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## Transition pathways for a UK low-carbon electricity system: comparing scenarios and technology implications

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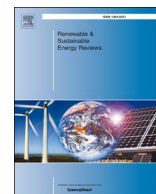
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## Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications

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## ABSTRACT

The United Kingdom (UK) has placed itself on a transition towards a low-carbon economy and society, through the imposition of a goal of reducing its 'greenhouse' gas emissions by 80% by 2050. A set of three low-carbon 'Transition Pathways' were developed to examine the influence of different governance arrangements on achieving a low-carbon future. They focus on the power sector, including the potential for increasing use of low-carbon electricity for heating and transport. These transition pathways were developed by starting from narrative storylines regarding different governance framings, drawing on interviews and workshops with stakeholders and analysis of historical analogies. Here the quantified pathways are compared and contrasted with the main scenarios developed in the UK Government's 2011 *Carbon Plan*. This can aid an informed debate on the technical feasibility and social acceptability of realising transition pathways for decarbonising the UK energy sector by 2050. The contribution of these pathways to meeting Britain's energy and carbon reduction goals are therefore evaluated on a 'whole systems' basis, including the implications of 'upstream emissions' arising from the 'fuel supply chain' ahead of power generators themselves.

## 1. Introduction

## 1.1. Background

The United Kingdom (UK) has set itself on a transition to a low carbon economy and society, through the imposition of a goal, under the 2008 *Climate Change Act* [1], of reducing its 'greenhouse gas' (GHG) emissions by 80% by 2050 (against a 1990 baseline) and the creation of an institutional framework in order to secure this target. Much attention has been given to long-term scenarios and pathways for the reduction of carbon emissions from the electricity system, because there exist a range of options for decarbonising electricity generation and supply. Technological options also exist for the use of low-carbon electricity for heating and transport (as well as other energy services). This type of pathway and scenario analysis is therefore useful to enable 'actors' to reflect on how current energy system decision-making relates to the potential for achieving long-term energy and carbon reduction goals [2]. In the present contribution, a set of low-carbon electricity pathways developed under a research project (supported by Research

Councils UK and, initially jointly, by *E.On UK*: the integrated energy company) are compared and contrasted with 'official' pathways developed by the UK *Department for Energy and Climate Change* (DECC) for the UK Government's *Carbon Plan* [3]. This *Carbon Plan*, produced in 2011, set out measures for reducing the GHG emissions from the UK by 50% by the period 2023–27 (from 1990 levels), on a pathway to reducing emissions by 80% by 2050, as required under the 2008 *Climate Change Act* [1]. The UK Government is due to produce an updated plan in 2017, setting out further measures for reducing emissions by 57% by the period 2028–32.

The low-carbon 'Transition Pathways' were developed by the authors and their colleagues [4,5] to examine the influence of different governance arrangements on potential pathways. They follow the main scenarios developed by the UK Government's independent *Committee on Climate Change* (CCC) and DECC, in that they also focus on low-carbon electrification as the key first step in the transformation of the UK energy system needed to meet the 80% carbon reduction target for 2050. However, unlike these scenarios, the *Transition Pathways* were developed by starting from narrative storylines around the potential

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consequences of different governance framings, drawing on interviews and workshops with stakeholders and analysis of historical analogies [6]. An iterative process of technical elaboration between social science and engineering researchers, informed by energy system modelling, was then followed to produce a quantification of the narrative for each pathway [7,8], as described in Foxon [9] and Robertson et al. [10]. This yielded a way of examining the potential influence of qualitative social and institutional and technological changes on the development of low-carbon pathways [11].

## 1.2. The transitions approach

The *Transition Pathways* analysed here drew on a Dutch transitions approach or transitions theory that has influenced their national policy on promoting energy system transitions [12–15], and stimulated historical case studies [16], including applications to the Dutch electricity system [17,18]. It has been used to examine the dynamic interaction of technological and social factors at different levels [19,20], and has generated significant international policy and research interest [4,5,9,11,21–24]. This analytical framework is typically coupled with a *multi-level perspective* (MLP) for analysing socio-technical transitions, based on co-evolution at and between three levels [21,22]: *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* (see, for example, Fig. 1 [4]). The *landscape* represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly [11]. The *socio-technical regime* reflects the prevailing set of routines or practices used by actors, which create and reinforce a particular technological system [25]. In contrast, the existing *regime* is thought of as generating incremental innovation, whilst radical innovations are generated in *niches* [11,21,22]. The latter are spaces that are at least partially insulated from normal market selection in the regime. *Niches* provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user-producer relationships. Winskel [26] observed that major system changes often arise from developments within the existing regime, rather than from radical innovations at niche-level. He believes that it would be of greater value to analyse the regime-level dynamics. The representation of MLP niche-regime interactions might then be improved by the adoption of ideas and methods stemming from other fields, such as ‘strategic management research’ [26].

The transitions theory or socio-technical approach is not without its

critics [27–33]. Although Shove and Walker [28] recognised the value of sustainable transitions management for stimulating change towards predefined beneficial goals, they argued that analyses based on the MLP typically have an over-simplified view of the social realm, being rooted in ‘innovation studies’ [26]. In a response, Rotmans and Kemp [29] noted that it is an approach that has been used in the Netherlands in particular (see also [12–15,17,18]) to aid the achievement of better futures. Transitions management helps secure incremental system improvements and innovations within the planning framework; often in the face of complexity and uncertainty. Indeed, Grubler [33] drew on ‘real world’, historical energy transitions in order to highlight the long duration of transitions (many decades) and their slow rates of change, the importance of energy end-uses as drivers of change, and the distinctive patterns needed for the scale-up of technological solutions. But even Grubler [33] provided cautionary tales. He suggested that low-carbon transitions require persistence and continuity of policies, their alignment (e.g., regarding fossil fuel subsidies), and balanced innovation portfolios (e.g., public sector R&D investment and niche market incentives). Geels and Schot [27] developed a more detailed typology of transition pathways, focused on refinements to the MLP, in response to critiques and insights in the academic literature [28–30] that were followed-up by Geels [31,32]. Although many successful transition paths reflect a sequence of events [27], they are not automatic or deterministic. Many of the pathways may not, in reality, turn out to have a pure format [27,31,32], and shifts between them can result in those exhibiting mixed characteristics.

An initial theoretical analysis of past and possible future decarbonisation pathways for the UK [34] showed the potential for the application of the transitions approach in Britain. Shackley and Green [34] identified a number of key socio-technical factors that would influence future pathways in terms of policy drivers for change. They also argued in favour of policy learning and experimentation in a similar manner to Winskel [26]. A number of studies have applied the MLP for a comparative analysis of low-carbon electricity transitions in, for example, Germany, the Netherlands and the UK [35,36]. Laes et al. [35] selected these countries as exemplars of the deployment of renewable energy technologies (RET), of a transition management framework [12–14,18], and of legislative commitment to climate change mitigation [1] respectively. They identified best governance practices, e.g., creating communities of interest, target setting to link long-term strategies with shorter-term (energy or carbon) budgets, and the adoption of policy incentives. Geels et al. [36] built on the revised typology of

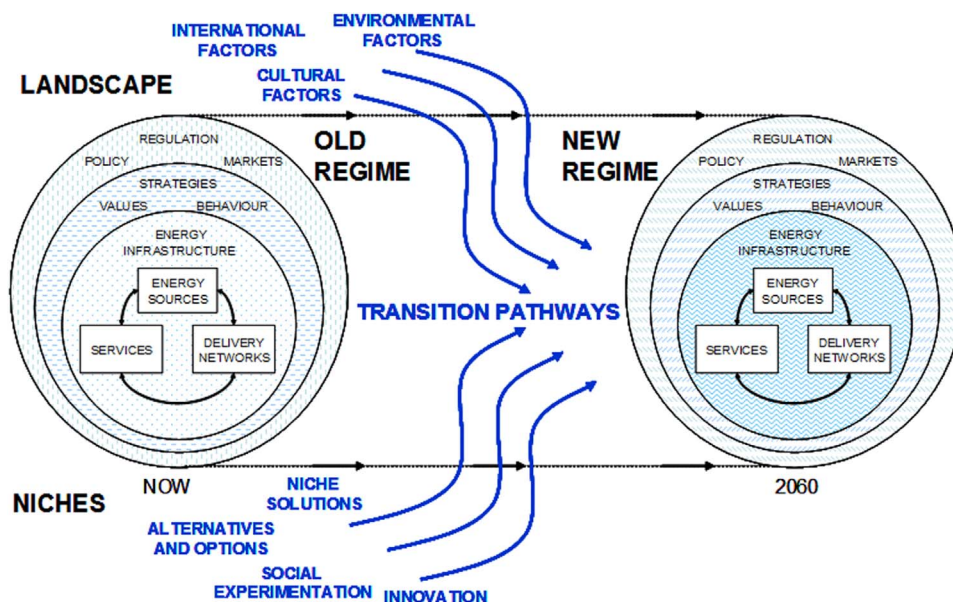


Fig. 1. Possible ‘Transition Pathways’ and the factors that influence them. (Source: The Transition Pathways Consortium [4]).

Geels and Schot [27] in their comparison of Germany and the UK electricity transitions. They observed that the dominant transition pathway in Germany was based largely on technological substitution enacted by new entrants who have led the deployment of small-scale RET [35]. In contrast, incumbent actors (such as the *Big Six* electricity utilities) led the deployment of large-scale RET in the UK. However, the British policy incentives for RET have recently been significantly weakened with a result that Geels et al. [36] believe it is unlikely that the UK will meet its current renewable electricity target of 30% by 2020 under the (pre-Brexit) *European Union* agreement. Likewise, the take-up of new nuclear power stations and *carbon capture and storage* (CCS) facilities coupled to fossil-fuelled power stations and industrial process plants have been significantly delayed in comparison with what was envisaged in the original version of the UK *Carbon Plan* [3]. The delay by the UK government in publishing its update of the *Carbon Plan* until 2017 may reflect the challenges in ensuring that the UK remains on track for further emissions reductions in the late 2020s and early 2030s.

### 1.3. The issues considered

In this paper, the features and technology implications of the set of British *Transition Pathways* for a low carbon electricity system to 2050, developed by the authors and colleagues, are compared with key scenarios produced by the UK Government for meeting its 80% GHG emissions reduction target by 2050. This aims to provide an overview of how different framings and assumptions on demand reduction and generation mix can lead to significantly diverse low-carbon futures. More detailed discussion of the framing assumptions, demand side and generation and network implications of the *Transition Pathways* can be found in the papers by the project team [5,7–9]. The present contribution focuses on assessing the technical feasibility of these pathways by examining their outcomes in terms of annual electricity demand and supply and generation capacity in 2050, and the annual build rates for different technologies needed to achieve these, in comparison with the projection in the *Carbon Plan* scenarios. This aims to inform debate on the technical feasibility, social acceptability and climate change impact of the latest version (2.1) of the pathways in relation to how decarbonisation of the UK electricity system can contribute to meeting the country's energy and carbon reduction goals. Nevertheless, it does not attempt to draw conclusions on the role or desirability of any particular technology or pathway. Lessons can be drawn for other European countries attempting to decarbonise their electricity generation systems, although local circumstances will limit the wider applicability of the present findings.

## 2. Transition Pathways for a UK low carbon electricity system

The '*Transitions Pathways*' study [5,7–9] approaches pathways from different governance logics, and technology scenarios are produced under these perspectives. An initial set of transition pathways for a UK low carbon energy system were developed by applying three main steps [4]: (1) characterising the existing energy regime, its internal tensions and landscape pressures on it; (2) identifying dynamic processes at the niche level (see again Fig. 1 [4]); and (3) specifying interactions giving rise to or strongly influencing transition pathways. They were devised

via stakeholder workshops (involving UK energy researchers, industrialists, and policy advisers and decision-makers), a narrative descriptive of each pathway [9], and their subsequent technical elaboration. Stakeholder workshops were employed by the consortium to distinguish the logics of three core sets of actors: driven by the market, central government intervention, and local community initiatives respectively. Consequently, the three transition pathways were named *Market Rules* (MR), *Central Co-ordination* (CC) and *Thousand Flowers* (TF); each being dominated by a single group's logic [4,5,9]. Foxon [9] describes these three pathways, based on different dominant governance framings:

- 1) The *Market Rules* (MR) pathway is based on a governance system similar to the present one in the UK, with a liberalised and privatised electricity and gas sector. Thus, the dominant logic is that of the market, although government objectives are achieved via high-level policy targets whilst large actors – in this case primarily large energy companies – deliver them.
- 2) The *Central Co-ordination* (CC) pathway represents a world in which the government comes to the conclusion that meeting security of supply, affordability and emissions objectives requires direct intervention. This might involve a government agency letting supply contracts for different low-carbon technology types to develop areas which are of importance to both the UK grid and in the strategic interest of the wider economy. In addition, public/private partnerships develop the technologies, which lead to significant supply-side advances in marine renewables, CCS and electric vehicles. On the demand side, incentives are provided for household energy efficiency, although electrification of heating and transport drives up electricity demand.
- 3) The *Thousand Flowers* (TF) pathway envisages a low-carbon transition led by civil society. This bottom-up approach focuses on decentralised solutions to energy problems and has at its heart a society which is aware and informed on environmental issues, and adopts a proactive approach. Energy service companies (ESCOs) also emerge, which have incentives more aligned with energy efficiency improvements that aid the transition to a low-carbon economy.

Full details of the demand and supply projections associated with version 2.1 of the pathways are presented in a '*Realising Transition Pathways*' (RTP) Consortium Working Paper [37]. Nevertheless, the extent to which the resulting emissions reductions in the electricity sector contribute to meeting the 80% GHG reduction target depends on projections of the effectiveness of the technologies used to achieve the savings, particularly when life-cycle impacts are included (see, for example, Hammond et al. [38], who appraised the earlier version 1.1 of the pathways).

## 3. Low carbon Transition Pathways – demand projections

The starting point for the quantification of version 2.1 these pathways was the projection of annual electricity demand by sector from 2010 to 2050: see Table 1. In the *Market Rules* pathway, annual electricity demand rises from 337 Tera Watt hours (TWh) in 2010 to about 512 TWh in 2050 [7,37], due to increasing use of electricity for

Table 1

Electricity used for space heating and hot water in domestic, industry and commerce sectors under the three UK *Transition Pathways*.  
Source: version 2.1 of the UK *Transition Pathways*; based on calculations by Barton et al. [7]

UK Transition Pathway	Market Rules		Central Co-ordination		Thousand flowers	
	2010	2050	2010	2050	2010	2050
Total Electricity for Heat and Hot Water (TWh)	23	108	22	94	22	18
Domestic Electricity for Heat and Hot Water (TWh)	19	73	19	60	18	13
Industrial & Commercial Electricity for Heat and Hot Water (TWh)	3	35	3	34	4	6



industry, commercial, transport and domestic space heating and hot water. This means that the electricity system needs to provide 50% more output by 2050 than it currently does, requiring significant expansion of low-carbon generation beyond just replacing existing capacity.

In contrast, annual electricity demand under the *Central Co-ordination* pathway rises from 337 TWh in 2010 to some 410 TWh in 2050 [7,37]. This pathway sees electricity demand rising and then levelling off from 2030 onwards, due to increasing use of electricity for transport and domestic space heating and hot water. However, it suggests higher rates of energy efficiency improvements in the domestic sector, and a smaller, highly-efficient industrial sector with lower levels of output. This would imply that some energy-intensive UK production has moved to other countries, increasing the national consumption of goods produced abroad, implying that UK carbon emissions calculated on a consumption basis would continue to diverge from those on a production basis (see Barrett et al. [39]).

Finally, under the *Thousand Flowers* pathway, the annual electricity demand falls from 337 TWh in 2010 to only around 310 TWh in 2050 [7,37]. Despite similar levels of electrification of transport to that in the other pathways, electricity demand falls due to even higher rates of energy efficiency improvements in the domestic and commercial sectors. A large proportion of the resulting domestic space heating and hot water demand is met by renewable (biogas) community-scale and micro-scale *combined heat and power* (CHP) systems, rather than electric heating systems, helping to reduce electricity demand. In addition, the power generated by these local-scale CHP systems replaces a significant proportion of centralised electricity supply. Again, a small, highly-efficient industrial sector with low levels of output aids the reduction in electricity demand.

It is clear that in all pathways (see again Table 1) a significant amount of energy is used in industry and commerce for space heating and water heating. The provision of this heat is mostly via the same technologies as in the domestic sector of each pathway but often on a larger scale. Thus, in the MR and CC pathways, an increasing amount of electricity is used in heat pumps in the industrial and commercial sectors. This increase in demand for electricity for heating and hot water is additional demand to that required for electrification of transport, and it leads to a significant rise in total final electricity demand in these pathways. However, under the TF pathway, the total final electricity demand remains stable up to 2050, as the increase in transport electricity consumption is offset by reductions in demand as a result of energy efficiency improvements. Thus, there is no rise in electricity demand for heating and hot water under the TF pathway, mainly due to the expansion of community-scale renewable CHP.

#### 4. Low carbon Transition Pathways – supply projections

In the ‘Transition Pathways’ study [5,37] the demand projections for version 2.1 of all three pathways are met by rising levels of low-carbon electricity generation, including different generation capacities of renewables, nuclear power and fossil fuels (e.g., coal and gas) with CCS, operating at different capacity factors. The detailed generation capacity schedule for each pathway from 2010 to 2050 is reported by Barnacle et al. [8] and Barton et al. [37]: see Figs. 2 and 3. In 2010, the UK had around 95 *Giga Watts* (GW) of electricity generation capacity, including 29 GW of coal and dual-fuel generation, 33 GW of gas-fired generation, 11 GW of nuclear power, 9 GW of renewable generation and 6 GW of combined heat and power (CHP) cogeneration [8,37].

In the *Market Rules* (MR) pathway, investment occurs in all three main types of low-carbon generation, driven by a high carbon price. Significant amounts of capacity come on stream in the 2020s (see Fig. 2), so that, by 2030, there are 21 GW of coal and gas with CCS, 15 GW of nuclear power and 47 GW of renewables (47 GW); giving a total capacity of around 130 GW by 2030 [8,37]. Subsequent deployment leads to further increases in capacity in order to meet rising

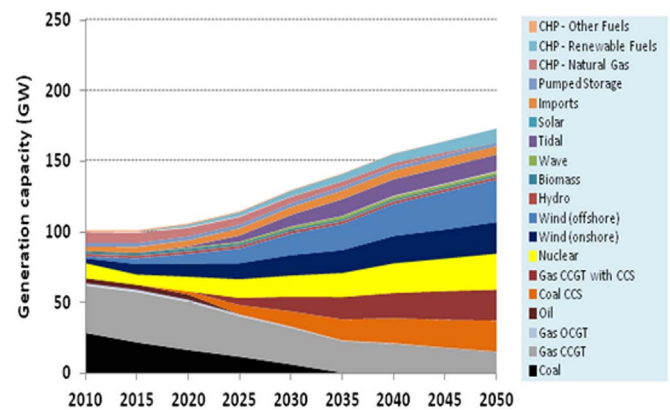


Fig. 2. Generation capacity in the *Market Rules* pathway (Source: Version 2.1; based on Barnacle et al. [8]).

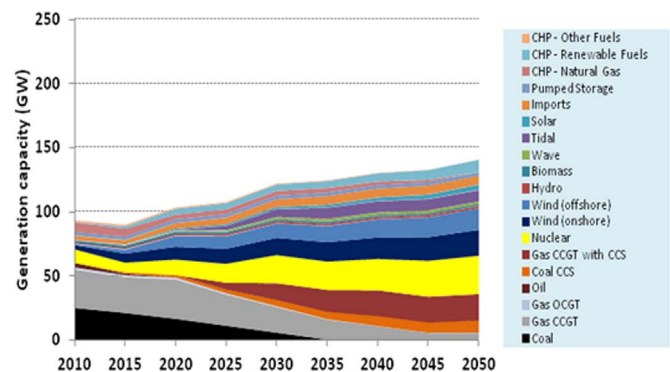


Fig. 3. Generation capacity in the *Central Co-ordination* pathway (Source: Version 2.1; based on Barnacle et al. [8]).

electricity demand, particularly from industry and electrification of heating and transport, over following decades. By 2050, this results in a total of some 168 GW of capacity, including 44 GW of coal and gas generation with CCS, 26 GW of nuclear power, and 80 GW of renewable capacity, principally from onshore (23 GW) and offshore (30 GW) wind turbines, tidal power (12 GW) and renewable CHP (9 GW). This provides a total supply for the MR pathway of about 539 TWh in 2050 [8,37].

There are similar investments during the 2020s in all types of low-carbon generation capacity under the *Central Co-ordination* (CC) pathway (see Fig. 3); co-ordinated by what might perhaps be a *Strategic Energy Agency*. This leads to a total of some 122 GW in 2030, though with high levels of nuclear power (22 GW), and slightly lower levels of coal and gas-fired power generation with CCS (18 GW) and renewables (43 GW) [8,37]. Despite the subsequent levelling off of demand under this pathway, further deployment is needed to increase the capacity to a total of around 151 GW by 2050, of which the largest single contribution comes from nuclear power (30 GW). There are similar investments (30 GW) in coal and gas-fired generation with CCS, but this operates at a lower capacity factor (36%), as it partly provides back-up to intermittent renewables. There is a total of 65 GW of renewable generation, of which the largest contributions are from onshore (21 GW) and offshore (17 GW) wind. This provides a total supply of about 427 TWh in 2050 [8,37]. Finally, in the *Thousand Flowers* (TF) pathway, action by community groups and local and regional ESCOs leads to a significant expansion of community-based and micro-scale renewable CHP installed from 2020 onwards, reaching a total of 37 GW by 2030 (see Fig. 4). The total capacity under the TF pathway reaches around 149 GW by 2050 [8,37]. This is similar to that of CC pathway, but most of the capacity is made up of renewable generation (112 GW). As noted above, a significant proportion of demand under the TF pathway is met

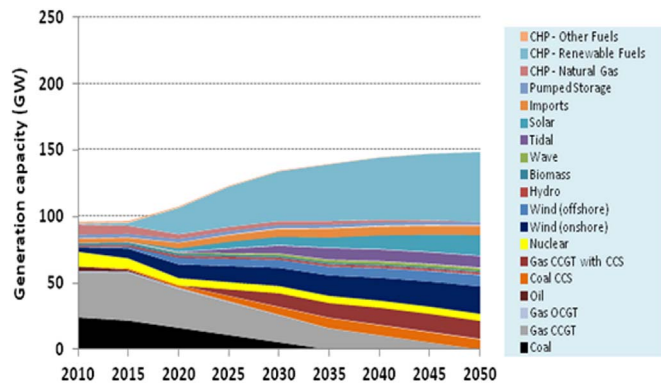


Fig. 4. Generation capacity in the *Thousand Flowers* pathway (Source: Version 2.1; based on Barnacle et al. [8]).

by local-scale renewables, reducing the need for centralised electricity supply. The largest single contribution to generation comes from renewable (biogas) community-scale and micro-CHP systems (44 GW), followed by onshore wind turbines (21 GW), solar photovoltaic (PV) arrays (16 GW), and offshore wind ‘farms’ (8 GW). There is some investment in other low-carbon generation technologies in earlier periods, resulting in 22 GW of coal and gas-fired power plant with CCS and 5 GW of nuclear capacity by 2050. This provides a total supply of some 313 TWh in 2050 [8,37].

## 5. UK Carbon Plan pathways

### 5.1. Background

The *Carbon Plan* [3] sets out the range of measures and incentives that the UK Government intends to put in place in order to ensure that the country is on track to meet the target of reducing its GHG emissions by 80% by 2050, as required by the *Climate Change Act* [1]. It also seeks to address the so-called energy policy ‘trilemma’: “to make the transition to a low carbon economy, whilst maintaining energy security and minimising costs to consumers, particularly those in poorer households” [3]. Thus, the main focus of the *Carbon Plan* [3] is the additional measures needed to meet the *Fourth Carbon Budget* [40], covering 2023–27, which was set into law 12 years in advance. It requires UK GHG emissions to be reduced by 50% below 1990 levels by 2023–27. The main measures that initially aimed to achieve this included the so-called ‘*Green Deal*’ [41], a scheme for households to finance energy efficiency improvements at no upfront cost which began operating in January 2013 (but which was subsequently stopped by the UK Government in October 2015, because the take-up was claimed to have been too low), and the *Electricity Market Reform* (EMR) programme [40] for stimulating investment in low carbon electricity generation. The latter was embodied in the *Energy Act 2013* [42], and negotiations with the French energy company EDF have provided a guaranteed ‘strike price’ for two initial new nuclear power stations, under the new ‘Contract for Difference (CfD) Feed-in Tariffs’; a key part of the reforms. Thus, the main challenge for the UK government will be to balance these incentives for investment in low-carbon generation (including renewables, nuclear and CCS demonstrators) with ensuring energy security and maintaining affordability of energy to consumers. This faces a number of uncertainties, such as future levels of energy service demand - which depend on up-take of energy efficiency measures and end-use technologies and levels of economic activity - and the technical and economic feasibility and acceptability of a range of low-carbon energy options, particularly for electricity generation. The *Carbon Plan* [3] therefore explored four 2050 futures, which are potential scenarios that could meet the 80% GHG reduction target by 2050. The first is based on a ‘core’ simulation run of the UK MARKAL cost-optimising

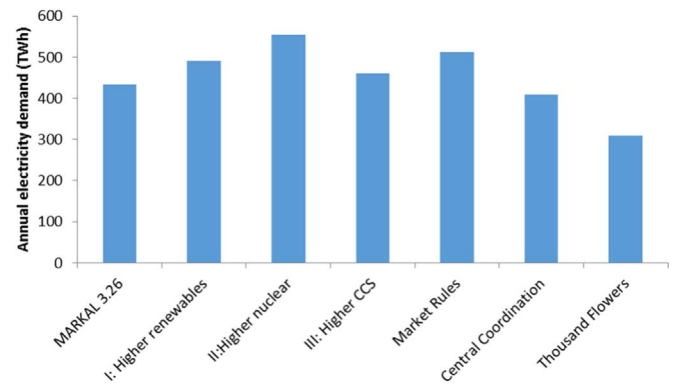


Fig. 5. Electricity demand (TWh) in 2050 under the DECC energy scenarios (left) and the three UK *Transition Pathways* (right).

energy system model, and the three other scenarios were developed using the *DECC 2050 Calculator* tool [43]: (i) ‘*Higher renewables, more energy efficiency*’, (ii) ‘*Higher nuclear, less energy efficiency*’, and (iii) ‘*Higher CCS, more bioenergy*’ futures respectively.

### 5.2. Key features of the DECC energy scenarios

In the core UK MARKAL (updated UK MARKAL 3.26) scenario, the cost-optimised parameterisation indicates a sharp reduction in overall *per capita* energy demand, thanks to end-use energy efficiency improvements and switch to more efficient electric heating and vehicles. However, as a result, electricity demand rises by 46% to 433 TWh by 2050 (see Fig. 5), and almost all of this needs to be met by low carbon generation sources. Under this core UK MARKAL scenario, by 2050, capacity rises to a total of 112 GW, including 31 GW of nuclear, 25 GW of coal, biomass and gas generation with carbon sequestration, and 49 GW of renewable generation, with 7.5 GW of standby/peaking gas capacity (see Fig. 6). This provides a total of 560 TWh of supply, of which 89 TWh is exported. This is driven by the expansion of the use of low carbon electricity in transport for electric vehicles and in heating via air- and ground-source heat pumps, as well as for domestic and industrial power and lighting services. This core UK MARKAL scenario implies an overall increase in the average capacity factor of electricity generation from 43% in 2010 to 58% in 2050; thanks partly to a projected capacity factor of 80% for new nuclear power stations. It reflects a rapid expansion of onshore and offshore wind to 2030 to replace declining coal capacity, though there remains significant *combined cycle gas turbine* (CCGT) capacity out to 2030. Nuclear power capacity expands rapidly after 2030 to become three times as large as current nuclear capacity by 2050. There is a slower expansion of solid

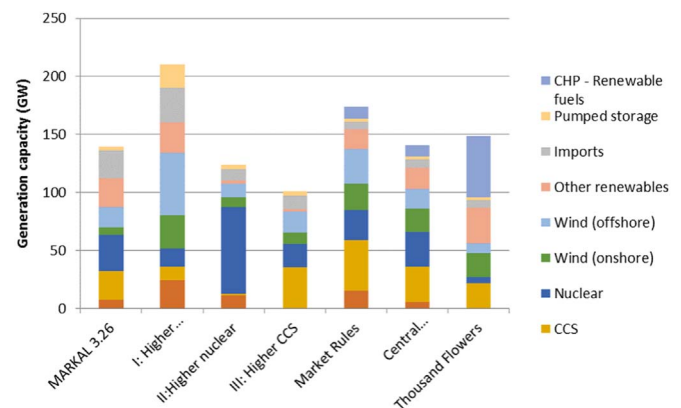


Fig. 6. Generation capacity (GW) for the DECC scenarios and the three UK *Transition Pathways* in 2050, including peaking gas, interconnection and pumped storage in the DECC scenarios.

**Table 2**

Approximate number of plants required to meet installed capacity in core UK MARKAL scenario.

Source: RTP Working Paper 2013/5 (Barton et al. [10]); HC - hydrocarbon

	2010	2020	2030	2040	2050	Description
<b>Coal</b>	14	8	1	0	0	2 GW plant
<b>Biomass</b>	12	12	12	12	0	50 MW Plant
<b>Gas CCGT</b>	26	24	24	8	0	1 GW plant
<b>Solid HC CCS</b>	0	0	1	4	8	1.2 GW locations
<b>Pre Comb</b>						
<b>Solid HC CCS</b>	0	1	3	5	6	1.2 GW locations
<b>Post Comb</b>						
<b>Gas CCGT with CCS</b>	0	0	2	4	7	1.2 GW locations
<b>Nuclear</b>	6	4	8	14	20	1.5 GW plant
<b>Wind (onshore)</b>	1623	4363	4723	3183	2413	2.5 MW Turbines
<b>Wind (offshore)</b>	232	1592	3154	3345	3103	5.8 MW Turbines
<b>Hydro</b>	16	17	18	18	19	100 MW Sites
<b>Wave</b>	0	54	268	2410	6427	1.5 MW Machines
<b>Tidal Stream</b>	1	17	152	1037	2854	Approximate number of 1.2 MW 'Seagen' devices
<b>Tidal Range</b>	0	2	10	31	31	Approximate number of 240 MW tidal range sites
<b>Standby/Peak Gas</b>	0	0	3	7	4	2 GW Plant

hydrocarbons (solid HC; roughly equal coal and biomass) with pre- and post-combustion coal CCS, and CCGT (roughly equal quantities of natural gas and biogas) with CCS after 2030. There are significant contributions after 2030 from offshore renewables, including tidal range, tidal stream and wave power, and a maintained capacity of offshore wind, though the amount of onshore wind reduces (see Table 2).

The three other variants of the DECC scenarios were developed using the *DECC 2050 Calculator* tool [43]: (i) 'Higher renewables, more energy efficiency', (ii) 'Higher nuclear, less energy efficiency', and (iii) 'Higher CCS, more bioenergy' futures respectively. Under scenario (i) there are significant improvements in energy efficiency in homes and industry. However, there is also a high degree of electrification in transportation, space heating and hot water, and industry. This leads to a 45 per cent increase in electricity-demand from 2010 to a value of 490 TWh in 2050 [37,43]; see again Fig. 5. To meet this growth, generating capacity including balancing generation increases by 161% over the same period to reach 210 GW (see Fig. 6). This is the highest electricity generation capacity of all the scenarios with renewables dominating the system and accounting for 52% of capacity including backup in 2050. Of the renewables in this scenario, most of the capacity is in onshore and offshore wind; 28.4 and 54 GW by 2050. They have comparatively low load factors (30% for onshore wind and 45% for offshore wind) and therefore require increased capacity to meet the demand. In addition, this 'Higher renewables, more energy efficiency' scenario requires a significant proportion of the capacity to be accounted for by generation capacity having a grid balancing function: 24.4 GW of gas, 20 GW of storage, and 30 GW of interconnection (see again Fig. 6).

The 'Higher nuclear, less energy efficiency' future (ii) sees a very limited effort to reduce energy demand across the economy through behaviour change or energy efficiency measures. Large-scale electrification of transport and heating drives increases in electricity demand, which increases by 60%. Of the four DECC scenarios, the electricity demand in 2050 is the highest a 555 TWh [37,43]; see Fig. 5. However, electricity generation capacity growth grows by only 51% to reach 123 GW, which is less than the increase in demand because of the high penetration of nuclear generation in 2050 with a high capacity factor of 80%. This deployment of nuclear increases the average capacity factor of generation on the grid. Due to the long 'lead times' for

nuclear, significant new rollout does not begin until around 2025. 3.2 GW of new plant is added to the system by 2020, although some 6.4 GW of legacy plant is closed in the previous 10 years. Consequently there is a minimum penetration of nuclear power at this time. New nuclear build rates are ramped so that beyond 2025 to almost 2.5 GW of new plant is built per year. 75 GW of nuclear plant are installed by 2050 (see again Fig. 6), by which time the electricity generation system is dominated by nuclear power; accounting for 61% of capacity [37,43]. There is also a small, but significant, role played by storage, interconnection and gas power in 2050: 11.3 GW of back-up gas capacity, 4 GW of storage, and 10 GW of interconnection.

Finally, the 'Higher CCS, more bioenergy' scenario (iii) results in a medium requirement for investment in energy efficiency measures. Likewise, there is only limited electrification of transportation leading to minimal growth in annual electricity demand to 461 TWh in 2050 [37,43] (see Fig. 5); an increase of 34% on 2010 levels. The generation capacity added by 2030 is primarily from the renewables, which offsets the decline of coal, as natural gas stays roughly flat. Over the same period, new nuclear build compensates for legacy plant closures. From 2030 onwards, when a large deployment of CCS is assumed to commence, with new build rate increases to around 1.5 GW per year [37,43]. Over the same time, natural gas declines rapidly to zero in 2045 being replaced by biogas, while nuclear power begins to accumulate on the system and the proportion of capacity accounted for by nuclear plant increases. Between 2045 and 2050 the expansion of CCS drives generation capacity up to its highest level over the modelled period [37,43]. Biomass co-firing with coal CCS and biogas CCS implies the potential for *net negative* carbon dioxide (CO<sub>2</sub>) emissions. The high capacity factor of CCS (~85%) means that generation capacity of this type can have a large impact on generation. While electricity generation matches electricity demand (plus losses) for most of the modelled period, the large increases in capacity from 2045 to 2050 result in excess electricity production and net exports of 14.7 TWh [37,43].

## 6. Comparison between the Transition Pathways and the DECC scenarios

The UK demand for electricity in 2050 under all seven scenarios considered here are compared in Fig. 5. The *Thousand Flowers* pathway is the only one in which electricity demand decreases from 2010 to 2050. The one in which demand is the largest is the second of the DECC scenarios (II: 'Higher nuclear'; Fig. 5), which focuses on nuclear power and does not prioritise energy efficiency. The comparison between these pathways and scenarios suggests that, in the absence of a motivated civil society which takes responsibility for climate change mitigation, electricity demand reductions are unlikely to be secured. This applies even with very high levels of energy efficiency, as seen in the first DECC alternative scenarios (I: 'Higher renewables'; see again Fig. 5) – a higher renewables, higher energy efficiency future. However, this latter scenario is not inconsistent with 80 per cent GHG emissions reductions by 2050.

Assumed capacity factors for each of the generation pathways/scenarios are important because they affect the amount (GW) of capacity that is necessary for the operation of the UK electricity grid, and influence the amount of demand-side management and the back-up requirements for the grid. A comparison of the maximum capacity factors for the DECC scenarios and *Transition Pathways* are shown in Table 3. The resulting generation capacity for the different pathways/scenarios, including back-up gas capacity, storage and interconnection in the case of the DECC scenarios, are shown in Fig. 6. Although all except the *Thousand Flowers* pathway rely heavily on CCS, nuclear and wind, there is seen to be quite a diverse variation in generation mixes. Renewable power plants have lower capacity factors, and those mixes with a large amount of this type of generation therefore tend to require a higher generating capacity. All of the pathways/scenarios, except the higher CCS scenario, show a large increase in generation capacity by 2050 over



**Table 3**

Maximum UK power generator capacity factors in 2050 under the different models/scenarios/pathways. Sources: <sup>1</sup>DECC 2050 Pathways [16]; <sup>2</sup>RTP Working Paper 2013/5 (Barton et al. [10]).

	DECC scenarios <sup>1</sup>	Transition Pathways <sup>2</sup>
Coal	60%	48%
Gas	70%	56%
Oil	6%	13%
CCS	85%	90%
Nuclear	80%	61%
Onshore wind	30%	29%
Offshore wind	45%	43%
Hydro	38%	37%
Biomass	90%	61%
Wave	23%	28%
Tidal range	20–24%	24%
Tidal stream	40%	24%
Solar	10%	11%

NB: (1) The *capacity factor* of an electricity generating plant is ratio of the average power generated divided by the rated peak power (or full ‘nameplate’ capacity over the same period of time).

(2) The *Transition Pathways* capacity factors are the maximum values across the three pathways.

the present level of around 90 GW.

Back-up generation makes no contribution to annual electricity generation figures according to the modelling undertaken using the DECC 2050 Calculator [43]. Consequently, the capacity factors for gas in the DECC scenarios and the *Transition Pathways*, based on the calculated generation data, reduce to close to zero by 2050. When the need for back-up generation is included in capacity factor calculations, the capacity factors for gas power stations in the DECC scenarios move closer to those in the *Transition Pathways* estimates, but there are still considerable differences between the pathways/scenarios. However, the gas generation capacities in the models are broadly similar, at least until 2030 (see Table 4).

Annual UK electricity generated in 2010 and 2050 according to the DECC scenarios and *Transition Pathways* are shown for comparison purposes in Fig. 7. This suggests that the total electricity generation in 2050 for the *Market Rules* pathway is similar to that for the MARKAL scenario, though with a higher proportion of renewables. The total generation is lower under the *Central Co-ordination* pathway, and significantly lower in the *Thousand Flowers* pathway: falling below the output in 2010, despite the expansion of electric vehicles in this pathway.

## 7. Technology implications

### 7.1. The context

Many challenges facing the British energy sector [5] will require a portfolio of energy options to surmount them: energy demand reduction and efficiency improvements, fossil fuel power plants with CCS, and a switch to low or zero carbon energy sources [such as CHP, nuclear power stations, and renewable energy technologies on a large and small

**Table 4**

Gas capacity (GW) in 2030 and 2050 for different pathways/scenarios. Source: <sup>1</sup>DECC 2050 Pathways [16]; <sup>2</sup>RTP Working Paper 2013/5 (Barton et al. [10])

Pathways/Scenarios	2030	2050
DECC I – Renewables <sup>1</sup>	25.5	24.0
DECC II – Nuclear <sup>1</sup>	30.5	11.0
DECC III – CCS <sup>1</sup>	21.9	0.0
Market Rules <sup>2</sup>	26.7	0.0
Central Co-ordination <sup>2</sup>	20.7	5.4
Thousand Flowers <sup>2</sup>	20.7	15.0

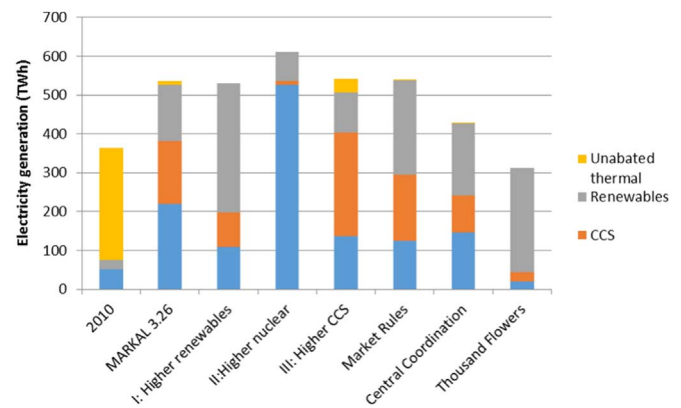


Fig. 7. Annual UK electricity generation (TWh) in 2010 and 2050 under the DECC scenarios and the three UK *Transition Pathways*.

scale]. The above comparisons show that all the pathways/scenarios imply high levels of deployment of some or all of the low-carbon generation technologies, as well as significant differences in the take-up of energy efficiency improvements. Such improvements result from using less energy for the same level of output or service, where the output can be measured in terms of either physical or economic units (i.e., tonnes or pounds sterling). But consumers can also be encouraged to reduce their energy use by changing their service demands. One obvious way of doing that is via the adoption of a lower comfort temperature in the home or at the workplace, thereby requiring less energy to deliver it. Human behavioural changes of this type can be aided by the introduction of regulatory interventions (e.g., on boilers), fiscal measures, or by devices such as ‘smart’ meters or appliances.

In general, the build-up of energy efficiency improvement measures can be deployed at a much faster rate than supply technologies. They have been incorporated into the demand-side modelling associated with the development of the *Transition Pathways* [37]. Thus, the present section considers the implied deployment rates (or ‘build rates’) for some of the key low-carbon power technologies under the different pathways/scenarios. This is done by reference to the deployment trajectory levels within the *DECC 2050 Calculator* [43], which range from Level 1 (little or no effort being made) to Level 4 (extremely ambitious targets) that push towards the technical or physical limits of what can be achieved.

### 7.2. Key low carbon power technologies

#### 7.2.1. Nuclear power

The core MARKAL and ‘higher nuclear, less energy efficiency’ scenarios, as well as the MR and CC pathways, all imply a significant expansion of British nuclear capacity from the current value of 11 GW from around 2030 onwards. The ‘higher renewables, more energy efficiency’ and ‘higher CCS, more bioenergy’ scenarios show a smaller increase in nuclear capacity. Only in the TF pathway, does nuclear play no significant role (in line with DECC 2050 Calculator [43] baseline trajectory, i.e., Level 1). Rising nuclear generation capacity reflects the UK Government’s belief that nuclear power has a role to play in the future UK energy mix, alongside other low carbon technologies. They seek to encourage energy utility companies to invest in new nuclear build [44]. In order to meet the deployment levels seen in the pathways/scenarios there would need to be clear support by both the public and government, with regulatory certainty regarding the acceptability of reactor design and market certainty; thereby giving operators’ confidence that they will see a return over the lifetime of the project [43]. The consequent installed capacity and annual build rates for all the pathways/scenarios are illustrated in Figs. 6 and 8 respectively [37]. The DECC (ii) scenario (‘Higher nuclear, less energy efficiency’) suggest the highest build rates of any of the pathways/scenarios considered



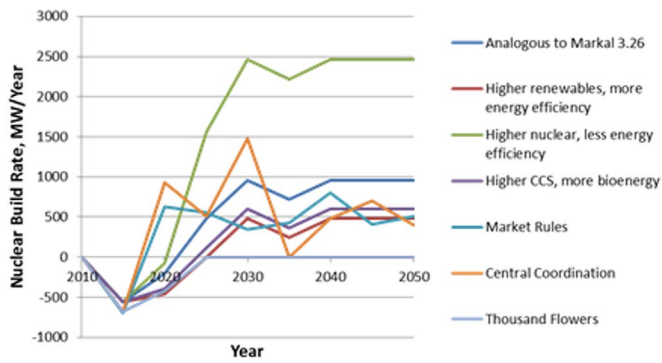


Fig. 8. Annual build rates (MW/year) for nuclear power to 2050 in the UK MARKAL projections, the DECC scenarios and the three *Transition Pathways* (net of closures to 2030).

here (see Fig. 8). However, the high capital costs of new nuclear power stations (particularly when taking into account so-called ‘back end’ costs [45], such as for decommissioning and waste disposal), as well as continuing public concern over safety, waste management and nuclear proliferation, remain significant barriers to a large scale-up of nuclear power in the UK. The construction of the first new nuclear power in the UK for over 20 years began in 2016, following the signing of contracts between the UK Government, EDF and China General Nuclear (CGN) for the ‘Hinkley Point C’ (HPC) nuclear power station, which is predicted to take 10 years to build.

#### 7.2.2. Carbon capture and storage

CCS plays a significant role in most of the pathways/scenarios, and accounts for a similar percentage of the total generation in all the scenarios, except the *Thousand Flowers* pathway and the DECC ‘*Higher nuclear*’ scenario. Installed capacities and annual build rates for CCS plants across all the pathways/scenarios are illustrated in Figs. 6 and 9 respectively [37]. Annual build rates are marginally higher under the three *Transition Pathways* than the DECC scenarios (see Fig. 9), but not unrealistically so. However, there is an energy penalty associated with CO<sub>2</sub> capture that reduces the overall efficiency of the power plant. In the *DECC 2050 Calculator* [43], this is assumed to range initially from 13% to 27%, depending on the type of power plant, gas, pre-combustion solid or post-combustion solid. This energy penalty is assumed to reduce, as the efficiency of the capture process improves, to 12–16% from 2020 [46,47]. In addition, attention must be given to the reduction of carbon emissions by installing CCS technology. The *DECC 2050 Calculator* [43] assumes that 90% of CO<sub>2</sub> emissions are captured, but research by the *Transition Pathways* team shows that, when life-cycle effects are taken into account, this can reduce to a 70% capture rate over the life-cycle [38,48]. The UK Government is currently working with industry to support the development of a cost-competitive CCS

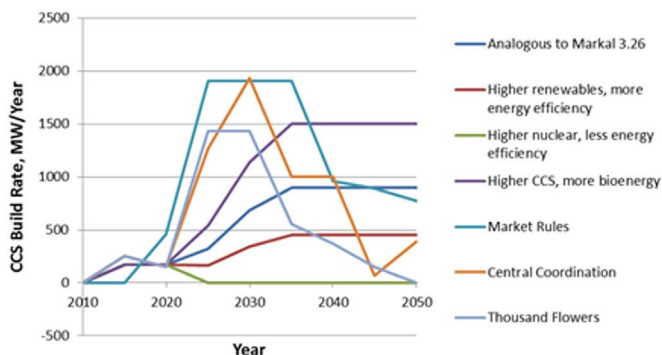


Fig. 9. Annual build rates (MW/year) for fossil-fuelled [coal and gas] power plants with carbon capture and storage (CCS) to 2050 in the UK MARKAL projections, the DECC scenarios and the three *Transition Pathways*.

industry in the 2020s, through a £1 billion commercialisation competition [47], support for R & D and innovation, and the EMR programme, though only a small number of small-scale CO<sub>2</sub> capture demonstrations have so far been implemented [3]. However, the £1 billion support for a CCS demonstration project was withdrawn by the UK Government in 2015, creating uncertainty over the future of this technology in the UK.

#### 7.2.3. Onshore wind turbines

In the core MARKAL scenario, 0.7 GW of onshore wind are added annually from 2010 to 2025, with 0.3 GW added annually thereafter [43]. However, as turbines are only projected to have lifetimes of 20 years, this is below the replacement rate, and so the installed capacity peaks at 13 GW in 2025, reducing to 6 GW by 2050. This corresponds to a maximum of over 4700 turbines of size 2.5 MW, reducing to around 2400 turbines by 2050. A similar final level of deployment of 21–23 GW by 2050 is seen in all three *Transition Pathways*, although the deployment is more uniformly timed, with only 14–15 GW of installed capacity by 2030. It is assumed that onshore wind will be present in the form of both large-scale wind farms and smaller-scale community wind projects [22]. The key support mechanisms for reaching the high deployment levels was the *Renewables Obligation* until 2017, and then the CfD Feed-in Tariffs, which was implemented from 2014 [40]. However, obtaining local planning permission remains a difficult issue, because of local resistance to wind turbine in the rural landscape, mainly due to aesthetic concerns.

#### 7.2.4. Offshore wind turbines

In the core MARKAL scenario, rates of installation of offshore wind farms increases from 0.7 GW per year to 1.2 GW per year by 2025, thereafter levelling off at 0.9 GW added per year (equalling the replacement rate). Installed capacities and annual build rates for offshore wind across all the pathways/scenarios are illustrated in Figs. 6 and 10 respectively [37]. This implies that offshore wind capacity increases to 18 GW by 2030, before remaining approximately constant to 2050. That corresponds to a maximum of over 3100 turbines of a typical size of 5.8 MW (see Table 2 for details of the approximate number of plants required to meet installed capacity core UK MARKAL scenario). In contrast, the MR pathway leads to 30 GW of installed capacity by 2050 (see Fig. 6), though with a more even ramp-up, reaching 15 GW by 2030. Lower rates of installation are seen in the other two pathways [37], only reaching 17 GW of offshore wind by 2050 in the CC pathway and 8 GW of offshore wind by 2050 in the TF pathway. In order to reach the high level deployment of offshore wind farms, the UK Government is supporting technology innovation and demonstration, supply chain development, access to finance through the *Green Investment Bank* [3,44], planning and consenting, grid connection, and incentives for investment under the *Renewables Obligation* until 2017 and CfD feed-in tariffs under EMR programme implemented after 2014 [3,40].

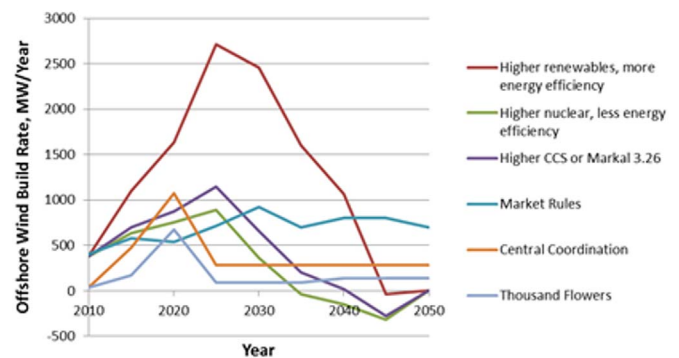


Fig. 10. Annual build rates (MW/year) for offshore wind to 2050 in the UK MARKAL, the DECC scenarios and the three *Transition Pathways*.

### 7.3. Other low carbon power options

#### 7.3.1. Tidal power

Tidal range has the potential to meet 13% of our electricity demand if fully exploited [3,42] and is present in all but the DECC nuclear and CCS pathways. The highest deployment is seen in the core MARKAL and *Market Rules* pathways with around 7.5 GW of tidal range and 5.7 GW of tidal stream installed capacity in 2050. The tidal range capacity equates around 31 sites comparable to the 240 MW *la Rance* site in Brittany (France), the only significant tidal range site presently in operation [42]. The use of technology that utilises the tidal range is well-established and typically has an estimated lifetime of 120 years [49]. The capital costs would be recouped, but only with very long pay-back periods [49]. The Severn Estuary is seen as one of the premium locations in the world for its tidal range but, due to these cost considerations, as well as the local environmental impacts, the UK Government decided that a proposed 8.64 GW Severn tidal power barrage was not required to meet 2020 renewable energy targets [49]. They argued that it should not be supported by public funds at the present time, although the project may still be considered in the future [3]. However, plans for a 320 MW tidal lagoon ‘pathfinder’ power plant in Swansea Bay, which aims to begin construction in 2018, have been supported by a government-commissioned review [49].

#### 7.3.2. Wave power and tidal stream devices

These are emerging technologies with the UK at the forefront of R & D through the National Renewable Energy Centre, the European Marine Energy Centre and the WaveHub demonstration facility [3]. In order to achieve commercial deployment of wave and tidal stream devices, pre-commercial demonstration sites have been recently deployed, with subsequent commercial deployment [42]. The core MARKAL pathway implies the highest deployment with 9.6 GW of wave power from over 6,400 devices and 5.7 GW of tidal stream energy from 2,850 turbines by 2050 (see again Table 2). Consequently, the UK government’s priority actions for all marine energy systems are managing the risk and costs of RD & D, securing investment for commercial deployment, developing supply chain infrastructure, and ensuring planning and consenting.

#### 7.3.3. Bioenergy

In each of the DECC scenarios, the biomass power station level is fixed at 0.6 GW capacity in the form of co-fired power stations up to 2030; followed by dedicated biomass combustion. Biomass is also coupled with CHP, but without clearly defined inputs or capacities. In the *Transition Pathways*, biomass is largely used in community CHP plant, with around 10 GW of biogas CHP co-generation by 2050 in the MR and CC pathways, compared to over 52 GW of biogas CHP in the TF pathway [37]. This represents the most significant difference between any of the pathways/scenarios. The biogas CHP (community scale and micro-CHP) would meet around 63% of home and commercial heating demand under the TF pathway, providing 112 TWh of distributed electricity generation. Assuming a low electrical capacity factor of 30% for home and commercial CHP, together with industrial renewable CHP, this corresponds to 52 GW of installed CHP capacity by 2050 (see again Fig. 6 – ‘renewable CHP’). The biomass availability in order to meet this capacity is regarded as being constrained within the UK [50]. Until recently, there has been little policy support available for CHP in the UK, but the *Renewable Heat Incentive*, which has been in place for non-domestic properties from 2011 and for domestic properties from 2014, includes support for renewable micro-CHP. The UK Government is also supporting work in a number of large UK cities to determine the potential for community-scale heat networks.

### 8. Projections of ‘greenhouse gas’ emissions under the Transition Pathways

The UK MARKAL and DECC scenarios [43] seek to achieve an 80% reduction in GHG emissions for the whole UK economy by 2050 (against a 1990 baseline). For this to occur, the remaining CO<sub>2</sub> emissions from fuel combustion need to be almost completely cancelled out by the capture and storage of GHG emissions, and by presumed ‘negative emissions’ associated with the use of bioenergy with CCS. However, it is difficult to make a direct comparison with the *Transition Pathways* as the latter only cover the electricity sector. All three pathways have been evaluated in terms of their life-cycle energy and environmental performance within a wider sustainability framework [38,48]. An integrated approach was used to assess the impact of these pathways, employing both energy analysis and environmental life-cycle assessment (LCA), applied on a whole systems basis: from ‘cradle-to-gate’. Thus this analysis accounted for both upstream and operational activities right through to the point of delivery to the consumer, as described in Hammond et al. [38]. Upstream environmental burdens arise from the need to expend energy resources in order to extract and deliver fuel to a power station or other users. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakages from coal mining activities – a major contribution – and natural gas pipelines. GHG emissions, measured as *carbon dioxide equivalent* (CO<sub>2e</sub>) emissions, are one of 18 environmental impacts examined as part of this LCA study. The various life-cycle stages and processes within the system boundaries of the present study are illustrated in Fig. 11. The LCA software package was used to evaluate the environmental impacts of the *Transition Pathways* [48,51]. Projected ‘whole systems’ GHG emissions for the UK electricity supply industry (ESI) – both upstream and operational (or ‘stack’) emissions – can be seen here in Fig. 12. (Additionally, ‘whole systems’ GHG emissions per *kilo Watt hour* (kWh) [gCO<sub>2e</sub>/kWh<sub>e</sub>] of electricity produced were obtained [10]). Similar trends were seen by Hammond et al. [38] relating to version 1.1 of the pathways, although with less decarbonisation achieved by 2050. The present results relate to most recent version 2.1 of the pathways.

The 80% GHG emissions reduction target for the UK by 2050 only relates to territorial emissions [39]. These emissions are the result of direct operational activities only, i.e., those resulting from the fuel burnt at the site of the power generator. Consequently, the associated upstream activities are excluded, making direct emissions the primary focus. Direct GHG emissions projected for the UK ESI is shown in Fig. 13 (while the direct GHG emissions projected per kWh of electricity are reported by Barton et al. [37]). Clearly, by comparing Figs. 12 and 13, it can easily be observed that upstream emissions have a significant impact on the environmental performance of the electricity grid mix in all three pathways. About a third more emissions were actually emitted in 2008, and over three times the emissions for thousand flowers pathway in 2050. According to this analysis, the UK ESI was estimated to emit 230 million tonnes of GHG emissions in 2008 on a whole systems basis. The corresponding grid mix had a carbon intensity of 656 gCO<sub>2e</sub>/kWh<sub>e</sub> [37], although again this was much lower on an operational basis only.

The UK Government’s independent *Committee on Climate Change* (CCC) has advocated deep cuts in power sector operational emissions through the 2020s [40], with UK electricity generation largely decarbonised by 2030–2040. In contrast, the present *Transition Pathways* (see again Figs. 12 and 13) projections indicate that the UK ESI could not be fully decarbonised by 2050 on the ‘whole systems’ basis employed in the present analysis [48]. The disparity between the direct and whole systems emissions is largely due to the fact that both the CCC and DECC don’t currently take account of upstream emissions. However, even considering just direct GHG emissions, only the *Thousand Flowers* pathway is likely to achieve near complete decarbonisation of the electricity sector by 2050 (see Fig. 13). The pathways thus illustrate the stringent challenge facing the ESI in order to bear its fair (global)

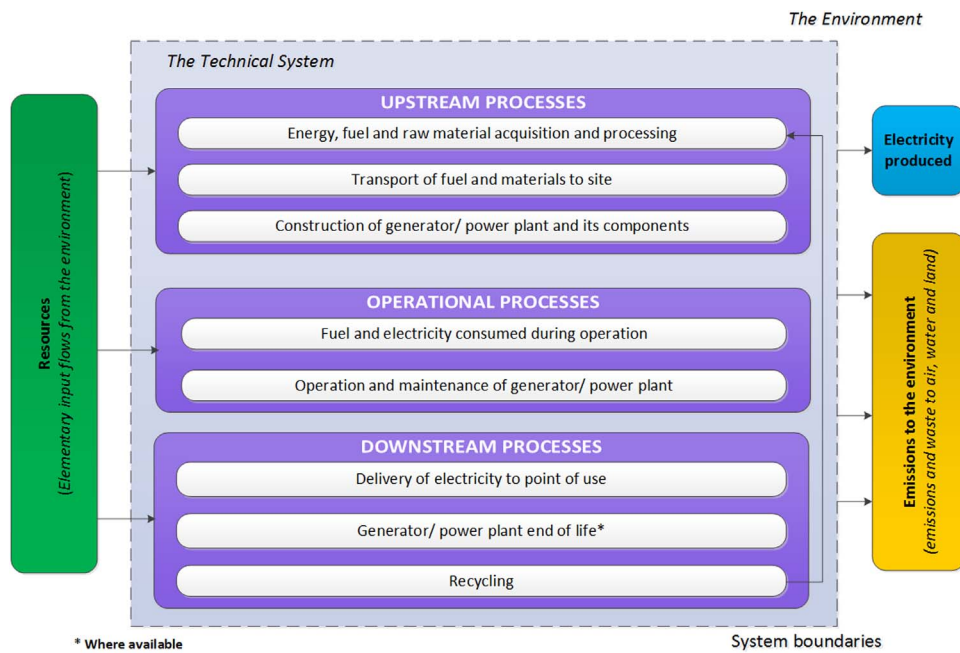


Fig. 11. System boundary diagram of the life-cycle 'cradle-to-gate' carbon emissions assessment of the UK Transition Pathways (Source: Adapted from Hammond et al. [51]).

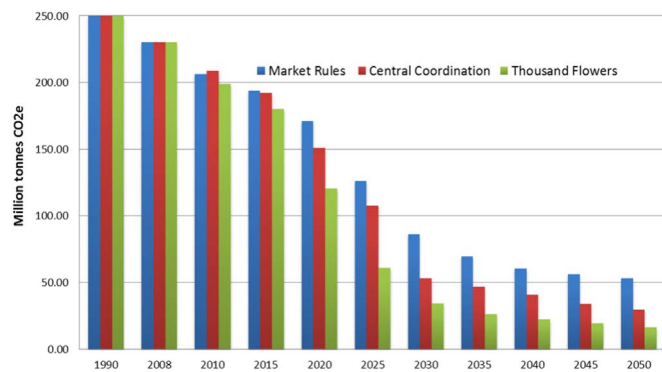


Fig. 12. Projected UK 'Whole Systems' [operational ('stack') plus upstream] GHG Emissions for the Electricity Sector (MtCO<sub>2e</sub>) 1990–2050 under the three Transition Pathways (Source: Version 2.1; calculations by Hammond and O'Grady [48]).

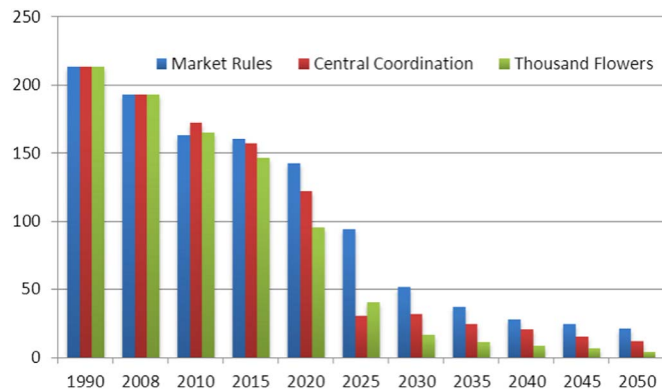


Fig. 13. Projected UK Direct GHG Emissions for the Electricity Sector (MtCO<sub>2e</sub>) 1990–2050 under the three Transition Pathways.

share of the overall 80% carbon reduction target by 2050. The CCC analysis suggests that an optimal scenario to reach this target would require average operational emissions from generation to fall to around 50gCO<sub>2e</sub>/kWh<sub>e</sub> by 2030 (CCC, 2010). Of the three Transition Pathways, only the TF pathway is projected to reach this target, with GHG emissions falling to 49 gCO<sub>2e</sub>/kWh<sub>e</sub> by 2030. In contrast, the MR and CC

pathways indicate, accounting for direct emissions only, falling to around 109 gCO<sub>2e</sub>/kWh<sub>e</sub> and 74 gCO<sub>2e</sub>/kWh<sub>e</sub> respectively by 2030 [37].

## 9. Concluding remarks

This paper has provided support for the technical feasibility of the Transition Pathways, developed by the authors and colleagues [5,9,11], by showing that the required technological build rates to achieve a UK low carbon electricity system by 2050 are comparable to those assumed in the UK Government's Carbon Plan scenarios [3,43]. The outcomes in terms of generation capacity and annual electricity generation in 2050 are also broadly comparable, with the exception of the Thousand Flowers pathway, which projects a lower level of electricity generation in 2050, due to achieving greater reductions in electricity demand. Nevertheless, the findings illustrate the scale and urgency of deployment of key technologies that would be needed to realise any of these pathways. For example, the Market Rules pathway would require annual build rates for carbon capture and storage (CCS) of 1900 MW/year from 2025 to 2035. This would now seem to be at the limit of technical feasibility, given that the UK Government abandoned its £1 billion support for a CCS demonstration plant in 2015.

Both the Thousand Flowers and Central Co-ordination pathways project fast progress in restraining electricity demand [5,7,9] will require technological or behavioural energy efficiency measures in order to reduce the levels of generation deployment needed out to 2050. It has been shown here that the challenges facing the realisation of any of the pathways/scenarios examined will need rapid rates of deployment of some or all of the available key low carbon electricity generation options. Version 2.1 of the UK Transition Pathways have been shown to have levels of deployment broadly comparable to those in the DECC scenarios, though with rates of renewable deployment in the Market Rules pathway falling between those of the core UK MARKAL scenario and the DECC 'higher renewables, more energy efficiency' scenario. The Central Co-ordination and Thousand Flowers pathways have lower levels of electricity demand than the DECC scenarios, due to greater energy efficiency improvements. However, these still imply high installed capacities, due to the greater proportion of renewable generation with lower capacity factors. The most significant difference is the high level of renewable CHP (both community scale and micro-CHP) in the TF pathway. This reduces the amount of centralised generation needed to



meet electric heating demand, as well as the power generated by this form of distributed generation. It significantly offsets the level of centralised generation needed in this pathway.

Upstream environmental burdens (expressed as CO<sub>2e</sub> emissions) associated with various power generators and UK electricity transition pathways towards a low carbon future have been evaluated on a 'whole systems' basis [37,38,48,51]. CO<sub>2e</sub> capture facilities coupled to fossil-fuelled plants were found, for example, to deliver only a 70% reduction in GHG emissions (including both upstream and operational emissions), in contrast to the normal presumption of a 90% saving. In addition, the present UK GHG trajectories associated with transition pathways out to 2050 are found to differ significantly from those produced by both DECC and the British Government's independent *Committee on Climate Change*. These bodies do not currently account for upstream, 'fugitive' GHG emissions. Thus, there will actually remain further emissions upstream that are unaccounted for, even if the current UK CO<sub>2e</sub> reduction targets are apparently met.

The present comparison exercise highlights the fact that significantly different technological pathways to a low carbon electricity system in the UK by 2050 are possible, though any of these pathways will be challenging to realise. They imply different levels of efforts and different patterns of risks and uncertainties, in relation to energy efficiency and behavioural changes and in technology choices and deployment challenges. How these are addressed and resolved will depend on the governance arrangements of the transition including policy measures and regulatory frameworks. So, as discussed in more detail elsewhere [5,9,52,53], the roles and choices of government, market and civil society actors are crucial to realising any of these pathways. These choices will be affected by expectations of the technical feasibility and social acceptability of future pathways, which can be informed by the type of analysis presented here. There are obvious lessons from this work for other European countries attempting to decarbonise their electricity generation systems, although local circumstances will limit the wider applicability of the present findings.

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