PATHWAYS project

Exploring transition pathways to sustainable, low carbon societies

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<u>Deliverable D2.5</u>: 'Forward-looking analysis of transition pathways with socio-technical scenarios'

<u>Country report 2</u>: The UK electricity system

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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 UK 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 that is shared between the different contributors to WP2 to enable comparative analysis of findings between countries (UK, Netherlands, Sweden, Portugal, Germany) and empirical domains (electricity, heat, mobility, agro-food and land-use).

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Executive summary

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

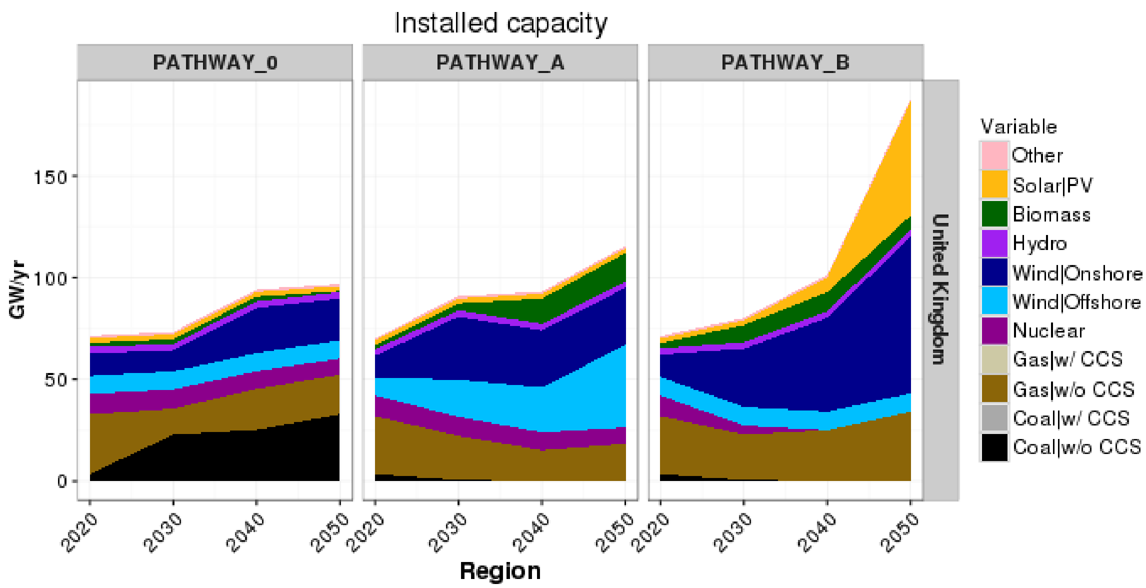

Figure A: Installed capacity in power generation in the UK (from D1.3)

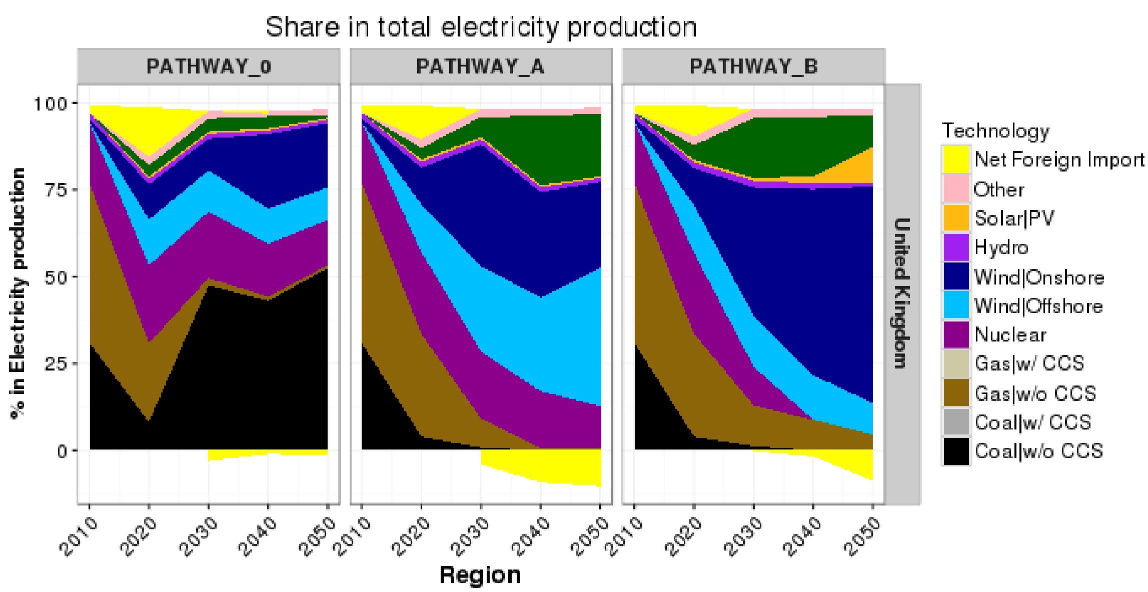

Figure B: Power generation in the UK (from D1.3)

As an intermediate step, the report articulates several 'transition challenges', which are the tensions between contemporary trends (documented in D2.1 and D2.2) and future model outcomes (Figure A and B). The socio-technical scenarios develop endogenous storylines for how these 'transition challenges' (Table C) can be overcome through (inter)actions between relevant actors, which vary between both Pathways. It is important to develop these more sociologically sensitive scenarios since Table C shows that policy commitment and social acceptance create obstacles for the diffusion of various low-carbon innovations in Figures A and B.

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

Innovation	Pathway A	Pathway B	Constraint
1. Biomass	Pathway A and B assume high amounts of biomass in electricity use. This contradicts with current UK policy, which intends to increase biomass for electricity until 2020, but downscale this afterwards (re-directing biomass towards transport and heat). The assumption of high biomass is also sensitive to public acceptance problems around imported biomass (as visible in NGO actions, public debates, legal contestation).	Same as A, but less in quantitative terms. But bio-energy will be based on distributed, small-scale generation, which will create special challenges.	Policy and social acceptance
2. BECCS (biomass energy with CCS)	BECCS plays a large role in European scenarios (especially after 2050 to generate 'negative emissions'). BECCS also plays a substantial role in UK pathway A (after 2030). This creates three tensions with WP-2 1) BECCS is not studied in WP2 (because it is not yet viable and there is not much happening 'on-the-ground'). It is therefore difficult to make connection in our storylines. (It is seems risky to base future scenarios on something that hardly exists in the present) 2) The upscaling of bio-energy is controversial in the UK (see above) and currently not pursued in government policy. 3) Pathway A in the UK does not include CCS (for coal and gas), but does assume BECCs from about 2030 (linked to use of biomass). This seems internally contradictory.	No CCS in pathway B (and no BECCS)	Technology readiness, Economics; Social acceptance
3. Onshore wind	Both pathways (but particularly B) assume a major expansion of onshore wind (because it is the most cost-effective renewables option). This contradicts with WP2-findings that onshore wind faces major social acceptance problems. The new UK government has also introduced a moratorium on building more onshore wind farms after 2020, and subsequently downscaled subsidies.	The upscaling of onshore wind is particularly large in pathway B (which creates tensions with social acceptance). Another tension is who will deploy these onshore wind turbines. Pathway B assumes that new entrants are the main actors (e.g. community energy, activists, farmers). But WP-2 showed that there are relatively few	Social acceptance; lack of policy and political will

		new entrants in the UK.	
4. Electricity grid expansion	Both scenario s assume strong grid expansion. This creates tension with current grid trajectories (particularly in distribution grids), where there is much inertia and some local resistance to grid-projects.	Same as pathway A.	Integration; Social acceptance; lack of political will
5. Nuclear	Nuclear power is somewhat increased in pathway A. This fits with government plans, but creates a tension with WP-2 findings, which show that on-the-ground delivery of nuclear power plants is very slow and already 5 years behind schedule. The UK government intends to build 8 new nuclear plants, but is still struggling to build one (Hinkley Point C). This first plant is very expensive (more than twice current electricity retail price).	No nuclear in pathway B.	Economics; socio-political acceptance
6. Import and export	Scenarios A and B assume that the UK will be exporting low-carbon electricity after 2030 (because UK onshore wind is the most cost-effective options in the models). This contradicts with current government policy, which builds new interconnectors with European countries to *import* low-carbon electricity, e.g. from Norway, Iceland.	The same as under pathway A, but to somewhat lesser extent	Political acceptance.

Both scenarios are presented below. Underlying argumentation and lessons can be found in the report.

Scenario 1 (Pathway A)

Core characteristics, logics and challenges

This scenario provides a socio-technical storyline for pathway A (in Figure A and B). In conceptual terms this pathway focuses on large-scale technologies, which represent disruptive technical change, but leaves many elements of the socio-technical system intact. Incumbent actors are the dominant actors in Pathway A, where a core logic is that governments change market institutions (regulations, financial incentives) to stimulate the reorientation of large firms. The introduction of new policies needs to be underpinned by 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 onshore wind, biomass, BECCS and grid expansion (table 3 above), and 2) the need for *political U-turns* in specific climate change strategies. These problems needs to be addressed in the first period (2015-2025) to prepare the ground for further roll-out of renewable electricity technologies (RETs) in the second and third period.

Changing gear and gearing up (2015-2025)

In the Paris agreement, the newly elected (2015) Conservative government pledged to cut greenhouse gas emissions by 40% by 2030 compared to 1990. Since the heat/buildings and transport sectors were envisaged to decarbonize more slowly, this commitment meant that most GHG reductions should come from the electricity sector by 2030. Although the government did not specify post-2020 targets, their strategy for substantial decarbonisation was based on a ‘partial reorientation’, which included changes in existing regimes (nuclear, coal/gas) and some upscaling of niche-innovations (with stated targets of 30% of renewable electricity generation by 2020, but no clear statements post-2020).

Regime developments: The government envisaged expansion of nuclear power (with plans to build and operate 8 new nuclear plants by 2030, delivering 16 GW new capacity), the introduction of CCS for coal and gas, and the phase-out of unabated coal by 2025 *if* viable alternatives were available by then. However, the political commitment of the new government was lower than previous government, leading to the removal of subsidies for CCS demonstration projects. This was a major setback for CCS deployment in the UK, which damaged investor confidence and future visions. R&D investments in CCS therefore remained low in subsequent years, with the UK falling behind international efforts (e.g. in the US and Canada). The lack of a domestic support coalition made it difficult to implement CCS in the 2020s in the UK.

The government also struggled to build the first new nuclear power plant (at Hinkley C). In 2015 and 2016, EDF postponed decisions several times, because of the technical complexity of the plant and the size of the financial commitment. In 2017, EDF finally committed as a result of top-level negotiations between the UK and French governments (which owned 80% of EDF). These difficulties created social and political problems for the UK's further nuclear plans. Nevertheless, the government pushed ahead with two other nuclear plants (Wylfa and Moorside), starting concrete negotiations in 2018, which by 2020 resulted in concrete plans. Meanwhile, Hinkley C faced construction problems, which led to further delays in the opening until 2025 (more than 7 years late compared to initial plans). Final construction costs were higher than planned (£20 billion instead of £16 billion), which caused major embarrassment for the government. In combination with the high price (more than twice the whole sale price), which was guaranteed for 30 years, this led to a negative discourse of nuclear power being too expensive. The government spent much political capital to push through the other two nuclear plants, but after that there was little appetite, nor political opportunity to build the remaining 5 nuclear plants. Since several old nuclear plants were decommissioned, the installed capacity did not increase very much.

The problems with CCS and nuclear power created major challenges for the government's climate change strategy as well as a capacity gap, which created major energy security concerns. The newly elected (2020) government acknowledged these problems and changed direction. It embarked on an ambitious plan to upscale renewable electricity production and accelerate the deployment of green niche-innovations. Since this would take time, the sector still faced a capacity gap in the late 2020s. While the government did not abandon the commitment to phase-out unabated coal, it felt nevertheless compelled to postpone this to 2030.

Niche developments:

In July 2015, the Conservative government down-scaled a range of support policies for renewable electricity technologies, because the projects that were in the pipeline would be sufficient to reach the 30% target for 2020. Feed-in-tariffs for solar-PV were slashed by 80%. And in response to public concerns about the countryside, the government announced that it would build no more onshore wind turbines after 2020 and consequently down-scaled financial support instruments. The conversion of coal plants to biomass also faced problems, firstly because of down-scaled subsidies and, secondly, because of public concerns about the sustainability of imported biomass pellets (which led to strong NGO protests).

The slashing of renewable electricity policies led to bankruptcies, especially in the emerging solar installation industry. But it also damaged investor confidence and many utilities, project-developers and large investors complained about the unreliability and fickleness of UK energy policy, which seemed to change every 5 years. Nevertheless, the government was right in the sense that the 2020 targets for renewable electricity were met.

By 2020, however, it had become clear that other parts of the government's strategy (particularly CCS and nuclear) had not worked as well, which created a major gap in their plans to reach the 2030 targets. Meanwhile, the sales of hybrid and electric cars had increased from 2.8% of new sales in 2015 to 9% in 2020. This increased the pressure (also from international car companies) to reduce the carbon intensity of electricity (since this affects the climate mitigation potential of electric cars). The newly elected (2020) government also faced international pressure, both from the EU and the pledge-and-review process agreed in Paris, to continue its commitment to the 2030 targets. In this context, the new government changed the direction of its climate change strategy: a) it downscaled its nuclear plans from eight to three nuclear reactors, b) it cancelled its CCS plans for coal and gas, but kept its commitment to coal phase-out by 2025, c) it increased its commitment to RETs, which had to be substantially increased to fill the gaps created by the failed nuclear and CCS strategies, d) it would continue and expand the building of interconnectors to European countries to enable the import of more low-carbon electricity (from Iceland, Norway, France).

RET-expansion plans included all options, except solar-PV where the earlier disruption had wiped out most businesses. Onshore wind was the main plank of the government's strategy, because this was the cheapest option, which resonated with the government's goal to keep costs down. Offshore wind was also important, because it offered commercial prospects for diversification for the UK's offshore industries (gas, oil). The conversion of coal plants to biomass increased more gradually because of concerns over the sustainability of imported pellets. These concerns gave rise to supply chain standardization efforts, which took several years to reliably implement and certify.

The new government strategy faced many hurdles, which required additional tailored policies.

- Investors, utilities and project developers were initially reluctant to deploy new RETs because they did not trust the government after earlier U-turns had caused losses and disrupted their long-term planning. To convince and attract companies, the government therefore had to offer very attractive conditions with penalties against future policy change.
- Onshore wind, in particular, faced large social acceptance problems, because of concerns over the countryside and because of the poor quality of earlier consultation processes (which led local citizens to contest permit procedures because they did not feel listened to). Addressing these problems required a wide range of initiatives which unfolded over several years: a) in exchange for financially attractive support policies, the government required utilities and project developers to improve their consultation procedures, leading to real involvement of local residents in project planning, b) firms were also required to pay 2.5% of revenues to local residents as compensation for burdens, c) a 'Broad Societal Discussion' was organized to discuss the pros and cons of the new government strategy with a broad range of stakeholders and citizens. Environmental NGOs were important in this discussion, because they helped articulate a discourse that prioritized climate change over the countryside. Not everyone agreed with this prioritization, which led to heated debates. But increasing consumer experience with electric vehicles and smart meters (which were installed in many households by 2020) enhanced engagement with, and interest in, clean electricity. d) a broad business coalition, including electric utilities, car companies (who became increasingly interested in electric cars), and ICT-firms (who deployed RETs themselves and had an eye on future smart grids) increasingly supported the new strategy, offering support for a green growth discourse. The alignment of these developments gradually enhanced the public support for increased deployment of onshore wind.

- Offshore wind faced less public acceptance problems, because the turbines were out of sight and because the higher costs were de-prioritized in a green growth discourse, supported by a broad coalition, including the Carbon Trust, Energy Technologies Institute, Technology Strategy Board, Department of Business, Innovation and Skills, the Crown Estate (which sold licenses for the seabed), environmental NGOs. National and international utilities (including Vattenfall, RWE) and energy companies (Dong, Statoil) also supported offshore wind, because this aligned with their large-scale generation routines and business models. These incumbent energy companies extracted attractive financial incentives and guarantees from the government in exchange for their commitment.

The substantial increase of RETs between 2020 and 2025 enabled a parallel down-scaling of coal-fired plants, many of which had reached the end of their life. To deal with the intermittency problem of onshore and offshore wind, gas-fired power plants remained prominent because they offered flexible back-up capacity that could be switched on/off rapidly.

The roll-out of smart meters, which was pushed by the government and utilities, experienced major social acceptance problems, because people felt they had not asked for this technology, which cost about £240. They also distrusted the utilities, which had been given responsibility for the roll-out program. Since much political capital had been invested, the government pushed ahead anyway, reaching less than its original goal (80% instead of 100% roll-out by 2020).

Rolling out renewables and transforming the grid (2025-2035)

The changes in the early 2020s, particularly in government strategy and public acceptance, prepared the ground for the further roll-out of RETs in the 2025-2035 period. The various RETs (onshore and offshore wind, biomass) developed into dedicated technical regimes with stabilized design rules and specialized communities. These 'new' regimes competed with the 'old' regimes (gas, nuclear, coal) in the context of a newly introduced carbon tax. The expansion of RETs also required major transformations in the electricity network regime (expansion, smart grids, storage) and greater flexibility in the electricity consumption regime (including smart meters and time-of-use tariffs). So, the earlier supply-side changes began to have knock-on effects on other parts of the electricity system.

Political concerns about climate change strengthened in the 2020s as extreme weather events and melting polar ice seemed to validate climate science predictions. The pledge-and-review process, agreed in Paris 2015, also proved remarkably successful, with many countries increasing their carbon reduction pledges. At the 2025 review meeting, the UK confirmed its 2050 commitment to 80% GHG reduction, which cemented policy delivery momentum. In this political context, politicians hotly debated an economy-wide carbon tax, which economists and modellers had long proposed, but which proved difficult to implement. In 2028, however, the government finally agreed to introduce an economy-wide carbon tax, which provided unambiguous market signals about the desired way forward, away from fossil fuels and towards low-carbon options. This tax was not only supported by environmental NGOs, scientists and green parties, but, importantly, also by several powerful industries, including the car industry (which desired clarity to enable a full strategic reorientation towards electric vehicles), the financial sector (which wanted clarity about long-term investments) and utilities (who saw opportunities in converting the remaining coal plants to biomass and CCS). The tax aimed to provide general direction as well as increase the amount of private capital available for low-carbon investments, including RETs, grid improvements, battery-charging facilities, etc. And indeed, the reorientation of financial capital from fossil fuel industries (which came to be perceived as not having a viable future) towards low-carbon options provided an important stimulus for the roll-out of RETs in this period.

'New' renewables regimes

Onshore wind expanded fastest until 2030, but subsequently faced some decreases because of a confluence of several developments: a) it became more difficult to find good wind sites, which reduced the price/performance characteristics of new wind parks (which were increasingly build in the interior as coast lines were already filled), b) public acceptance deteriorated again, as new wind turbines were built in very visible places, c) the introduction of the carbon tax in 2028 favoured Bio-Energy with Carbon Capture and Storage (BECCS) more strongly than was anticipated (see below), with the unintended effect of replacing onshore wind to some degree.

Offshore wind, which was more expensive than onshore wind, also faced competition from BECCS. Nevertheless, it continued to expand strongly because it was supported by a powerful advocacy coalition (see above), which translated into attractive financial incentives. The relative shift towards offshore wind also offered a way to circumvent the social acceptance problems of onshore wind, while boosting renewable energy production.

Biomass had expanded gradually until 2028 because of renewables support. After the 2028 carbon tax, biomass diffused much more rapidly than was foreseen because of several reasons: 1) utilities with coal-fired power plants were keen to convert to biomass, because this offered a way to further milk their assets, which were threatened by the planned coal phase-out by 2030, 2) these utilities could offer double carbon credits by implementing BECCS, which worked well on large-scale plants; this possibility was initially under-estimated because the UK had no experience or domestic firms in the CCS area, because of earlier policy failures; but CCS had been further developed internationally, and UK utilities successfully imported the technology and installed it on their plants; this enabled them to earn double carbon credits, one for biomass and one for storing CO2 emissions; BECCS thus created the possibility of *negative* emissions, which fitted well with the increasing socio-political concerns about climate change, 3) another advantage was that biomass offer low-carbon generation flexibility and back-up capacity for the increasing amount of intermittent renewables; this enabled gradual replacement of gas-fired power plants, which had previously fulfilled most of this function, 4) the public concerns about the sustainability of imported biomass was also alleviated by that time, because of the articulation of standards and inspections for sustainable biomass supply chains.

Initial BECCS installations faced technical teething problems, particularly with regard to dimensioning and operation. Once these problems were overcome, the attractive financial incentives stimulated existing utilities to build a raft of large-scale biomass combustion plants with integrated CCS facilities.

Despite ongoing cost improvements and international enthusiasm, solar-PV did not take off in the UK, because incumbent firms lobbied against dedicated solar-PV policies, which could undermine their reorientation towards biomass and wind. Since many solar installation firms had gone bankrupt in the previous period, the solar advocacy coalition was relatively small and uninfluential. Furthermore, significant PV capacities installed in continental Europe led to low electricity prices during the day, decreasing the potential revenue for PV installation in the UK.

'Old' regimes

The 2028 carbon tax rapidly reduced the *use* of natural gas for power generation. But policymakers wanted to maintain a certain amount gas-fired capacity for reasons of flexibility and back-up. They therefore introduced 'capacity markets' which paid utilities for the availability of gas-fired power plants, even if these were not used much. These plants provided additional back-up capacity (besides biomass) for those days in the year that there was very little wind.

Coal-power was entirely phased-out by 2030, as the remaining coal plants switched entirely to biomass. Nuclear power was somewhat expanded, as Hinkley C came online in 2025 and Wylfa and Moorside in 2030. Several other nuclear plants were decommissioned, however. But since the new plants were run at higher load factors, total nuclear power generation increased.

The high shares of onshore and offshore wind required major changes in the electricity network regime: 1) long-distance transmission grids were expanded to connect remote wind farms to centres of use, 2) an entirely new offshore grid was constructed, based on seabed cables, 3) the continued construction of interconnectors to European countries gradually linked the UK into an emerging European super-grid. Several tactics were pursued to lo limit *social acceptance problems* of building new pylons in the countryside: a) local residents were better consulted in the design and planning process, b) new pylon designs with less visual intrusion were deployed, and, in some instances, cables were constructed underground, c) the National Grid was forced to offer compensation, either financially or, in most instances, by planting new trees that would mask the pylons.

Another problem was the inertia and unwillingness of the National Grid and the Distribution Network Operators (DNOs) to engage with radical innovation. These infrastructure actors had been resisting change since the policy U-turns of the early 2020s. By 2025, politicians were deeply frustrated by the intransigence of these actors. As they strengthened their international climate change commitments, politicians also overhauled the network regime. The remit of the regulator Ofgem was changed to make climate mitigation as important as low costs. Politicians also changed the rules to enable them to set performance goals that market actors were free to meet in ways they wanted, but with the threat of stiff penalties, which Ofgem had to enforce. These rule changes and associated pressures enhanced the speed of infrastructure change, which also included the introduction of smart grids, which greatly enhanced the monitoring and management of electricity flows.

The pressure to increase flexibility (to deal with intermittency issues) also led to a push for new demand-side tariffs, which were enabled by the smart meters that had been installed in previous years. The introduction of ‘time-of-use tariffs’ (in which electricity prices vary with specified times) went relatively smoothly in 2026, leading to some demand shifts away from peak times. By 2028, it was clear that this shift was less pronounced than was hoped. Utilities and policymakers therefore pushed for the introduction of ‘dynamic tariffs’, in which electricity prices varied per hour, depending on supply and demand. This led to a major controversy, with consumer groups warning that the unpredictability and volatility of prices could lead to huge bills for older and non-ICT savvy households (if they would not reduce electricity demand during price spikes, e.g. when low wind would limit supply and push up prices). Policymakers and utilities went ahead anyway and introduced dynamic tariffs in 2030. Within half a year, however, disadvantaged consumers rose up in protest, causing a major backlash against the utilities and government, which were forced to withdraw and postpone the new tariffs.

Meanwhile, an interesting reversal was underway in electricity import/export with Europe. Since the 2010s, UK governments had expanded interconnectors to allow the *import* of low-carbon electricity from Iceland, Norway and France. By 2030, however, the UK was generating so much low-carbon electricity that it could start to export to European countries. This trend continued strongly after 2030 when the emergence of a European super-grid enabled continent-wide coordination and economic trading. Because of its excellent wind resources, UK renewable electricity was relatively cheap, which stimulated increasing demand from European countries with less renewable options. This reversal was not intended when the interconnectors were build, but gradually emerged as infrastructures linked European countries closer together.

A low-carbon flexible electricity system (2035-2050)

Changes in this period were less dramatic than previous ones, consisting mainly of changes in the relative size of RET-regimes.
* Offshore wind expanded substantially after 2040, to become the largest RET. The main driver were cost reductions due to technical reasons: 1) turbine size was further increased, which improved efficiency and decreased cost, 2) technical innovations made floating wind turbines viable, which removed the need for constructing expensive seabed platforms.
* Biomass and BECCS also expanded substantially, because policymakers realized they needed negative emissions in the electricity sector to compensate for mitigation problems in other sectors (e.g. manufacturing, heating/buildings). High biomass and BECCS capacity was also needed to provide back-up capacity and flexibility for the high degree of intermittent renewables.
* Onshore wind decreased in this period, because of competition from offshore wind and BECCS, and because of social acceptance problems (due to crowding the countryside).
* Although gas capacity was maintained (via capacity markets) for days with very little wind, actual use of gas for power generation became very small in this period.

The intermittency problem was further addressed with changes in the electricity network regime. Smart grids were further optimized, leading to high degrees of control of electricity flows which were linked to precise and accurate weather forecasts and measurement stations. The introduction of *voluntary* dynamic tariffs also became popular, because 'smart appliances' (which could switch themselves off when prices reached certain thresholds) reduced the risk that consumers would be faced with high bills due to price volatility. Some consumers were even willing to accept 'direct load control' options (which enabled grid managers to remotely switch off appliances such as washing machines, fridges/freezers), for which they were financially compensated. These options enhanced system flexibility by 10-15%. Further additional flexibility came from international spot markets, which allowed the UK to buy and import electricity (via interconnectors) in emergencies (e.g. days with no wind at all). This combination of options created a low-carbon flexible electricity system by 2050.

Scenario 2 (Pathway B)

Core characteristics, logics and challenges

This scenario provides a socio-technical storyline for pathway B from D1.3 (Figure A and B above). In conceptual terms this pathway focuses on a wider set of changes across several system dimensions. New entrants play an increasingly large role in electricity generation based on the growth and stabilization of new technical regimes (e.g. distributed generation). Wider shifts in cultural discourses and social legitimacy for an energy transition emerge, which are supported and support a broader, inclusive governance approach (beyond large firms and technologies), reflecting deeper changes in policy paradigms. Initially, social acceptance starts to grow; this is followed by increasing social *pressure* for change. Major 'transition challenges' concern: 1) *social acceptance problems*, which need to be overcome before a shift towards *increasing social pressure*; 2) the need for *policy instrument U-turns*, which precede more radical shifts in *policy paradigms*; 3) the dominance of *incumbent actors*, who will resist change in general and competition from *new entrants* more specifically.

The nuclear option: more wind! (2015-2025)

In the Paris agreement, the newly elected (2015) Conservative government pledged to cut greenhouse gas emissions by 40% by 2030 compared to 1990. Since the heat/buildings and transport sectors were envisaged to decarbonize more slowly, this commitment meant that most GHG reductions should come from the electricity sector by 2030. Although the government did not specify post-2020 targets, their strategy for substantial decarbonisation was based on a 'partial reorientation', which included changes in existing regimes (nuclear, coal/gas) and some upscaling of niche-innovations (with stated targets of 30% of renewable electricity generation by 2020, but no clear statements post-2020).

Regime developments: The government envisaged expansion of nuclear power (with plans to build and operate 8 new nuclear plants by 2030, delivering 16 GW new capacity), the introduction of CCS for coal and gas, and the phase-out of unabated coal by 2025 *if* viable alternatives were available by then. However, the political commitment of the new government was lower than previous government, leading to the removal of subsidies for CCS demonstration projects. This was a major setback for CCS deployment in the UK, which damaged investor confidence and future visions. R&D investments in CCS therefore remained low in subsequent years, with the UK falling behind international efforts (e.g. in the US and Canada). By 2020, CCS was eventually abandoned as a viable component of a low carbon future, because commercial and technical viability had still not been demonstrated at scale and coal generation was decreasing rapidly. However, the coal phase-out plan was stretched to 2030 to accommodate capacity issues stemming from problems with nuclear generation.

The government struggled to build the first new nuclear power plant (at Hinkley C). In 2015 and 2016, EDF postponed decisions several times, because of the technical complexity of the plant and the size of the financial commitment. By 2017, public debates also started to escalate about the prospects of escalating costs and delays (based on the experience of other countries attempting to build similar nuclear plants) and increasing concerns about the effects of supporting nuclear for future electricity prices. After several further postponed decisions, EDF pulled out of the deal in early 2018 on the basis of irreconcilable reputational and financial risk. This marked the end of nuclear as a central, base load, pillar for UK energy policy.

Anticipating the potential risk to their nuclear strategy, by early 2017 the government had already accelerated deployment of international interconnectors with Norway, France and Iceland, which meant that nearly 10% of annual electricity use was imported in 2020. This was used to mitigate the reduction of base load electricity supply from coal, gas and nuclear to 2020. However, during this period and after the Hinkley debacle, energy security became a hot public and political issue, reopening a political window for a renewed debate about the UK's energy policy.

Niche developments:

In July 2015, the Conservative government down-scaled a raft of support policies for renewable electricity technologies, because the projects that were in the pipeline would be sufficient to reach the 30% target for 2020. Feed-in-tariffs for solar-PV were slashed by 80%. And in response to public concerns about the countryside, the government announced that it would build no more onshore wind turbines after 2020 and consequently down-scaled financial support instruments. The conversion of coal plants to biomass also faced problems, firstly because of down-scaled subsidies and, secondly, because of public concerns about the sustainability of imported biomass pellets (which led to strong NGO protests).

The slashing of support for renewables had particularly damaging effects for the fledgling UK solar industry. This led to bankruptcies and a crisis of investor confidence, the effects of which lasted for some time in the absence of any solar specific government policy. However, the high profile debate around a new energy strategy created impetus for a new raft of pro-renewable policies and was touted in the media as the ‘renewable-reset’ (a direct dig at the previous government energy-reset). Incumbent-operated offshore wind farms remained stable, despite being costly, and enjoyed a broad base of support from across government. While very little additional capacity was installed (because of the high costs), offshore wind’s contribution to overall generation rose from around 5% in 2015 to 10% by 2025 through completion of projects already in the planning pipeline. So, while the niche remained small in overall terms, it started to take on regime qualities through increasing institutionalization within the long-standing large-scale, centralized model for generation.

But, because the debate at the time was focused on energy security and cost containment (and less on climate change concerns), onshore wind took centre-stage as the cheapest renewable energy technology. The political image of onshore wind was rebranded from ‘green crap’ to ‘cheap and British’ through ministerial speeches and briefing to the media. Emboldened by the shift, energy incumbents, who had already developed strong capabilities in plant installation and operation, quickly developed further plans for expansion. These initial moves were met by a high degree of resistance and controversy. For the general public it reignited frustrations about large firms trampling over the planning process and disregarding local concerns. For international environmental NGOs, the renewable-reset lacked ambition by failing to recognize opportunities for alternative models for energy provision. Facing a potential crisis of social legitimacy, incumbents and government hatched plans for new policies and business models to overcome problems of social acceptance.

In this context, by 2018 incumbent electricity suppliers started to experiment with new business models for smaller scale wind-farms. This was seen as an opportunity to reduce negative public opinion, by actively including local stakeholders (community groups, farmers) into the ownership structures of wind-farms. Several high profile Private-Community Partnerships (PCPs) generated significant interest as an alternative model for distributed generation. By 2018, government responded to these incipient initiatives by promoting a new PCP wind-power scheme, guaranteeing a fixed price for wind-generated energy for 20 years (set at a generous level and bolstered by high levels of social and political legitimacy, based on fall-out from the Hinkley Point debacle). From 2020, emboldened by the success of early initiatives, community groups and new project management companies started to form consortia to develop and manage new wind farms. By 2020, the new PCP initiatives became very popular with local residents, and started to erode longer-standing NIMBYism. To much surprise (as usual), in 2021 the annual Turner Prize art prize was awarded to a community wind-farm in Norfolk, accompanied by photographic art depicting the blending of turbines with the natural landscape. While this was largely derided in the media and by most of the population, it did introduce an alternative aesthetic presenting wind-power and nature in a symbiotic relationship. In time, this would prove to be an increasingly popular and enduring image.

By 2025, onshore wind alone was providing 23% of all electricity generation with increasing prominence and cultural enthusiasm for the PCP business model. The onshore sector was stabilizing as a new regime based on small-scale, distributed generation.

In a parallel development, some coal-to-biomass conversion continued from 2015 to 2020 as coal plant operators sought to sweat their assets in the face of the coal phase out. Big biomass remained unpopular, but was financially viable through government regulated ‘capacity markets’; this capacity became especially important from 2020-2025, leading to reduced reliance on electricity imports. However, smaller, dedicated biomass started to emerge as an unanticipated consequence of the government-supported PCP model, initially introduced to support deployment of wind. Incumbents joined forces with regional cooperatives of farmers to install medium sized anaerobic digesters and develop the supply chain logistics for agricultural waste. Supermarkets also became partners, benefitting from the opportunity to make money from their post-retail waste streams. This renewed interest in dedicated biomass, re-ignited dormant innovation pipelines for much for efficient biomass-to-energy conversion.

The government mandated roll-out of smart meters, planned for completion in 2020, met with delays, largely through problems with implementing the ICT infrastructure. However, by 2022, nearly all homes had been fitted with smart meters and in-house-displays. Research accompanying the mass roll-out showed that many consumers initially enjoyed ‘playing’ with their electricity consumption, but quickly became bored. However, appliance manufacturers started R&D programmes to develop smart appliances in anticipation that a smarter electricity system was starting to emerge.

Climate change received little attention during the first half of the period, with policy principally oriented towards security and cost. The 2020 ‘pledge and review’ process of the Paris agreement came and went without any significant public interest, largely because the UK had met targets via the reductions in coal powered generation and the increase in onshore wind generation. However, the 2025 pledge and review process ignited more public debate about carbon emissions. While the UK had met its 2025 target, there was mounting criticism from scientists, environmental NGOs and the Committee for Climate Change. They argued that while the renewable-reset and subsequent policies had been successful in injecting momentum to the deployment of renewables, there was still very little in the way of long-term plans to meet carbon targets for 2050. Pressure mounted on government to re-visit national energy policy again, with increasingly prominent calls for a new Energy Act.

Distributing control and controlling distribution (2025-2035)

The willingness of utilities to work in partnership with community groups had started to restore their social license to operate in the UK. Equally significant was the start of a slow shift in the deeper beliefs of incumbent energy utilities. Initially, their motivations to engage in PCPs were based on the generous government support and because, for many locations, it was the only way to install biomass and onshore wind generation without massive negative public pressure. Based on early successes, they started to adopt mixed strategies, thereby weakening the belief that large-scale, centralized generation was the only way.

The debate that had started around the 2025 pledge and review grew and started to gain traction in public arenas. Not only was there growing concern that targets would be missed, there was also a growing confidence that renewable generation could and would be central to the UK’s electricity system. Furthermore, electricity became the dominant focus for debate about the future of energy and climate change, because of the faster that anticipated rise of electric vehicle and electric heating system. This brought a range of new commercial actors (international car companies and heating equipment manufacturers) into the arena, who lobbied government for action to accelerate the de-carbonisation of electricity to legitimate their own strategies for low carbon transitions in mobility and heating.

This mounting pressure from many sectors of society resulted in the 2028 Low Carbon Electricity Act (LCEA). The Act introduced a carbon tax and a suite of further policies to support and grow renewable generation into a viable supply mix that could deal with intermittency problems. The Act had variable effects on the different niches and regimes, some designed and some unanticipated. Given the earlier concerns about energy security after the Hinkley debacle, the Act also planned for the UK to achieve net-electricity independence (i.e. to balance imports and exports) by 2030 and this was achieved as planned.

‘Old’ regime developments

The LCEA retained the planned 2030 phase out of coal and also mandated a phase out of nuclear. By 2028, there was little resistance to this from plant operators, who were acquiescent to nuclear and coal decline, but could further sweat assets over the phase out period because capacity markets continued to be used to maintain overall generation capacity.

Given the strategy to phase out nuclear and coal, the LCEA included provision for gas generation via the capacity market, but with plans to increasingly use gas only when required to deal with intermittency problems after 2030. Incumbents came to treat gas as a low margin business operation, stable, but with minimal prospects for growth meaning that R&D became increasingly unattractive. They turned to renewables for the core of their growth strategies.

New regime developments

The carbon tax privileged onshore wind above other renewable technologies, stimulating further investment plans through PCP arrangements and through incumbent only operated plant. The former flourished especially in areas in close proximity to rural towns and villages; the latter, in more remote rural areas. Conservationists, who had initially been resistant to massive onshore development, started to shift their position. This was partly stimulated by the deepening appreciation of the new wind-nature aesthetic, combined with new models of deployment that fostered re-wilding and the promotion of biodiversity. By 2030, very broad societal support for onshore wind had developed, considerable momentum for further expansion. The rapidly growing UK market for wind turbines and central role for onshore wind in the LCEA for future deployment created significant inducement effects for wind turbine R&D in the UK. New university-industry consortia formed with high levels of public and private investment. UK-based R&D focused on technical optimization for distributed onshore wind generation, including renewed interest for rooftop wind turbines. The rise of distributed generation, with strong involvement from community groups in the PCP model and lead user households for rooftop wind started to create interest and evidence for the viability and attractiveness of low carbon lifestyles, further propagated through links with innovations for smart grids and other low carbon technologies (see below).

The LCEA was relatively neutral towards offshore wind. It remained expensive compared to other generation technologies, but continued to have support from a strong advocacy coalition. As such, operation of existing offshore wind-farms formed a second (alongside gas), fairly low margin revenue stream for incumbent energy companies. Little additional capacity was added, but operations were maintained for diversity in the renewable supply mix and because repowering existing sites remained relatively cheap.

During the period 2025-2030, biomass remained a fragmented niche, struggling to stabilize into a regime. The LCEA envisaged biomass as a further contributor to base load generation. Coal-to-biomass conversion continued, but remained unpopular. Dedicated and more decentralized biomass generation was more popular, but less well developed in terms of dominant technology designs and actor configurations. However, by 2030 new developments in high-throughput anaerobic digestion had begun to demonstrate very promising results in terms of biomass-to-energy conversion efficiency. By 2035, converted coal plants using imported pellets were being decommissioned due to long-standing unpopularity and inferior carbon performance compared to local biomass waste and highly efficient conversion technologies.

The increasing prevalence of distributed generation and the intermittency of onshore wind power generation had intensified pressure on the grid. With little offshore wind capacity added, and the commitment to become electricity independent by 2030, most attention was focused on accommodating the massive up-scaling of onshore wind. The expanded transmission grid required installation of new pylons and overhead cables throughout the UK countryside. Lessons had been learned from the past, so this was approached through considerable multi-stakeholder consultation and planning, including conservationists and the many local community groups most affected. The Design Council launched a competition for pylon design, which generated considerable attention amongst the industrial design firms; the competition was put to a public vote. Landscaping firms and the Countryside Alliance collaborated with installers and local communities to accommodate the transmission lines with the maximum degree of sensitivity to the landscape.

The LCEA had also established a new role for Ofgem, tasked in 2028 with a remit to deliver a smarter grid to enable progress towards carbon targets, with 'least cost' now re-interpreted over the whole time-frame to 2050, including potential costs associated with missing 2050 carbon emission targets, and refocused to also accommodate the shift to a much more decentralized generation system. The new strategy had four specific goals: 1) to upscale integration of ICT into the grid to enable improved management and monitoring of electricity flows; 2) build more international inter-connectors; 3) to deliver on potential gains from the installed smart meters already installed in most UK homes; 4) to deliver local level micro-grids and flexible load matching to establish stable generation. The new cost assessment frame created a window for up-front investment into large scale ICT integration, via government-back loans to the National Grid. Given the ambition to balance imports and exports, the UK's interconnector policy was guided to deal with intermittency, rather than to make a net contribution to overall generation. The third goal was perceived to be more demanding, because smart meters had become largely ignored within households after the initial novelty of a 'new gimmick' had dissipated in the early 2020s. In 2030, the Government introduced 'time-of-use' tariffs to reduce peaks in electricity demand. These were surprisingly popular, so in 2033 the Government pushed ahead with more ambitious 'dynamic tariffs', based on real time fluctuations in renewable supply. These met with some resistance, but were accepted, in part because the wider electrification in mobility and heating had made electricity use much more prominent in people's everyday lives and in public discourse. Many consumers became used to planning their car charging routines during low tariff times and there was a strong uptake of smart appliances, which were designed to work with the dynamic tariffs. Tesla's home battery technology had been around since 2015 and other companies imitated creating an innovation race for high capacity, long-life, low cost batteries. However, there had been little adoption in the UK until the introduction of variable tariffs. The introduction of dynamic tariffs in 2033 led to significant acceleration of battery adoption in UK homes, used to reduce costs by taking advantage of low tariff periods. However, these policy instruments were highly disadvantageous for low-income families, who struggled to meet their heating needs in particular and could not afford battery storage technology. In order to avoid de-railing the largely popular tariffs, the Government acted swiftly to introduce low-set-tariffs on a means-tested basis.

The rapid development of distributed generation and the introduction of micro-grids and flexible load matching had knock-on effects for community groups and lead-user households leading to much higher 'energy awareness' and increasing engagement with the idea of a low carbon lifestyle. Community groups and households not only installed small-scale power generation, but also engaged in distribution, sales and accounting, creating new mindsets and routines, which spilled over to further actions, including acquisition of electric vehicles, insulation and increased use of smart meters. Linking these innovations created a new 'package' to underpin the idea of low carbon lifestyles. Whilst this lead-user group was relatively small, it was growing rapidly and by 2035, their experimentation with low carbon lifestyles was providing increasingly strong evidence for their viability, leading to sustained interest in the media.

Niche development

The government's LCEA enacted a 'wait-and-see' strategy for solar-PV. Despite falling equipment costs internationally, the Government and most social groups viewed solar as the least preferable renewable option because of the sunlight potential of the UK, and also because the incipient industry had been crushed after the 2015 energy policy reset. The longer term plan envisaged waiting for further significant changes in technology to further reduce costs and conversion efficiency.

In light of this, it was somewhat surprising at the time that some high profile schemes started to emerge, sponsored by large companies and organizations. These were oriented at branding opportunities to raise corporate reputations during a time when social enthusiasm for renewables was growing quickly. Commercial organizations including football clubs and supermarkets adopted solar to become fully carbon neutral and self-sufficient and used this to successfully garner significant positive PR. This in turn started to create a small project-based solar installation sector, leading to skill formation and supply chain formation. Seeing the positive PR led some large utilities to invest in several large-scale demonstration facilities, despite receiving little support through the LCEA. Finally, domestic rooftop solar started to grow among the lead-user households that had been closely involved with the growth of distributed energy and experimentation with low-carbon lifestyles. As such, enthusiasm for solar was growing in advance of any specific support or vision from government policy and this was placing increasing pressure on government to integrate solar into the national energy strategy.

Chasing the sun (2035-2050)

By 2035, growing cultural enthusiasm for a low carbon system and for low carbon lifestyles led to intensified social pressure and mobilization for meeting 2050 carbon targets.. The period of needing to consider social acceptance problems had been superseded by high levels of commitment within civil society for completion of the low carbon transition and this had spilled over into industries.

This major shift in social and cultural context made policy implementation much easier, but still generated significant debate about policy visions. The 2035 pledge and review process was anticipated with a sense of national pride on the progress achieved to date and stimulated massive societal debate about the remaining transition challenge. Further electrification of mobility and heating continued, placing electricity at the core of the low carbon transition to 2050. Soon after the 2035 pledge and review, the government launched its Electrification and Low Carbon Society Strategy (ELCS), signaling the following priorities: 1) Continued support for further deployment of onshore and offshore wind as the central pillars for generation and distributed biomass; 2) Further development of a multi-level, highly flexible grid at European, national and local levels; 3) Final decommissioning of remaining nuclear plants; 4) Support for gas generation for back-up capacity; 5) Support for massive expansion of solar-PV.

Regime developments

By 2035, onshore wind had become the single largest source of electricity generation. The R&D efforts that around 2030 were bearing fruit by 2040, especially in the use of new materials (e.g. graphene and carbon nano-tubes) for lighter and stronger blades, greatly enhancing the conversion efficiency of wind-power. Different turbine designs (much larger), also using new materials, were used in offshore wind farms. Despite cost reductions in offshore wind technology, onshore wind remained a much cheaper option, consequently retaining its central role in the Government’s strategy, which planned for a further doubling of a capacity within one decade.

The final nuclear plant was decommissioned in 2040. While biomass-to-energy generation had grown steadily over the past two decades, its future became uncertain, because biomass was increasing seen as key input for a high value bio-economy, oriented to serve the agricultural, health and materials industries. As such, old biomass plants were sometimes not renewed, leading to a slight reduction in overall capacity. This had a knock-on effect for the gas regime, which was increasingly seen as an important for back-up capacity.

Capacity market incentives were instituted to stimulate a new boom for gas-powered generation.

Smart grid management had become routine and efficient. During the 2040s, onshore wind capacity was growing so quickly that on windy days supply outstripped domestic demand. The international interconnectors built in the earlier periods and originally intended for energy security had become a strategic economic asset for the UK, which started exporting increasing amounts of electricity. The European super-grid had facilitated a high functioning European market for electricity, with prices regulated from Brussels. Within this European context, the UK also had a stabilized multilevel approach, with a national grid of high voltage transmission lines and micro-grids for local generation and consumption. With ICT fully integrated at all levels and high levels of battery storage, this smart network system allowed for significant flexibility for managing generation and consumption.

Niche-to-regime developments

In the run up to the 2035 ELCS strategy, social pressure started to grow for solar, initially coordinated by a well-funded NGO campaign, "The Wait is Over", which capitalized on the growing cultural enthusiasm for solar and growing evidence from lead user experiments for solar as a part of a low carbon lifestyle. The earlier high profile schemes of football clubs and supermarkets had struck a chord with the public. China had long been the global leader in solar panel innovation and manufacture, with panel costs significantly lower and conversion efficiency much higher. The 2035 ELCS strategy introduced solar for the first time as a major component of the national energy strategy.

In 2038, a ten-year trade deal was struck with the Chinese government to secure supply of solar panels and in 2040 the UK government committed to installing solar-PV on all viable state-owned buildings. Caught up in the widespread cultural enthusiasm, many other organizations followed. The RLCS also re-instituted a very generous feed-in-tariff to encourage the adoption of domestic solar + in-home-battery packages. Diffusion sky-rocketed leading to a six-fold increase in installed capacity in one decade. In the early 2040s, supply could barely keep up with demand. By 2043, European installation companies, which had formed two decades before set up offices in the UK to take advantage.

Cultural embedding of low carbon ways of living

By 2040, based on increasingly prominent attention to earlier experimentation with low carbon lifestyles, deeper cultural shifts towards sustainability in general and low carbon ways of living were diffusing rapidly. Domestic wind and solar pro-sumption, further stimulated a general cultural awareness for low carbon living, with ever greater numbers of consumers actively pursuing energy conversation as a normal way of life. By 2050, low carbon lifestyles had become highly embedded in mass culture, based on the interlinked innovations that had developed over the previous periods. 2050 targets were met with a significant sense of collective societal achievement.

Concluding comments

Scenario A and B both show that transitions towards low-carbon societies, which meet the European and UK targets, are possible. However, they both deviate substantially from business as usual scenarios (pathway 0), entailing major changes compared to recent and contemporary developments.

In terms of technologies, there are important *similarities* between pathway A and B:

- Wind is the largest option in both pathways accounting for about 65% of power generation in 2050 in Pathway A and 72% in Pathway B. The relative importance of onshore and offshore wind varies, with offshore being largest in Pathway A (since offshore fits well with incumbent interests and practices) and onshore being largest in pathway B.

- Biomass is important in both pathways, although mainly as large-scale BECCS (biomass energy with CCS) in Pathway A and as small-scale dedicated biomass in Pathway B.
- Unabated coal is phased out by 2030 in both pathways.
- Gas-fired capacity is maintained in both pathways, because of flexibility and back-up capacity for intermittent renewables. Actual *use* of gas is very small after 2040 in Pathway B, but remains significant in Pathway B.
- Innovations in the transmission and distribution grid will be crucial in both scenarios, both to connect wind parks to the grid and to enhance the ability to monitor and manage electricity flows (via more smartness and flexibility).
- Smart meters are also important in both pathways, although the knock-on effects on household behaviour are larger in Pathway B.

The similarities, mentioned above, imply several ***policy risks***, which relate mostly to political and social acceptance issues:

One risk is that the government does not persist with its intended coal phase-out by 2025. This risk is real since the government has stated that this policy depends on the availability of feasible alternative. And the delays in nuclear power and CCS may mean that this is not the case. This risk is addressed in the scenarios by a rapid increase in renewables (especially wind), which links to the next point.

A second risk is that onshore wind develops slower than anticipated. This risk is pertinent since both pathways substantially rely on onshore wind. Alleviation of this risk would require a political U-turn, since the new UK government has downscaled onshore wind subsidies, and said it would not build new onshore wind after 2020 (in response to social acceptance problems and political debate). Both socio-technical scenarios assume such a U-turn by 2020 (because of regime problems with nuclear and CCS). They also assume that the government will change its policy style (e.g. pay more attention to stakeholder consultation via different procedures) and create financial incentives that compensate local communities.

A third risk is that grid improvements will be made too late, which could limit the system's ability to deal with increasing amounts of intermittent renewables. This risk is real since network regime actors are locked in to old ways of doing things and reluctant to engage with much radical innovation. The scenarios address this risk by assuming that policymakers overhaul the network regime by the mid-2020s and change the remit of Ofgem, set clear targets, and introduce penalties for not meeting these.

A fourth risk is that social acceptance problems of biomass may exacerbate (due to concerns about sustainability). The current government pays relatively limited attention to these problems, which are leading to stronger concerns from environmental NGOs, activists, and wider publics. The scenarios address this risk by assuming that sustainability standards and inspections will be developed in the coming years and, in Pathway B, that new entrants (e.g. farmers, food and drink processors, local communities) will develop local biomass supply chains with greater social acceptance.

A fifth risk is that the current smart meter roll-out project may fail or have limited effects. This is a risk since both scenarios assume that the project will succeed (although with delays) and will have knock-on effects (e.g. galvanizing behaviour change, enable new time-of-use tariffs). The risk is real, because the project is already facing delays and increasing protests, since people feel insufficiently consulted and confronted with high bills for a technology they did not ask for. The socio-technical scenarios don't give much detail about how these problems will be overcome (because of they focus mostly on the supply side).

We can draw the following broader policy implications from the scenarios.

First, both scenarios are demanding and require major reorientations ('bending the curve') in the next 10 years. Both scenarios therefore convey a high degree of urgency to speed up ongoing developments and strengthen commitments.

Second, the actions of policymakers are crucial in both scenarios to overcome current lock-ins and accelerate the momentum of relevant niche-innovations. Their roles vary, however, in both scenarios.

- In pathway A, policymakers are the main driver of low-carbon reorientation, because they introduce new policies (specific support policies and a carbon tax from 2028) that incentivize incumbent firms to change their investment patterns. Policymakers are constrained, however, by dependencies on other actors. Business support coalitions are particularly important in pathway A, shaping the political feasibility of tough policies. Achieving public support is also important to achieve legitimacy, but less so than business support (in pathway A).
- In Pathway B, the main push for low-carbon orientation initially comes from civil society, new entrants and changes in public debate and culture. These changes subsequently create credibility pressures on policymakers to enact policy changes that further enable broad transformations.

Third, social acceptance is a crucial problem for many low-carbon options (biomass, BECCS, onshore wind, grid enhancement, nuclear power), as documented in Table C on 'transition challenges'. Social and cultural dimensions should therefore receive much more attention in UK energy and climate policies, which tend to privilege techno-economic dimensions. The socio-technical scenarios suggest several possibilities for this, including:

- Requiring utilities and project developers to improve their consultation procedures, leading to real involvement of local residents in project planning
- Requiring firms to financially compensate local residents for their burdens
- Organizing a Broad Societal Discussion to debate the pros and cons of low-carbon options with a broad range of stakeholders and citizens.
- Stimulating low-carbon deployment by new entrants and communities, which is likely to lead to greater engagement, awareness and social debate.

This would require a change in the UK political culture, which is currently characterized as a 'working with incumbents' pattern (Geels et al., 2016) and a 'bulldozer style', which pushes through plans that are concocted by firms and policymakers without consulting with citizens and societal actors. This style is likely to exacerbate social acceptance problems in the coming years, creating serious policy risks for sustainability transitions as indicated above.

1. Introduction

Goals and aims

D2.5 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.

Figure 1 below may be useful to elaborate the goals and strategy of D2.5. The revised WP1-scenarios provide potential transition paths for the green line in Figure 1, which suggest how societies can move from the present to future sustainable development goals, such as reducing European greenhouse gas emissions to a level consistent with the 2^{o}C target, and the European biodiversity target. However, from the perspective of WP2 there are two problems with these WP1-scenarios.

1. The outcomes from D2.1, D2.2 and D2.3, which analysed the historical trajectories (black line in Figure 1) in electricity, heat/buildings, transport agro-food and land-use in specific countries, suggest that contemporary developments appear more likely to develop in the 'wrong' direction (i.e. along the blue line in Figure 1). That is because (in most empirical domains), the path dependencies of existing regimes are quite strong and the radical green niche-innovations have limited or moderate momentum. So, in most empirical domains there is a substantial discrepancy (or 'transition challenge') between current trajectories (black and blue lines) and the required 'turn-around' to move towards sustainable transition pathways (green line). Overcoming this 'transition challenge' requires more explicit attention as well as more sophisticated analysis that acknowledges the problems of lock-in and path dependence.
2. The explanation of this turn-around in the quantitative scenarios is a bit simplistic from a socio-technical point of view, because they pay limited attention to actors, struggles, strategies and lock-in.

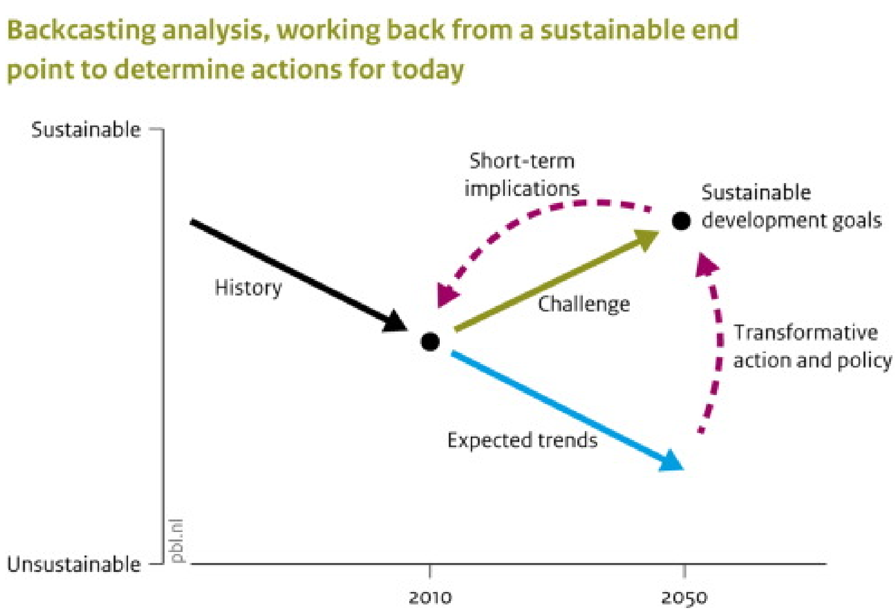

Figure 1: Transitions from historical trajectories towards future goals (Van Vuuren et al., 2015: 305)

Against this background, the task for D2.5 is to develop more nuanced storylines that indicate and explains how turn-arounds and transitions can be made in specific domains and countries. 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 (the black lines in Figure 1):
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 asses 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. Before describing basic characteristics of this methodology, we identify several weaknesses in existing scenario methods.

Problems in current scenario methods
A range of methods has been developed over the past decades to formalise and structure anticipation efforts, e.g. trend extrapolation and curve fitting, computer modelling, cross impact analysis, Delphi methods, scenarios and foresight exercises. There has been a gradual shift from forecasting and planning towards 'looser' methods that accommodate uncertainty, stakeholder interaction, learning, vision building, consensus creation, public participation (Wack, 1985a, 1985b; Martin, 1995, Street, 1997).

Scholars from the futures community have recognized the difficulty of exploring discontinuities and transitions:

> "Discontinuities are so difficult to forecast. (...) We don't know enough about the underlying structure or the key driving forces" (Amara, 1988: 395-396

Many transition scenarios suffer from four specific problems:
1. Many scenarios focus too much on technologies and too little on wider socio-technical systems (which also include behavioural change, infrastructure, culture and politics). This often leads to truncated views on potential transition pathways. It also leads to a limited understanding of potential constraints or bottlenecks for transition pathway. Many (model-based) scenarios tend to focus narrowly on economic constraints (e.g. cost-competiveness, investments, learning curves that drive cost down). Loftus et al. (2015) propose a broader set of four key constraints for energy system transformation: 1) technology readiness, 2) economics, 3) integration issues (intermittency, infrastructure, storage, back-up), 4) social and non-cost barriers.
2. Many scenarios are insufficiently guided by a theoretical understanding of transition dynamics. Many scenarios embody simplistic assumptions about the dynamics of technological development or transitions. Some examples: a) Neo-classical economics often assumed that technological development happens exogenously ('manna from heaven'), sometimes conceptualised in computer models with an independent exogenous parameter, b) technological change may be conceptualised via learning curves (where costs are assumed to decrease by a fixed amount when production/installation is doubled), c) transitions are assumed to be driven mainly by exogenous dynamics, e.g. economic growth, population growth, demographics (which is related to the typical 'scenario axes technique' that varies two macro-variables in a 2×2 matrix). From a socio-technical perspective, these approaches "lack attention for actors, their decisions, interactions and

learning processes, and the way these shape twisting transition paths" (Hofman et al., 2004: 349). They pay insufficient attention to *endogenous dynamics* of transitions, which relate to beliefs, decisions, struggles and interactions between various actors and social groups

3. Many scenarios have a macro-bias (Geels, 2002), in which the dynamics and outcomes of the scenarios depend too much on exogenous macro-aspects. This macro-bias is the result from the practice of creating scenarios by combining uncertain and influential macro-developments in a 2x2 matrix (e.g. combining high/low economic growth and high/low environmental awareness). The 'logic' of such scenarios is deterministic and top-down, because processes and actions at meso- and micro- level are seen as caused by macro-developments. As a result, the scenario dynamics are unsurprising and tautological (Schoonenboom and Van Latensteijn, 1997). It is, for instance, no surprise that environmentally friendly technologies become dominant in scenarios with high environmental awareness and high economic growth. Most of these 2x2 matrix scenarios ('Boston technique') tend to lack particular *tensions*, which is why they are often a bit boring and predictable. In Venice, we therefore agreed that the *tensions* between present (WP2) and future (WP1) are relevant and useful, not only to provide focus for the socio-technical scenarios, but also to make them more interesting.
4. Existing scenario techniques often have too *many degrees of freedom*, i.e. anything can happen, particularly if one also allows for the possibility of external shocks (or 'miracles'). Phrased differently, there is a lack of constraints to guide the development of qualitative scenario storylines:

Socio-technical scenarios

To address some of the above problems, some scholars have developed ***socio-technical scenarios*** to think in a structured way about possible future transition pathways (Geels, 2002; Elzen *et al*., 2004; Hofman *et al*., 2004; Hofman and Elzen, 2010; Verbong and Geels, 2010; Marletto, 2014; Nilsson and Nykvist, 2016). These socio-technical scenarios (STSc) have the following characteristics that can help address (to some degree) the problems identified above.

1. STSc should address changes in the various dimensions of socio-technical systems. Hofman and Elzen (2010: 656) suggest that suggest that socio-technical scenarios "should show *socio-technical* development, i.e. they should describe the co-evolution of technology and its societal embedding (a continuous action–reaction dynamic of technical and societal change). This implies a scenario should pay attention to technical development as well as to societal or behavioural aspects such as institutional change, different types of actors, their goals, strategies and resources, etc."
   The PATHWAYS project acknowledges this point with the difference between pathway A (which is mainly based on techno-economic change) and pathway B, which also includes broader changes in socio-technical systems, including cultural, consumption, political.
2. The storylines in STSc should be guided by a logic that draws on socio-technical theories. The STSc references provided above all build on the Multi-Level Perspective (MLP), and discuss interactions between niche-innovations, incumbent regimes and broader 'landscape' dynamics. Elzen *et al*. (2004), for instance, suggest that socio-technical scenarios should have the following features:
   - Learning processes and niche dynamic should be visible in the scenarios. Important questions to deal with are: What happens in niches? Which innovations are developed? What are the problems and possibilities? In which direction are solutions

    sought? What learning takes place on technology, new user practices, regulation, etc.? Which actors are involved in the learning processes?
    - Spread of novelties should not only describe diffusion of individual innovations but also have attention for their development and the interaction between niches, e.g. in linking of individual technologies (hybridisations) and synergistic effects.
    - Market take-up should also address the development of innovations through successive niches (niche-cumulation).
3. Socio-technical scenarios focus on the ***endogenous logic*** of transition pathways, based on choices, decisions, strategies, and beliefs of actors, which are of course shaped by changing contexts (micro- and meso-logics). While external macro-developments may still play a role, the scenarios would articulate how such developments affect choices, attitudes and strategies." Hofman and Elzen (2010: 656) suggest that: "transition scenarios should also describe how certain attitudes and behaviour of actors change in the course of new developments. Also, concrete developments like the uptake of new technologies, investments and infrastructures should not appear as the result of an 'automatic diffusion process' but must be made plausible as a result from interactions between actors. Thus, a transition path does not come out of the blue but it becomes clear *why* it develops."
4. To mitigate (but not entirely solve) the 'degrees of freedom' problem, the socio-technical scenarios in the PATHWAYS project are guided by the following constraints:
    - The STSc will be guided by the MLP (and possibly more specific patterns and mechanisms), and by the logic of the pathway A and B, with incumbent actors being the main actors in pathway A and new entrants in pathway B.
    - A recognition of lock-in mechanisms and path dependencies *in the present*. The findings from WP2 offer useful constraints for thinking about future pathways. The 'turning point' towards more sustainable futures cannot immediately start in the next few years, because of path dependencies which we have empirically identified in WP2 (in most of our empirical domains, we found that regimes are still relatively stable and niche-innovations have moderate momentum). These constraints should be the starting point when thinking about future scenarios.
    - The socio-technical scenarios are also constrained by the quantitative model outcomes from WP1. So, the STSc in Deliverable 2.5 take the quantitative scenarios from WP1 for granted, and will develop plausible endogenous storylines for how the end goals can be reached. So, the qualitative socio-technical storylines will be constrained by the quantitative model outcomes)
    - The STSc will particularly focus on overcoming the *tensions* between WP1 future (quantitative) scenarios and WP2-findings. The challenge will be to develop an endogenous storyline of how interactions between various actors (and changes in technology, institutions, beliefs, social networks, etc) can generate dynamics that make it possible to overcome the 'transition challenges'. To facilitate this, we agreed in Paris that all scenario reports will **include an intermediate step that explicates the tensions** between the quantitative future scenarios from WP1 and the dynamics in the last 10-15 years from WP2.

<u>Design specifics of socio-technical scenarios</u>

The scenarios in chapter 5 and 6 will meet the following design specifics that have been outlined in a shared protocol

- Each scenario will be about 5-10 pages

- The scenarios will be sub-divided into two or three periods, which do not have to be of equal length. Periods where crucial changes happen (e.g. addressing ‘transition challenges’ should receive most attention)
- The scenarios will be written in the past tense (as ‘history of the future’), which means we describe one trajectory.
- Nevertheless, it may be worthwhile to mention that ‘forks in the road’ (branching points) were possible at some points in time, and how/why actors decided to go down one road instead of the other. This may include controversies, setbacks and power struggles. It may be interesting to ‘zoom in’ a bit on these branching points.
- The scenario will be address the various dimensions of socio-technical systems (the breadth varies between pathway A and B)
- The scenarios use the MLP as a ‘plot’ for the storylines. 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.
- Scenarios should acknowledge the various constraints: a) pathway A and B logic, b) path dependencies and barriers in the present, c) the quantitative developments (and turning points) from WP1-scenarios, d) focus on overcoming the ‘transition challenges’.

Structure of report

The report is structured as follows.

Chapter 2 describes the quantitative scenarios for Pathway A and B, which lead to the stated climate change targets by 2050. These quantitative scenarios, which were constructed with computer models in D1.3, have some limitations from a socio-technical perspective (described above).

Chapter 3 describes the empirical findings about contemporary developments in green-niche innovations and existing regimes in the UK electricity domains. These findings come from D2.1 and D2.2, based on socio-technical analysis.

As an intermediate step, chapter 4 articulates the ‘transition challenges’ by comparing outcomes from chapter 2 and 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 describe two socio-technical scenarios for pathway A and B. These scenarios, which pay more 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 UK electricity domain which have been developed in D1.3, using two computer models: the integrated assessment model IMAGE (which provides Europe-wide scenarios and boundary conditions like electricity demand, deriving from developments in transport and heating, e.g. electric vehicles, heat pumps) and PowerACE (which is a detailed energy model, which was used to provide electricity generation scenarios for the UK and Germany). The quantitative scenarios include three pathways, which are based on different assumptions:

- ***Scenario 0*** shows the model tendencies *without any new climate-policy interventions*, based on market-driven developments of fuel prices and technology cost. However, it is assumed that the EU countries meet their RES targets as defined in their National Renewable Energy Action Plans (NREAPs).
- ***Scenarios A*** and ***B***, with strong climate policies, are assumed to both reach an 80% reduction in GHG emissions in 2050 compared to 1990 levels. The specifics of the transition pathways are quite different, however, 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 0: Business as Usual	**Pathway A: Technical component substitution**	**Pathway B: Broader regime transformation**
Departure from existing system performance	Minor (no transition)	Substantial	Substantial
Lead actors	Incumbent actors (often established industry and policy actors)	Incumbent actors (often established industry and policy actors)	New entrants, including new firms, social movements, civil society actors.
Depth of change	Incremental 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	Dynamic stability across multiple dimensions	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 and their defining elements

Scenarios 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 cap. By imposing a price burden on CO2, it also leads to price-based energy efficiency improvements throughout the economy (driving overall demand reduction).

- It is assumed that the EU countries meet their RES targets for 2020 as defined in their National Renewable Energy Action Plans (NREAPs).

Scenario A further includes the following specific assumptions and boundary conditions:
- Pathway A is dominated by incumbent actors with a preference for large-scale technologies (onshore and offshore wind parks, nuclear power, big biomass combustion).
- Offshore wind is stimulated with policies (e.g. subsidies, state-aided loans) so that the price becomes the same as onshore wind. Interest rates are also assumed to be low (1%), which makes it easier to mobilize finance for more expensive investment in larger offshore wind facilities.
- Nuclear energy generation capacity is defined exogenously (because of the models struggle to with the lumpiness of these large-scale facilities, often leading to unrealistic 'all or nothing' pathways.
- The land availability is used as an indicator to represent social and political acceptance of RETs. Compared to pathway 0, 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 IMAGE-model indicates that electricity demand slowly decreases until the mid-2030s (because of efficiency improvements and assumed carbon tax). Electric vehicles receive subsidies for upfront purchasing price, but their diffusion remains limited. Electricity demand increases substantially after 2035, when electric cars diffuse more widely.

Scenario 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 and nuclear are excluded in this scenario, because they face social acceptance problems (due to their large-scale and perceived risks)
- Onshore wind is privileged in this scenario because the UK is the windiest country in Europe.
- Solar-PV is privileged in this scenario because its decentralized characteristics with well with new entrants (such as citizens, local communities, farmers, schools). This privileging is represented in the quantitative models by assuming extra policies (e.g. subsidy) faster technical learning rates, which both lower PV-costs and thus stimulate diffusion. Land availability for solar-PV has been increased by one third compared to Pathway 0. Interest rates for solar-PV investments are also assumed to be low, reflecting societal preferences.
- The IMAGE-model indicates that electricity demand decreases substantially until 2035, because of lifestyle changes (e.g. more localized, less travel, more public transport, smarter appliance use, refusing appliances like clothes dryer). Electricity demand increases after 2035 because of electric vehicles, but less than in pathway A.

2.2. Quantitative scenarios for UK electricity system

Figure 2 and 3 show the quantitative model results from PowerACE for different transition pathways, both in terms of capacity and actual power generation. The difference between both indicators may be especially large for intermittent renewables (like solar-PV and wind) which have a relatively low load factor since they only produce power during parts of the day and season.[1] This also means that intermittent renewables require back-up capacity (e.g. gas-fired power stations) that can be 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.

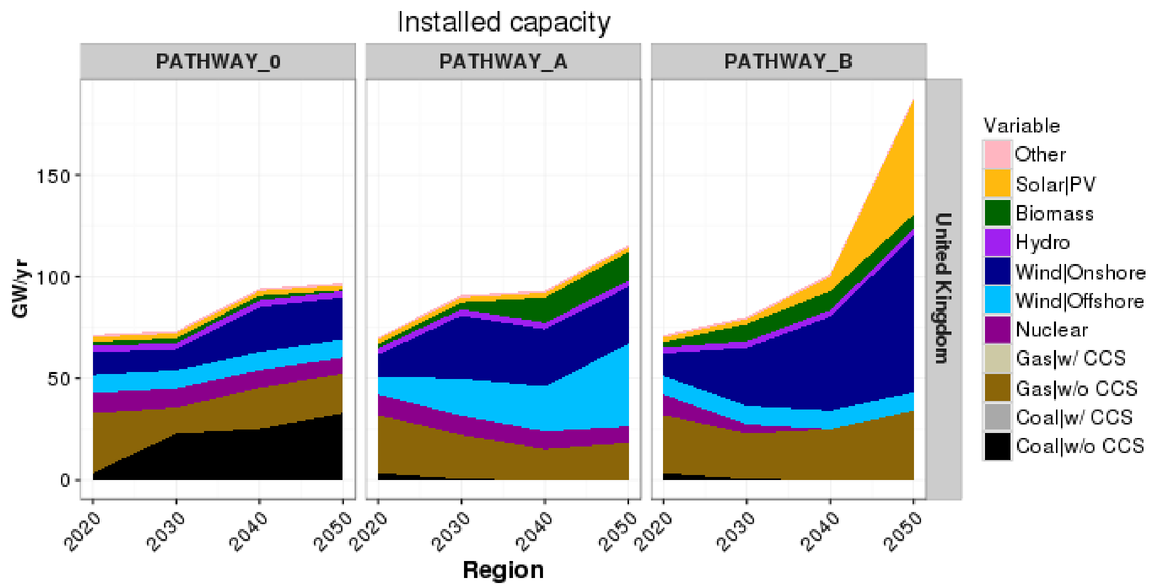

Figure 2: Installed capacity in power generation in the UK (from D1.3)

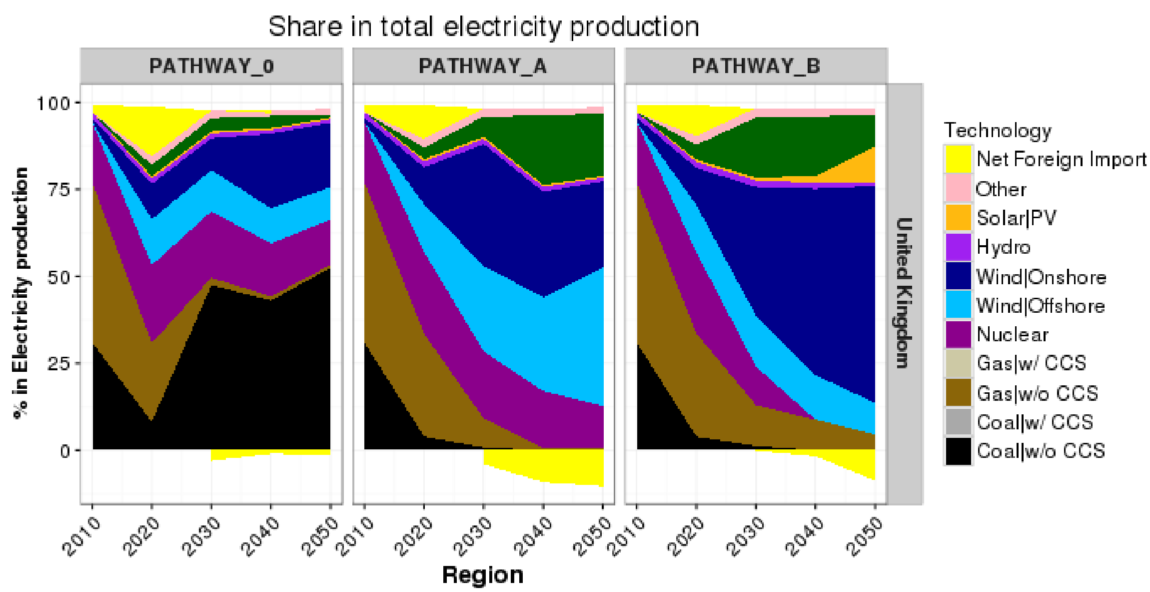

Figure 3: Power generation in the UK (from D1.3)

Pathway 0 in the UK electricity system

In Pathway 0, the lack of climate policy leads to a replacement of natural gas plants by cheaper coal plants. Some nuclear plants remain and serve as a static base load supply. The

[1] Solar-PV, in particular, does not generate power when it is cloudy or dark, which for European countries creates problems during winter periods with long nights.

generation mix for Pathway 0 also includes a substantial amount of wind power, because the UK has the best wind conditions of Europe, which means that ongoing price/performance improvements will make wind economically attractive in the UK, even without strong climate policy.

Pathway A in the UK electricity system

Pathway A in the UK has the following characteristics:

- The main dynamic in Pathway A is that coal and gas power plants are replaced by relatively large-scale renewable energy technologies (RETs) and nuclear power.
- Unabated coal (without CCS) is phased out by 2030.
- Coal with CCS does not take off, because it is not commercially viable compared with cheaper options such as wind.
- The decline of natural gas is similar to Pathway 0, though slightly slower. After 2030, natural gas mainly serves flexibility options (providing back-up capacity for wind energy).
- Wind power rapidly becomes the largest power generating technology, producing 60% of all power in 2030, gradually expanding its contribution afterwards.
- In 2050, the main technology is offshore wind, which is highly favoured by the big incumbent actors, making use of the UK's wind energy potential. Onshore and offshore wind both expand rapidly. Before 2030, onshore wind expands fastest, because it is cheaper. After 2030, offshore wind expands further at some expense of onshore wind, because offshore wind becomes cheaper due to large turbines and higher wind speeds.
- In the 2020s and 2030s, nuclear power manages a slightly higher utilisation of the existing plants, but in the long run capacity and generation declines, contributing about 12% of power generation in 2050.
- Power from biomass expands slowly until 2030 and then accelerates because the combination with CCS creates the possibility of *negative* emissions. BECCS (Bio-Energy with Carbon Capture and Storage) becomes financially attractive in pathways A, because gains two carbon credits per unit of power generation: one because biomass is a renewable energy source and one because CO2 emissions are captured and stored. Since biomass is a flexible option, it takes over the back-up capacity function from gas, which it steadily replaces from about 2030.
- Around 2030, the UK switches from importing to exporting electricity (from wind) to the rest of Europe. By 2050, the UK exports about 12% of its domestic demand.
- The high shares of onshore and offshore wind require a strong expansion of the electricity grid, particularly long-distance transmission grids, offshore grids, and interconnectors to European countries.

Pathway B in UK electricity

Pathway B in the UK has the following characteristics:

- Natural gas declines (as in Pathway A), but still accounts for 4.5% of power generation in 2050 (without CCS). The gas turbines are mostly used as 'peakers' to cover demand in times of low generation from RETs.
- Unabated coal (without CCS) is phased out by 2030.
- Nuclear energy is gradually phased out by the 2030s, meaning that existing plants reach the end of their lifetime of 40 year, but are not replaced afterwards.
- After 2023, onshore wind increases much faster than in Pathway A, and becomes the central pillar of the electricity supply. It is the cheapest RETs, which benefits from the high 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.

Figure 4 shows that onshore wind turbines are initially deployed in the windiest (coastal) areas, but in subsequent decades also appear on inland sites. By 2050, a capacity of 77.1 GW is installed, equalling about 15,500 wind turbines of 5 MW capacity. This means that wind turbines will be highly visible everywhere in the country.

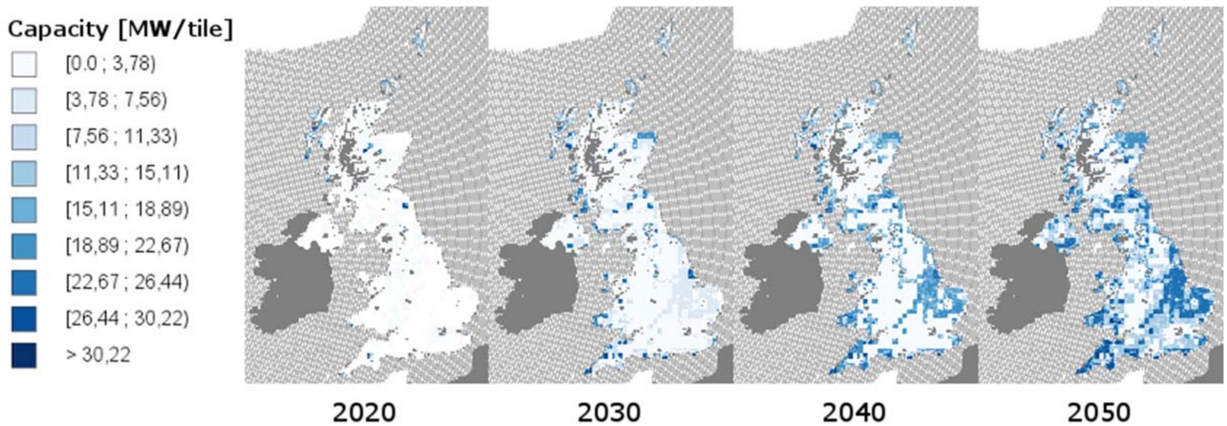

Figure 4: Development of the spatial distribution of onshore wind turbines in the UK for Pathway B[2]

- Offshore wind also increases, but far less than in Pathway A (because incumbent actors are less active in Pathway B).
- Solar-PV increases only gradually to 2040, because of high costs, but then diffuses rapidly to generate about 11% of power in 2050 (but the installed capacity of 56 GW represents over 25 % of the total installed capacity). One reason is that the price of *additiona*l onshore wind increased by then, because the best wind sites are already taken. The high proportion of onshore wind by 2040 (representing about 54% of the total electricity generation) also creates grid stability problems, so solar-PV becomes extra attractive to increase diversity and a mixed portfolio.
- Biomass increases to 2030 in the form of smaller dedicated biomass plants (which differ from the large biomass (CCS) plants in Pathway A). Biomass also acts as a flexibility option with regard to intermittent renewables. After 2040, biomass generation is partly replaced by solar-PV.
- After 2030, the UK becomes an exporter of cost-efficient wind power, which reaches substantial amounts by 2050.
- The high shares of onshore wind require a strong expansion of the electricity grid, particularly long-distance transmission grids, and interconnectors to European countries.

‘Transition challenge’

Scenario A and B, which reach 80% reductions in CO2 emissions by 2050, both represent substantial changes compared to the historical and contemporary trajectories in UK electricity. To further articulate this ‘transition challenge’, we will first describe the current momentum of green niche-innovations and existing regimes in the UK electricity system (chapter 3) and then compare these with the two future-oriented scenarios, described above.

[2] Each “tile” reflects an area of 7 times 7 km. The model has been programmed to keep a certain distance to residential areas and nature protection areas.

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 niche-analysis of UK electricity from D2.1. With regard to electricity generation options, Table 2 offers the following relative ranking and assessments of current momentum:

- Offshore wind: Moderate (and increasing)
- Bio-power: Moderate
- Onshore wind: Moderate (and decreasing)
- Solar-PV: Low.

Table 2 also includes the assessments of the specific 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), and our interpretation of whether the niche fits better with Pathway A or B.

Table 2: Summary findings from D2.1 on momentum of UK electricity niche-innovations

Niche innovation and ranking	**Momentum**	**Assessment of momentum through techno-economic, socio-cognitive and governance dimensions**
1. Energy saving lighting	**Very High**	*Techno-economic momentum* is high with high diffusion of halogen and CFLs, and with incandescent bulbs almost completely replaced. LEDs are a new, potentially revolutionary lighting technology with high-energy efficiency and steep learning curves. *Socio-cognitive momentum* is generally high because all international industry actors work on energy-efficient lighting, with European companies focusing on LEDs (since Chinese firms dominate the CFL market); retailers, utilities, NGOs and policymakers also work to stimulate adoption of energy-efficient lighting. One problem are lingering consumer perceptions of lower quality of CFLs. Another problem is uncertainty about the precise temporality of a shift towards LEDs, and whether or not this shift will be hindered by a lock-in into CFLs and halogens. *Governance momentum* is high because of the ban on ILBs, which provided a very clear signal to market players about the direction of travel (i.e. more energy efficient lighting). Policymakers are also committed to energy-efficient lighting, because it represents one of the few successes of demand reduction.
2. Smart meters	**High (but could drop significantly if problems arise in early implementation phase)**	*Techno-economic momentum* is still relatively low in terms of actual diffusion (only 1% of the expected 53 million smart meters was implemented by 2014), but the growth rate is very high, starting from almost zero in 2012. Diffusion is expected to ramp up very quickly in the coming years, which would boost techno-economic momentum. There has also been considerable technology and system development in recent years, which contributes to momentum. *Socio-cognitive momentum* is high, with the creation of substantial social networks (mainly from the production domain) by the government and the articulation of positive visions about the benefits of smart meters, which largely crowd out some marginal dissenting voices. *Governance momentum* is high because the government has strongly committed to a very ambitious roll-out programme (without waiting for outcomes of the 2007-2010 trial).
3. Offshore wind	**Moderate (and increasing)**	*Techno-economic momentum* has been growing from a low base to the UK taking a world leading position, despite high costs cf. other RETs. Significant learning occurred during the 2000s, but technical obstacles remain, especially with envisaged expansion into deeper, more hostile

		marine environments. <u>*Socio-cognitive momentum*</u> is high, with the formation of a powerful network of actors from industry, government and NGOs, with aligned interests, which created high socio-political legitimacy and enthusiastic visions for future expansion. More recently, there have been some signs of erosion in legitimacy and support because of concerns over high costs, which have created uncertainty and affected investment decisions. <u>*Governance momentum*</u> has been very high due to strong interest across many government departments, but has been wavering in the most recent period because of cost concerns.
4. Biopower	**Moderate**	<u>*Techno-economic momentum*</u> for most sub-niches is medium but decreasing, with slow or limited anticipated future growth (e.g. landfill gas, energy-from-waste). The momentum for biomass conversion of coal plants is high, however, with very rapid growth in recent years. The technical combination of bio-power and CCS is an enticing long-term prospect, but not yet leading to much concrete development. <u>*Socio-cognitive momentum*</u> is medium and perhaps decreasing, with prominent future visions now anticipating a boom-and-bust pattern with attention shifting away from dedicated biomass to coal conversion for the transitional period to 2020. Controversies about the sustainability of certain forms of biomass could undermine socio-political legitimacy. <u>*Governance momentum*</u> has shifted unevenly across the sub-niches of bio-power, currently favouring coal conversion the prior to 2020, with withdrawal of support thereafter.
5. Onshore	**Moderate (and decreasing)**	<u>*Techno-economic momentum*</u> is now decreasing after an early period of high diffusion, associated with its close-to-market status and learning curves that generated price/performance improvements. <u>*Socio-cognitive momentum*</u> is weakening because early implementation problems (poor stakeholder engagement) and a narrow support base (mainly of policymakers, utilities and project developers) have generated an increasingly negative public discourse, leading to local opposition and social acceptance problems. <u>*Governance momentum*</u> has been positive, but has weakened as a result of increasingly negative public discourse and visions, especially for the period beyond 2020. The newly elected (2015) Conservative government promised not to build new wind turbines after 2020 and has downscaled subsidies after this date.
6. Solar-PV	**Low**	<u>*Techno-economic momentum*</u> was relatively slow until 2010, when diffusion increased rapidly and beyond (government) expectations. Techno-economic momentum increased substantially in recent years, because of decreasing PV module costs and rapidly increasing deployment. Further diffusion will require ongoing cost reduction, which may be more difficult for Balance-of-System costs and wider system (grid) costs. <u>*Socio-cognitive momentum*</u> has been high, supported by strongly aligned actor-network of technology suppliers, installers, famers, consumers, NGOs and public science. There has been a largely positive public discourse and high social legitimacy, especially amongst advocates for decentralised (including ‘prosumer’) energy generation. <u>*Governance and policy momentum*</u> was low until the introduction of the Feed-in-Tarriff in 2010, but increased after the inclusion of solar-PV in government renewable energy plans from 2012 and dedicated solar-PV strategy documents in 2013 and 2014. Reductions in feed-in tariffs have recently created some uncertainty about future deployment and government commitment.

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 UK electricity regime, and the degree of tensions and cracks, which offer opportunities for wider change.

The UK **electricity *generation* regime** is characterized by a relative stability of the core alliance between policymakers and utilities, which led some scholars to characterize the UK policy style as ‘working with incumbents’ (Geels *et al*., 2016). The electricity generation regime has also been remarkably resilient in terms of ongoing commitment to regime technologies:

- The UK government has committed to a ‘nuclear renaissance’, based on plans to build 8 new nuclear plants by 2025, delivering 16 GW new capacity. The plan for the first new plant (Hinkley C) is already 5 years delayed, with the opening date pushed back from 2018 to 2023. Negotiations for two more nuclear plants are under way, but not yet concluded. Discussions about the other five plants have not yet started.
- The government and utilities plan a substantial expansion of up to 40 new gas-fired power stations, delivering 16-25 GW by 2030. These power stations are not expected to use CCS, which led the Committee on Climate Change (CCC) to warn that such an expansion would be incompatible with climate change targets. The government is pushing strongly to develop UK shale gas (despite great uncertainties about availability and economic feasibility), offering attractive incentives for private firms.
- Many of the relatively old coal-fired power plants are supposed to be phased-out in the next 8 years under the European LCPD-directive. The utilities wanted to build new coal-fired power plants, but the government stipulated that this could not happen without the use of CCS. CCS is progressing very slowly, however, without a great sense of urgency. Plans for two subsidized demonstration projects have been delayed several times. So, although the government envisages a future for coal-with-CCS in the 2020s, developments are not pointing in that direction. In 2015, the new Conservative government scrapped a £1 billion subsidy scheme for potential CCS demonstration projects, which further hinders this option.

There are no major tensions or cracks in the electricity generation regime, although the planned phase-out of unabated coal could create capacity problems, since nuclear power and CCS are both seriously delayed. The government therefore announced a caveat, namely that they would only phase out unabated coal *if* feasible alternatives are available.

The climate change problem does exert some pressure on the electricity regime, but changes are usually negotiate between policymakers and utilities, which consult in many ways. The 2008 Climate Change was a radical policy, which has been followed by a raft of implementation plans and changes in policy instruments (e.g. 2009 amendments in the Renewables Obligation, the 2013 Electricity Market Reform with ‘strike prices’ for various low-carbon options).

Since financial-economic crisis, however, the political commitment to climate change policies has been weakening, especially under the Conservative-Liberal Democrat coalition (2010-2015) and the new Conservative government (Geels *et al*., 2016). First, public attention to climate change diminished, leading politicians to realize that they were ahead of their voters (Lockwood, 2013). Especially the right-wing of the Conservative party became more vocal, criticizing subsidies for onshore wind and questioning climate change science. Second, the financial-economic crisis enhanced concerns about jobs, competitiveness and energy prices. The Treasury used these concerns to regain influence over climate policy (Carter and Jacobs, 2014), issuing warnings that green policies should not hinder the economy. In 2013, cost concerns escalated into a full-scale political row over rising energy bills, which led the government to scrap, delay or water down various green policies. Third, the government refused to commit to long-term renewable electricity targets beyond 2020, despite repeated recommendations from the Committee on Climate Change. In July 2015, these political counter-trends culminated in decisions by the newly elected Conservative government to slash support for onshore wind, solar-PV (especially 1–5 MW installations), and biomass plants. So, the government's vision of a low-carbon transition seems oriented towards a 'partial reorientation', based on some large-scale RETs (around 30% of electricity generation by 2020), and expansion of nuclear power and coal/gas with CCS.

The **electricity *network* regime** has remained relatively stable, despite various pressures stemming from increasing electricity production from renewable sources:

- The creation of new wind farms in remote locations (e.g. Scottish islands, Welch coast, offshore) requires the creation of new transmission networks, both onshore and offshore, to connect them to the grid.
- Increasing electricity flows from Scotland and Wales (where most wind parks are situated) to England (where most electricity is used) requires upgrading, extension and intensification of the onshore transmission grid.
- The intermittency of wind and solar power creates problems for matching supply and demand, and requires changes in the electricity networks to better manage and direct electricity flows.
- The gradual increase of *distributed generation* (e.g. roof-top solar PV, community energy, small dedicated biomass plants) needs to be connected to (local) electricity distribution grids and requires two-way flows instead of traditional one-directional flows (from generators to users).

These pressures have, so far, been met with *incremental changes* in the high-voltage *transmission* networks:

- extensions of *onshore* power lines and cables to remote locations; new *onshore* connections between Scotland and England.
- the creation of a new *offshore* grid.
- the building of *inter-connectors* that link the UK to other countries (currently France, Netherlands, Ireland with future plans for sub-sea connection cables to Iceland, Norway and Denmark).

These changes don't substantially change the transmission architecture, but are very costly: about £17 billion between 2010-2013, and much greater investments up to 2020, up to £35 billion.

The actors in the electricity network regime form a closed-knit network, operating a form of 'club governance', which means that they share mind-sets and take each other's interests into account when negotiating future plans and policies. So far, these actors have mainly implemented incremental innovations that keep the regime relatively stable. There are some pressures from policymakers (who worry that electricity networks need to be adjusted quicker in low-carbon directions) and local communities (who protest against new power lines), but these are not (yet) causing major regime tensions. Various lock-in mechanisms stabilize the network regime:

- Ofgem, which is dominated by economists and engineers, has been reluctant to accommodate climate change and sustainability as an additional criterion besides its traditional focus on competition and low costs.
- Ofgem has also been created as an independent regulator, which has provided substantial shelter from increasing criticisms from policymakers and politicians.

- Distribution Network Operators (DNOs) have long been low-risk firms that focused on cost improvements and efficiency instead of innovation. Despite various policies (which aimed to stimulate R&D and innovativeness), DNOs are reluctant to engage with radical innovations, because they have lost technical capabilities, have limited future planning skills, and are constrained by business models that focus on efficiency and cost reduction.

These lock-in mechanisms and social protests may complicating more radical changes to the grid in coming decades.

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 six 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 ***policy commitment and social acceptance are most prevalent, creating obstacles for all six innovations***.

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 UK electricity generation and WP-2 findings of niche-momentum and path dependencies

Innovation	**Pathway A**	**Pathway B**	**Constraint**
1. Biomass	Pathway A and B assume high amounts of biomass in electricity use. This contradicts with current UK policy, which intends to increase biomass for electricity until 2020, but downscale this afterwards (re-directing biomass towards transport and heat). The assumption of high biomass is also sensitive to public acceptance problems around imported biomass (as visible in NGO actions, public debates, legal contestation).	Same as A, but less in quantitative terms. But bio-energy will be based on distributed, small-scale generation, which will create special challenges.	Policy and social acceptance
2. BECCS (biomass energy with CCS)	BECCS plays a large role in European scenarios (especially after 2050 to generate 'negative emissions'). BECCS also plays a substantial role in UK pathway A (after 2030). This creates three tensions with WP-2 1) BECCS is not studied in WP2 (because it is not yet viable and there is not much happening 'on-the-ground'). It is therefore difficult to make connection in our storylines. (It is seems risky to base future scenarios on something that hardly exists in the present) 2) The upscaling of bio-energy is controversial in the UK (see above) and currently not pursued in government policy. 3) Pathway A in the UK does not include CCS (for coal and gas), but does assume BECCs from about 2030 (linked to use of biomass). This seems internally contradictory.	No CCS in pathway B (and no BECCS)	Technology readiness, Economics; Social acceptance

3. Onshore wind	Both pathways (but particularly B) assume a major expansion of onshore wind (because it is the most cost-effective renewables option). This contradicts with WP2-findings that onshore wind faces major social acceptance problems. The new UK government has also introduced a moratorium on building more onshore wind farms after 2020, and subsequently downscaled subsidies.	The upscaling of onshore wind is particularly large in pathway B (which creates tensions with social acceptance). Another tension is who will deploy these onshore wind turbines. Pathway B assumes that new entrants are the main actors (e.g. community energy, activists, farmers). But WP-2 showed that there are relatively few new entrants in the UK.	Social acceptance; lack of policy and political will
4. Electricity grid expansion	Both scenario s assume strong grid expansion. This creates tension with current grid trajectories (particularly in distribution grids), where there is much inertia and some local resistance to grid-projects.	Same as pathway A.	Integration; Social acceptance; lack of political will
5. Nuclear	Nuclear power is somewhat increased in pathway A. This fits with government plans, but creates a tension with WP-2 findings, which show that on-the-ground delivery of nuclear power plants is very slow and already 5 years behind schedule. The UK government intends to build 8 new nuclear plants, but is still struggling to build one (Hinkley Point C). This first plant is very expensive (more than twice current electricity retail price).	No nuclear in pathway B.	Economics; socio-political acceptance
6. Import and export	Scenarios A and B assume that the UK will be exporting low-carbon electricity after 2030 (because UK onshore wind is the most cost-effective options in the models). This contradicts with current government policy, which builds new interconnectors with European countries to *import* low-carbon electricity, e.g. from Norway, Iceland.	The same as under pathway A, but to somewhat lesser extent	Political acceptance.

5. Scenario 1 (Pathway A)

Core characteristics, logics and challenges
This scenario provides a socio-technical storyline for pathway A from D1.3 (Figures 2 and 3 above). In conceptual terms this pathway focuses on large-scale technologies, which represent disruptive technical change, but leaves many elements of the socio-technical system intact. Incumbent actors are the dominant actors in Pathway A, where a core logic is that governments change market institutions (regulations, financial incentives) to stimulate the reorientation of large firms. The introduction of new policies needs to be underpinned by 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 onshore wind, biomass, BECCS and grid expansion (table 3 above), and 2) the need for *political U-turns* in specific climate change strategies. These problems needs to be addressed in the first period (2015-2025) to prepare the ground for further roll-out of renewable electricity technologies (RETs) in the second and third period.

5.1. Changing gear and gearing up (2015-2025)

In the Paris agreement, the newly elected (2015) Conservative government pledged to cut greenhouse gas emissions by 40% by 2030 compared to 1990. Since the heat/buildings and transport sectors were envisaged to decarbonize more slowly, this commitment meant that most GHG reductions should come from the electricity sector by 2030. Although the government did not specify post-2020 targets, their strategy for substantial decarbonisation was based on a 'partial reorientation', which included changes in existing regimes (nuclear, coal/gas) and some upscaling of niche-innovations (with stated targets of 30% of renewable electricity generation by 2020, but no clear statements post-2020).

Regime developments: The government envisaged expansion of nuclear power (with plans to build and operate 8 new nuclear plants by 2030, delivering 16 GW new capacity), the introduction of CCS for coal and gas, and the phase-out of unabated coal by 2025 *if* viable alternatives were available by then. However, the political commitment of the new government was lower than previous government, leading to the removal of subsidies for CCS demonstration projects. This was a major setback for CCS deployment in the UK, which damaged investor confidence and future visions. R&D investments in CCS therefore remained low in subsequent years, with the UK falling behind international efforts (e.g. in the US and Canada). The lack of a domestic support coalition made it difficult to implement CCS in the 2020s in the UK.

The government also struggled to build the first new nuclear power plant (at Hinkley C). In 2015 and 2016, EDF postponed decisions several times, because of the technical complexity of the plant and the size of the financial commitment. In 2017, EDF finally committed as a result of top-level negotiations between the UK and French governments (which owned 80% of EDF). These difficulties created social and political problems for the UK's further nuclear plans. Nevertheless, the government pushed ahead with two other nuclear plants (Wylfa and Moorside), starting concrete negotiations in 2018, which by 2020 resulted in concrete plans. Meanwhile, Hinkley C faced construction problems, which led to further delays in the opening until 2025 (more than 7 years late compared to initial plans). Final construction costs were higher than planned (£20 billion instead of £16 billion), which caused major embarrassment for the government. In combination with the high price (more than twice the whole sale price), which was guaranteed for 30 years, this led to a negative discourse of nuclear power being too expensive. The government spent much political capital to push through the other two nuclear plants, but after that there was little appetite, nor political opportunity to build the remaining 5 nuclear plants. Since several old nuclear plants were decommissioned, the installed capacity did not increase very much.

The problems with CCS and nuclear power created major challenges for the government's climate change strategy as well as a capacity gap, which created major energy security concerns. The newly elected (2020) government acknowledged these problems and changed direction. It embarked on an ambitious plan to upscale renewable electricity production and accelerate the deployment of green niche-innovations. Since this would take time, the sector still faced a capacity gap in the late 2020s. While the government did not abandon the commitment to phase-out unabated coal, it felt nevertheless compelled to postpone this to 2030.

Niche developments:
In July 2015, the Conservative government down-scaled a range of support policies for renewable electricity technologies, because the projects that were in the pipeline would be sufficient to reach the 30% target for 2020. Feed-in-tariffs for solar-PV were slashed by 80%. And in response to public concerns about the countryside, the government announced that it would build no more onshore wind turbines after 2020 and consequently down-scaled financial support instruments. The conversion of coal plants to biomass also faced problems, firstly because of down-scaled subsidies and, secondly, because of public concerns about the sustainability of imported biomass pellets (which led to strong NGO protests).

The slashing of renewable electricity policies led to bankruptcies, especially in the emerging solar installation industry. But it also damaged investor confidence and many utilities, project-developers and large investors complained about the unreliability and fickleness of UK energy policy, which seemed to change every 5 years. Nevertheless, the government was right in the sense that the 2020 targets for renewable electricity were met.

By 2020, however, it had become clear that other parts of the government's strategy (particularly CCS and nuclear) had not worked as well, which created a major gap in their plans to reach the 2030 targets. Meanwhile, the sales of hybrid and electric cars had increased from 2.8% of new sales in 2015 to 9% in 2020. This increased the pressure (also from international car companies) to reduce the carbon intensity of electricity (since this affects the climate mitigation potential of electric cars). The newly elected (2020) government also faced international pressure, both from the EU and the pledge-and-review process agreed in Paris, to continue its commitment to the 2030 targets. In this context, the new government changed the direction of its climate change strategy: a) it downscaled its nuclear plans from eight to three nuclear reactors, b) it cancelled its CCS plans for coal and gas, but kept its commitment to coal phase-out by 2025, c) it increased its commitment to RETs, which had to be substantially increased to fill the gaps created by the failed nuclear and CCS strategies, d) it would continue and expand the building of interconnectors to European countries to enable the import of more low-carbon electricity (from Iceland, Norway, France).

RET-expansion plans included all options, except solar-PV where the earlier disruption had wiped out most businesses. Onshore wind was the main plank of the government's strategy, because this was the cheapest option, which resonated with the government's goal to keep costs down. Offshore wind was also important, because it offered commercial prospects for diversification for the UK's offshore industries (gas, oil). The conversion of coal plants to biomass increased more gradually because of concerns over the sustainability of imported pellets. These concerns gave rise to supply chain standardization efforts, which took several years to reliably implement and certify.

The new government strategy faced many hurdles, which required additional tailored policies.

- Investors, utilities and project developers were initially reluctant to deploy new RETs because they did not trust the government after earlier U-turns had caused losses and disrupted their long-term planning. To convince and attract companies, the government therefore had to offer very attractive conditions with penalties against future policy change.
- Onshore wind, in particular, faced large social acceptance problems, because of concerns over the countryside and because of the poor quality of earlier consultation processes (which led local citizens to contest permit procedures because they did not feel listened to). Addressing these problems required a wide range of initiatives which unfolded over several years: a) in exchange for financially attractive support policies, the government required utilities and project developers to improve their consultation procedures, leading to real involvement of local residents in project planning, b) firms were also required to pay 2.5% of revenues to local residents as compensation for burdens, c) a 'Broad Societal Discussion' was organized to discuss the pros and cons of the new government strategy with a broad range of stakeholders and citizens. Environmental NGOs were important in this discussion, because they helped articulate a discourse that prioritized climate change over the countryside. Not everyone agreed with this prioritization, which led to heated debates. But increasing consumer experience with electric vehicles and smart meters (which were installed in many households by 2020) enhanced engagement with, and interest in, clean electricity. d) a broad business coalition, including electric utilities, car companies (who became increasingly interested in electric cars), and ICT-firms (who deployed RETs themselves and had an eye on future smart grids) increasingly supported the new strategy, offering support for a green growth discourse. The alignment of these developments gradually enhanced the public support for increased deployment of onshore wind.
- Offshore wind faced less public acceptance problems, because the turbines were out of sight and because the higher costs were de-prioritized in a green growth discourse, supported by a broad coalition, including the Carbon Trust, Energy Technologies Institute, Technology Strategy Board, Department of Business, Innovation and Skills, the Crown Estate (which sold licenses for the seabed), environmental NGOs. National and international utilities (including Vattenfall, RWE) and energy companies (Dong, Statoil) also supported offshore wind, because this aligned with their large-scale generation routines and business models. These incumbent energy companies extracted attractive financial incentives and guarantees from the government in exchange for their commitment.

The substantial increase of RETs between 2020 and 2025 enabled a parallel down-scaling of coal-fired plants, many of which had reached the end of their life. To deal with the intermittency problem of onshore and offshore wind, gas-fired power plants remained prominent because they offered flexible back-up capacity that could be switched on/off rapidly.

The roll-out of smart meters, which was pushed by the government and utilities, experienced major social acceptance problems, because people felt they had not asked for this technology, which cost about £240. They also distrusted the utilities, which had been given responsibility for the roll-out program. Since much political capital had been invested, the government pushed ahead anyway, reaching less than its original goal (80% instead of 100% roll-out by 2020).

5.2. Rolling out renewables and transforming the grid (2025-2035)

The changes in the early 2020s, particularly in government strategy and public acceptance, prepared the ground for the further roll-out of RETs in the 2025-2035 period. The various RETs (onshore and offshore wind, biomass) developed into dedicated technical regimes with stabilized design rules and specialized communities. These 'new' regimes competed with the 'old' regimes (gas, nuclear, coal) in the context of a newly introduced carbon tax. The expansion of RETs also required major transformations in the electricity network regime (expansion, smart grids, storage) and greater flexibility in the electricity consumption regime (including smart meters and time-of-use tariffs). So, the earlier supply-side changes began to have knock-on effects on other parts of the electricity system.

Political concerns about climate change strengthened in the 2020s as extreme weather events and melting polar ice seemed to validate climate science predictions. The pledge-and-review process, agreed in Paris 2015, also proved remarkably successful, with many countries increasing their carbon reduction pledges. At the 2025 review meeting, the UK confirmed its 2050 commitment to 80% GHG reduction, which cemented policy delivery momentum. In this political context, politicians hotly debated an economy-wide carbon tax, which economists and modellers had long proposed, but which proved difficult to implement. In 2028, however, the government finally agreed to introduce an economy-wide carbon tax, which provided unambiguous market signals about the desired way forward, away from fossil fuels and towards low-carbon options. This tax was not only supported by environmental NGOs, scientists and green parties, but, importantly, also by several powerful industries, including the car industry (which desired clarity to enable a full strategic reorientation towards electric vehicles), the financial sector (which wanted clarity about long-term investments) and utilities (who saw opportunities in converting the remaining coal plants to biomass and CCS). The tax aimed to provide general direction as well as increase the amount of private capital available for low-carbon investments, including RETs, grid improvements, battery-charging facilities, etc. And indeed, the reorientation of financial capital from fossil fuel industries (which came to be perceived as not having a viable future) towards low-carbon options provided an important stimulus for the roll-out of RETs in this period.

'New' renewables regimes

Onshore wind expanded fastest until 2030, but subsequently faced some decreases because of a confluence of several developments: a) it became more difficult to find good wind sites, which reduced the price/performance characteristics of new wind parks (which were increasingly build in the interior as coast lines were already filled), b) public acceptance deteriorated again, as new wind turbines were built in very visible places, c) the introduction of the carbon tax in 2028 favoured Bio-Energy with Carbon Capture and Storage (BECCS) more strongly than was anticipated (see below), with the unintended effect of replacing onshore wind to some degree.

Offshore wind, which was more expensive than onshore wind, also faced competition from BECCS. Nevertheless, it continued to expand strongly because it was supported by a powerful advocacy coalition (see above), which translated into attractive financial incentives. The relative shift towards offshore wind also offered a way to circumvent the social acceptance problems of onshore wind, while boosting renewable energy production.

Biomass had expanded gradually until 2028 because of renewables support. After the 2028 carbon tax, biomass diffused much more rapidly than was foreseen because of several reasons: 1) utilities with coal-fired power plants were keen to convert to biomass, because this offered a way to further milk their assets, which were threatened by the planned coal phase-out by 2030, 2) these utilities could offer double carbon credits by implementing BECCS, which worked well on large-scale plants; this possibility was initially under-estimated because the UK had no experience or domestic firms in the CCS area, because of earlier policy failures; but CCS had been further developed internationally, and UK utilities successfully imported the technology and installed it on their plants; this enabled them to earn double carbon credits, one for biomass and one for storing CO2 emissions; BECCS thus created the possibility of *negative* emissions, which fitted well with the increasing socio-political concerns about climate change, 3) another advantage was that biomass offer low-carbon generation flexibility and back-up capacity for the increasing amount of intermittent renewables; this enabled gradual replacement of gas-fired power plants, which had previously fulfilled most of this function, 4) the public concerns about the sustainability of imported biomass was also alleviated by that time, because of the articulation of standards and inspections for sustainable biomass supply chains.

Initial BECCS installations faced technical teething problems, particularly with regard to dimensioning and operation. Once these problems were overcome, the attractive financial incentives stimulated existing utilities to build a raft of large-scale biomass combustion plants with integrated CCS facilities.

Despite ongoing cost improvements and international enthusiasm, solar-PV did not take off in the UK, because incumbent firms lobbied against dedicated solar-PV policies, which could undermine their reorientation towards biomass and wind. Since many solar installation firms had gone bankrupt in the previous period, the solar advocacy coalition was relatively small and uninfluential. Furthermore, significant PV capacities installed in continental Europe led to low electricity prices during the day, decreasing the potential revenue for PV installation in the UK.

'Old' regimes

The 2028 carbon tax rapidly reduced the *use* of natural gas for power generation. But policymakers wanted to maintain a certain amount gas-fired capacity for reasons of flexibility and back-up. They therefore introduced 'capacity markets' which paid utilities for the availability of gas-fired power plants, even if these were not used much. These plants provided additional back-up capacity (besides biomass) for those days in the year that there was very little wind.

Coal-power was entirely phased-out by 2030, as the remaining coal plants switched entirely to biomass. Nuclear power was somewhat expanded, as Hinkley C came online in 2025 and Wylfa and Moorside in 2030. Several other nuclear plants were decommissioned, however. But since the new plants were run at higher load factors, total nuclear power generation increased.

The high shares of onshore and offshore wind required major changes in the electricity network regime: 1) long-distance transmission grids were expanded to connect remote wind farms to centres of use, 2) an entirely new offshore grid was constructed, based on seabed cables, 3) the continued construction of interconnectors to European countries gradually linked the UK into an emerging European super-grid. Several tactics were pursued to lo limit *social acceptance problems* of building new pylons in the countryside: a) local residents were better consulted in the design and planning process, b) new pylon designs with less visual intrusion were deployed, and, in some instances, cables were constructed underground, c) the National Grid was forced to offer compensation, either financially or, in most instances, by planting new trees that would mask the pylons.

Another problem was the inertia and unwillingness of the National Grid and the Distribution Network Operators (DNOs) to engage with radical innovation. These infrastructure actors had been resisting change since the policy U-turns of the early 2020s. By 2025, politicians were deeply frustrated by the intransigence of these actors. As they strengthened their international climate change commitments, politicians also overhauled the network regime. The remit of the regulator Ofgem was changed to make climate mitigation as important as low costs. Politicians also changed the rules to enable them to set performance goals that market actors were free to meet in ways they wanted, but with the threat of stiff penalties, which Ofgem had to enforce. These rule changes and associated pressures enhanced the speed of infrastructure change, which also included the introduction of smart grids, which greatly enhanced the monitoring and management of electricity flows.

The pressure to increase flexibility (to deal with intermittency issues) also led to a push for new demand-side tariffs, which were enabled by the smart meters that had been installed in previous years. The introduction of 'time-of-use tariffs' (in which electricity prices vary with specified times) went relatively smoothly in 2026, leading to some demand shifts away from peak times. By 2028, it was clear that this shift was less pronounced than was hoped. Utilities and policymakers therefore pushed for the introduction of 'dynamic tariffs', in which electricity prices varied per hour, depending on supply and demand. This led to a major controversy, with consumer groups warning that the unpredictability and volatility of prices could lead to huge bills for older and non-ICT savvy households (if they would not reduce electricity demand during price spikes, e.g. when low wind would limit supply and push up prices). Policymakers and utilities went ahead anyway and introduced dynamic tariffs in 2030. Within half a year, however, disadvantaged consumers rose up in protest, causing a major backlash against the utilities and government, which were forced to withdraw and postpone the new tariffs.

Meanwhile, an interesting reversal was underway in electricity import/export with Europe. Since the 2010s, UK governments had expanded interconnectors to allow the *import* of low-carbon electricity from Iceland, Norway and France. By 2030, however, the UK was generating so much low-carbon electricity that it could start to export to European countries. This trend continued strongly after 2030 when the emergence of a European super-grid enabled continent-wide coordination and economic trading. Because of its excellent wind resources, UK renewable electricity was relatively cheap, which stimulated increasing demand from European countries with less renewable options. This reversal was not intended when the interconnectors were build, but gradually emerged as infrastructures linked European countries closer together.

5.3. A low-carbon flexible electricity system (2035-2050)

Changes in this period were less dramatic than previous ones, consisting mainly of changes in the relative size of RET-regimes.
* Offshore wind expanded substantially after 2040, to become the largest RET. The main driver were cost reductions due to technical reasons: 1) turbine size was further increased, which improved efficiency and decreased cost, 2) technical innovations made floating wind turbines viable, which removed the need for constructing expensive seabed platforms.
* Biomass and BECCS also expanded substantially, because policymakers realized they needed negative emissions in the electricity sector to compensate for mitigation problems in other sectors (e.g. manufacturing, heating/buildings). High biomass and BECCS capacity was also needed to provide back-up capacity and flexibility for the high degree of intermittent renewables.
* Onshore wind decreased in this period, because of competition from offshore wind and BECCS, and because of social acceptance problems (due to crowding the countryside).
* Although gas capacity was maintained (via capacity markets) for days with very little wind, actual use of gas for power generation became very small in this period.

The intermittency problem was further addressed with changes in the electricity network regime. Smart grids were further optimized, leading to high degrees of control of electricity flows which were linked to precise and accurate weather forecasts and measurement stations. The introduction of *voluntary* dynamic tariffs also became popular, because ‘smart appliances’ (which could switch themselves off when prices reached certain thresholds) reduced the risk that consumers would be faced with high bills due to price volatility. Some consumers were even willing to accept ‘direct load control’ options (which enabled grid managers to remotely switch off appliances such as washing machines, fridges/freezers), for which they were financially compensated. These options enhanced system flexibility by 10-15%. Further additional flexibility came from international spot markets, which allowed the UK to buy and import electricity (via interconnectors) in emergencies (e.g. days with no wind at all). This combination of options created a low-carbon flexible electricity system by 2050.

6. Scenario 2 (Pathway B)

Core characteristics, logics and challenges
This scenario provides a socio-technical storyline for pathway B from D1.3 (Figure 2 and 3 above). In conceptual terms this pathway focuses on a wider set of changes across several system dimensions. New entrants play an increasingly large role in electricity generation based on the growth and stabilization of new technical regimes (e.g. distributed generation). Wider shifts in cultural discourses and social legitimacy for an energy transition emerge, which are supported and support a broader, inclusive governance approach (beyond large firms and technologies), reflecting deeper changes in policy paradigms. Initially, social acceptance starts to grow; this is followed by increasing social *pressure* for change. Major 'transition challenges' concern: 1) *social acceptance problems*, which need to be overcome before a shift towards *increasing social pressure*; 2) the need for *policy instrument U-turns*, which precede more radical shifts in *policy paradigms*; 3) the dominance of *incumbent actors*, who will resist change in general and competition from *new entrants* more specifically.

6.1. The nuclear option: more wind! (2015-2025)

In the Paris agreement, the newly elected (2015) Conservative government pledged to cut greenhouse gas emissions by 40% by 2030 compared to 1990. Since the heat/buildings and transport sectors were envisaged to decarbonize more slowly, this commitment meant that most GHG reductions should come from the electricity sector by 2030. Although the government did not specify post-2020 targets, their strategy for substantial decarbonisation was based on a 'partial reorientation', which included changes in existing regimes (nuclear, coal/gas) and some upscaling of niche-innovations (with stated targets of 30% of renewable electricity generation by 2020, but no clear statements post-2020).

Regime developments: The government envisaged expansion of nuclear power (with plans to build and operate 8 new nuclear plants by 2030, delivering 16 GW new capacity), the introduction of CCS for coal and gas, and the phase-out of unabated coal by 2025 *if* viable alternatives were available by then. However, the political commitment of the new government was lower than previous government, leading to the removal of subsidies for CCS demonstration projects. This was a major setback for CCS deployment in the UK, which damaged investor confidence and future visions. R&D investments in CCS therefore remained low in subsequent years, with the UK falling behind international efforts (e.g. in the US and Canada). By 2020, CCS was eventually abandoned as a viable component of a low carbon future, because commercial and technical viability had still not been demonstrated at scale and coal generation was decreasing rapidly. However, the coal phase-out plan was stretched to 2030 to accommodate capacity issues stemming from problems with nuclear generation.

The government struggled to build the first new nuclear power plant (at Hinkley C). In 2015 and 2016, EDF postponed decisions several times, because of the technical complexity of the plant and the size of the financial commitment. By 2017, public debates also started to escalate about the prospects of escalating costs and delays (based on the experience of other countries attempting to build similar nuclear plants) and increasing concerns about the effects of supporting nuclear for future electricity prices. After several further postponed decisions, EDF pulled out of the deal in early 2018 on the basis of irreconcilable reputational and financial risk. This marked the end of nuclear as a central, base load, pillar for UK energy policy.

Anticipating the potential risk to their nuclear strategy, by early 2017 the government had already accelerated deployment of international interconnectors with Norway, France and Iceland, which meant that nearly 10% of annual electricity use was imported in 2020. This was used to mitigate the reduction of base load electricity supply from coal, gas and nuclear to 2020. However, during this period and after the Hinkley debacle, energy security became a hot public and political issue, reopening a political window for a renewed debate about the UK's energy policy.

Niche developments:
In July 2015, the Conservative government down-scaled a raft of support policies for renewable electricity technologies, because the projects that were in the pipeline would be sufficient to reach the 30% target for 2020. Feed-in-tariffs for solar-PV were slashed by 80%. And in response to public concerns about the countryside, the government announced that it would build no more onshore wind turbines after 2020 and consequently down-scaled financial support instruments. The conversion of coal plants to biomass also faced problems, firstly because of down-scaled subsidies and, secondly, because of public concerns about the sustainability of imported biomass pellets (which led to strong NGO protests).

The slashing of support for renewables had particularly damaging effects for the fledgling UK solar industry. This led to bankruptcies and a crisis of investor confidence, the effects of which lasted for some time in the absence of any solar specific government policy. However, the high profile debate around a new energy strategy created impetus for a new raft of pro-renewable policies and was touted in the media as the 'renewable-reset' (a direct dig at the previous government energy-reset). Incumbent-operated offshore wind farms remained stable, despite being costly, and enjoyed a broad base of support from across government. While very little additional capacity was installed (because of the high costs), offshore wind's contribution to overall generation rose from around 5% in 2015 to 10% by 2025 through completion of projects already in the planning pipeline.. So, while the niche remained small in overall terms, it started to take on regime qualities through increasing institutionalization within the long-standing large-scale, centralized model for generation.

But, because the debate at the time was focused on energy security and cost containment (and less on climate change concerns), onshore wind took centre-stage as the cheapest renewable energy technology. The political image of onshore wind was rebranded from 'green crap' to 'cheap and British' through ministerial speeches and briefing to the media. Emboldened by the shift, energy incumbents, who had already developed strong capabilities in plant installation and operation, quickly developed further plans for expansion. These initial moves were met by a high degree of resistance and controversy. For the general public it reignited frustrations about large firms trampling over the planning process and disregarding local concerns. For international environmental NGOs, the renewable-reset lacked ambition by failing to recognize opportunities for alternative models for energy provision. Facing a potential crisis of social legitimacy, incumbents and government hatched plans for new policies and business models to overcome problems of social acceptance.

In this context, by 2018 incumbent electricity suppliers started to experiment with new business models for smaller scale wind-farms. This was seen as an opportunity to reduce negative public opinion, by actively including local stakeholders (community groups, farmers) into the ownership structures of wind-farms. Several high profile Private-Community Partnerships (PCPs) generated significant interest as an alternative model for distributed generation. By 2018, government responded to these incipient initiatives by promoting a new PCP wind-power scheme, guaranteeing a fixed price for wind-generated energy for 20 years (set at a generous level and bolstered by high levels of social and political legitimacy, based on fall-out from the Hinkley Point debacle). From 2020, emboldened by the success of early initiatives, community groups and new project management companies started to form consortia to develop and manage new wind farms. By 2020, the new PCP initiatives became very popular with local residents, and started to erode longer-standing NIMBYism. To much surprise (as usual), in 2021 the annual Turner Prize art prize was awarded to a community wind-farm in Norfolk, accompanied by photographic art depicting the blending of turbines with the natural landscape. While this was largely derided in the media and by most of the population, it did introduce an alternative aesthetic presenting wind-power and nature in a symbiotic relationship. In time, this would prove to be an increasingly popular and enduring image.

By 2025, onshore wind alone was providing 23% of all electricity generation with increasing prominence and cultural enthusiasm for the PCP business model. The onshore sector was stabilizing as a new regime based on small-scale, distributed generation.

In a parallel development, some coal-to-biomass conversion continued from 2015 to 2020 as coal plant operators sought to sweat their assets in the face of the coal phase out. Big biomass remained unpopular, but was financially viable through government regulated 'capacity markets'; this capacity became especially important from 2020-2025, leading to reduced reliance on electricity imports. However, smaller, dedicated biomass started to emerge as an unanticipated consequence of the government-supported PCP model, initially introduced to support deployment of wind. Incumbents joined forces with regional cooperatives of farmers to install medium sized anaerobic digesters and develop the supply chain logistics for agricultural waste. Supermarkets also became partners, benefitting from the opportunity to make money from their post-retail waste streams. This renewed interest in dedicated biomass, re-ignited dormant innovation pipelines for much for efficient biomass-to-energy conversion.

The government mandated roll-out of smart meters, planned for completion in 2020, met with delays, largely through problems with implementing the ICT infrastructure. However, by 2022, nearly all homes had been fitted with smart meters and in-house-displays. Research accompanying the mass roll-out showed that many consumers initially enjoyed 'playing' with their electricity consumption, but quickly became bored. However, appliance manufacturers started R&D programmes to develop smart appliances in anticipation that a smarter electricity system was starting to emerge.

Climate change received little attention during the first half of the period, with policy principally oriented towards security and cost. The 2020 'pledge and review' process of the Paris agreement came and went without any significant public interest, largely because the UK had met targets via the reductions in coal powered generation and the increase in onshore wind generation. However, the 2025 pledge and review process ignited more public debate about carbon emissions. While the UK had met its 2025 target, there was mounting criticism from scientists, environmental NGOs and the Committee for Climate Change. They argued that while the renewable-reset and subsequent policies had been successful in injecting momentum to the deployment of renewables, there was still very little in the way of long-term plans to meet carbon targets for 2050. Pressure mounted on government to re-visit national energy policy again, with increasingly prominent calls for a new Energy Act.

6.2. Distributing control and controlling distribution (2025-2035)

The willingness of utilities to work in partnership with community groups had started to restore their social license to operate in the UK. Equally significant was the start of a slow shift in the deeper beliefs of incumbent energy utilities. Initially, their motivations to engage in PCPs were based on the generous government support and because, for many locations, it was the only way to install biomass and onshore wind generation without massive negative public pressure. Based on early successes, they started to adopt mixed strategies, thereby weakening the belief that large-scale, centralized generation was the only way.

The debate that had started around the 2025 pledge and review grew and started to gain traction in public arenas. Not only was there growing concern that targets would be missed, there was also a growing confidence that renewable generation could and would be central to the UK's electricity system. Furthermore, electricity became the dominant focus for debate about the future of energy and climate change, because of the faster that anticipated rise of electric vehicle and electric heating system. This brought a range of new commercial actors (international car companies and heating equipment manufacturers) into the arena, who lobbied government for action to accelerate the de-carbonisation of electricity to legitimate their own strategies for low carbon transitions in mobility and heating.

This mounting pressure from many sectors of society resulted in the 2028 Low Carbon Electricity Act (LCEA). The Act introduced a carbon tax and a suite of further policies to support and grow renewable generation into a viable supply mix that could deal with intermittency problems. The Act had variable effects on the different niches and regimes, some designed and some unanticipated. Given the earlier concerns about energy security after the Hinkley debacle, the Act also planned for the UK to achieve net-electricity independence (i.e. to balance imports and exports) by 2030 and this was achieved as planned.

'Old' regime developments

The LCEA retained the planned 2030 phase out of coal and also mandated a phase out of nuclear. By 2028, there was little resistance to this from plant operators, who were acquiescent to nuclear and coal decline, but could further sweat assets over the phase out period because capacity markets continued to be used to maintain overall generation capacity.

Given the strategy to phase out nuclear and coal, the LCEA included provision for gas generation via the capacity market, but with plans to increasingly use gas only when required to deal with intermittency problems after 2030. Incumbents came to treat gas as a low margin business operation, stable, but with minimal prospects for growth meaning that R&D became increasingly unattractive. They turned to renewables for the core of their growth strategies.

New regime developments

The carbon tax privileged onshore wind above other renewable technologies, stimulating further investment plans through PCP arrangements and through incumbent only operated plant. The former flourished especially in areas in close proximity to rural towns and villages; the latter, in more remote rural areas. Conservationists, who had initially been resistant to massive onshore development, started to shift their position. This was partly stimulated by the deepening appreciation of the new wind-nature aesthetic, combined with new models of deployment that fostered re-wilding and the promotion of biodiversity. By 2030, very broad societal support for onshore wind had developed, considerable momentum for further expansion. The rapidly growing UK market for wind turbines and central role for onshore wind in the LCEA for future deployment created significant inducement effects for wind turbine R&D in the UK. New university-industry consortia formed with high levels of public and private investment. UK-based R&D focused on technical optimization for distributed onshore wind generation, including renewed interest for rooftop wind turbines. The rise of distributed generation, with strong involvement from community groups in the PCP model and lead user households for rooftop wind started to create interest and evidence for the viability and attractiveness of low carbon lifestyles, further propagated through links with innovations for smart grids and other low carbon technologies (see below).

The LCEA was relatively neutral towards offshore wind. It remained expensive compared to other generation technologies, but continued to have support from a strong advocacy coalition. As such, operation of existing offshore wind-farms formed a second (alongside gas), fairly low margin revenue stream for incumbent energy companies. Little additional capacity was added, but operations were maintained for diversity in the renewable supply mix and because repowering existing sites remained relatively cheap.

During the period 2025-2030, biomass remained a fragmented niche, struggling to stabilize into a regime. The LCEA envisaged biomass as a further contributor to base load generation. Coal-to-biomass conversion continued, but remained unpopular. Dedicated and more decentralized biomass generation was more popular, but less well developed in terms of dominant technology designs and actor configurations. However, by 2030 new developments in high-throughput anaerobic digestion had begun to demonstrate very promising results in terms of biomass-to-energy conversion efficiency. By 2035, converted coal plants using imported pellets were being decommissioned due to long-standing unpopularity and inferior carbon performance compared to local biomass waste and highly efficient conversion technologies.

The increasing prevalence of distributed generation and the intermittency of onshore wind power generation had intensified pressure on the grid. With little offshore wind capacity added, and the commitment to become electricity independent by 2030, most attention was focused on accommodating the massive up-scaling of onshore wind. The expanded transmission grid required installation of new pylons and overhead cables throughout the UK countryside. Lessons had been learned from the past, so this was approached through considerable multi-stakeholder consultation and planning, including conservationists and the many local community groups most affected. The Design Council launched a competition for pylon design, which generated considerable attention amongst the industrial design firms; the competition was put to a public vote. Landscaping firms and the Countryside Alliance collaborated with installers and local communities to accommodate the transmission lines with the maximum degree of sensitivity to the landscape.

The LCEA had also established a new role for Ofgem, tasked in 2028 with a remit to deliver a smarter grid to enable progress towards carbon targets, with ‘least cost’ now re-interpreted over the whole time-frame to 2050, including potential costs associated with missing 2050 carbon emission targets, and refocused to also accommodate the shift to a much more decentralized generation system. The new strategy had four specific goals: 1) to upscale integration of ICT into the grid to enable improved management and monitoring of electricity flows; 2) build more international inter-connectors; 3) to deliver on potential gains from the installed smart meters already installed in most UK homes; 4) to deliver local level micro-grids and flexible load matching to establish stable generation. The new cost assessment frame created a window for up-front investment into large scale ICT integration, via government-back loans to the National Grid. Given the ambition to balance imports and exports, the UK’s interconnector policy was guided to deal with intermittency, rather than to make a net contribution to overall generation. The third goal was perceived to be more demanding, because smart meters had become largely ignored within households after the initial novelty of a ‘new gimmick’ had dissipated in the early 2020s. In 2030, the Government introduced ‘time-of-use’ tariffs to reduce peaks in electricity demand. These were surprisingly popular, so in 2033 the Government pushed ahead with more ambitious ‘dynamic tariffs’, based on real time fluctuations in renewable supply. These met with some resistance, but were accepted, in part because the wider electrification in mobility and heating had made electricity use much more prominent in people’s everyday lives and in public discourse. Many consumers became used to planning their car charging routines during low tariff times and there was a strong uptake of smart appliances, which were designed to work with the dynamic tariffs. Tesla’s home battery technology had been around since 2015 and other companies imitated creating an innovation race for high capacity, long-life, low cost batteries. However, there had been little adoption in the UK until the introduction of variable tariffs. The introduction of dynamic tariffs in 2033 led to significant acceleration of battery adoption in UK homes, used to reduce costs by taking advantage of low tariff periods. However, these policy instruments were highly disadvantageous for low-income families, who struggled to meet their heating needs in particular and could not afford battery storage technology. In order to avoid de-railing the largely popular tariffs, the Government acted swiftly to introduce low-set-tariffs on a means-tested basis.

The rapid development of distributed generation and the introduction of micro-grids and flexible load matching had knock-on effects for community groups and lead-user households leading to much higher 'energy awareness' and increasing engagement with the idea of a low carbon lifestyle. Community groups and households not only installed small-scale power generation, but also engaged in distribution, sales and accounting, creating new mind-sets and routines, which spilled over to further actions, including acquisition of electric vehicles, insulation and increased use of smart meters. Linking these innovations created a new 'package' to underpin the idea of low carbon lifestyles. Whilst this lead-user group was relatively small, it was growing rapidly and by 2035, their experimentation with low carbon lifestyles was providing increasingly strong evidence for their viability, leading to sustained interest in the media.

Niche development

The government's LCEA enacted a 'wait-and-see' strategy for solar-PV. Despite falling equipment costs internationally, the Government and most social groups viewed solar as the least preferable renewable option because of the sunlight potential of the UK, and also because the incipient industry had been crushed after the 2015 energy policy reset. The longer term plan envisaged waiting for further significant changes in technology to further reduce costs and conversion efficiency.

In light of this, it was somewhat surprising at the time that some high profile schemes started to emerge, sponsored by large companies and organizations. These were oriented at branding opportunities to raise corporate reputations during a time when social enthusiasm for renewables was growing quickly. Commercial organizations including football clubs and supermarkets adopted solar to become fully carbon neutral and self-sufficient and used this to successfully garner significant positive PR. This in turn started to create a small project-based solar installation sector, leading to skill formation and supply chain formation. Seeing the positive PR led some large utilities to invest in several large-scale demonstration facilities, despite receiving little support through the LCEA. Finally, domestic rooftop solar started to grow among the lead-user households that had been closely involved with the growth of distributed energy and experimentation with low-carbon lifestyles. As such, enthusiasm for solar was growing in advance of any specific support or vision from government policy and this was placing increasing pressure on government to integrate solar into the national energy strategy.

6.3. Chasing the sun (2035-2050)

By 2035, growing cultural enthusiasm for a low carbon system and for low carbon lifestyles led to intensified social pressure and mobilization for meeting 2050 carbon targets.. The period of needing to consider social acceptance problems had been superseded by high levels of commitment within civil society for completion of the low carbon transition and this had spilled over into industries.

This major shift in social and cultural context made policy implementation much easier, but still generated significant debate about policy visions. The 2035 pledge and review process was anticipated with a sense of national pride on the progress achieved to date and stimulated massive societal debate about the remaining transition challenge. Further electrification of mobility and heating continued, placing electricity at the core of the low carbon transition to 2050. Soon after the 2035 pledge and review, the government launched its Electrification and Low Carbon Society Strategy (ELCS), signaling the following priorities: 1) Continued support for further deployment of onshore and offshore wind as the central pillars for generation and distributed biomass; 2) Further development of a multi-level, highly flexible grid at European, national and local levels; 3) Final decommissioning of remaining nuclear plants; 4) Support for gas generation for back-up capacity; 5) Support for massive expansion of solar-PV.

Regime developments

By 2035, onshore wind had become the single largest source of electricity generation. The R&D efforts that around 2030 were bearing fruit by 2040, especially in the use of new materials (e.g. graphene and carbon nano-tubes) for lighter and stronger blades, greatly enhancing the conversion efficiency of wind-power. Different turbine designs (much larger), also using new materials, were used in offshore wind farms. Despite cost reductions in offshore wind technology, onshore wind remained a much cheaper option, consequently retaining its central role in the Government's strategy, which planned for a further doubling of a capacity within one decade.

The final nuclear plant was decommissioned in 2040. While biomass-to-energy generation had grown steadily over the past two decades, its future became uncertain, because biomass was increasing seen as key input for a high value bio-economy, oriented to serve the agricultural, health and materials industries. As such, old biomass plants were sometimes not renewed, leading to a slight reduction in overall capacity. This had a knock-on effect for the gas regime, which was increasingly seen as an important for back-up capacity. Capacity market incentives were instituted to stimulate a new boom for gas-powered generation.

Smart grid management had become routine and efficient. During the 2040s, onshore wind capacity was growing so quickly that on windy days supply outstripped domestic demand. The international interconnectors built in the earlier periods and originally intended for energy security had become a strategic economic asset for the UK, which started exporting increasing amounts of electricity. The European super-grid had facilitated a high functioning European market for electricity, with prices regulated from Brussels. Within this European context, the UK also had a stabilized multilevel approach, with a national grid of high voltage transmission lines and micro-grids for local generation and consumption. With ICT fully integrated at all levels and high levels of battery storage, this smart network system allowed for significant flexibility for managing generation and consumption.

Niche-to-regime developments

In the run up to the 2035 ELCS strategy, social pressure started to grow for solar, initially coordinated by a well-funded NGO campaign, "The Wait is Over", which capitalized on the growing cultural enthusiasm for solar and growing evidence from lead user experiments for solar as a part of a low carbon lifestyle. The earlier high profile schemes of football clubs and supermarkets had struck a chord with the public. China had long been the global leader in solar panel innovation and manufacture, with panel costs significantly lower and conversion efficiency much higher. The 2035 ELCS strategy introduced solar for the first time as a major component of the national energy strategy.

In 2038, a ten-year trade deal was struck with the Chinese government to secure supply of solar panels and in 2040 the UK government committed to installing solar-PV on all viable state-owned buildings. Caught up in the widespread cultural enthusiasm, many other organizations followed. The RLCS also re-instituted a very generous feed-in-tariff to encourage the adoption of domestic solar + in-home-battery packages. Diffusion sky-rocketed leading to a six-fold increase in installed capacity in one decade. In the early 2040s, supply could barely keep up with demand. By 2043, European installation companies, which had formed two decades before set up offices in the UK to take advantage.

Cultural embedding of low carbon ways of living

By 2040, based on increasingly prominent attention to earlier experimentation with low carbon lifestyles, deeper cultural shifts towards sustainability in general and low carbon ways of living were diffusing rapidly. Domestic wind and solar pro-sumption, further stimulated a general cultural awareness for low carbon living, with ever greater numbers of consumers actively pursuing energy conversation as a normal way of life. By 2050, low carbon lifestyles had become highly embedded in mass culture, based on the interlinked innovations that had developed over the previous periods. 2050 targets were met with a significant sense of collective societal achievement.

7. Concluding comments

Scenario A and B both show that transitions towards low-carbon societies, which meet the European and UK targets, are possible. However, they both deviate substantially from business as usual scenarios (pathway 0), entailing major changes compared to recent and contemporary developments. Both pathways require substantial reorientations of current trajectories, as indicated in Chapter 4 on ‘transition challenges’. Although the challenges are substantial, both the quantitative pathways (described in Chapter 2) and the socio-technical scenarios (described in Chapter 5 and 6) suggest that the transitions can be made if relevant actors change their commitments, strategies, investments, and behaviours.

Similarities and differences in transition pathways

In terms of technologies, there are important *similarities* between pathway A and B:

- Wind is the largest option in both pathways accounting for about 65% of power generation in 2050 in Pathway A and 72% in Pathway B. The relative importance of onshore and offshore wind varies, with offshore being largest in Pathway A (since offshore fits well with incumbent interests and practices) and onshore being largest in pathway B.
- Biomass is important in both pathways, although mainly as large-scale BECCS (biomass energy with CCS) in Pathway A and as small-scale dedicated biomass in Pathway B.
- Unabated coal is phased out by 2030 in both pathways.
- Gas-fired capacity is maintained in both pathways, because of flexibility and back-up capacity for intermittent renewables. Actual *use* of gas is very small after 2040 in Pathway B, but remains significant in Pathway B.
- Innovations in the transmission and distribution grid will be crucial in both scenarios, both to connect wind parks to the grid and to enhance the ability to monitor and manage electricity flows (via more smartness and flexibility).
- Smart meters are also important in both pathways, although the knock-on effects on household behaviour are larger in Pathway B.

Important technology *differences* between both Pathways (which are largely due to upfront scenario assumptions) are:

- Nuclear phase-out in Pathway B, but maintenance of nuclear in Pathway A.
- No CCS (or BECCS) in in Pathway B. No CCS with coal in Pathway A, but (imported) CCS does exist combined with biomass energy.
- Solar-PV becomes substantial in Pathway B (after 2040), but remains small in Pathway A.

Policy risks

The similarities, mentioned above, imply several *policy risks*, which relate mostly to political and social acceptance issues:

One risk is that the government does not persist with its intended coal phase-out by 2025. This risk is real since the government has stated that this policy depends on the availability of feasible alternative. And the delays in nuclear power and CCS may mean that this is not the case. This risk is addressed in the scenarios by a rapid increase in renewables (especially wind), which links to the next point.

A second risk is that onshore wind develops slower than anticipated. This risk is pertinent since both pathways substantially rely on onshore wind. Alleviation of this risk would require a political U-turn, since the new UK government has downscaled onshore wind subsidies, and said it would not build new onshore wind after 2020 (in response to social acceptance problems and political debate). Both socio-technical scenarios assume such a U-turn by 2020 (because of regime problems with nuclear and CCS). They also assume that the government will change its policy style (e.g. pay more attention to stakeholder consultation via different procedures) and create financial incentives that compensate local communities.

A third risk is that grid improvements will be made too late, which could limit the system's ability to deal with increasing amounts of intermittent renewables. This risk is real since network regime actors are locked in to old ways of doing things and reluctant to engage with much radical innovation. The scenarios address this risk by assuming that policymakers overhaul the network regime by the mid-2020s and change the remit of Ofgem, set clear targets, and introduce penalties for not meeting these.

A fourth risk is that social acceptance problems of biomass may exacerbate (due to concerns about sustainability). The current government pays relatively limited attention to these problems, which are leading to stronger concerns from environmental NGOs, activists, and wider publics. The scenarios address this risk by assuming that sustainability standards and inspections will be developed in the coming years and, in Pathway B, that new entrants (e.g. farmers, food and drink processors, local communities) will develop local biomass supply chains with greater social acceptance.

A fifth risk is that the current smart meter roll-out project may fail or have limited effects. This is a risk since both scenarios assume that the project will succeed (although with delays) and will have knock-on effects (e.g. galvanizing behaviour change, enable new time-of-use tariffs). The risk is real, because the project is already facing delays and increasing protests, since people feel insufficiently consulted and confronted with high bills for a technology they did not ask for. The socio-technical scenarios don't give much detail about how these problems will be overcome (because of they focus mostly on the supply side).

Wider policy implications

We can draw the following broader policy implications from the scenarios.

First, both scenarios are demanding and require major reorientations ('bending the curve') in the next 10 years. Both scenarios therefore convey a high degree of urgency to speed up ongoing developments and strengthen commitments.

Second, the actions of policymakers are crucial in both scenarios to overcome current lock-ins and accelerate the momentum of relevant niche-innovations. Their roles vary, however, in both scenarios.

- In pathway A, policymakers are the main driver of low-carbon reorientation, because they introduce new policies (specific support policies and a carbon tax from 2028) that incentivize incumbent firms to change their investment patterns. Policymakers are constrained, however, by dependencies on other actors. Business support coalitions are particularly important in pathway A, shaping the political feasibility of tough policies. Achieving public support is also important to achieve legitimacy, but less so than business support (in pathway A).
- In Pathway B, the main push for low-carbon orientation initially comes from civil society, new entrants and changes in public debate and culture. These changes subsequently create credibility pressures on policymakers to enact policy changes that further enable broad transformations.

Third, social acceptance is a crucial problem for many low-carbon options (biomass, BECCS, onshore wind, grid enhancement, nuclear power), as documented in Table 3 on 'transition challenges'. Social and cultural dimensions should therefore receive much more attention in UK energy and climate policies, which tend to privilege techno-economic dimensions. The socio-technical scenarios suggest several possibilities for this, including:

- Requiring utilities and project developers to improve their consultation procedures, leading to real involvement of local residents in project planning

- Requiring firms to financially compensate local residents for their burdens
- Organizing a Broad Societal Discussion to debate the pros and cons of low-carbon options with a broad range of stakeholders and citizens.
- Stimulating low-carbon deployment by new entrants and communities, which is likely to lead to greater engagement, awareness and social debate.

This would require a change in the UK political culture, which is currently characterized as a 'working with incumbents' pattern (Geels et al., 2016) and a 'bulldozer style', which pushes through plans that are concocted by firms and policymakers without consulting with citizens and societal actors. This style is likely to exacerbate social acceptance problems in the coming years, creating serious policy risks for sustainability transitions as indicated above.

Methodological reflections

Since the methodology of combining quantitative and socio-technical scenarios is new, we end with some methodological reflections.

First, the construction of reasonable scenario storylines was harder for pathway B than for pathway A. The reason is that pathway A assumes a reformist pathway where social and institutional arrangements remain stable and are closer to the current situation. In contrast, pathway B assumes deeper changes in institutions and social interaction patterns, which can potentially develop in a variety of directions.

Second, it proved difficult to develop 'pure' versions of the pathway, based entirely on their ideal type conceptualisations (Table 1). Particularly for pathway B, it is difficult to envisage that all renewable deployments will primarily be done by new entrants and none will be done by incumbents (utilities, project developers), which in recent years have reoriented themselves towards RETs. Constructing these scenarios therefore required judgement to blend some aspects of both ideal types into the two scenarios. In Pathway B, for instance, we introduced the business model of 'Private-Community Partnerships' based on collaborations of incumbent firms with community energy initiatives.

Third, some storylines required some technology developments to be created elsewhere internationally. Pathway A, for instance, assumed that CCS would be imported into the UK and combined with biomass energy around 2030. This acknowledges the fact that CCS development in the UK is currently very minimal (since the new government removed all subsidies), but also that international development may continue. The wider implication is that country-focused scenarios (like the UK in this report) cannot only focus on dynamics in the focal country, but also should also pay some attention to international developments.

Fourth, the overall conclusion, however, is that the combination of both methods is both doable and interesting, leading to new ways of thinking about future transitions which pay more attention to social, political and cultural developments.

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