both in terms of capacity (which is almost doubled between 2040 and 2050) and generation.
- Solar PV, in stark contrast to pathway A, maintains a high share in electricity generation capacities and more than doubles these between 2040 and 2050 to become the largest

share of overall capacities, followed by onshore wind and gas). However, load factors remain low, so that the overall share in electricity generation increases to roughly 15% by 2050 only.

- After 2023, onshore wind increases much faster than in Pathway A, and becomes the central pillar of Germany's electricity supply. It is the cheapest renewable electricity technology, which benefits from high public acceptance. An increasing part of onshore wind comes from new entrants (e.g. community energy, farmers), which deviates from Pathway A, where incumbents are the main actors.
- In contrast, offshore wind does not increase beyond 2020, but only maintains 2020 levels up to 2050 (through repowering).
- Biomass remains fairly stable at current figures, and if anything is being slightly reduced (mainly between 2040 and 2050).
- Even earlier than in pathway A Germany becomes an importer of cost-efficient renewables, which reaches substantial amounts by 2050 (ca. 25%).
- The high shares of solar PV and onshore wind require a strong expansion of the electricity grid, particularly long-distance transmission grids, interconnectors to European countries, and storage solutions.
- Electricity demand follows a similar pattern as in pathway A, but demand reductions are slightly stronger, therefore demand in 2050 is smaller under pathway B. Also, demand increases caused by the surge of electric vehicles kicks in slightly earlier than in pathway A (already around 2035).

'Transition challenge'

Scenario A and B, which reach 80% reductions in CO_2 emissions by 2050, both represent substantial changes compared to the historical and contemporary trajectories in German electricity. To further articulate this 'transition challenge', we will first describe the current momentum of green niche-innovations and existing regimes in the German electricity system (chapter 3) and then compare these with the two future-oriented scenarios, described above. This will result in the identification of particular 'transition challenges' (chapter 4), which will then guide the development of actual qualitative scenarios (chapter 5 and 6).

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

3.1. Niche-innovations

Table 2 summarises the conclusions of the analysis of selected niches within the German electricity system which was conducted in 2014 and published 2015 in D2.1. In its assessments it covers three dimensions of niche-momentum*: techno-economic* (market share, price/performance improvements), *socio-cognitive* (size of social networks, learning processes, coherence of future vision), and *governance* (degree of policy support). It also includes our interpretation of whether the niche fits better with Pathway A or B. With regard to electricity generation options, the results show a clear relative ranking and assessments of current momentum (as of 2014):

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

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

Table 2: Findings from D2.1 on momentum of German electricity niche-innovations

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

3.2. Electricity regime developments

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

Over the period from 1990 until today the **German electricity *generation* regime** has witnessed major landscape pressures – most importantly a strong anti-nuclear movement paired with concerns about climate change. Additional tensions have resulted from the increasing impacts of the emerging niches of wind, solar PV and bioenergy, which have expanded significantly and can now start to be viewed as new sub-regimes. The sheer size, different ownership structure and characteristics of these emerging green sub-regimes have meant fundamental changes along many dimensions of the German electricity regime. This regime is now transforming from one characterized by centralized, large-scale electricity generation dominated by large utilities to a much more decentralized, and smaller scale electricity generation regime based on renewable energies, with the ownership of generation capacities spread across a multitude of new entrants, including a high share of citizens, farmers and cooperatives. In addition, the established business models of the incumbent utilities are eroding. Indeed, while the large incumbents have undergone multiple changes in beliefs and are now investing in large-scale renewable energies, their long-term survival is still at stake because of their lack of business model capabilities to harness the chances and opportunities from the ongoing energy transition. In 2012 and 2013, however, the decarbonisation of the electricity generation system experienced a setback due to rising shares of lignite and hard coal in the generation mix – despite declining capacities. There have also been recent changes in the key policy instrument supporting the expansion of renewable energies, the EEG, which indicate a change in policy favouring larger investors. This is partly due to pressures to advance the market integration of renewables, and partly due to political concerns about the ever-increasing EEG surcharge, which is largely borne by private electricity consumers because of the exemptions for energy-intensive industries. Hence, while nuclear phase-out and the transition towards renewable energies are not being questioned, there are ongoing disputes about what the future regime will look like (e.g. regarding the degree of decentralization) and who the winners and losers will be.

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

Over the period from 1998 until 2015, the **German electricity *network* regime** has been experiencing major challenges to the traditional operating strategies of the power system. Major drivers were developments in the generation structure with the emerging niches of wind, solar PV and bioenergy as well as the nuclear phase-out driven by the anti-nuclear movement. Another major factor at landscape level was the push for liberalization and unbundling of the electricity sector initiated and pursued by the EU from 1996 to 2009 with three waves of liberalization directives. Changes in generation structure have challenged and are still challenging the system physically and require network expansions. However, since network expansion is not keeping pace with the changes, is plagued by acceptance issues and might not always be the most efficient solution, adaptations in network operation and management are also required. To some extent, this is taking place already with network operators engaging in redispatch and generation management. However, so far, this is mainly being managed centrally via the network operators and (nearly) limited to emergency situations. A wider use of flexibility options is being discussed, but the framework to implement this is still missing. This shifts the focus to the flexible management of generation and supply, optimization via smart grids using intelligent control and metering as well as storage solutions. It may therefore push the niche development of smart metering. Overall, the system is moving from centralized, top-down management towards a more decentralized, interactive system, but so far this is mainly happening on a physical level. This represents a challenge for the networks, some of which are approaching their limits already, but which cope mainly using existing measures. In the future, roles, responsibilities and regulations will have to be modified to be able to adapt operations to these changes. At the same time, transmission networks are also being enhanced by innovative technologies and it is not yet clear what the network regime of the future will look like and how it will combine smarter distribution and expanded and enhanced transmission (probably also long-distance, high-voltage transmission to connect with other countries). The network business as a centrally regulated activity is relatively stable per se, but is undergoing reconfiguration. Changes to regulation have been made to adapt it to the investment needs and quality demands which enable further changes in the future.

4. Specifying 'transition challenges'

Before developing socio-technical scenarios, we articulate several tensions and contradictions between the quantitative scenarios from WP-1 (described in chapter 2) and socio-technical findings from WP-2 (described in chapter 3). These tensions form the 'transition challenges' between contemporary trends and developments, on the one hand, and the future changes that are needed to achieve the climate change goals. 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.

Table 3 describes these tensions for key low-carbon innovations, disaggregated for Pathway A and B. The last column also qualifies the transition challenges in terms of different *kinds* of constraints, using categories from Loftus *et al*. (2015): 1) technology readiness, 2) economics, 3) integration issue (especially new grid infrastructure, intermittency problem, storage, back-up capacity, 4) social and non-cost barriers (both policy commitment and social acceptance). Interestingly, this column shows that ***social acceptance is creating obstacles for all innovations,*** but many also raise concerns in terms of political commitment.

The socio-technical scenarios in chapter 5 and 6 aim to offer plausible pathways for how these transition challenges can be overcome via socio-technical interactions.

Table 3: Tensions between future model scenarios for German electricity generation and WP-2 findings of niche-momentum and path dependencies

Innovation	**Pathway A**	**Pathway B**	**Constraint**
Biomass	Pathway A assumes a moderate expansion of biomass in electricity use in 2040 and 2050, which contradicts with today's sustainability and cost concerns as well as competing uses of biomass use, which together have led to a downscaling of the further growth prospects of biomass within the German EEG.	Only intermediary upscaling, but by 2050 reduction to 2010 levels, therefore smaller and only temporary tensions.	Political commitment, social acceptance, environmental sustainability
BECCS (biomass energy with CCS)	BECCS plays a large role in European scenarios (especially after 2050 to generate 'negative emissions'). BECCS is introduced in 2030 and reaches a 90% share of all German/EU bioenergy use by 2050. This creates two main tensions: 1) BECCS is not yet viable and not much is happening 'on-the-ground', making it risky to base future scenarios on something that hardly exists in the present. 2) CCS faces significant public resistance (see below).	No CCS in pathway B (and no BECCS).	Technology readiness, economic costs, political commitment, social acceptance
Onshore wind	Onshore wind capacities are assumed to decrease and remain	Until 2040 onshore wind develops like	Social and business

Innovation	Pathway A	Pathway B	Constraint
	stable from 2030 onwards (through repowering); generation is assumed to slightly increase until 2020, and thereafter is expected to stabilize at this level. This is in stark contrast to the currently very high momentum of onshore wind, which can be traced back to it being the most cost-effective renewables option and favourable past policy support. The pending policy changes partly support the model outcomes, with only residual growth corridors for onshore wind foreseen in the short term (after offshore and PV), which has raised protests from onshore wind advocates and cost-effectiveness concerns.	pathway A, with similar concerns. But thereafter it more than doubles its capacity and generation. This long-term jump is in conflict with the need for continuous industry build, and raises questions of public acceptance due to conflicting land-uses and NIMBY effects (depending on its implementation).	acceptance; industrial dynamics; neglect of cost-minimization
Offshore wind	Offshore wind capacities and generation increase dramatically, particularly from 2020-2030 and 2040-2050, which due to the technologies high costs is in conflict with Germany's new focus on cost-minimization. Resistance from excluded new entrants can also be expected. Technological risk due to missing long-term experience.	No further growth of offshore wind after 2020, thereby endangering economic development and jobs in Northern Germany.	Political and social acceptance, techno-economic costs and risks
Solar PV	Solar PV is phased out by 2050, which is completely unthinkable from today's perspective, given the technologies declining costs, legitimacy and public acceptance.	No further growth of solar PV between 2020 and 2040 (apart from repowering after 2030), and then doubling of capacities & generation between 2040 and 2050.	Social, business and political acceptance, lack of technological diversity, industrial dynamics
5. CCS + lignite	CCS roll-out starts around 2040 and is implemented for lignite only. CCS is in conflict with the lack of public acceptance for CO_2 storage and would require renewed policy commitment. It enables a growth of lignite use, which may address resistance against the phase-out of lignite (losses of income & jobs) but also cause turmoil of environmental groups.	No CCS. Therefore continuous phase out of lignite which is completed by 2050. This is in conflict with resistance from lignite regions, unions and incumbents opposing the phase-	Social acceptance, political commitment, economic development, jobs

Innovation	Pathway A	Pathway B	Constraint
		out of lignite.	
Unabated hard coal	While the share of coal based capacities and generation declines until 2040 it does not shrink further, implying that coal is not completely phased out (nor complemented through CCS) by 2050. This is in conflict with climate policy ambitions and lack of public acceptance for a continuation of coal.	Similar to Pathway A, but phase-out continues in 2050, with much lower load hours of the remaining coal capacities, and therefore smaller tensions.	Social acceptance, political credibility, climate policy concerns
Unabated gas	Stabilization of gas capacities with very low load hours, implying a challenge to the business model and necessitating much debated capacity mechanism.	After initial decline of gas capacities and generation after 2030 gas capacities grow, particularly after 2040, and generation reaches almost a third of German electricity, raising concerns about the achievement of renewable and decarbonisation targets.	Business model, social acceptance; political commitment, energy security
Electricity grid expansion	The (at least economically) indicated strong grid expansion creates tensions with current grid trajectories where there is much inertia and local resistance to grid-projects. The transnational interconnector capacity has to be more than doubled until 2050, leading to the construction of new overhead lines at borders, but also within the countries.	Pathway B suggests even stronger grid expansion, more than tripling the transnational interconnector capacity due to the higher share of renewables. The higher share of PV also calls for a stronger expansion of the distribution grid, with associated NIMBY and cost concerns.	Social acceptance; political commitment; finance; organizational slack; regulatory conservatism
Import and export	Both pathways turn Germany from a net exporter of electricity to a net importer (in A ca. 110 TWh in 2050). This assumes a massive expansion of cheap renewables in other European countries, e.g. onshore wind in the UK (which	After 2040 import is significantly higher than in Pathway A (ca. 160 TWh in 2050), while up to 2040 it is lower, leading to similar	Political and social acceptance; dependence on success of decarbonisation on

Innovation	Pathway A	Pathway B	Constraint
	currently faces serious barriers, see UK study) and requires the construction of new interconnectors.	tensions – but energy security concerns may be significantly larger in B in 2050.	developments abroad; finance

5. Scenario 1 (Pathway A): The renaissance of large-scale electricity generation based on offshore wind and CCS for lignite

Core characteristics, logics and challenges

This scenario provides a socio-technical storyline for Pathway A, using the quantitative PowerACE modelling results for this pathway reported in D1.3 (see Figures 2 and 3 above). In conceptual terms this pathway focuses on large-scale low-carbon technologies, such as offshore wind and CCS, which mainly represents disruptive technological change which is in contrast to how the German electricity system has been unfolding sofar – where many elements of the socio-technical system had been affected. Incumbent actors are the dominant actors in Pathway A, where a core logic is that governments change market institutions (regulations, financial incentives) to facilitate the low-carbon reorientation of large firms. The introduction of new policy targets and instruments needs to be underpinned by societal and cultural discourses (to create societal legitimacy) and support coalitions (especially firms in Pathway A, but also other actors). Major 'transition challenges' concern: 1) *social acceptance problems* with regard to the further roll-out of offshore wind by incumbents, the survival of the lignite industry through the role-out of CCS, grid expansion and the discontinuation of solar PV and limited role of onshore wind as well as the slow phase-out of coal (table 3 above), and 2) the need for *political decisions* regarding preferred technologies (offshore wind, CCS with lignite, gas as back-up) and the implementation of a favourable policy mix. These problems start to become visible in the first period (2015-2022) in which the policy paradigm changed from new entrant friendly feed-in tariffs to a more market-based auctioning system. However, many further policy mix changes are postponed until later periods, as this period's renewables targets are easily achieved and much attention focuses on the termination of nuclear power by 2022. However, extra climate policy efforts are required since the German government's greenhouse gas reduction target would otherwise not be met. Finally, resistance from less progressive EU Member States needs to be overcome to install a clear decarbonisation signal.

5.1. Phase 1 (2015-2022): first experiences with renewables auctions and completion of nuclear phase-out

In its Energy Concept from 2010 the German government had committed itself to a reduction of its greenhouse gas emissions by 40% by 2020 (compared to 1990 levels), and to a reduction of 80-95% by 2050. These targets were reiterated at several occasions, including in the coalition agreement of Merkel's Grand Coalition government (2013-2017) and in the context of the Paris agreement from December 2015. Since a great share of emissions stemmed from the energy system, the government's initial focus was on decarbonising the energy system. In addition, given the strong public opposition to nuclear power the Red-Green Schröder government had introduced the Renewable Energy Sources Act (EEG) in 2000, providing long-term, technology-specific investment incentives for renewable energies. Over time, the EEG continuously led to a faster than anticipated increase of the share of renewable based electricity generation from less than 5% in 2000 to more than 33% in 2015. This Act, which had been regularly amended based on evaluation results, still represented the core instrument pushing the further expansion of renewable energies, but was significantly redesigned in its revision of 2016.

The second core policy influencing the development of the German electricity system in this period was the nuclear phase-out policy which the Red-Green Schröder government had negotiated with incumbents in 2002. While Merkel's Conservative-Liberal government had originally annulled the phase-out deal in 2010, after the Fukushima incident the nuclear phase-out became a central part of Germany's Energiewende, with a cross-party consensus supporting the step-wise close-down of the remaining nuclear power plants until 2022 (which is why this first phase ends in 2022).

However, at the same time it was clear that without additional policy support Germany would miss its climate policy targets for 2020 by 7%, despite being on track with its target of expanding the use of renewable energies within electricity generation to a share of 40-45% by 2025, and at least 80% by 2050.

In the first phase from 2015-2022 the government's strategy for the decarbonisation of the electricity system thus was based on the continued expansion of renewable energies – but largely due to rising cost concerns and a desire to move to the next level of the energy transition with a more market-based support policy – and further integration of renewable energies into the electricity system, which included major changes in existing regimes (nuclear, coal, lignite, gas, network) and further upscaling of niche-innovations (toward the end of the phase particularly offshore wind, prior to that also onshore wind).

Old regime developments:

By 2015, the electricity *generation regime* in Germany was undergoing radical changes, given the rapid expansion of renewable energies, and in particular of wind and solar PV. However, while no actor questioned anymore the transition towards renewable energies, there was a dispute about the final regime dimensions. Resistance from regime actors focused on reducing losses (e.g. by law suits, asset sweating), while they were mainly busy with trying to identify new business models to ensure their survival in the new renewable-based regime. There were major tensions and cracks in the electricity generation regime. The climate change problem and anti-nuclear movement led to significant institutional changes, e.g. ambitious targets for GHG reduction, RES expansion and nuclear phase-out and specific policy instruments. The resulting structural changes in infrastructure (renewable energy made up 50% of generation capacity, with a negligible share owned by large incumbents) with their reduction of electricity market prices and thus decreased profitability of existing conventional plants were forcing large incumbents to rethink their beliefs, strategies and organisational structures. A closer look at the different technological sub-regimes reveals the following developments:

- Germany's *nuclear* phase-out proceeded as planned, with a step-wise closing down of the remaining eight nuclear power plants, with plant closures in 2015 (Grafenrheinfeld), 2017 (Gundremmingen B), 2019 (Philippsburg 2), 2021 (Grohnde, Brokdorf, Gundremmingen C) and the last ones at the end of the period in 2022 (Isar 2, Neckarwestheim 2, Emsland). These closures were highly celebrated across society. Interestingly, they also created new jobs in decommissioning nuclear power plants, with the government providing training programs to help build up the required expertise. While three of the four affected plant operators sued the government for its abrupt phase-out decisions in the wake of the Fukushima disaster in Japan in 2011, this was not about reversing the decision but about who carries the costs of closing down the nuclear power plants prior to their retirement age. When the supreme court finally ruled against the large incumbents, this did not come as big of a surprise, but further disrupted large incumbents and was just seen as another pointer for them to face the new realities. However, policy makers still struggled with identifying a suitable final deposit site for Germany's radioactive waste, with an expert commission that worked hard but only managed to establish generic search criteria in 2016, which marked the beginning of a new and systematic scientific search process.

- Regarding *coal and lignite* there were hardly any new plants being built, but existing plants reached very high load factors, exporting the excess electricity abroad. The attractiveness of coal and lignite was largely based on low resource prices and low CO_2 prices, the latter resulting from the overallocation and built up surplus of allowances in the EU Emission Trading System (EU ETS). Particularly the nearly exhausted load hours of lignite power plants contributed to a rise in the CO_2 emissions of Germany's electricity system, which were coined as Paradoxon of the Energiewende. It became increasingly clear that a phase-out policy for lignite fired power plants was needed, but the proposal made by Gabriel made prior to COP21 in Paris and which was based on the polluter-pays-principle faced heavy political resistance from a coalition of incumbents, unions and federal states dependent on the income generated by the industry. Yet, given the gap in CO_2 target fulfilment and the endangered international credibility of the German government a set of additional climate policy measures was adopted, including financial compensation for the closure of the dirtiest lignite power plants. Environmental NGOs were complaining that instead of the polluter paying Germany had opted for paying the polluter not to pollute. Still, the move reduced CO_2 emissions and helped Germany take a strong position in the Paris climate negotiations. However, later attempts of the environment ministry and environmental NGOs and think tanks to work out a lignite phase out policy were not successful in the political process and only appeared in a very watered down version in Germany's climate protection plan for 2050.
- The government decided to revisit the *carbon capture and storage (CCS)* technology after follow up attempts by the German government to phase out coal were facing equally strong resistance from incumbents, and EU ETS prices continued to remain low. Given that its most important barrier had been the public opposition at storage sites, in 2017 the new government issued a call for model regions for economically deprived regions which was equipped with substantial national funds to support the economic development of the region towards green technologies while at the same time implementing a CCS demonstration plant with CO_2 storage to go online in 2030. This was set up in a highly participatory and transparent way, with vision building workshops and roadmap development for the model region. Given the high financial attractiveness and participatory nature of the CCS model regions the government in 2020 was able to select two model regions. In 2018, i.e. two years prior to the nomination of the two CCS model regions the government announced a long-term phase-out strategy for unabated lignite and coal with a time horizon of 2050, which it had negotiated with incumbents alongside the implementation of the CCS model regions. It included that the most inefficient lignite and coal fired power plants were going offline already in 2019, to help the government to achieve its climate target for 2020.
- The existing capacities for g*as fired power generation* had to significantly reduce their load hours, thereby further endangering the business model for gas-fired power plants. Main reasons included the low CO_2-price which continued in the fourth trading phase of the EU ETS due to the large remaining surplus of EUAs, and the rising shares of intermittent renewables which lowered electricity costs. In order to keep operators from mothballing their gas fired power plants, even those with highest efficiencies, the government implemented a partial capacity mechanism, which kept existing gas plants as back-up capacity. However, it was not attractive enough to

generate any interest in constructing new gas fired power plants, leaving operators to search for alternative investment options.

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

Finally, the *network regime* initially remained fairly stable with moderate lock-in due to its long-lived assets structure and conservative mind-set and regulation. While some regulatory changes were implemented, such as targeted investment incentives to spur certain developments, their implementation was rather slow and did initially not result in radical changes but only gradual adaptations of the regulatory framework. However, given the ever increasing share of intermittent renewables both industry and policy pressures on the network regime grew, as they shared a keen interest on making the Energiewende an attractive business case and political success story. There was a common understanding that the increase in decentralized and intermittent generation required adaptations to the network management and structure. Policy makers therefore implemented some changes to the regulatory framework allowing and encouraging network operators to make such adaptations. The changes also improved the incentives for network expansion, increased acceptance and streamlined administrative processes. Also, a strong consensus emerged among policy makers and industry that network expansion was needed at the transmission and distribution level, and that distribution networks needed to become more intelligent. However, the actual expansion of networks was much delayed, given some strong resistance of locally affected populations and some Federal States to proposed network routes. While solutions were sought and identified through elaborated stakeholder engagement processes these often implied delays in construction and higher costs due to the increased use of underground cables. However, rather than implementing further changes to network regulation the government reacted to these delays by implementing policy changes which were meant to slow down the speed of the expansion of renewable energies (see below), thereby alleviating some pressures on the network regime. Nonetheless these concessions were seen as temporary and in the long run the electricity network was expected to be increased significantly to allow for high shares of renewable energy.

Emerging new regimes and niches:

In 2016 and after long and difficult negotiations Merkel's Grand Coalition government introduced a paradigm change to the Renewable Energy Sources Act (EEG) – changing its main incentive component from feed-in-tariffs to auctions. Based on experiences made in a pilot with free field PV auctions implemented in the EEG reform of 2014, and having worked out a similar auctioning scheme for offshore wind, starting in 2017 investments in renewable energies were no longer incentivized through ex-ante known feed-in tariffs but determined by technology-specific auctions. The idea behind these auctions was to reduce the costs of the further expansion of renewable energies by allowing for competitive bidding. The government also hoped to be better able to control the rate of expansion of renewable energies to keep each technology's and overall renewables' growth within the foreseen expansion corridor (40-45% in 2025, and 55-60% in 2035). These changes were heavily contested by many new entrants, such as cooperatives and renewable energy industry associations, but also by leading economists and the media as being short-sighted and unduly benefiting large incumbents. As a consequence, the atmosphere in the renewables advocacy coalition towards the government seriously cooled down, and many players lost their belief in the government being a strong promoter of the Energiewende. However, the government defended the implemented policy change by stating that the nurturing phase was over, and that it was time for renewables to grow up and face competition so as to reduce the costs of the Energiewende. Later results initially supported these claims, as the early auctions indeed resulted in surprisingly low tariffs. However, given the strong support of the public for the promotion of renewable energies, pressure from federal states and concerns about public acceptance the government allowed some exemptions for small-scale investors and cooperatives.

- *Onshore wind* experienced massive additional investments prior to the adoption of EEG 2016, because the industry and cooperatives wanted to benefit from the old feed-in tariff system and because onshore wind so far kept its role as cheapest renewable energy technology. However, this boom in onshore wind led to investments exceeding the foreseen expansion corridor. While the industry with its green advocacy coalition argued for an increase of these corridors, which was also supported by calculations of leading experts in light of reaching Germany's 2050 targets, the government remained firmly committed to stay within these corridors. Therefore, despite onshore wind being the cheapest technology the government tried to compensate for the most recent spike in investment in its EEG 2016. However, the government had to make some upwards adjustments in their yearly allowance for onshore wind auctions to address opposition from federal states: it was agreed that from 2017-19 the government would auction off 2.800 MW annually, and thereafter 2.900 MW. However, the government set these as gross figures, thereby incorporating the upcoming repowering of old wind farms. These policy changes led to much reduced activities by cooperatives and farmers which had been the backbone of the Energiewende's take off phase, as many of them could not afford the risks associated with the tendering process. Even though the government claimed to support cooperatives by designing inclusive stakeholder engagement processes and a simple auctioning process, in the end the winning bids came from specialized wind energy project developers and the renewable subsidiaries of incumbents. This change in investors led to a decline in public acceptance for onshore wind in local communities, and a general dissatisfaction of citizens with the Energiewende policy of their government.

- In the negotiations for the reform of the EEG the *offshore wind* advocacy coalition managed to strike an attractive deal with the government, securing sufficient room for the continued expansion for offshore wind despite it being more expensive than onshore wind, namely 6,5GW until 2020, and 15 GW until 2030. One advantage may have been that offshore wind had already contributed to the economic development of deprived coastal regions, and therefore had keen supporters within the affected federal states. Also, after the bottle neck of grid access for offshore wind had been largely resolved in the beginning of the period, a number of new parks went online in 2015 which performed very well, clearly exceeding expectations regarding load hours. This further contributed to incumbents fully embracing the technology as large-scale renewable energy technology which worked well with their capabilities and provided them with an attractive business model in a time of fundamental change. Also, incumbents did not mind the introduction of auctions as they expected to be winners of this policy change. Some policy makers also argued that by allowing incumbents to invest in offshore wind, this may help the survival of incumbents which were struggling to adopt to the changed realities in the energy system, but were increasingly seen as system relevant to keep the lights on in the medium-term. Ironically and against the stated will of the offshore wind advocacy coalition, the preferential treatment of offshore wind ended up harming the cheaper onshore wind technology, as the government's clinging to the expansion corridors implied much reduced room for the continued expansion of onshore wind.
- *Solar PV*, which had boomed between 2010 and 2012, experienced a further reduction of its momentum. This had started with large cutbacks in the level of feed-in tariffs to account for cost reductions and the introduction of a correcting mechanisms (a "breathing cap") to keep a check on its future growth. However, the resulting industry consolidation and losses in PV jobs as well as rising levels of the EEG levy (mainly paid by households and SME) undermined previously high levels of legitimacy. By 2015 investments in decentralized small-scale rooftop PV systems had collapsed dramatically, although calculations had shown that if largely used for self-consumption the technology would be financially attractive even without feed-in tariffs. In 2016, the government decided to roll out auctioning more widely after having made positive experiences with a pilot schemes for large-scale PV auctions, leading to lower costs (but also lower investor diversity). Acknowledging the benefits of a diversified technology portfolio, the government foresaw yearly auctions of 600MW. However, given public opposition to the proposed policy change to auctions rooftop PV and other small-scale PV plants (up to 750kW) continued to receive feed-in tariffs, albeit reduced ones in an attempt to accommodate concerns of private investors and environmental NGOs. Yet, with all these changes private households became increasingly hesitant to invest in rooftop PV, so that further capacity additions were mainly driven by free-field PV.
- The government continued to limit the further expansion of *bioenergy* for a variety of reasons: high costs combined with limited cost reduction potential, wider sustainability concerns and competing uses of biomass for the decarbonisation of other sectors. Given its technological advantage of being a non-fluctuating renewable energy source the industry actively lobbied for a more supportive policy mix, but with very limited success: the amended EEG foresaw yearly auctions of 150MW in 2017-19 and 200MW in 2020-2022, which implied hardly any further growth. Ultimately,

the actual use of existing bioenergy plants was very low, so that biomass could be put to more productive uses. By the end of phase 1, its consideration for electricity generation was sidelined.

Overall, by the end of 2022 all nuclear power had been phased-out which was enthusiastically celebrated by policy makers and society alike. The expansion path foreseen for renewable energies was only marginally exceeded, the least efficient lignite and coal plants had been shut down, offshore wind had started to kick off, and auctions became the new normal in determining the level of support, thereby twisting the discourse more towards cost-effectiveness. In fact, by the end of the period cost-efficiency had been established as a prime motive within Germany's renewables policy. However, the resulting policy changes (auctions within narrow expansion corridors) had started to exclude new entrants, such as cooperatives, farmers or private households as investors into renewable energies. As a result, new entrants became increasingly frustrated and citizens appeared to become somewhat disconnected from the Energiewende vision. This also fed back to limited enthusiasm for smart meters, as the Energiewende was increasingly seen as technological transition project managed by the big guys, with many households eventually becoming less enthusiastic about the idea of producing and consuming their own energy. However, a major concern was that Germany's 2020 climate targets – despite several additional measures across various sectors – could not fully be met, which was seen by many as a wake-up call for more ambitious climate policies.

5.2. Phase 2 (2023-2035): offshore wind rules as public acceptance for onshore wind declines, CCS moves forward, and PV goes abroad

With the chapter of nuclear power closed, attention shifted to enabling CCS, rolling out offshore wind and integrating an increasing share of intermittent renewables into the electricity system. Based on the difficulties experienced with achieving the 40% greenhouse gas reduction target by 2020 - which Germany had missed – the government initially only confirmed its climate policy target of a reduction of greenhouse gas emissions by 80% by 2050 under the pledge-and-review process agreed in Paris. However, given rising international pressures and in the hope to rebuilt its reputation as climate champion Germany added a clause which indicated its further aspirations to achieve a reduction up to 95% if major emitters and competitors, such as China and the US, would also tighten their commitments.

With the positive experiences made with cost-reductions achieved by auctioning as new means to determine payments for renewable energies, the impressive energy efficiency gains under the white certificate pilots and growing interest around the world in linking emission trading schemes, Germany started to become more enthusiastic about a broader use of market-based instruments, even if this meant the discontinuation of successful national support instruments. Therefore, in 2025 it joined a voluntary European auctioning scheme for onshore wind with its neighbouring countries. This raised some opposition from local activist, and therefore was first set-up with equally ambitious countries, including Denmark and the Netherlands. However, due to its success in reducing renewable expansion costs country membership grew, including the joining of the UK in 2028. Overall, these developments were celebrated as major success by industry and policy makers, whereas civil society became further disconnected from the Energiewende and started to see this less as a societal project but something jointly managed by their government and industry players. Yet, since shares in renewable continued to rise this discontent with the pursued pathway was largely muted, and over time the general public started to accept their more passive role in the further expansion of renewable energies.

In 2030, the success of the supranational onshore wind pilot inspired a similar cross-country auctioning scheme for solar PV, with Germany and the other member states partnering up with more southern EU member states, such as Spain and Italy. Germany had helped to negotiate these agreements in an effort to channel investments to the cheapest locations, as cost-efficiency had become a prime motive within Germany's renewables policy. This initiative had been driven by the large project developers and incumbents who pushed for growth opportunities outside of Germany, given that they had experienced increasing public resistance of their big projects by local communities. While local activists were deeply concerned about these developments, their protests were largely unheard as the rising electricity surcharge (which had mainly risen due to offshore wind, though) and much better solar conditions in the South provided a strong economic rationale. Also, with the policy changes in the field of renewable energy favouring large investors, the expansion of renewables going according to plan (mainly offshore wind in Germany, and solar PV and onshore wind abroad) and the government proceeding stubbornly on their cost-effectiveness policy narrative, many local activists eventually shifted their attention to other decarbonisation priorities. These included lobbying for policies supporting the phase-out of unabated coal and lignite, but also much greater attention on decarbonising transport – two areas which wer still lagging behind in policy ambition.

In a similar move towards an increased reliance on market based instruments, Germany also became a main promoter of the strengthening of the carbon price signal from the EU ETS. This seemed to be particularly relevant given Germany's aspiration to address the coal phase out by introducing CCS and lignite, which was thought to need EUA prices higher than 30 Euros/ t CO_2e in order to become economically attractive. However, resistance from coal-based EU Member States remained high. Therefore, after several failures to fix the EU ETS at a European level, Germany finally joined a club of progressive EU Member States promoting stringent market-based climate policies, whose founding members agreed to buying out and surrendering a certain number of EUAs between 2025 and 2035. Over time this commitment of public money of a few was ultimately fixing the carbon price signal arising from the EU ETS across Europe, including in those MS which had resisted the strengthening of the scheme. This move send strong signals across industry and the financial sector that the German and partnering governments were seriously committed to the decarbonisation of the economy, and even prepared to take creative and previously unthinkable detours to fix European climate policy inertia. Together, these moves prepared the foundations for a green investment climate and helped strengthen the outcomes from international climate policy negotiations after 2025.

Finally, based on the experience gained from the ten pilot regions with white certificate schemes and in the spirit of increased use of market-based instruments, in 2026 the government managed to roll-out this white certificate scheme on a national level, taking on board some modifications based on the lessons learned from the pilot schemes. This scheme initiated a change in thinking about electricity demand and led to substantial improvements in energy efficiency, but the associated reductions in electricity demand were largely eaten up by increased consumption elsewhere (rebound effect) and new users (e.g. ICT, electric vehicles)

However, despite these largely positive developments the government was faced with a new main concern: the decreasing public acceptance for large investment projects planned by incumbents. Towards the end of phase 2 this put the government under significant pressure to address this rising concern.

'New' renewables regimes and niches

In the beginning of this phase it became increasingly clear that under the auctioning scheme (adopted in 2016) *onshore wind* – depite it being the cheapest renewable energy technology – would not emerge as winner of the energy transition, as it faced significant public acceptance problems. Given the cost-pressures introduced by the auctioning scheme the winning bids of tended to be for very large wind parks by large investors, while community energy parks – which had to compete with all other bids since the limit for FIT remuneration was way too low (750kW) – tended to be too expensive. However, the winning large project developers and incumbents faced public resistance from local communities who were much in favour of their community energy projects, and very upset for them being kicked out. As a result, many winning bids went through lengthy and unpleasant stakeholder consultation procedures, which often increased the implementation costs beyond the auctioning price, but even then often did not receive local approval, and as a consequence by the beginning of the second phase these initiatives had significantly died down. The situation looked slightly better for onshore wind investments repowering turbines at existing locations with larger, more technically advanced ones. Still, even their implementation only succeeded in those cases were large project developers offered local park owners a benefit sharing model for selling their onshore wind sites to them for repowering purposes.

As one response to the difficulties of incumbents getting new onshore wind parks built, these investors started to heavily lobby for the opportunity to invest abroad. While initially there was much public resistance against the idea of Germany fulfilling its renewable targets abroad, the government's desire to portray the auctioning scheme as success story made them more willing to design a supranational auctioning scheme for onshore wind. Therefore, in an attempt of the government to save face, they increased the speed of their ongoing negotiations with neighbouring countries to set up a supranational auctioning scheme. However, this did not go down well with local activists, who rather argued for improved conditions for community energy projects. Therefore, the government did not manage to go forward as quickly as it desired, but as time proceeded and more problems occurred, in 2025 the government managed to install a supranational onshore wind pilot. This led to a rapid shift of the onshore wind investments of the internationally positioned incumbents to other countries, while leaving the repowering business to national project developers. As a result of these developments, onshore wind capacities declined, but given the technical improvements in the newest generation of wind turbines overall electricity generation remained fairly stable. Wind project developers mainly used existing sites to replace old, smaller turbines by fewer, but larger and more effective turbines. In addition, as policy makers became very wary of the difficulties encountered in expanding onshore wind they therefore had an open ear for calls to increase the target for offshore wind, since this technology fared much better.

A second response from incumbents resulting from the difficulties of implementing onshore wind was that they focused their attention on *offshore wind*. Compared to the difficulties encountered in rolling out onshore wind the capacity additions in offshore wind were very unproblematic and proceeded with a very high success rate. Therefore, the expansion target of 15 GW by 2025 was easily met, even a couple of years early, and incumbents were eager to keep investing beyond 2025. In addition, the offshore wind farms continued to reach very high load factors, thereby leading to a significant increase in offshore wind's share in electricity generation. Also, the positive impact on the economic development of previously deprived coastal regions was saluted by local policy makers, industry associations and unions. Costs had also come down faster and stronger than originally expected, based on technological learning, reduced finance costs of the now less risky parks, and competition created by the auctioning scheme. Given these successes the lobbying initiative launched by big incumbents to introduce an extended offshore wind expansion target for 2035 of 25 GW was joined by a powerful advocacy coalition of regional and local policy makers, industry associations, and unions. The main concern of the still higher costs compared to onshore wind was addressed by the industry committing to an ambitious cost reduction strategy, and incumbents pointing to public acceptance problems of onshore wind. Advocates of onshore wind who argued for an increase of the FIT-threshold to allow for more community-driven onshore wind farms remained unanswered, as the policy climate had by now fully swung to working with market-based instruments. Smaller companies and other new entrants had been forced to downscale their activities or even close their operation, thereby reducing the power of the new entrant's advocacy coalition. Also, the major investors in offshore wind had established a positive image around offshore wind, by means of advertisement, producing material for social media, cooperating with tourism committees in organizing boat tours to offshore wind locations, and providing various promotional material on offshore wind. Given the resulting change in attitude towards offshore wind as cool and powerful renewable energy technology and rising import shares there was not much resistance against continuing the support for offshore wind. Therefore, in 2024 the German government announced the issuance of another 10 GW of auctions up to 2035, hoping to provide clear investment signals for the offshore wind industry which was competing with neighbouring countries. This move was much applauded by the advocacy coalition and media coverage was positive as well, portraying offshore wind as the green success story. And indeed, the industry kept its promises by quadrupling capacities between 2020 and 2030 alone, reaching the 2035 target already ahead of time which further confirmed its positive image as green technology that delivers.

After the initially large interest in freefield *solar PV* it turned out that the winning bids of the first rounds of solar PV auctions experienced a much lower rate of return than expected. The main reasons were high costs of installing large free field PV plants in Germany due to high cost for renting and labour in combination with relatively low full-load hours. Another concern was that public opposition increased towards large investors coming in and installing large fields of solar PV, without the community financially benefitting from them. At the same time, Southern countries had demonstrated their low costs due to higher sunshine hours, cheaper labour and welcoming communities, which left large-scale investors in solar PV eye investments within these countries, rather than forging deals with local communities. Therefore, already in 2020 incumbents had started to advocate for a supranational auctioning scheme and by 2023 intensified these efforts, mainly by arguing for a further reduction of the costs for renewable expansion. Yet, the government was reluctant as it aimed at a diversified portfolio of renewable power generation technologies, in which solar PV was seen as an important pillar. The government feared that if it opened its scheme that all of the investments would go abroad. However, incumbents eagerly pointed to positive experiences made in the first years of the onshore wind supranational auctioning pilot scheme. Furthermore, in subsequent rounds smaller investors shied away from bidding due to the high risk of failure, not knowing that incumbents were adjusting their pricing upwards to allow for a better return of investment. This increase in the price of winning bids paired with the positive experience made with onshore wind supranational auctions eventually made the government reconsider. Therefore, in 2030 the German government joined as founding member of the "Solar South Scheme", which enabled cross-country auctions. This agreement, breathing the spirit of cost-reductions was partly enabled by improved interconnectors and extended grids, and led to massive solar PV deployment in Southern member countries such as Spain, Italy and Greece. Importantly, participating countries pledged to charge a 10% grid levy to finance the further expansion of the grid infrastructure between participating countries. Finally, with small-scale rooftop PV not eligible for feed-in tariffs anymore, while paying full grid costs and taxes even for self-consumed electricity, private investment died down. As a matter of fact, when reaching their twenty year life time many of the installed rooftop PV capacities were decommissioned while only a few of them were repowered. This led to some arguing that the citizen driven investment into solar PV was simply an attractive investment opportunity, while the number of pioneers was fairly low after all. Yet others claimed that citizens had simply given up the idea of generating their own electricity and got used to the idea of large investors finishing the energy transition for them. Still others argued this was a silent protest of citizens who felt disempowered in influencing the path of the Energiewende.

As for *bioenergy*, as before, there were rarely any changes in capacity nor generation. The little investment that took place was the replacement of existing plants, but much more was also not possible in the realm of the foreseen expansion corridor. News about the unsustainable use of biomass in the rest of the world and alternative uses, including the emergence of biomaterials in the chemical industry, made the German government stick firmly with its low expansion corridor. To soothe the consolidation of industry the government assisted manufactures with exporting their products and technological know how abroad. However, biomass co-firing was experimented with in the two CCS+lignite demonstration regions which took shape towards the end of the period.

'Old' regimes

With the chapter of nuclear power closed policy makers' attention concentrated on turning CCS into a viable option, which was mainly a question of public acceptance for storing CO_2 underground.

While the negotiated phase-out of unabated coal and lignite worked according to plan, the government's attention focused on the two *CCS+lignite* model regions which had been selected in 2020. For these model regions, the government had established a cross-departmental CCS task force which – in close cooperation with the affected regions – designed a participatory visioning process for the clean energy future of the two regions. They were supported by a consortium of researchers specialized in participatory decision-making and regional development. A state of the art stakeholder engagement process was designed which over the period of three years brought together all affected parties in creating a shared vision of the future of both model regions. This vision did not only include lignite with CCS but also addressed all other areas of economic, social and environmental development of the region. After initial hesitance the citizens, companies and universities in the region got increasingly enthusiastic about the model region project, particularly when in the subsequent roadmapping exercise concrete steps for achieving the vision were identified, taking on board as much of the input from stakeholders as was possible. In 2025, both regions proudly presented their visions and roadmaps to the chancellor at the officially signing ceremony marking the start of the implementation of these roadmaps. While the media and much of the general population were reacting very reserved to the announced plans and criticized the attached enormous budget, the regions and the task force themselves were highly motivated and very committed to turn these plans into reality. After the successful visioning phase the task force took on the job of a monitoring, evaluation and learning agency which facilitated joint learning between the regions, but also provided transparent information about the progress of the two model regions – to the general population, but increasingly to an international community. When the carbon price started to steadily increase as a consequence of the EUA buy-out initiated by Germany and the coalition of the willing (the EU ETS saving countries) and reached 25 Euros in 2027, lignite plant operators announced that they would accelerate their plans to construct the two demonstration CCS-lignite fired power plants. Construction started in 2029 and 2030, respectively, and after a very quick construction time plants went online in 2034 and 2035, respectively. Their opening received a lot of media attention, which not only reported about the economic attractiveness of the investment due to carbon prices having reached 33 Euros in 2035, but also about the associated transition of the model regions within the past ten years – including the relocation of CCS technology providers to the model regions, the green transformation of the region's universities with new interdisciplinary chairs and study programs, a green entrepreneurial boom, a rejuvenation of the population due to attractive job offers, a reduction of unemployment rates, the improvement of key sustainability indicators, and multiple other green economy initiatives proceeding with unusually high levels of citizen engagement. Given its large success, several other regions' contacted the model regions and the task force to learn about its strategy and started to lobby for a second round of CCS model regions. This was supported by the big incumbents with interests in further investments in CCS+lignite, as by 2035 these investments would be economically attractive. However, in order to go forward with them it was necessary to overcome public resistance on a local level, and the model regions had impressively shown how this could be done. In addition, with the determination of a final nuclear waste storage site moving nowhere, several parties suggested that a similar approach should be applied to the most promising locations.

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

The ever increasing shares of intermittent renewables (with growth occurring for offshore wind only), which by 2035 covered exactly half of the electricity generated in Germany, necessitated a much greater rate of change in the conservative e*lectricity network regime* than witnessed before. Therefore, the government started to put much more pressure on network operators to increase the speed of the further expansion of long-distance transmission grids but also interconnectors with other countries. To facilitate the implementation of investment plans, in 2025 the government initiated an independent grid stakeholder consultation task force to negotiate the best possible routes for the construction of new transmission lines but also possible compensation measures for affected communities. When it became clear that the task force was not taking very seriously given its limited power in making recommendations with budget implications, such as the construction of underground cabling or landscaping, in 2027 the government equipped the task force with a significant budget thereby granting it greater flexibility and power in stakeholder consultations. This budget was financed through part of the proceeds of EUA auctions which started to increase significantly in the period between 2025 and 2035, resulting from the interventions of the MS coalition of the willing.

The government also made the further expansion of the offshore wind grid a high priority, partly in response to industry pressure to avoid grid access delays, as had been experienced in the past. For this, in 2026 it implemented several regulatory changes which provided a clear incentive structure for delivering grid expansion in time and respecting social and environmental criteria – but also penalties for delays and underperformance in terms of sustainability criteria. When evaluating the impact of these changes in 2030, an expert commission came to the conclusion that a similar incentive structure should be rolled out for the mainland grids as well. In 2031 this was taken up by a yearlong consultation process which resulted in the adoption of a revamped energy system law (EnWG) in 2032. This EnWG amendment was inspired by the modifications made for offshore wind but also took on board other long-overdue changes which were intended to provide the proper incentives for a faster low-carbon reorientation of the network regime. It also included the introduction of ‘time-of-use tariffs’ to allow for dynamic pricing of electricity, thereby providing consumers with monetary incentives to shift demand accordingly, such as charging electric vehicles at noon when electricity is abundantly available and thus cheaper. However, due to distributional concerns this was first rolled out for large users only. Yet, pilot schemes experimenting with dynamic pricing in private households were allowed under the condition that no customer would be made worse of than under the standard pricing scheme, which, however, led to limited experimentation.

Finally, Germany intensified its collaboration with neighbouring countries for the continued construction of interconnectors to create an emerging European super-grid. While up to 2019 Germany had been a net exporter of electricity, by 2020 Germany had started to become a net importer of electricity in an effort to meet its climate targets. The main reason for this was that balancing demand and supply through the im- and export of electricity at the time were much cheaper than storage solutions. Also, based on the experience made with the rise and decline of the German solar PV industry policy makers had become more reluctant to make strategic investments into the build up of an industry. Domestic policy support was disregarded given the uncertainties of this industry eventually not being able to withstand international competition, particularly from Asia, despite academic policy advice suggesting otherwise. Instead, the government preferred to focus on the support of increasing the number and capacity of interconnectors. This topic received new momentum when Germany started to collaborate with its neighbouring countries on the supranational auctioning schemes for onshore wind (2025) and later solar PV (2030). Naturally, one of the preconditions for a successful roll-out of these pilot schemes was the existence of large enough interconnector capacities, so Germany was actively pushing for an agreement to jointly finance these essential infrastructures which was struck in 2023. One of the first great successes was when in 2030 a new interconnector between the UK and continental Europe was opened, as it lay the foundation for an increased import of cheap UK electricity generated by its vast onshore wind potential which was increasingly harnessed by the UK electricity system.

In conclusion, in the second phase which was offshore wind emerged as winning new regime, while onshore wind and solar PV experienced stagnation and even negative momentum, with much of the investment eventually being channelled to locations abroad with higher resource endowments. The CCS model regions witnessed great success in creating public acceptance for CCS and lignite, by pursuing a holistic regional development strategy, with the first plant going online in 2034. As for unabated coal and lignite, their phase out was occurring to plan. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. auction pilots onshore wind, EUA buy-out, interconnectors), a continuation of market-based policies (e.g. auctioning for renewable, EU ETS, roll out of white certificate scheme), and a recognition of the need for active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental CCS task force), and new regulatory institutions (e.g. dynamic pricing). Together, these changes enabled Germany to meet both its renewable and energy efficiency targets as well as its climate targets, and put it on track for an electricity system dominated by offshore wind and lignite+CCS.

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

In the beginning of the third phase changes continued along the line of the path set out in phase 2, but with slightly reduced momentum. Initially most investments into on- and offshore wind were mainly concerned with repowering existing sites with technologically advanced turbines, which further reduced electricity generation costs. Smart grids and smart pricing had made significant advances and became business as usual for industry, making the electricity system more flexible. However, three major changes occurred already by 2040:

(1) With the introduction of the supranational auctioning scheme for *solar PV* no more new investments went into Germany. Therefore, with many plants reaching the end of their lifetime, solar PV capacities and hence national PV generation shrank by a factor of 6 between 2030 and 2040. However, there was not a large outcry as citizens had slowly gotten used to this trend and a fatigue and growing disinterest in self-generation together with the inhalation of the cost-minimization narrative of the government led them to value the decreasing electricity prices. The incumbents had shown that they could deliver the same decarbonisation without the hassles of personal involvement. Also, much of the attention of private investors had been channelled to electric vehicles, which were rolled out massively and turned each driver into a smart storage agent.
(2) Due to the globally necessity for negative emissions and the relatively successful introduction of BECCS power plants in the CCS+lignite model regions some new investments in biomass and co-firing plants were made. BECCS also became more attractive for balancing demand and supply.
(3) By 2040, the *nuclear storage* commission had identified three suitable regions for the permanent storage of Germany’s radioactive waste. As none of the regions was volunteering to be chosen the government implemented a visioning and roadmap process after which the winning region would receive the necessary funds to turn the vision into reality. The participatory procedure followed the one which had been developed for CCS, and it was hoped that one of the regions would turn into an enthusiastic proponent on becoming Germany’s permanent nuclear storage site, enabling the closure of this lengthy chapter of Germany’s nuclear energy policy by 2050.

After 2040 electricity demand increased significantly due to the diffusion of electric vehicles kicking in, but also due to other new users, such as heat pumps. Also, carbon prices reached levels of above 40 Euros / t CO_2e, thereby providing incentives for CCS but also for new gas plants. Finally, international coal prices dropped quite significantly due to decreased demand on the world market, following developments around the world to phase out coal. As a consequence of these developments, four main developments could be observed after 2040:

(1) The government set an ambitious expansion target for *offshore wind* of 42 GW by 2050. Consequently, many new parks were built by incumbents between 2040 and 2050. However, given the relatively sudden spike in electricity consumption between 2040 and 2050, offshore wind could not deliver all of this at once. In an attempt to keep costs down, to avoid unnecessary imports or even unsecure supply (given that the spike in demand from e-mobility is a European phenomenon, not a purely German one), incumbents suggested to extend the usage of *coal* fired power plants beyond 2050. This raised large debates even though Germany would still have been on track in reaching its climate targets. However, when the first black-outs occured the public opposition to the plan of letting coal-fired power plants run longer vanished, so that

by 2050 Germany was still generating 11% of its electricity based on coal (though in mostly in CHP power plants or in BECCS co-firing power plants), and even still had one last lignite power plant running.

(2) After a further decline in gas capacities and generation this changed towards the end of the phase: for the first time in over 25 years the construction of new *gas* plants became a lucrative investment, based on the prospects of steadily increasing carbon prices, and the continued existence of a capacity mechanism. Actual generation, however, increased only slightly, and remained at a very low level since most balancing continued to occur through the import and export of electricity (with Germany remaining a net importer of electricity, covering a share of 17% of its electricity demand).

(3) New CCS-lignite power plants with a capacity 13 GW were built on the existing lignite sites, after the initial success of the two model regions. With extensive BECCS co-firing, these plants effectively turned into carbon sinks, helping to prove the large-scale feasibility of the concept of negative emissions. Overall, all CCS related investments were embedded in a very well managed process, in which all CCS regions were redeveloped through an intense stakeholder visioning process, as was done in the original model regions. However, while this approach was able to secure local public acceptance for carbon storage, the general population remained sceptical of CCS. Yet, Germany's success story received lots of attention in neighbouring countries and beyond, and started to be exported abroad, as once the FIT of the EEG had diffused widely. With CCS gaining momentum around the world, Germany succeeded not only in exporting its participatory and holistic model region approach, but also benefited from increased exports of its CCS technological expertise to China, India, the USA and many other countries, thereby contributing to the economic success of the original CCS model regions as new clusters of Germany's CCS industry.

In conclusion, phase 3 was characterized by the continued expansion of offshore wind and CCS+lignite (and export of these technologies), further increases in the flexibility of demand, an almost complete discontinuation of solar PV located in Germany, an increase in bioenergy and gas generation capacities as back-up of the system, and an increase in electricity demand which led to an extension of the coal phase-out to secure cost-effective and secure electricity supply. At the end of phase 3, electricity generation capacities were once again fairly large-scale and mainly owned by a handful of incumbents.

6. Scenario 2 (Pathway B): Solar PV and onshore wind with flexible gas back up for the rest of Europe

Core characteristics, logics and challenges

This scenario provides a socio-technical storyline for Pathway B, using the quantitative PowerACE modelling results for this pathway reported in D1.3 (see Figures 2 and 3 above). In conceptual terms this pathway focuses on a wider set of changes across several system dimensions. New entrants continue to play a large role in electricity generation based on the growth and stabilization of new technical regimes (e.g. distributed generation based on onshore wind and solar PV). Wider shifts in cultural discourses and social legitimacy for an energy transition continue to develop, which are supported and support a broad, inclusive governance approach (beyond large firms and technologies), reflecting a return to the new entrant friendly policy paradigm which had emerged under the Red-Green Schröder government (2000-08). Initially, social acceptance for the introduced policy regime changes (from feed-in tariffs to auctions) starts to decrease; this is followed by increasing social *pressure* for a return to policies more favourable for investments by new entrants. Major 'transition challenges' concern: 1) *social acceptance problems* associated with grid extensions, large scale onshore wind parks and free field solar PV by incumbents, 2) the need for *policy instrument reversal* to allow for favourable investment conditions for new entrants, 3) the struggle of *incumbent actors* to find new business models to ensure their survival, 4) opposition from the *lignite advocacy coalition* against phase out plans, 5) major *investment needs* in the network regime for extended smart grids, and 6) *behavioural change* regarding the smart and reduced use of electricity at home and beyond. These challenges start to become visible in the first period (2015-19), and are started to be addressed by the new government, but with many of the impacts of a changed policy mix only kicking in at later periods.

6.1. Phase 1 (2015-2019): first experiences with renewables auctions alongside nuclear phase-out and experimentation with energy efficiency

In its Energy Concept from 2010 the German government had committed itself to a reduction of its greenhouse gas emissions by 40% by 2020 (compared to 1990 levels), and to a reduction of 80-95% by 2050. These targets were reiterated at several occasions, including in the coalition agreement of Merkel's Grand Coalition government (2013-2017) and in the context of the Paris agreement from December 2015. Since a great share of emissions stemmed from the energy system, the government's initial focus was on decarbonising the energy system. In addition, given the strong public opposition to nuclear power the Red-Green Schröder government had introduced the Renewable Energy Sources Act (EEG) in 2000, providing long-term, technology-specific investment incentives for renewable energies. Over time, the EEG continuously led to a faster than anticipated increase of the share of renewable based electricity generation from less than 5% in 2000 to more than 33% in 2015. This Act, which had been regularly amended based on evaluation results, represented the core instrument pushing the further expansion of renewable energies. However, in 2016 Merkel's Grand coalition government significantly redesigned it by introducing auctions for renewable energy. Reasons for this much debated change in the German policy paradigm included rising cost concerns and a desire to move to the next level of the energy transition which was thought to be best accomplished through a market-based instrument. In order to provide stability the new government sticked to the introduced changes, but pledged to thoroughly assess the impact of these EEG design changes and take the findings into consideration for the next EEG reform due in 2019.

The second core policy influencing the development of the German electricity system in this period was the nuclear phase-out policy which the Red-Green Schröder government had negotiated with incumbents in 2002. While Merkel's Conservative-Liberal government had originally annulled the phase-out deal in 2010, after the Fukushima incident the nuclear phase-out became a central part of Germany's Energiewende, with a cross-party consensus supporting the step-wise close-down of the remaining nuclear power plants until 2022.

However, at the same time it was clear that without additional policy support Germany would miss its climate policy target for 2020 of a greenhouse gas reduction of 40% by 7%, despite being on track with its target of expanding the use of renewable energies within electricity generation to a share of 40-45% by 2025, and at least 80% by 2050. The main reason for this was the high utilization of lignite and coal fired power plants. This led to a raft of measures being introduced at the beginning of the phase to close the gap.

Together, the policy mix led to major changes in existing regimes (nuclear, coal, lignite, gas, network) and further upscaling of niche-innovations (particularly onshore wind and solar PV).

Old regime developments:

By 2015, the electricity *generation regime* in Germany was undergoing radical changes, given the rapid expansion of renewable energies, and in particular of wind and solar PV. However, while no actor questioned anymore the transition towards renewable energies, there was a dispute about the final regime dimensions. Resistance from regime actors focused on reducing losses (e.g. by law suits, asset sweating), while they were mainly busy with trying to identify new business models to ensure their survival in the new renewable-based regime. There were major tensions and cracks in the electricity generation regime. The climate change problem and anti-nuclear movement led to significant institutional changes, e.g. ambitious targets for GHG reduction, renewables expansion and nuclear phase-out and specific policy instruments. The resulting structural changes in infrastructure (renewable energy made up 50% of generation capacity, with a negligible share owned by large incumbents). The reduction of electricity market prices and thus decreased profitability of existing conventional plants were forcing large incumbents to rethink their beliefs, strategies and organisational structures. A closer look at the different technological sub-regimes reveals the following developments:

- Germany's *nuclear* phase-out proceeded as planned, with a step-wise closing down of the remaining eight nuclear power plants, with plant closures in 2015 (Grafenrheinfeld), 2017 (Gundremmingen B), and 2019 (Philippsburg 2). Interestingly, they also created new jobs in decommissioning nuclear power plants, with the government providing training programs to help build up the required expertise. While three of the four affected plant operators sued the government for its abrupt phase-out decisions in the wake of the Fukushima disaster in Japan in 2011, this was not about reversing the decision but about who carries the costs of closing down the nuclear power plants prior to their retirement age. When the supreme court finally ruled against the large incumbents, this did not come as big of a surprise, but further disrupted large incumbents and was just seen as another pointer for them to face the new realities. At the end of the period, policy makers were, however, still struggling with identifying a suitable final deposit site for Germany's radioactive waste. Yet, the established expert commission had worked hard and in 2016 managed to establish generic search criteria, which marked the beginning of a new and systematic scientific search process.

- Regarding *coal and lignite* there were hardly any new plants being built, but existing plants reached very high load factors, exporting the excess electricity abroad. The attractiveness of coal and lignite was largely based on low resource prices and low CO_2 prices, the latter resulting from the overallocation and built up surplus of allowances in the EU Emission Trading System (EU ETS). Particularly the nearly exhausted load hours of lignite power plants contributed to a rise in the CO_2 emissions of Germany's electricity system, which were coined as "Paradoxon" of the Energiewende. It became increasingly clear that a phase-out policy for lignite fired power plants was needed, but the proposal made by Gabriel, the Minister responsible for the Energy Transition, prior to COP21 in Paris, which was based on the polluter-pays-principle, faced heavy political resistance from a coalition of incumbents, unions and federal states dependent on the income generated by the industry. Yet, given the gap in CO_2 target fulfilment and the endangered international credibility of the German government a set of additional climate policy measures was adopted, including financial compensation for the closure of the dirtiest lignite power plants. Environmental NGOs were complaining that instead of the polluter paying what Germany had opted for was paying the polluter not to pollute. Still, the move reduced CO_2 emissions and helped Germany take a strong position in the Paris climate negotiations. However, later attempts of the environment ministry and environmental NGOs and think tanks to work out a lignite phase out policy were not successful in the political process and only appeared in a very watered down version in Germany's climate protection plan for 2050. Given these national difficulties in 2017 the new government started to lobby much stronger on a European level for a clear carbon signal arising from the EU ETS, however with limited success.
- The pilot and planned demonstration programs for *carbon capture and storage (CCS)* technologies faced significant problems with public acceptance and lacking incentives from the EU ETS. When incumbents decided to drop their plans for demonstration plans, the government eventually also rolled back its CCS R&D funding. There was an unspoken agreement among policy and industry that CCS would not work in Germany. Also, modelling results had suggested that if at all then the limited CO2 storage capacities would be needed for decarbonising industry with its process based emissions, while the electricity sector could be decarbonized without CCS.
- The existing capacities for *gas fired power generation* had to significantly reduce their load hours, thereby further endangering the business model for gas-fired power plants. Main reasons included the low CO_2-price which continued in the beginning of the fourth trading phase of the EU ETS due to the large remaining surplus of EUAs, and the rising shares of intermittent renewables which lowered electricity costs. In order to keep operators from mothballing their gas fired power plants, even those with highest efficiencies, the government declared them as system-relevant back-up capacity which had to stay online. This raised significant opposition from operators, calling for the introduction of some sort of capacity mechanism, which, however, remained unanswered.

In contrast, the electricity *consumption regime* remained partly strongly locked-in. The trend towards greater electrification in some fields (ICT, electric mobility, heat pumps) and some rebound effects (e.g. in lighting) partly counteracted the efforts to reduce electricity consumption, but not yet to a big extent as particularly the diffusion of electric vehicles had a very slow start, and only slightly accelerated after the government had introduced purchase subsidies for electric vehicles in 2016. Initially, several important actors remained reluctant to see energy efficiency as a top priority (esp. electricity utilities, retailers and wholesale trade) which undermined the efforts to increase efficiency and reduce electricity demand. Yet, given the initial problems of phasing out coal and lignite and the immense reputational pressure from the international community resting on Germany to achieve its 2020 climate target, a relatively broad consensus of affectted groups emerged on the benefits of energy efficiency. As a consequence, energy efficiency saw some increased political attention, so that the government slowly started to shift its policy approach, which so far was largely based on voluntary policy measures (such as learning energy efficiency networks) and financial support for investments in energy efficiency improvements (e.g. through KfW funding), to a more ambitious market-based approach. A visible sign of this shift was the new government's turnaround regarding a mandatory white certificate trading scheme, which they initially rolled out in ten model regions in 2017. These model regions benefited from generous financial support for the implementation, monitoring and evaluation of the scheme to allow for policy learning and later full roll-out.

Finally, the *network regime* initially remained fairly stable with moderate lock-in due to its long-lived assets structure and conservative mind-set and regulation. While some regulatory changes were implemented, such as targeted investment incentives to spur certain developments, their implementation was rather slow and did initially not result in radical changes but only gradual adaptations of the regulatory framework. However, given the ever increasing share of intermittent renewables both industry and policy pressures on the network regime grew, as they shared a keen interest on making the Energiewende an attractive business case and political success story. There was a common understanding that the increase in decentralized and intermittent generation required adaptations to the network management and structure. Policy makers therefore implemented some changes to the regulatory framework allowing and encouraging network operators to make such adaptations. The changes also improved the incentives for network expansion, increased acceptance and streamlined administrative processes. Also, a strong consensus emerged among policy makers and industry that network expansion was needed at the transmission and distribution level, and that distribution networks needed to become more intelligent. However, the actual expansion of networks was much delayed, given some strong resistance of locally affected populations and Federal States to proposed network routes. While solutions were sought and identified through elaborated stakeholder engagement processes these often implied delays in construction and higher costs due to the increased use of underground cables. However, rather than implementing further changes to network regulation in 2016 the Merkel government reacted to these delays by implementing policy changes which were meant to slow down the speed of the expansion of renewable energies (see below), thereby attempting to alleviate some pressures on the network regime. In the meantime, smart meters had started to been rolled-out to large electricity consumers, which prepared the ground for them to become acquainted with the idea of thinking about the flexibility of their demand and also stimulated intensified engagement with the idea of electricity demand reductions. Also, construction companies started to jump on the idea of smart homes, and thus automatically included smart meters in new builds, thereby spreading the technology also among first private households.

Emerging new regimes and niches:

In 2016 and after long and difficult negotiations Merkel's Grand Coalition government introduced a paradigm change to the Renewable Energy Sources Act (EEG) – changing its main incentive component from feed-in-tariffs to auctions. Based on experiences made in a pilot with free field PV auctions implemented in the EEG reform of 2014, and having worked out a similar auctioning scheme for offshore wind, starting in 2017 investments in renewable energies were no longer incentivized through ex-ante known feed-in tariffs but determined by technology-specific auctions. The idea behind these auctions was to reduce the costs of the further expansion of renewable energies by allowing for competitive bidding. The government also hoped to be better able to control the rate of expansion of renewable energies to keep each technology's and overall renewables' growth within the foreseen expansion corridor (40-45% in 2025, and 55-60% in 2035). These changes were heavily contested by new entrants, such as cooperatives and renewable energy industry associations, but also by leading economists and the media as being short-sighted and unduly benefiting large incumbents. As a consequence, the atmosphere in the renewables advocacy coalition towards the government seriously cooled down, and many players lost their belief in the government being a strong promoter of the Energiewende. However, the government defended the implemented policy change by stating that the nurturing phase was over, and that it was time for renewables to grow up and face competition so as to reduce the costs of the Energiewende. Yet, given the strong support of the public for the promotion of renewable energies and pressure from federal states with their own ambitious renewable expansion targets, the government allowed some exemptions for small-scale investors and cooperatives. The desired speed of the Energiewende became a hotly debated topic in the run up to the next national elections in 2017, with those parties opting for a faster expansion casting in additional votes. However, for reasons of policy stability the newly elected government did not implement any immediate changes but pledge for a thorough evaluation of the impacts of EEG auctions, including impacts on costs, ownership structure, and public acceptance.

- *Onshore wind* experienced massive additional investments prior to the adoption of EEG 2016, because the industry and cooperatives wanted to benefit from the old feed-in tariff system, and because onshore wind clearly emerged as cheapest renewable energy technology. However, this boom in onshore wind led to investments exceeding the foreseen expansion corridor. While the industry with its green advocacy coalition argued for an increase of these corridors, which was also supported by calculations of leading experts in light of reaching Germany's 2050 targets, the government remained firmly committed to stay within these corridors. However, the government had to make some upwards adjustments in their yearly allowance for onshore wind auctions to address opposition from federal states: it was agreed that from 2017-19 the government would auction off 2.800 MW annually, and thereafter 2.900 MW. However, the government set these as gross figures, thereby incorporating the upcoming repowering of old wind farms. These policy changes led to much reduced activities by cooperatives and farmers which had been the backbone of the Energiewende's take off phase, as many of them could not afford the risks associated with the tendering process. However, the government claimed to support cooperatives by designing inclusive stakeholder engagement processes and a simple auctioning process. Yet, given the cost-pressures introduced by the auctioning scheme the winning bids tended to be for very large wind from specialized wind energy project developers and the renewable subsidiaries of incumbents. In contrast, community energy parks – which had to compete with all other bids since the limit for FIT remuneration was way too low (750kW) – tended to be too expensive, or did not even apply due to limited capacities and risk aversion. However, the winning large project developers and incumbents faced public resistance from local communities who were much in favour of their community energy projects, and mad for them being kicked out. As a result, many winning bids went through lengthy and unpleasant stakeholder consultation procedures, which often increased the implementation costs beyond the auctioning price, but even then often did not receive local approval. Overall, this led to a general dissatisfaction of citizens with the Energiewende policy of their government.

- In the negotiations for the reform of the EEG the *offshore wind* advocacy coalition managed to strike an attractive deal with the government, securing sufficient room for the continued expansion for offshore wind despite it being more expensive than onshore wind, namely 6.5GW until 2020, and 15 GW until 2030. One advantage may have been that offshore wind had already contributed to the economic development of deprived coastal regions, and therefore had keen supporters within the affected federal states. Also, after the bottle neck of grid access for offshore wind had been largely resolved in the beginning of the period, a number of new parks went online in 2015 which performed very well, clearly exceeding expectations regarding load hours. This further contributed to incumbents fully embracing the technology as large-scale renewable energy technology which worked well with their capabilities and provided them with an attractive business model in a time of fundamental change. Also, incumbents did not mind the introduction of auctions as they expected to be winners of this policy change, which, however, turned out to be a false hope. Some policy makers also argued that by allowing incumbents to invest in offshore wind, this may help their survival in the changed realities of the energy system.
- *Solar PV,* which had boomed between 2010 and 2012, experienced a further reduction of its momentum. This had started with large cutbacks in the level of feed-in tariffs to account for cost reductions and the introduction of a correcting mechanisms (a "breathing cap") to keep a check on its future growth. However, the resulting industry consolidation and losses in PV jobs as well as rising levels of the EEG levy (mainly paid by households and SME) undermined previously high levels of legitimacy. By 2015 investments in decentralized small-scale rooftop PV systems had collapsed dramatically, although calculations had shown that if largely used for self-consumption the technology would be financially attractive even without feed-in tariffs. In 2016, the government decided to roll out auctioning more widely after having made positive experiences with pilot schemes for large-scale PV auctions, leading to lower costs (but also to lower investor diversity than was the case for rooftop PV). Acknowledging the benefits of a diversified technology portfolio, the government foresaw yearly auctions of 600MW. However, given public opposition to the proposed policy change smaller rooftop PV and other small-scale PV plants (up to 750kW) continued to receive feed-in tariffs, albeit reduced ones in an attempt to accommodate concerns of private investors and environmental NGOs. Yet, with all these changes private households became increasingly hesitant to invest in rooftop PV, so that further capacity additions were mainly driven by free-field PV.
- The government continued to limit the further expansion of *bioenergy* for a variety of reasons: high costs combined with limited cost reduction potential, wider sustainability concerns and competing uses of biomass for the decarbonisation of other sectors. Given its technological advantage of being a non-fluctuating renewable energy source the industry and some Southern Fedearl States benefiting from biomass support actively lobbied for a more supportive policy mix, but with very limited success: the amended EEG foresaw yearly auctions of 150MW in 2017-19 and 200MW in 2020-22, which implied hardly any further growth. Ultimately, the actual use of existing bioenergy plants was very low, so that biomass could be put to more productive uses. By the end of phase 1, its consideration for electricity generation was sidelined.

In conclusion, the expansion path foreseen for renewable energies was only marginally exceeded, the least efficient lignite and coal plants had been shut down, offshore wind reached its 2020 target of 6.5GW, and climate targets could be met, but only barely, with several additional measures across all sectors. However, evaluation results showed that experience with auctions was mixed: on the one hand, costs had gone down, but on the other hand winning bids had experienced implementation difficulties due to massive public acceptance concerns. Also, the cost-effectiveness discourse was challenged, arguing that offshore wind should not be expanded any further due to its high costs and corresponding impact on the EEG surcharge. Also, the public discourse towards large incumbents became very unfavourable, arguing that they should be no longer subsidized for their offshore wind adventure. This incumbent bashing was further fuelled by evaluation results which had revealed the increasing exclusion of new entrants, such as cooperatives, farmers or private households, as investors into renewable energies. The government was very anxious to counteract this development, to avoid further frustration of new entrants, and enacted a large consultation process on the revision of the EEG due in 2019 which turned into a larger visioning process for the desired shape of the decarbonized future electricity system.

After long and difficult debates, in the summer of 2019 it was decided that (1) the EEG would return to feed-in premiums for all technologies but offshore wind, (2) Germany would forge a supranational auctioning scheme for offshore wind, ideally on a European level, (3) the white certificate scheme would be rolled out on a national level, and (4) a economy-wide carbon tax of initially 20 Euros/tCO_2 would be introduced whose proceeds were to be split in equal parts into (i) funding local experimentation with behavioral change regarding a range of activities, including in areas of reducing electricity consumption (e.g. lower room temperatures), changing mobility patterns (e.g. higher bike use), and adjusting nutritional habits (e.g. Veggie-Thursday in cafeterias and restaurants), (ii) supporting radical low-carbon and low-energy innovation in industry, (iii) retiring EUA in an effort to increase the carbon price signal from the EU ETS, and (iv) financing the structural change in two model regions willing to phase-out lignite. These changes were generally applauded by citizens, environmental NGOs, renewable energy and energy efficiency representatives, and COP25 participants. In contrast, incumbents and industry, though protesting heavily, failed to lobby alternative support schemes and in turn tried to make sense of the implications of these radical changes for their survival strategies. These announcements send strong signals across industry and the financial sector that the German governments was seriously committed to the decarbonisation of the economy, and even prepared to take creative and previously unthinkable detours to fix European climate policy inertia. It became clear that if implemented these moves would put Germany again in the position of a European climate champion – and many equally progressive European Member States announced they would join Germany's efforts to fix the EU ETS and support the introduction of a European auctioning scheme for offshore wind.

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

The second phase marked the implementation of the changes announced in the summer of 2019. In addition to the feed-in-premiums being reintroduced in 2020 the government was particularly quick in introducing the first round of the novel experimentation scheme meant to incentivize activities targeting low-carbon and low-energy behavioural change. Funding for the first round of projects was made available from the climate and energy innovation fund, to cover the gap until carbon tax revenues came in. When it became clear that the government did not lose any time in implementing their announced plans and even put aside additional funding, this reinfused new entrants to take forward previously shelved plans and develop new ones, as well. Particularly the experimentation scheme sparked a search for innovative ideas bubbling up from a variety of actors, including local communities, schools, universities, sport clubs, environmental NGOs, businesses and even public administrations.

Based on the experience made in its ten pilot regions the government was also quick in implementing the national launch of an improved white certificate trading scheme which went online in 2021. The introduction of the economy-wide carbon tax of 20 €/t CO_2 took a bit longer because a number of technical questions had to be solved, but at the closing ceremony of the last nuclear power plant the government was proud to announce its launch for 2023. This further intensified the search process for low-carbon solutions, with many of the more ambitious initiatives ending up applying for radical innovation grants which the government had introduced alongside the introduction of the carbon tax. To facilitate knowledge exchange and learning across actors the government launched a central platform making available information about funded projects, and held various conferences and workshops, and supported other networking activities.

Germany was also joined by a club of progressive EU Member States which were equally frustrated in the low carbon price arising from the EU ETS. In 2021, countries pledged to buy out and surrender EUAs until the EU allowance price had reached 20 €/t CO_2. While some were simply using public money to do so, others required coal users to surrender twice or even three times as many EUA per t of CO_2. Over time this commitment of the "Climate Club", as this group of EU MS became to be known, reduced the huge surplus of EUAs which had accumulated over the first two trading phases of the EU ETS. Ultimately, the action of the "Climate Club" helped fix the carbon price signal arising from the EU ETS across Europe, including in those MS which had resisted the strengthening of the scheme. While the price of 20 €/t CO2 was reached not earlier than in 2027, the signal sent out by this joined activity of these proactive Member States nonetheless arrived at boardrooms of industry and the financial sector, as it was interpreted as a sign of policy commitment to the pledges made at Paris. With hindsight, many managers later said that it was this unexpected sign of a strong political will to move forward in the fight against climate change – against all odds – which marked the starting point of their strategic reorientations towards a carbon constrained world.

Overall, the whole period was marked by a blossoming of decarbonization activities across sectors and actors at a level previously unthinkable. This eventually resulted in a change in attitudes and way of thinking about decarbonising the economy and society. It seemed like an increasing number of citizen and businesses wanted to be on board. Industry associations and social media became a key means in distributing knowledge about the next cool thing being done to reduce CO_2 emissions, lower energy consumption or change mobility patterns. The topic was even picked up in soap-operas, movies, festivals, and regulars' tables. Also, sport and movie stars were starting their own initiatives or were recruited for serving as glamorous spokesperson of existing or new initiatives. This led to tabloids starting to report about the many initiatives being developed and implemented across the board, thereby leading to a further spreading of the new thinking about climate change action, resulting in a "Let a thousand flowers" and "We can do it!" atmosphere.

As a consequence of these initiatives, over the period from 2020 to 2035 Germany's electricity consumption and CO_2 emissions decreased significantly. This change in thingking was supported through a variety of instruments, for example: In the industry and tertiary sector, new standards limited new appliances in cross-cutting technologies (electric motors and lighting) to the highest efficiency classes and additional support programs supported a quicker change towards low-carbon solutions. In the residential sector similar programmes penalized sub-standard appliances, while monetary incentives, like the ”Blue Fridge Programme”, incentivized the replacement of old, inefficient appliances. These activites led to a significant numbers of new green jobs and rising exports of the improved green products.

The least efficient lignite and coal plants were steadily being phased out due to the combined effect of rising EU ETS prices and the additional CO_2 tax. All this progress and enthusiasm made Germany confident to be able to ratchet-up its commitment under the Paris Agreement to a reduction of its greenhouse gas emissions by 95% in 2050. In order to motivate others to step up their aspirations as well, Germany put extra efforts into actively sharing its experiences with transitioning to a low carbon economy. In 2028 Germany ceased to buy and retire EUAs from parts of its proceeds from the carbon tax as EUA prices had reached 20 Euro/t. In the same year at COP34 Germany announced it would earmark the freed-up carbon-tax revenues to fund low-carbon, low energy behavioural change experimentation programs in interested developing countries. After several successful trials in a handful of countries these were enthusiastically embraced and included in the NDCs of partnering countries. By the end of phase 2, Germany, China, the US and other major emitters had all tightened up their commitments under the Paris pledge-and-review process, and many developing countries were equally ratcheting up their efforts, thereby bringing life to the Paris Agreement.

‘New’ renewables regimes and niches

Overall, the second period was marked by a stabilization of most renewable regimes and niches, with solar PV and bioenergy seeing a slight expansion, offshore wind remaining stable at 2020 levels, and a slight reduction of onshore wind capacities with albeit slightly higher load factors. Therefore, much activity focused on repowering rather than constructing plants at new sites, with old and new players returning to old or finding new roles and business models. However, most attention was being devoted to novel ways of reducing electricity demand or making it more flexible, as well as to the expansion of transmission and distribution grids and interconnectors.

- While the EEG had returned to feed-in tariffs there was no immediate boom in *onshore wind*. One reason for this reluctance was that the internationally positioned incumbents were fed up with the public acceptance problems they had encountered prior to 2020, and therefore had decided to reorient their activities to other countries. Another reason was that many new entrants focused their attention on initiatives saving electricity or developing integrated solutions, rather than pure projects rolling out more wind parks. Therefore, most activities focused on the repowering of turbines at existing locations with larger, more technically advanced ones. For this, new business models emerged in which specialized project developers offered local park owners a benefit sharing model while supplying their services in retrofitting and operating the parks. However, not all park owners were ready for these organisational changes and therefore adopted a wait-and-see strategy, with some of them continuing the operation of their existing turbines while others were decommissioning them. As a result of these rather slow developments, onshore wind capacities declined slightly, but given the technical improvements in the newest generation of wind turbines overall electricity generation remained fairly stable.

- In contrast, *offshore wind* came to a temporary halt since no more national auctions were being put forward. This made incumbents and affected industry players actively promote the implementation of the European auctioning scheme. While negotiations were still ongoing large incumbents already started to forge strategic alliances with partners in EU member States with high wind conditions, low water depths and short distances from the shore. When in 2022 the first round of the European auctioning scheme for offshore wind was launched, German incumbents were well represented in the winning bids, but for cost reasons none of these were located in Germany. Therefore, construction activities in Germany came to a halt, yet without substantial outcries by German players. In fact, with their good references German manufacturers, construction firms and service providers managed to tap into the newly opened European market and played a leading role. Still, a number of local jobs focusing on operation and maintenance of existing farms were still placed in Germany. Towards the end of the second phase, a small number of German repowering projects won European bids, thereby keeping overall offshore wind capacities at the 6.5 GW which had been reached in 2020. This did not mean, however, that the government had abandoned their previous expansion target of 15GW by 2025, but rather that these capacities were built up at more profitable locations, thereby contributing to turning Germany into a net importer of electricity.
- Whereas much hope of the previous government had been put on free field *solar PV*, by 2020 little interest had remained to invest in such free field PV plants. On the one hand, large incumbents were eying more profitable investment opportunities in Southern countries with higher sunshine hours and less public resistance. On the other hand, in the wake of the creative rethinking of the future energy system a societal consensus emerged for rooftop PV solutions which could be linked to smart consumption and storage solutions. Therefore, specialized project developers applied for radical innovation funding to test such creative new solutions. Similarly, cooperatives developed proposals experimenting with smart prosuming, for which funding from the experimentation scheme was sought. As a result, in the beginning of the period capacity additions remained small, but the search for new ideas for solar PV boomed. When experiments and innovation projects showed partly promising results, lessons were drawn from both promising and failing experiments, and led to modified solutions which again applied for public funding. Through this process new integrative products and services were developed which were brought to the market starting in 2030. Initially, entrepreneurs mainly worked with those who owned rooftop solar PV which came to the end of its lifetime. Many of these solar PV owners signed on to contracts with specialized project developers or local municipalities who offered various business models which combined the repowering of solar PV plants with the installation of a smart meter, membership in user groups, and sometimes even integrated storage solutions. This created a greater dynamic in the solar PV and related markets. For example, the development of novel "Smart Apps" boomed, and appliance manufactures started to jump onto the trend of smart electricity solutions. In addition to private households also hotels, schools, local businesses and other companies were equally eager to not only replace their solar PV rooftop solution, but to purchase an integrated solution adapted to their needs. All these developments prepared the ground for the breakthrough which these solar PV solutions would see after 2040.
- Finally, *bioenergy* initially benefitted from the EEG amendment of 2019, with some increases in generation capacities. However, they remained at fairly low absolute levels. Much of this increase was driven by carbon prices reaching levels of 20 Euros

and more, but growth was limited due sustainability concerns and the ever increasing interest in alternative uses, including the emergence of biomaterials in the chemical industry, which drove up biomass prices. However, given the great technological know how of German manufacturers and bioenergy system providers the government assisted manufactures in exporting their products and technological know how abroad.

'Old' regimes

At the beginning of the period Germany celebrated the closure of its last nuclear power plants. However, it was most occupied with supporting the structural change and associated social challenges resulting from the much needed closure of its lignite and coal fired power plants. Towards the end of the period Germany also became increasingly concerned that it needed more and not less flexible gas fired power plants to act as back-up for its largely intermittent renewables.

- While the carbon tax introduced in 2023 and the recovering EU ETS carbon price started to push the least efficient *coal and lignite* fired power plants out of the market, these policy changes had only been made possible by the government promising to introduce support for the affected regions, particularly those with lignite deposits. The idea behind this was to support the structural change associated with the gradual closure of the lignite industry, thereby alleviating concerns regarding the loss of jobs and regional income. Therefore, in 2020 one of the first moves of the government was to issue a call for applications to become a "green transformation region" willing to commit to a lignite phase-out plan in exchange for supporting the structural change of the region. One year later the government selected two green transformation regions for which the government established a cross-departmental transformation task force. This task force – in close cooperation with the affected regions – designed a participatory visioning process for the clean energy future of the two regions. They were supported by a consortium of researchers specialized in participatory decision-making and regional development. A state of the art stakeholder engagement process was designed which over the period of three years brought together all affected parties in creating a shared vision of the future of both model regions. This vision addressed all areas of economic, social and environmental development of the region. Given the overwhelmingly positive attitude towards climate action which had emerged across Germany citizens, companies and universities in the region were increasingly enthusiastic about the model region project, particularly when in the subsequent roadmapping exercise concrete steps for achieving the vision were identified, taking on board as much of the input from stakeholders as was possible. In 2024, after three years of an intensive visioning process both regions proudly presented their visions and roadmaps to the chancellor at the officially signing ceremony marking the start of the implementation of these roadmaps. After much applause from politicians, environmental NGOs and even the media the regions and the task force themselves were highly motivated and very committed to turn these plans into reality. After the successful visioning phase the task force took on the job of a monitoring, evaluation and learning agency which facilitated joint learning between the regions, but also provided transparent information about the progress of the two model regions – mainly targeting other affected regions but also the international community and particularly other countries which needed to phase out coal in a smart way. Indeed, there was great interest in the transition of the model regions which after ten years had already come a long way – including the green transformation of the region's universities with new interdisciplinary chairs and study programs, a green entrepreneurial boom, a rejuvenation of the population due to attractive clean teach and ICT job offers, a reduction of unemployment rates, the improvement of key sustainability indicators, and multiple other green economy initiatives proceeding with unusually high levels of citizen engagement. Given its large success, several other regions' started to lobby for a second round of lignite but also coal model regions. However, despite this success the ongoing phase-out of lignite and coal did not leave operators unaffected. As incumbents had split up into a conventional and a clean business unit, with the latter ones becoming more and more active at the European and international market rather than in Germany, the business units charged with the conventional power plants were facing several financial restrictions and accordingly had to lay off many of their employees. In 2030, the two operators of lignite fired power plants merged, but consolidation continued. Given rising CO2 prices but declining global prices for coal, the remaining coal plants ran with higher load hours, thereby enabling their survival. However, it was increasing clear that new business models were needed or the what had remained of the incumbents would also cease to exist.

- As for *gas*, the increase of carbon prices and introduction of the carbon tax initially was not sufficient to stop the closure of some gas fired power plants. However, in an act to enable the survival of incumbents and in foresight of a future increase of electricity demand governments around Europe got together and designed a European capacity mechanism for gas fired power plants. This mechanism was implemented in 2030 and ensured that the remaining capacities of gas-fired power plants remained online as back-up capacity and that companies started to invest into new capacity. This became a highly profitable business opportunity as the increasing intermittency of the European electricity market required an increasing use of these previously little used back-up capacities. Interestingly, German companies were among the fastest and most successful in building these new gas fired power plants, which was argued to be the case because Germany's earlier investment into a gas pipeline with Russia and the readiness or desperation of incumbents to find a new role in the electricity system of the future.
- Germany's *nuclear* phase-out continued to proceed as planned, with the final plant closures taken place in 2019 (Philippsburg 2), 2021 (Grohnde, Brokdorf, Gundremmingen C) and the last ones in 2022 (Isar 2, Neckarwestheim 2, Emsland). These final closures were highly celebrated across society. While it had originally planned that a new site for nuclear storage could be announced, the commission charged with the task of coordinating the scientific screening of suitable locations could only report intermediary results of the progress made so far. However, by 2030 three suitable regions for the permanent storage of Germany's radioactive waste had been identified. As none of the regions was volunteering to be chosen the government implemented a visioning and roadmap process after which the winning region would receive the necessary funds to turn the vision into reality. The participatory procedure followed the one which had been developed for the two model regions for the phase out of lignite. It was hoped that one of the regions would turn into an enthusiastic proponent of becoming Germany's permanent nuclear storage site, enabling the closure of this lengthy chapter of Germany's nuclear energy policy. However, by the end of the period the regions were still heavily debating their vision and roadmaps.

Given the reduction in fossil generation the shares of wind and solar PV within overall electricity generation by 2035 had increased to approximately half of the electricity generated in Germany. This had turned Germany into a net importer of electricity. Both developments necessitated a much greater rate of change in the conservative e*lectricity network regime* than witnessed before. Therefore, the government started to put much more pressure on network operators to increase the speed of the further expansion of long-distance transmission grids to connect the wind farms located mainly in Northern Germany to the further southwards centres of demand. To facilitate the implementation of investment plans, in 2023 the government initiated an independent grid stakeholder consultation task force to negotiate the best possible route for the construction of new transmission lines but also possible compensation measures for affected communities. When it became clear that the task force was not taking very seriously given its limited power in making recommendations with budget implications, such as the construction of underground cabling or landscaping, in 2025 the government equipped the task force with a significant budget thereby granting it greater flexibility and power in stakeholder consultations. This budget was financed through part of the proceeds of EUA auctions which started to increase significantly in the period between 2025 and 2035, resulting from the interventions of the climate coalition – or as some had started to call them, the "Coalition of the Willing" EU Member States. In 2026, the government also implemented several regulatory changes which provided a clear incentive structure for delivering grid expansion in time and respecting social and environmental criteria – but also penalties for delays and underperformance in terms of sustainability criteria. This had been preceeded by a yearlong consultation process which resulted in the adoption of a revamped energy system law (EnWG). This EnWG 4.0 (as it was jokingly called) took on board many long-overdue changes which were intended to provide the proper incentives for a faster low-carbon reorientation of the network regime. It also included the introduction of 'time-of-use tariffs' to allow for dynamic pricing of electricity, thereby providing consumers with monetary incentives to shift demand accordingly, such as charging electric vehicles at noon when electricity is abundantly available and thus cheaper. However, due to distributional concerns and reasons of cost-efficiency dynamic pricing was first rolled out for large users only. Yet, pilot schemes experimenting with dynamic pricing in private households were allowed under the condition that no customer would be made worse off than under the standard pricing scheme. Eagerly, several new entrants developed innovative projects which they tested out in the context of Germany's experimentation scheme. Some failed, but others were promising and were developed further. However, their time was yet to come in the third period.

Finally, Germany intensified its collaboration with neighbouring countries for the continued construction of interconnectors to create an emerging European super-grid. While up to 2019 Germany had been a net exporter of electricity, by 2020 it had turned into a net importer of electricity. The main reason for this was that balancing demand and supply through the im- and export of electricity at the time was much cheaper than storage solutions. However, promising radical innovations and integrated solutions were underway for future storage solutions, and a healthy industry had built up in Germany, with its main clusters being located in the lignite model regions. However, it was clear that a European super-grid would also be needed, so Germany was actively pushing for an agreement to jointly finance these essential infrastructures which was eventually struck in 2024 among the "Coalition of the Willing". One of the first great successes was when in 2029 a new interconnector between the UK and continental Europe was opened, as it lay the foundation for an increased import of cheap UK electricity generated by its vast onshore wind potential which was increasingly harnessed by the UK electricity system.

The perhaps most wide-reaching changes, however, occurred in the electricity *consumption regime*, which saw a remarkable reduction of electricity demand and flexibilisation of consumption patterns. These changes were mainly achieved by a combination of price incentives and a climate of open experimentation, which together ushered in an era of behavioural changes. These price incentives were largely originating from the national roll-out of a white certification scheme whose design had benefited significantly from the experience gained from the ten pilot regions which had introduced white certificate schemes in 2021 (as well as the further roll-out of smart meters). However, while substantial improvements in energy efficiency could be attributed to the former, the observed change in thinking about electricity demand was largely driven by the creative spirit introduced by the experimentation schemes. Together, these two new policy instruments – together with an active and increasing usage of smart meters - led to such significant reductions in electricity demand that even increased consumption elsewhere (through the rebound effect) and new users (e.g. ICT, electric vehicles) still allowed for absolute reductions of electricity demand.

In conclusion, in the second phase Germany witnessed a great dynamic which became largely visible in electricity demand reductions and many actors getting enthusiastically involved in experiments aiming at novel ways of smart electricity generation and use. At the same time, growth of offshore wind, onshore wind, bioenergy and solar PV more or less came to a halt, while conventional capacities were being reduced across the board. Lignite model regions witnessed great success in pursuing a holistic regional development strategy. In terms of policy initiatives the period was characterized by greater supranational initiatives of proactive countries (e.g. EUA buy-out, interconnectors), a strengthening of market-based policies (e.g. EU ETS, European auctioning for offshore wind, national roll out of a white certificate scheme), and a recognition of the need for active stakeholder engagement through explicit government bodies with budgetary independence (e.g. grid stakeholder consultation task force, cross-departmental lignite model region task force), as well as new regulatory institutions (e.g. dynamic pricing, European wide capacity mechanism for gas). Together, these changes enabled Germany to meet both its renewable and energy efficiency targets as well as its climate targets, and put it on track for an electricity system which was set to be dominated by solar PV, onshore wind and gas, while at the same time keeping a check on overall electricity demand. Overall, Germany's climate actions caught a lot of international attention due to the country's success with lifestyle changes and electricity demand reductions. However, Germany's electricity transition model was also criticized for too high a reliance on electricity imports rather than higher levels of domestic generation of renewable electricity.

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

The beginning of the third phase was marked by the take off of electric vehicles. After two decades of a reduction of electricity demand this wide diffusion implied a steady increase of electricity demand. These developments led to a massive expansion of onshore wind and solar PV which had emerged as cheapest and broadly accepted renewable electricity generation technologies. As the diffusion of e-vehicles continued and new models came on the market, some car manufactures linked up with project developers specialized in rooftop PV in order to provide buyers with their own low-carbon PV charging infrastructure. These combined deals became highly popular, which led to a further expansion of other car companies also offering these package solutions. By 2040 almost each electric car sold to a private household was purchased together with a freely-installed solar PV rooftop solution and smart charging interface. Similarly, car sharing companies and company car fleets started to cooperate with project developers to develop smart charging solutions connected to wind parks and solar PV on their premises. In essence, the e-mobility revolution implied that between 2035 and 2050 both *solar PV* and *onshore wind* capacities and generation nearly doubled. Given this massive expansion, project developers had to work closely with local communities to address any land-use concerns early on and ensured they would benefit from these newly installed plants. Despite this immense growth in generation capacities the cost burden on electricity consumers arising from support for the investment in renewables was not largely affected due to earlier cost reductions of both technologies.

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

Given the great increases in intermittent renewables, flexible back-up capacity together with a further expansion of the European super grid was needed. The former was incentivized by the previously negotiated European capacity mechanism but also benefited from a carbon price of by 2040 over 50 €/tCO_2. Therefore, the spike in investment in *gas* fired electricity generation plants continued, with a significant share of the needed capacities being built in Germany, providing a new business model for the remaining incumbents. As a result, within fifteen years Germany had almost tripled its gas capacities and became the European hub for flexible back-up electricity. In doing so, Germany took advantage of its geographical position in the middle of Europe, allowing it to export to a larger number of countries in times of low renewables generation. In that sense, to some degree Germany started to act as a balancing country for its neighboring countries. Although this increased Germany's emissions, over the past decade carbon accounting had already shifted form a national perspective to a European one. However, as electricity demand was that high a small number of *coal* fired power plants remained online, as high carbon prices were partly compensated by low coal prices, much to the dismay of environmental NGOs. However, when more and more of the new gas plants came online after 2040 the full load hours of these remaining coal plants reduced significantly. Yet, despite the overall spike in generation capacity Germany remained a net importer of electricity from countries with sites with better wind and sunshine conditions, with the net import share reaching over 25% in 2050.

These developments went along with the further expansion and flexible utilization of smart grids. In addition, smart pricing which varied according to time of use made significant advances and became business as usual for industry and households. Also, households and industry continued their quest for identifying options to reduce electricity demand, even though this was not sufficient to neutralize the increasing electricity demand from electric vehicles. Taken together, these changes made the electricity system highly flexible in its response to intermittent demand. Finally, in 2045 the nuclear waste commission announced the final location of Germany's permanent storage site after which a green transformation task force took on the redevelopment of the region and construction teams started the establishment of the storage site.

In conclusion, phase 3 was characterized by the doubling of capacities and generation from onshore wind, solar PV and gas. This was driven by the massive deployment of electric vehicles which increased electricity demand. At the end of phase 3, electricity generation capacities were largely small scale, and the ownership structure was diversified among citizens, cooperatives, project developers, industry and incumbents (for gas, and remaining coal). Given Germany’s role as flexible European back-up hub a full decarbonisation was, however, not achieved, which made some argue for a second look at CCS and others point to the European nature of carbon accounting.

7. Concluding comments

In this deliverable, two socio-technical scenarios were developed to explain the model outcomes of the PowerACE model for a pathway dominated by technological change only (Pathway A, scenario 1), and another characterized by broader changes to the electricity regime (Pathway B, scenario 2). The main emphasis in writing these histories of the future was to draft plausible stories of how the model parameters could be achieved through internal change rather than external shocks. In this concluding section we want to (i) emphasize the key technological similarities and differences between both pathways, (ii) derive the associated policy risk, (iii) draw broader policy implications and close with (iv) methodological reflections.

(i) Key technological similarities and differences

There are important technological similarities between pathway A and B:

- *Wind* is the largest option in both pathways accounting for about 51 % of power generation in 2050 in Pathway A and 41% in Pathway B. However, the relative importance of onshore and offshore wind varies tremendously, with offshore being by far exceeding onshore wind in Pathway A (since offshore fits well with incumbent interests and practices and overcomes local NIMBYism) and onshore being by far the largest in pathway B (since it works best for new entrants and smaller investors).
- *Bioenergy* remains of low importance in both pathways, given sustainability and cost concerns as well as competing uses in other sectors.
- *Gas-fired power plants* initially struggle in both pathways, but in the third phase gas emerges as winning conventional technology because of its flexibility and relatively low-CO_2 emissions which make it an essential back-up capacity for intermittent renewables. However, actual use of gas is only substantial in Pathway B only, in which after 2035 Germany becomes a European hub for flexible gas capacity. Yet, in both pathways gas is not combined with CCS, despite CCS becoming available in pathway A.
- *Unabated coal* is only partially being phased-out, despite high carbon prices – and it is not combined with CCS despite the technology becoming available in pathway A.
- The expansion of transmission and distribution *grids* and pan-European interconnectors as well as the greater smartness of the grid is crucial in both scenarios to integrate intermittent renewables. In this regard, smart meters become an important technology under both pathways, although the knock-on effects on household behaviour are larger in Pathway B.
- By 2020 Germany moves from being a net exporter of electricity to a *net importer* of electricity which ultimately reaches a higher level in Pathway B (25% in 2050) compared to Pathway A (17% by 2050).

Key technological differences concern the future of solar PV and CCS.

- *Solar PV* is phased out in Pathway A, while it becomes the technology with the greatest share in capacity in Pathway B.
- *Onshore wind* stops its growth and focuses on repowering in Pathway A, while the same is true for *offshore wind* in Pathway B.
- CCS enables the survival and renaissance of *lignite based power generation* in Pathway A, while lignite is being phased out in Pathway B.

(ii) Key policy risks

The technological similarities imply several policy risks, which relate mostly to political and social acceptance issues.

- *Political commitment to fixing weak carbon signal of EU ETS:* There is a risk that the German government will not take unilateral or bilateral action to address the oversupply of EU allowances and thereby contribute to a strengthening of the CO2 price. This risk could be addressed by Germany attempting to strike a European deal for reforming the EU ETS, or by using alternative measures, which, however, would likely lead to an increase in decarbonisation costs and less clearer carbon signals.
- *Political commitment to significantly improve energy efficiency:* While energy efficiency has been recently tried to be established as second pillar of the energy transition, there is a real risk that policy makers will not show the needed commitment to penalize electricity consumption in order to incentivize improvements in efficiency and reductions in electricity demand. There are currently no indications that Germany would change from a voluntary policy approach with the provision of financial support to a policy paradigm which pushes for radical improvements in energy efficiency rather than just incremental improvements.
- *Maintaining acceptance for massive role of wind:* while for offshore wind this risk is mainly associated with expected cost-reductions which might not materialize as well as concerns about incumbents becoming the main investors and beneficiaries of the Energiewende (Pathway A), for onshore wind the main risk is linked to increasing land-use, visibility and noise concerns at an ever greater roll-out of onshore wind parks. While in Pathway A it is mainly in the interest of the offshore wind advocacy coalition to reduce costs in order to expand its role in the German Energiewende, in Pathway B this risk is mitigated by stakeholders and communities benefiting from the construction of onshore wind parks, either directly through energy cooperatives or indirectly through new business models.
- *Grid access and expansion delays:* grid improvements and pan-European interconnectors might be made too late, which could limit the system's ability to deal with increasing amounts of intermittent renewables. To overcome this risk resulting from a conservative network regime the government is assumed to introduce major changes to the regulatory institutions governing the network regime, as well as negotiate European investments into the construction of a European smart grid.
- *Public acceptance for an Europeanization of renewables policy and decarbonisation targets:* The high reliance on import of renewable electricity implies a great dependence of the decarbonisation of Germany's electricity system from developments abroad, including policy commitment and social acceptance. While this might be ensured through the Europeanization of funding schemes for renewable electricity, by no mean it is clear that countries would agree to such a scheme and that German civil society would accept such a move of investing renewable abroad, as it would imply transferring public funds to other European Member States, with most of the associated co-benefits (such as local jobs) occurring there as well. Also, it is by no means certain that there would be public acceptance for the German energy mix of 2050 not being fully decarbonized due to remaining levels of coal and – in pathway B – high levels of gas. These developments imply a change in thinking about were renewable and decarbonisation targets need to be met – at the nation state level or at the European level. Therefore, policy makers may want to start a debate on the desirability of a future electricity system which is decarbonized within each nation

state or only at a European level, as well as a discussion of European vs national renewable targets, with the EU's 2030 target making a first step in that direction.

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

(iii) Broader policy implications

Based on our analysis we derive a number of broader policy implications. First, both decarbonisation scenarios are very demanding and require major reorientations within the next 5-10 years, but also a continued need to adjust the policy mix to unexpected circumstances. Therefore, both scenarios convey a high degree of urgency to strengthen policy commitments while at the same time remaining flexible to adjust the policy mix as the transition unfolds and new insights become available.

Second, German policymakers are recommended to keep and further strengthen their participatory and reflective policy making style, which incorporates close monitoring of policy effects, their evaluation and subsequent adjustment of policy instruments. Such a focus on inclusive policy making and policy learning is essential given the uncertainties and multiple challenges associated with the energy transition. Also, given recent changes in Germany's renewable energy policy paradigm – away from a close focus on risk reduction to enable investments of new entrants to a greater attention to cost-efficiency typically associated with larger players, including incumbents – policy makers should pay particular attention to the impact of this policy paradigm shift. For example, monitoring should include changes in the ownership structure and associated changes in the public acceptance of the Energiewende.

Third, social acceptance will be a crucial success factor – if not the main success factor – for the decarbonisation of the German electricity system (e.g. massive role-out of onshore wind by incumbents, phasing out of solar PV, introduction of CCS, grid enhancement). Therefore, public acceptance should continue to receive close attention in designing policies for the Energiewende, rather than just focusing on cost-efficiency concerns.

Fourth, resistance from incumbents is a major challenge of the success of the German electricity transition. Therefore, policy makers should explore creative and novel policy approaches, such as green model regions, or a partial role-out of new instruments, such as pilot schemes. Such novel approaches will be needed to manage and overcome resistance to change, as, for example, being the case for the difficult phase-out of lignite.

(iv) Methodological reflections

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

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

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

References

Elzen, B., Geels, F.W., Hofman, P. and Green, K., 2004, 'Sociotechnical scenarios as a tool for transition policy: An example from the traffic and transport domain', in: Elzen *et al*. (eds), *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*, Cheltenham: Edward Elgar, pp. 251-281

Geels, F.W. (2002), 'Towards sociotechnical scenarios and reflexive anticipation: Using patterns and regularities in technology dynamics', Sørensen, K.H. and Williams, R. (editors), *Shaping Technology, Guiding Policy: Concepts, Spaces and Tools*, Cheltenham, UK, Northhampton, MA, USA: Edward Elgar, 359-385

Hofman, P.S., B.E Elzen, and F.W. Geels, 2004, 'Sociotechnical scenarios as a new policy tool to explore system innovations: Co-evolution of technology and society in the electricity domain', *Innovation: Management, Policy & Practice*, 6(2), 344-360

Hofman, P.S. and Elzen, B., 2010, 'Exploring system innovation in the electricity system through sociotechnical scenarios', *Technology Analysis & Strategic Management*, 22(6), 653-670

Marletto, G., 2014, Car and the city: Socio-technical transition pathways to 2030, *Technological Forecasting and Social Change*, 87, 164-178

Nilsson, M. and Nykvist, B., 2016, Governing the electric vehicle transition: Near term interventions to support a green economy, *Applied Energy*, in press

Verbong, G.P.J. and Geels, F.W., 2010, 'Exploring sustainability transitions in the electricity sector with socio-technical pathways, *Technological Forecasting & Social Change*, 77(8), 1214-1221