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Valuing energy futures; a comparative analysis of value pools across UK energy system scenarios

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HIGHLIGHTS

- By 2050 up to 21 bnGBP per year of new financial value is available in the UK energy system.
- Carbon pricing is critical across all studied scenarios.
- Electric vehicle revenues are a key driver of sector growth.
- Flexibility markets are volatile and require more innovation policy.
- The value pool method is a useful tool for understanding firm strategy and innovation policy.

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ABSTRACT

Electricity markets in liberalised nations are composed primarily of private firms that make strategic decisions about how to secure competitive advantage. Energy transitions, driven by decarbonisation targets and technological innovation, will create new markets and destroy old ones in a re-configuration of the power sector. This research suggests that by 2050 up to 21 bnGBP per year of new financial value is available in the UK electricity system, and that depending on scenario, these new values represent up to 31% of the entire electricity sector. To service these markets business model innovation and new firm strategies are needed in electric power provision. Energy scenarios can inform strategic decisions over business model adaptation, but to date scenario modelling has not directly addressed firm strategy and behaviour. This is due in part to neo-classical assumptions of firm rationality and perfect foresight. This research adopts a resource based view of the firm rooted in evolutionary economics to argue that quantifying the relative size of the markets created and destroyed by energy transitions can provide useful insight into firm behaviour and innovation policy.

1. Introduction

Electricity systems in developed economies are undergoing fundamental transitions driven by international decarbonisation targets, technological innovation, and new market entrants [1,2]. These transitions create deep uncertainty for investors and power utilities [3,4]. These uncertainties are due, in part, to the multiple pathways energy systems can take to achieve environmental, social and economic goals [5,6]. The existence of multiple pathways increases risk perceptions of premature and even intentional asset stranding for power sector investments [7]. These challenges result in a lack of investor confidence [8], affect the market's ability to provide sufficient price signals to investors [9,10], and may increase the cost of capital for low-carbon energy transitions [11].

Existing energy system models address this uncertainty to some degree, by using climate change commitments, technology prices, and demand forecasts to set parameters for quantitative energy transition scenarios. These models often analyse scenario costs within constraints; i.e. no nuclear, high CCS, high decentralised renewables [12]. The majority of these models focus on cost optimisation or near-optimisation [13] and report in terms of 'total investment cost' [14].

Recent analysis has demonstrated that total investment needs globally for the energy sector to 2040 are between $3.9 and $4.9 trillion at 2015 prices [15]. Within this range there is a substantial reallocation of capital between sectors, and wide technological diversity depending on scenario [14,15]. Cost optimisation models have proved

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useful for policy makers seeking to achieve multiple energy system objectives within a credible cost framework [16]. However, energy modelling and scenario development has, to date, done less to address commercial imperatives and investment uncertainties created by multiple pathways.

2. Firm strategy and investment in energy transitions

Addressing the commercial uncertainties created by energy transitions is important because, in many developed nations, power sectors have been liberalised; they comprise private firms making decisions about how to compete in energy markets for wholesale generation and retail supply [17]. Contributors to this journal concerned with strategic investment decision-making in the power sector, have demonstrated how utility investment decisions affect wider energy markets [18], how critical investor perceptions of return are to expanding low-carbon generation [19], and the importance of adopting real options or other approaches to account for uncertainty in utility scale investment decisions [20,21]. Much subsequent research however, is aimed at understanding the performance of specific technologies or investments across a range of scenarios or experimental conditions [22–24]. Recently this work has been expanded to take account of longer term firm decision making over multi-technology portfolios, which better represents a traditional utility business model [25]. This is an important step as there is mounting evidence of multiple threats to utility firms which require long term business model transition and adaptation to address [26,27]. To date there has been a disconnect between the growing sophistication of the energy scenarios produced by cost-optimisation modelling, and the strategic investment decision-making literature.

To bridge this gap it is important to clarify how firm strategy is constructed, before asking how scenario modelling can inform strategic decision-making. Firm strategy is driven by a firm's perception of the markets it can earn a commercially viable profit in [28]. Grant [28] argues that this depends upon the 'attractiveness of the industry' in which the firm is located and its ability to establish 'competitive advantage' over rivals. The 'attractiveness of industries' is related to the level of competition within a sector and the industries' profit structure [29]. 'Competitive advantage' relates to both the cost advantages firms can realise through process innovation, scale economies, or resource efficiencies; and differentiation advantages such as brand trust or product performance [28]. Given a suitably 'attractive' industry, and a reasonable expectation of competitive advantage, a utility may choose to enter a new market or pursue new values by adapting its business model [26].

2.1. Understanding the firm in energy transitions

Most cost optimisation models do not address firm strategy or behaviour, because of two important assumptions; these are firm rationality and perfect competition [13,30]. Under these assumptions the resources of firms are mobile and their foresight is perfect. If one set of firms (such as incumbent utilities) fail, other firms will acquire the resources needed to exploit profit opportunities in the energy sector. The relative size of the various markets created or destroyed by various system pathways would not matter under neo-classical assumptions of firm behaviour, because all profit pools would be competed away under perfect competition. Following this, the behaviour of firms in energy scenario work has often been unproblematically assumed. However, insights from both evolutionary and institutional economics contest this assumption of actor foresight perfect competition between sectors [30,31].

Proponents of Resource Advantage theory argue that firms acquire substantial financial, physical, human, organisational, informational and relational resources which lead to competitive advantages (or disadvantages) over prospective rivals, particularly new entrants [28]. This resource based, firm theory in its evolutionary form [32], explains both why firms in large complex systems can secure incumbent advantage by trading on routines and replicated capabilities [33], and how these routines become a barrier to system change by creating path dependency and lock in [34,35]. The multi-level perspective or 'MLP' has demonstrated how path dependency and lock in can be overcome by fostering niche innovation [36]. The same school recognises that "although large incumbent firms will probably not be the initial leaders of sustainability transitions, their involvement might accelerate the breakthrough of environmental innovations if they support these innovations with their complementary assets and resources" [37].

To summarise, utility investment decisions and return expectations are key determinants of market composition. Firms make decisions on which markets to enter based on size of market, ease of access, profit structure and competition within different segments. However, not all firms are equally able to enter all markets. Therefore, incumbent utility firms are more likely able to exploit new value opportunities created by energy transitions. The relative size of the markets created or destroyed by different energy system scenarios matters, because energy firms undertaking future market analysis will likely select strategies that are compatible with their resource endowments, the potential size of the market opportunity that might develop, and its robustness across several possible futures. For the development of innovation policy, understanding future market size and ease of access can define the timing and strength of 'market pull' [38] for system innovations and in turn define appropriate innovation policy instruments such as fiscal, regulatory or statutory interventions [39].

2.2. Mapping future values in energy transitions

It is from this starting point that we frame our research goal; to determine how energy firms, incumbent or otherwise, can understand potential profit structures and market sizes (industry attractiveness) over multiple future energy scenarios.

One technique used for industry attractiveness analysis is the profit pool approach [27,40,41]. The profit-pool-analysis is a strategy tool [29] which aims to map the total profits earned in an industry at discrete points along the industry's entire value chain [40]. Profit pool and value chain mapping facilitates insight into industry structure by visualising the economic and competitive forces driving the distribution of profits [29].

Eurelectric [42] adopt the framework to point out the declining profit pools available in electric utilities' core business, while further analysing new growth areas to offset this decline such as large-scale renewable energy sources (RES) and the emergence of "new downstream value pools from the 'green agenda' and decentralised generation and energy efficiency" [42]. Commercial energy consultancies have used the profit pool approach to quantify the implications of energy transitions for utilities strategy [43]. For example McKinsey adopted this methodology to explore EU power sector profit pools to 2020, by sizing the profits from performance improvements, capacity remuneration, RES and new down-stream growth [43].

Van Beek et al. [44] take an additional, critical methodological step by switching the terminology from 'profit' to 'value' pool. This work recognises that a *profit* pool analysis needs detailed understandings of the business models being used. Energy transitions create pools of value which can only be rendered into profit by business model innovation [45]. Van Beek et al. apply the value pool concept to quantify new financial opportunities available in energy transitions, prior to exploring the business models compatible with capturing those opportunities. However, while [42,43] use the EBIT as a measure, Van Beek et al. [44] measure the financial opportunity in 'new revenues' and 'avoided cost', across six discrete pools. The three studies above all analyse a pan-European geography, demonstrating the international applicability of the method. To date however, the value pool approach has only been used to analyse single future scenarios in energy transitions; it has not yet been applied to investigate how each value pool is created, modified, or destroyed in multiple energy system scenarios. To address this, the authors conducted a value pool analysis on a discrete selection of well-developed UK energy scenarios.

2.3. Study objectives

The research question was: *'what is the magnitude of different value pools in the UK's energy transition under a range of system scenarios?'* The purpose was twofold. First to demonstrate how a value pool approach can add to our understanding of the commercial opportunities in specific future energy scenarios. Second, using scenarios in this way would bridge the gap between scenario modelling and investment decision-making communities, by using a novel method to better evaluate market sizes across multiple, uncertain futures. The approach and outputs have application in both public and private sector strategic decision-making. For private sector decision making the value pool approach contributes to measuring industry attractiveness and can inform firm strategy and investment decision-making. For the public sector, the value pool approach can be used to show where there is likely to be substantial "market pull" [38] for energy innovations, i.e. in large pools, robust across several scenarios; and where more substantial innovation support maybe necessary due to weak market pull, i.e. in small value pools or those particularly vulnerable to future scenarios.

3. Methods

3.1. Selecting scenarios

The authors selected the UK to investigate as the UK has one of the most detailed and diverse range of energy system scenarios [12]. This method is replicable in any nation with a liberalised or liberalising energy market, and which has a diversity of energy scenarios to draw on which reference common criteria. Energy scenarios for the study were selected against four common criteria. First, the scenarios had to extend to at least the year 2040. Second, each scenario needed to be created by credible institution. Third, each scenario had to include: predictions of final demand, capacities of installed generation, peak demand, electric vehicle penetration, population, separation of commercial and residential demand, and clear assumptions on household numbers. Finally, each scenario (bar one) had to be 'climate compatible' i.e. compatible with the UKs 2050 target of reaching an 80% reduction in CO_2-emissions compared to 1990 levels set by the Climate Change Act 2008 [46]. Scenarios were also required to have a broad range of governance and control 'logics' [47] to capture the political economies of different possible futures. National Grid's 'No Progression' scenario was selected as the non-climate compatible scenario because it has low levels of green ambition and low prosperity, leading society to prioritise affordability over environmental ambitions [48] (see Table 1).

Headline characteristics of the scenarios in all analysis years (2030, 2040, & 2050) are reported in the supplementary information accompanying this paper [49]. Table 2 shows the headline characteristics for scenarios in the year 2050.

Table 1
Selected Scenarios according to the criteria.

Author	Name of the scenario
DECC – 2050 calculator (2010/2011)	High renewables, higher energy efficiency Higher nuclear, less energy efficiency Higher CCS, more bioenergy
National grid (2016)	Gone Green No Progression
Realising energy transition pathways (2008)	Market rules Central coordination Thousand flowers

3.2. Defining the value pools

The next step was to define the value pool narratives and data sources. The value pools for calculation were selected based on [44]. Further work may wish to identify other value pools beyond those used by [44], which have been adopted with limited amendments[1] for this analysis.

To understand each value pool in the UK context, 16 elite semi-structured interviews were undertaken. The interviews included: 3 × energy consultancies, 3 x utility companies, 2 × energy finance providers, 2 × consumer bodies, 1 × officer of the regulator, 2 × civil servants, 2 × technology companies, and 1 × sector membership organisation. These interviews explored how each of the value pools presented by [44] might be altered by UK market conditions. The interviews were also used to test authors' assumptions on individual value pools such as: discount rates, technology costs, replacement rates, operational expenditures and potential future efficiencies. The results from the semi-structured interviews were combined with an analysis of grey and academic literature to source key model assumptions.

Critically, there is no single 'business as usual' reference case in the value pool approach. All energy futures, including those with little climate ambition, comprise different generation fleets, demand profiles, electric vehicle penetrations, flexibility requirements etc. The approach aims to understand the 'new revenues' or 'cost savings' available in the system as it evolves through time. They represent the size of possible future energy opportunities, not cost increases or deviations from a single base year or counterfactual reference case. Model inputs and structure is summarised in Fig. 1:

In the methodological supplementary information provided, further detail is given on model inputs and structure [49]. In the model information provided [50] data sources, assumptions, calculations, and numerical results are presented for each constituent value pool. The narrative for each value pool is set out below before model results are presented.

4. Results

This section is structured in three parts. The first section defines the future market size in each scenario, then explains and quantifies each value pool in turn for each scenario and time step. The second section presents the cumulative size of all value pools across scenarios. The third section reports on sensitivity analysis.

4.1. Value pools and market size

It is useful to compare the magnitude of new value pools in the UK's energy transition against the projected size of the whole electricity market in each scenario. To analyse the full market size for each scenario the method applied was to multiply the projected domestic/commercial commodity price (p/kW h) against a decomposed annual final demand (TW h) for each scenario and decadal time step. This data is provided only as indicative context and does not include electrical standing charges for domestic or commercial customers.

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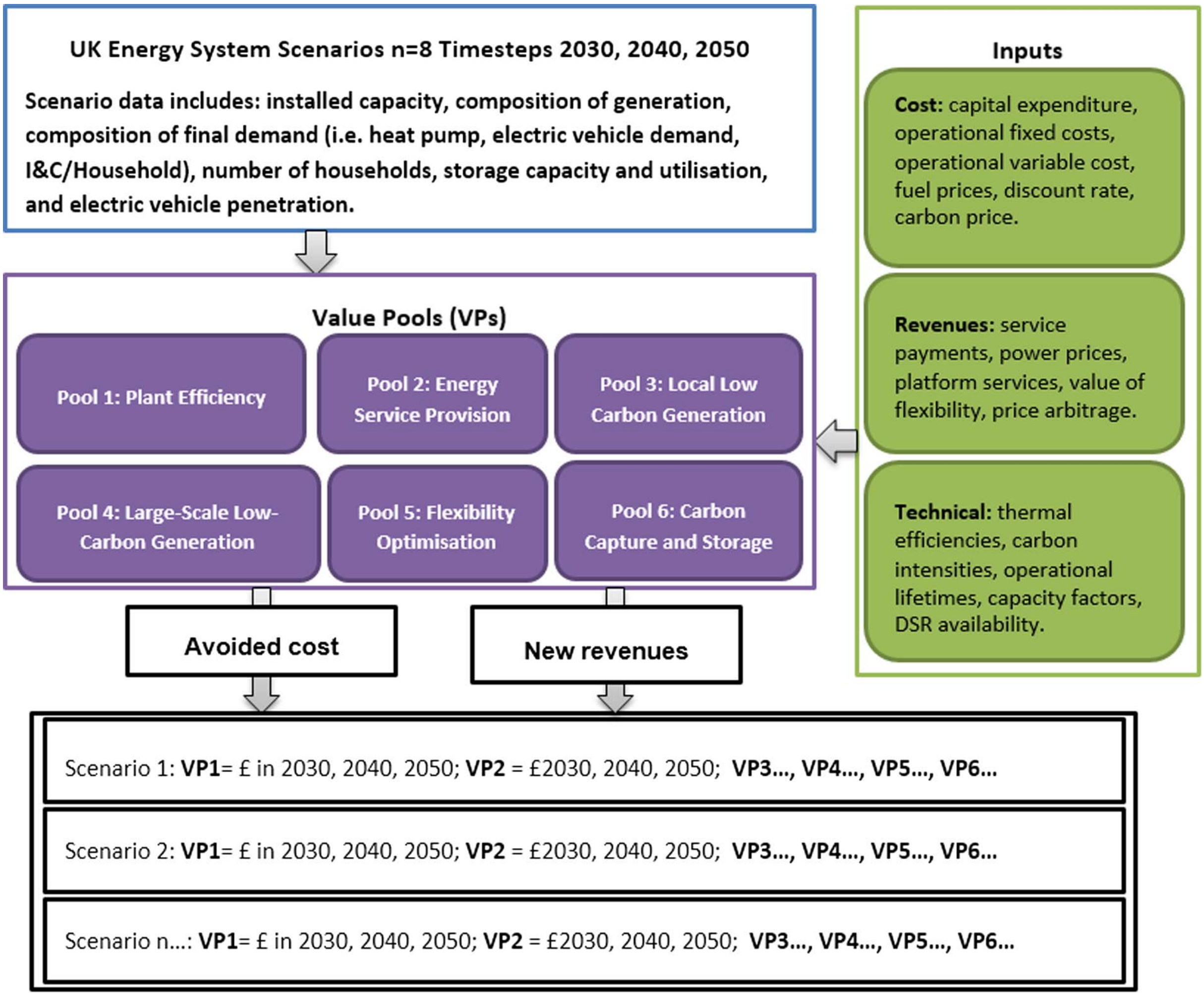
[1] Three name changes to the value pools were conducted: "Plant and Portfolio Efficiency" was renamed to "Plant Efficiency" and "Energy Demand Reduction" to "Energy Service Provision" since the services covered in this pool do not all trigger demand reductions, for example electric vehicle services. Further, "Carbon Capture and Use" was renamed to "Carbon Capture and Storage" since the use of the carbon is conceptualised by Accenture but no revenue streams are assumed. Additionally, an interviewee mentioned that the demand for carbon for industrial or agricultural purposes is limited in the UK, hence the more traditional concept of "Carbon Capture and Storage" was applied.

Table 2
Scenarios 2050: overview of the scenario data.

		NGrid – no progression[a]	DECC 2050 – higher RE, more EE	DECC 2050 – high nuclear, less EE	DECC 2050 – higher CCS, more bioenergy	NGrid – gone green[b]	RTP – market rules	RTP – central co-ordination	RTP – thousand flower
Electricity demand	TW h	309	490	555	461	361	504	402	301
Power generation (incl. import)	TW h	349	530	610	556	454	573	464	370
Conventional generation capacity (excl. CCS)	GW	49	0	0	0	18	15	5	0
CCS equipped generation Capacity	GW	0	13	2	40	11	46	32	23
Low-carbon generation capacity	GW	42	121	97	49	119	104	90	84
Number of electric vehicles	mln.	3.9	24.2	31.0	24.4	9.7	25.2	25.2	25.2

[a] The national grid future energy scenarios 2016 cover the time horizon till 2040, hence a stable system for the time horizon till 2050 was assumed.
[b] The national grid future energy scenarios 2016 cover the time horizon till 2040, hence a stable system for the time horizon till 2050 was assumed.



Scenario data includes: installed capacity, composition of generation, composition of final demand (i.e. heat pump, electric vehicle demand, I&C/Household), number of households, storage capacity and utilisation, and electric vehicle penetration.

Cost: capital expenditure, operational fixed costs, operational variable cost, fuel prices, discount rate, carbon price.

Revenues: service payments, power prices, platform services, value of flexibility, price arbitrage.

Technical: thermal efficiencies, carbon intensities, operational lifetimes, capacity factors, DSR availability.

Scenario 1: **VP1**= £ in 2030, 2040, 2050; **VP2** = £2030, 2040, 2050; **VP3…, VP4…, VP5…, VP6…**

Scenario 2: **VP1**= £ in 2030, 2040, 2050; **VP2** = £2030, 2040, 2050; **VP3…, VP4…, VP5…, VP6…**

Scenario n…: **VP1**= £ in 2030, 2040, 2050; **VP2** = £2030, 2040, 2050; **VP3…, VP4…, VP5…, VP6…**

Fig. 1. Value pools identified and model process map.

Fig. 2 shows that new revenues and avoided costs combined are a maximum of 31% and a minimum of 14% of the future market size across the scenarios. The higher percentages are in the RTP Thousand Flower scenario, followed by National Grid Gone Green. The higher percentage values are in system scenarios most different from today in terms of both fleet composition, ‘green ambition’ and consumer behaviour. Electric vehicle uptake is the overwhelming driver of new revenues. The scenarios with the highest capacities of centralised electricity generation plant (such as nuclear power or large fossil fuel thermal plants) achieve the highest cost savings. National Grid’s ‘No Progression’ scenario has the lowest cumulative value pools and is closest in composition to the system of today.

4.1.1. Value pool #1 plant and portfolio efficiency

The average conversion efficiencies of the UK thermal generation fleet are below the current optimum of 58% achievable by best available technologies in CCGT generation [51,52]. UK thermal efficiencies of gas, nuclear, and coal in 2015 were 48%, 35.6%, and 39.1%

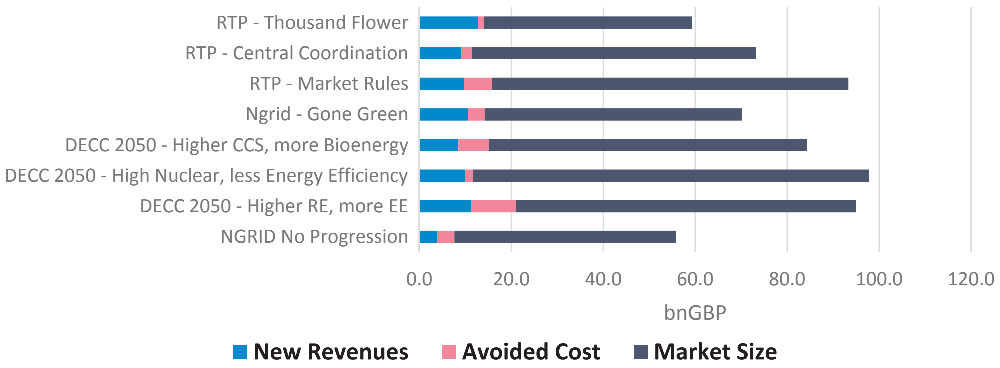


Fig. 2. Comparison of indicative market size against new revenues and avoided costs in 2050.

Table 3
Assumed thermal efficiency gain potential for value pool #1 (see [50]).

Plant type	Natural gas	Oil	Coal	Nuclear	CCS coal	CCS gas
Power plant (thermal) efficiency – 2015, before and till 2019	50%	30%	35%	36%	33%	50%
Power plant (thermal) efficiency – 2030–39	55%	30%	36%	36%	40%	54%
Power plant (thermal) efficiency – 2040–49	56%	30%	37%	36%	41%	56%
Power plant (thermal) efficiency – 2050 and onwards	57%	30%	37%	36%	43%	58%

respectively [52]. Existing value pool studies [44] include plant and portfolio efficiency as an important conventional value pool for utilities, one which is particularly susceptible to carbon pricing in the absence of nuclear. The portfolio efficiency improvements used in this study are shown in Table 3. Estimates were based on thermal efficiency potentials obtained from [51] and interview responses on realistic replacement rates and efficiency gains from utility executives.

For value pool #1 the variables affected by thermal efficiency improvements are the portfolio OPEX (in GBP/MW h), the thermal efficiency of the plants, and the emission factors of the plants. The summary equation for value pool #1 is:

$$\begin{aligned} \textit{avoided Cost} = {} & \textit{System Operating Cost}_{\textit{No Efficiency Improvement}} \\ & -\textit{System Operating Cost}_{\textit{with Efficiency Improvement}} \end{aligned}$$

The model showed that electric utilities can potentially avoid costs between 172–880 mGBP in 2030, 306–990 mGBP in 2040, and 75–1809 mGBP in 2050 through “Plant Efficiency” (Fig. 3).

The highest values arise in ‘DECC 2050-Higher CCS’ and ‘RTP-Market Rules’ scenarios with comparably large capacities of fossil thermal generation to 2050. From 2030 to 2040 a steady growth of the avoided cost is visible across the scenarios. The significant increase of the span in 2050 can be explained by a 25 GW addition of CCS capacity in the ‘DECC-Higher CCS’ scenario and a 10 GW reduction of gas power plants in the ‘DECC-High Nuclear scenario between 2040 and 2050. Low minimum value represent decommissioning of centralised generation fleet, while high values denote the opposite.

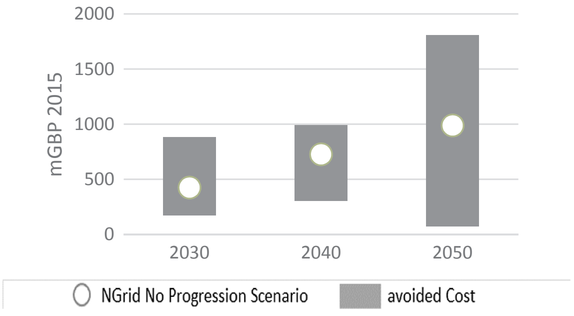


Fig. 3. Value Pool #1 - spread of avoided cost across the scenarios.

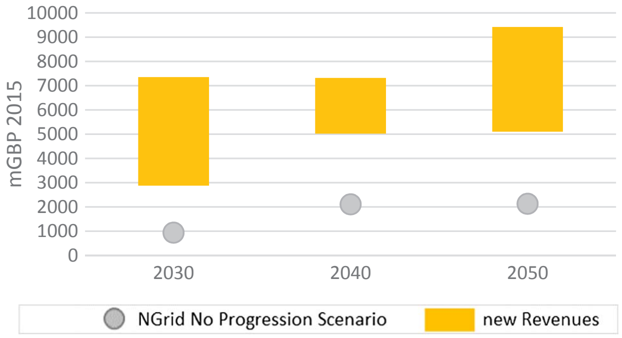


Fig. 4. Value Pool #2: new energy service provision revenues across scenarios.

4.1.2. Value pool #2 energy service provision

Energy efficiency increases and consequential energy demand reductions are a fundamental part of sustainable energy futures [53,54]. The UK’s final demand curve between 2011 and 2015 has been relatively flat, final electrical consumption was 302 TW h in 2015 [52]. A decreased demand for grid electricity is harmful to current utilities which operate on a units-sold business model [55]. Across the analysed energy scenarios there is substantial variation in demand predictions to 2050: final demand remains relatively constant in the ‘Thousand Flowers’ and ‘No Progression’ Scenarios (301 TW h and 309 TW h in 2050 respectively); demand increases substantially to 555 TW h in the DECC ‘High Nuclear’ scenario (Table 2). Increases in demand are driven by the electrification of heat and transport in the scenarios, while efficiency gains and demand reductions are largely industrial, buildings based, or assume appliance efficiency gains. Servicing the electrification of transport, along with charging for energy retrofit services, are new revenue streams that utilities can access and could, to an extent, compensate for the revenue losses caused by demand reductions elsewhere. Heat electrification is not included as a new revenue stream as it is likely to cannibalise other utility revenues, evidenced by the predominance of dual fuel utility customers in the UK [56]. Heat value pool mapping however has the potential to inform further work.

New revenue streams in the value pool are:

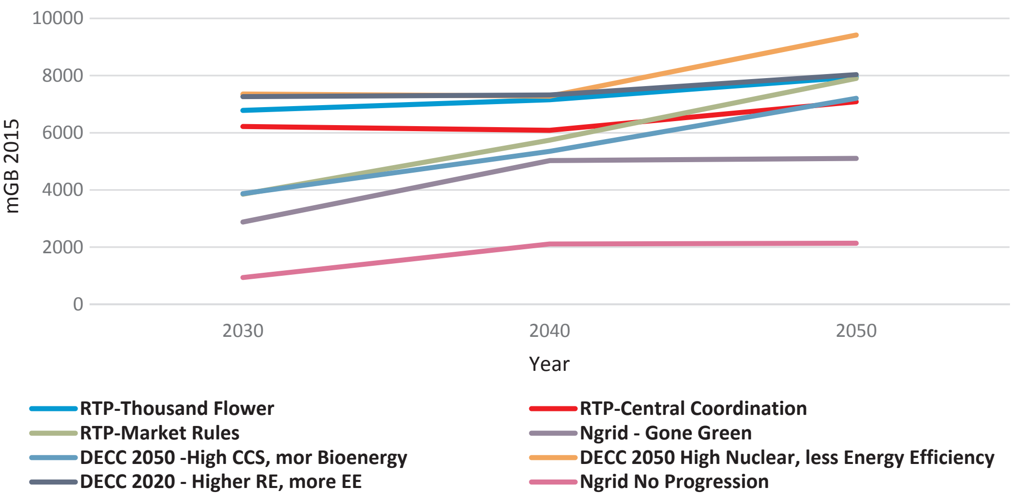


Fig. 5. Value Pool #2 disaggregated by scenario.

- energy efficiency measures/appliances: installation fee[2]
- home energy management system (HEMS): installation and annual maintenance fees
- electric vehicle (EV) services: charging fee and charging unit installation fee

The aim of the value pool calculation is to estimate the maximum potential for the UK. An important assumption for this value pool is, that by 2050 all existing households install energy efficiency measures and have a HEMS. This level of ambition is matched by recent work on efficiency retrofit needs in the UK, from both industry [57] and academic analysis [58]. Further, all new-build households are assumed to install a HEMS, see [50] for assumed fees.

The number of electric vehicle charging units installed was determined by assuming a share of new electric vehicles to be supplied with a home charger each year. Due to the currently low penetration of electric vehicles, at first a significant amount of car owners would opt for acquiring a charging unit, later an EV replaces another EV therefore new charge point installations reduce – a share of 60% in 2030 reducing to 50% in 2050 is assumed. The summary equation for value pool #2 is:

$$\begin{aligned}&\mathit{Revenues\ from\ Energy\ Service\ Provision}\\&\quad= \mathit{Revenues\ from\ EE\ Installations} + \mathit{HEMS\ Revenues}\\&\qquad+ \mathit{Electric\ Vehicle\ Service\ Revenues}\end{aligned}$$

The results show that across climate compatible scenarios new energy service revenues are between 2.8–7.3 bnGBP in 2030, 5.0–7.3 bnGBP in 2040 and 5.1–9.4 bnGBP in 2050 through VP “Energy Service Provision” (Fig. 4). ‘DECC 2050-High Nuclear’ and ‘DECC 2050-Higher RE’ scenarios provide the highest values. The ‘No Progression’ values are significantly lower than the other scenarios.

Electric vehicle services contribute 78–95% of new revenues in this value pool by 2050. National Grid’s ‘No Progression’ scenario has low electric vehicle penetration and has the lowest new revenue potential, (Fig. 5). HEMS and EE installation services contribute 5–17% and 1–5% respectively.

4.1.3. Value pool #3 local low-carbon generation

Decentralised generation, particularly microgeneration, across the EU and other OECD nations is problematic for both utilities and infrastructure operators because it undermines core revenues by reducing final demand [59]. While these revenue losses are difficult to avoid, there are related value opportunities in the services surrounding microgeneration technologies. Homeowners require system design, installation, and servicing. These all represent value propositions from which utilities, with their related expertise and customer relationships, may be well placed to capture [60].

Table 4
Assumptions made for the value pool calculations.

	Value assumed
Share solar PV roof-top-installations among the installed solar PV capacity[a]	50%
Installation fee of investment for roof-top solar PV system[b]	15%
Management fee for O & M roof-top solar PV as share of the total OPEX	70%

[a] According the latest national statistics released on solar PV deployment about 32% of the installed capacity is sized below 50 kW. However, due to the reduced UK subsidies regime for new large-scale plants as well as the emphasis on increased customer participation as well as distributed resources a share of 50% Roof-Top-Installations was adopted.

[b] Assumption made by accenture for calculations in 43.

The services considered in this value pool are: distributed generation lease service (solar PV), solar PV installation, O & M and decommissioning service, and local power brokerage or platform services (see[3]). Households are assumed to sign up for one or a maximum of two of the services offered as brokerage services and trading on a local power platforms are mutually exclusive. Subsidy payments of any type are not included in value pool 3 as they are assumed to accrue to the metered user (see Table 4).

The summary equations for value pool #3 are:

$$\begin{aligned}&\mathit{Revenues\ from\ Leasing\ Service}\\&\quad= \mathit{Number\ of\ Installation} \times \mathit{monthly\ Leasing\ Fee} \times 12\ \mathit{months\ per\ year}\end{aligned}$$

$$\begin{aligned}&\mathit{Revenues\ from\ Solar\ PV\ Roof\ Top\ Services}\\&\quad= \mathit{Revenues\ from\ Solar\ PV\ Roof\ Top\ Installations}\\&\qquad+ \mathit{Revenues\ from\ Solar\ PV\ Roof\ Top\ O\ \&\ M}\\&\qquad+ \mathit{Revenues\ from\ Solar\ PV\ Roof\ Top\ Decommissioning}\end{aligned}$$

$$\begin{aligned}&\mathit{Revenues\ from\ Local\ Power\ Brokerage\ for\ Solar\ Home\ System\ Owner}\\&\quad= \mathit{Number\ of\ Installations} \times \mathit{monthly\ Subscription\ Fee}\end{aligned}$$

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[2] For the installation fee a value of 15% of the avoided electricity cost over 10 years is assumed.

[3] https://www.openutility.com/.

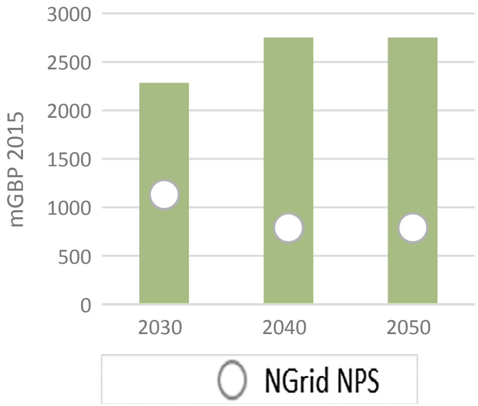

Fig. 6. Value Pool #3: local low-carbon electricity – distributed energy lease service – new revenue.

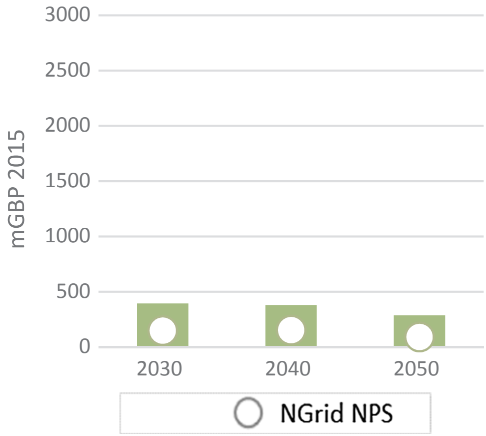

Fig. 7. Value Pool #3: local low-carbon electricity – solar PV services – new revenue.

Revenues from Local Power Plat form for all domestic Customers

= Number of House holds x monthly Subscription Fee

The maximum size of the value pool is the sum of the revenues from the distributed lease service as well as from the platform services for domestic customers – Figs. 6–9.[4]

The revenues from all solar PV services have a minimum value of zero, since the “DECC 2050-High Nuclear” and “DECC 2050-Higher CCS” scenarios incorporate no distributed solar capacity.

Electric utilities may generate new revenues up to 2.3 bnGBP in 2030 to 2.8 bnGBP in 2050 through distributed energy lease services (Fig. 6). From the solar PV services revenues up to 0.39 bnGBP in 2030 and 0.28 bnGBP in 2050 are available (Fig. 7). This decrease in the overall revenues is due to market saturation.

From platform services provided to households owning solar systems, new revenues are up to 650 mGBP in 2030 to 780 mGBP in 2050 (Fig. 8).

The provision of power platform services can generate new revenues in of 0.2–1.8 bnGBP in 2030, 0.1–1.9 bnGBP in 2040 and 0.05–2 bnGBP in 2050 (Fig. 9). The minimum values of the span are set by the “DECC 2050-High Nuclear” scenario with minimal local generation. The combined value pool for the two most substantial services (leasing and power brokerage) are between 42 mGBP and 4.6 bnGBP by 2050 depending on scenario.

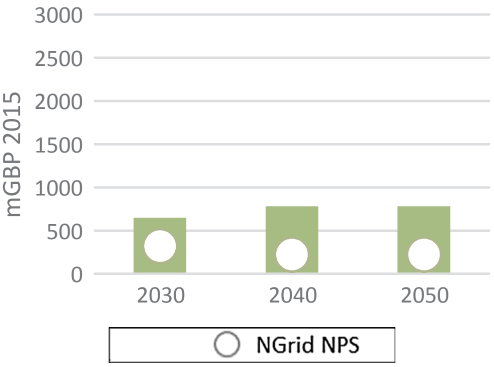

Fig. 8. Value Pool #3: local low-carbon electricity – platform service/solar PV – new revenue.

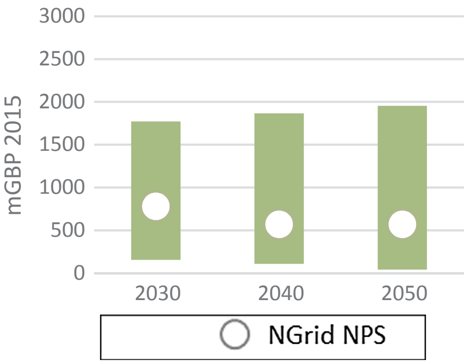

Fig. 9. Value Pool #3: local low-carbon electricity – platform service all domestic generation – new revenue.

4.1.4. Value pool #4 large scale low carbon generation

The cost of large-scale renewable energies decreased significantly over the past half-decade [61] posing a challenge to policy makers in matching subsidy requirements against changing levelised costs of electricity [62]. Continuous cost reductions are expected [63] and large scale low carbon generation sources are becoming competitive with new construction of conventional alternatives [64]. To make these investments competitive with the existing generation fleet active in the present market, they must be supported by either direct subsidy or their conventional competitors made more expensive, often through carbon pricing. In the UK the intention of the carbon price floor in electricity market reform is for a rising cost of carbon to £30/tonne by 2020 and £70/tonne by 2030 [62]. However since this carbon price mechanism is currently subject to a freeze [65], the model uses the Committee on Climate Change’s expected UK market prices to 2050 [66]. This value pool is defined as a cost saving which may be available to firms choosing to build large-scale low carbon generation instead of conventional gas power plants (excl. CCS). The large-scale, low-carbon generation value pool includes: onshore and offshore wind, hydro, biomass, nuclear and solar PV. This value pool represents the cost difference between constructing and running the large-scale, low-carbon generation and constructing and running the same net capacity and generating the same amount of electricity via gas CCGT power plants. Here a positive value denotes a real saving while a negative value denotes extra cost, i.e. value pools can identify negative cases for investment.

The most significant cost difference between most low-carbon generation and thermal power plants is between CAPEX and OPEX requirements. Subsidies will play a part in future value pools, however, the level of subsidy per technology is volatile, and different technologies are in or out of favour dependent on political commitments [67]. Thus, low carbon energy subsidy is not included in the value pool

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[4] The model further verifies if all households can be supplied by local decentralised sources (solar PV, onshore wind, biomass, CHP) by comparing annual domestic demand with annual distributed low-carbon generation. Should this not be the case, then the number of subscribers for the platform will be limited to the number of households that can be supplied with local power – based on the average household demand.

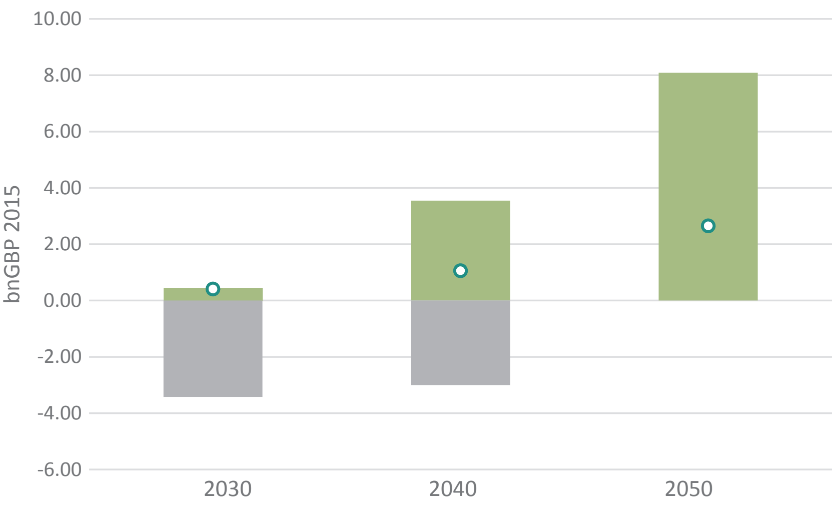

Fig. 10. Value pool #4 large scale low-carbon generation cost savings across scenarios.

calculation. The cost of carbon, however, is included. The rationale for this is that RE subsidies fluctuate annually, but the UK's carbon price floor gives some certainty that a common rate can be applied across all relevant power sector technologies. Future work may include subsidy as part of this value pool. The summary equations for value pool #4 are thus:

$$\mathit{Annual\ Cost\ per\ Technology} = \mathit{LCOI} + \mathit{OPEX}_{fix} + \mathit{OPEX}_{variable} + \mathit{CO}_2\ \mathit{Cost}$$

$$\mathit{Cost\ avoided} = \sum \mathit{Annual\ Cost\ all\ Low\ Carbon\ Technologies}$$
$$- \mathit{Annual\ Cost\ Gas\ Power} - \mathit{Annual\ Cost\ Coal\ Power}$$

'LCOI' is the levelised cost of investment. LCOI was used in place of the traditional Levelised Cost of Electricity (LCOE) approach. The LCOE method adds the initial investment as well as the discounted operation expenditures over the lifetime and divides the sum by the discounted power generation over the lifetime. The result is the cost of electricity levelised over the expected operational lifetime. However, the installed capacities and the load factors of plants fluctuate significantly between the scenarios. Therefore, the authors chose to exclude the annualised operational expenditures from the levelised cost approach and instead calculated the levelised cost of investment (LCOI) per technology and scenario year, see [49,50].

The results show that the large-scale low-carbon capacity does not generate cost savings in all scenarios across the first two periods under consideration (Fig. 10).

Six of the eight scenarios display negative values, hence additional cost through the deployment of large-scale low carbon generation in 2030. Only National Grid No Progression and DECC High RE display positive values in 2030 due to low and cost optimal deployment of RE respectively. These results are expected due to the higher cost of many low carbon generation technologies coupled with the fact that the model used the Committee on Climate Change's expected carbon prices which are below their 'target consistent values'. It therefore falls to direct subsidy to support various forms of low carbon energy in the absence of a sufficient market based price signal [17], or an increase in the carbon price within the price floor mechanism towards target consisted values. In 2040, the scenarios with positive values are 'National Grid No Progression, and 'DECC 2050 Higher RE More EE' and DECC 2050 - Higher CCS, more Bioenergy. This is largely driven by these scenarios deploying lowest cost low-carbon generation first. In 2050 the plant operators can achieve savings through the deployed large-scale low-carbon capacity across all scenarios. The potential cost savings are in the order of 0.45 to −2.9 bnGBP in 2030, 3.6 to −3 bnGBP in 2040 and 0.61–8.1 bnGBP in 2050. The authors' approach demonstrates that cost reductions, subsidy support and carbon pricing continue to be necessary for the deployment of large scale low carbon generation technologies across all scenarios until 2050 where a sufficient carbon price renders the value pool positive, i.e. free of direct subsidy in all scenarios. This underlines how important effective carbon pricing is to support large scale low carbon generation.

Table 5
Overview on the assumed remunerations for batteries and DSR per revenue stream.

	Remuneration	Unit	Value
Batteries	Frequency response – utilisation, battery	GBP/MW h	1.25
	Frequency response – availability, battery	GBP/MW/a	81,600
	Reserve provision – utilisation, battery	GBP/MW h	130
	Reserve provision – availability, battery	GBP/MW/a	7650
	Embedded benefits – triad avoidance[a]	GBP/MW	50,000
	Energy price arbitrage	GBP/MW h	30
DSR	Reserve provision	GBP/MW/a	50,000
	Frequency response	GBP/MW/a	50,000
	Average wholesale electricity price spread	GBP/MW h	30

[a] Every year there are three Triads during which the battery can discharge to earn revenues. According to the Investment Template for Batteries from Smarter Network Storage (UK Power Networks, 2013) a number of two successful discharges per year was assumed.

4.1.5. *Value pool #5 flexibility optimisation*

Flexibility services can serve a range of different purposes by either providing flexibility to the wholesale market, to a portfolio (supplier and generator), or balancing services to balance demand and supply and to ensure the security and quality of electricity supply across the transmission system [68]. The value pool considers the cost avoided through demand side response (DSR) moving consumption to off-peak periods, as well as the revenue potential for batteries and DSR by the provision of frequency response, reserve capacity provision, triad avoidance, and energy price arbitration as applicable. Values for the remuneration of battery storage and DSR, as displayed in Table 5 were adopted for the calculation.[5] Individual value sources and assumptions are available in the methods narrative and published model [49,50]. Key sources used were [69–71]. Battery storage is used as the single storage technology due to data availability and recent market penetration, future work should consider the effect of other storage technologies on this value pool, such as flywheels, and compressed air.

The value pool calculates the theoretical available potential in the market for new revenues and avoided costs. The theoretically shiftable load is modelled by dividing the load incurred by domestic (incl. EV)

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[5] Assumption: the value of balancing services remains constant during the review period due to sufficient flexible capacity to effectively provide competition in the flexibility market, thus keeping remuneration stable.

Table 6
Assumptions of share of shiftable load between domestic and I & C consumers.

	Demand component	Share of shiftable load
Domestic (incl. EV)	Heat	100%
	Lighting & appliances	50%
Industry & commercial (I & C)	Industrial demand	16%
	Commercial heat	100%
	Commercial light & appliances	65%

and non-domestic customers into shiftable and non-shiftable load, assumption values follow [72,73] (see Table 6).

As only a proportion of the theoretical maximum shiftable load is likely to be realised as achieved load shift, the final achieved load shift was varied between pathways based on the level of consumer engagement pre-supposed by each qualitative pathways narrative; see [49,50].

Variations in summer over winter shiftable loads were conducted thus:

$$\begin{aligned} \textit{Shifted Load} &= (\textit{Annual Electricity Demand}/(365 \times 24)) \\ &\quad \times \textit{Achieved Shift of Load}\,(\%) \times \textit{Seasonality Factor} \end{aligned}$$

Further the avoided cost was calculated by assuming load shifting occurred for 5 peak-hours per day (e.g. 6–8 am and 5–8 pm):[6]

$$\begin{aligned} \textit{avoided Wholesale Cost} &= \textit{Shifted Load}_{\textit{Summer}} \times 5\,\textit{hrs} \times 365/2\,\textit{days} \\ &\quad \times \textit{Average Electricity Price Spread} \\ &\quad + \textit{Shifted Load}_{\textit{Winter}} \times 5\,\textit{hrs} \times 365/2\,\textit{days} \\ &\quad \times \textit{Average Electricity Price Spread} \end{aligned}$$

The summary equations applied for value pool #5 were:

$$\textit{new Revenues} = \textit{Revenues from Battery Operation} + \textit{Revenues from DSR}$$

$$\textit{avoided Cost} = \textit{avoided Whole sale Cost from DSR}$$

Through the operation of battery storage technologies new revenue streams in the range of 46–565 mGBP in 2030, and 46–1040 mGBP in 2040 & 2050 can be accessed in the power and balancing market (Fig. 11).

Though the market can provide revenue streams for the provision of flexibility of battery storage, the level of annual remuneration as found in the literature and applied to the model is below the required level to create a viable investment at the current cost of the technology. Across the scenario suite the average annual remuneration is between 160 and 175 GBP_{2015}/kW, while the IEA show battery costs above these potential remunerations until at least 2025 [61] albeit conceding that learning rates in battery technologies are highly uncertain [15]. This underlines the need for direct subsidy in storage as it is a key system enabler, but does not benefit directly from higher carbon pricing.

Power firms can potentially can generate new revenues from DSR in the balancing market between 160–390 mGBP in 2030, 190–550 mGBP in 2040 and 210–610 mGBP in 2050 (Fig. 12). While at the same time DSR can avoid wholesale cost in the order of 115–270 mGBP in 2030, 140–375 mGBP in 2040 and 150–410 mGBP in 2050 (Fig. 13). Compared to other services across the different value pools DSR provides small revenue and cost reduction volumes in all scenarios apart from National Grid's 'Gone Green' scenario, in which flexibility optimisation is comparable in magnitude to Value Pool #3 (local low carbon generation) in other scenarios.

4.1.6. Value pool #6 carbon capture and storage

A possible option for continuous operation of dispatchable and

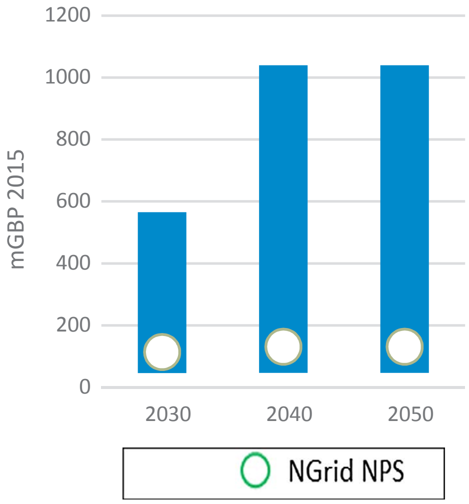

Fig. 11. Value Pool 5: new revenues from battery storage services.

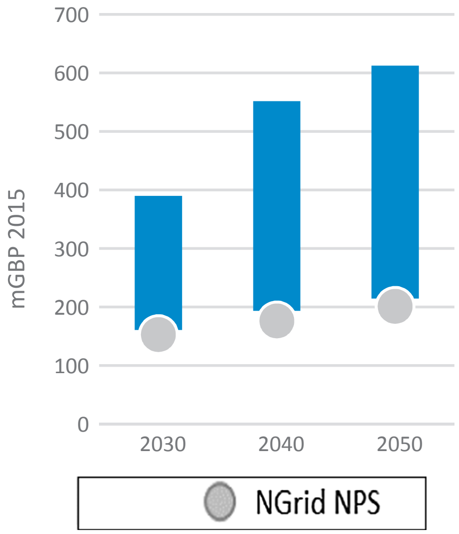

Fig. 12. Value Pool 5: new revenues from flexibility optimisation.

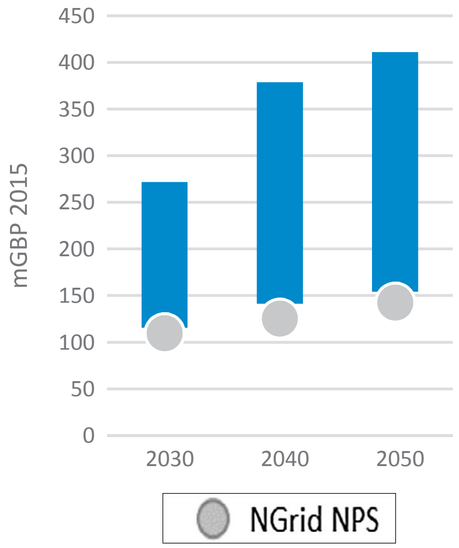

Fig. 13. Value Pool 5: avoided costs from demand side response flexibility.

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[6] Seasonality Factor: Due to the lack of applicable literature values a factor of 0.8 for summer and a factor of 1.2 for winter were assumed.

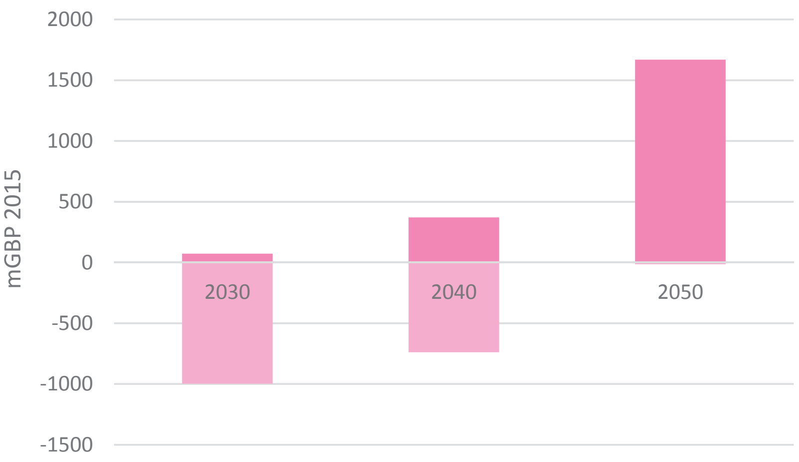

Fig. 14. Value Pool #6: CCS – avoided cost across scenarios.

large-scale, low-carbon electricity provision is the retrofitting and new build of fossil fuel power plants with carbon capture equipment. The carbon emissions released during the electricity generation process are captured and stored in geological storage facilities [74]. Though estimates vary, due to parasitic load and increased capital cost the power production in CCS equipped plants is more expensive than in unabated plants [75]. However, utilised sources assume emissions are reduced by around 90% [76], though note this is contested [77], therefore the incurred carbon costs are reduced and emissions are lowered towards achieving the 2050 target. However, the installation of capture plants will only reach commercial viability when the carbon costs saved outweigh the cost increases associated with the capture plant (notwithstanding non-energy payments / direct subsidy). The objective of this value pool is to evaluate the cost incurred by CCS equipped coal and gas power plants compared to the costs of equivalent unabated generation.

The summary calculation for value pool #6 is therefore:

$$Annual\ Cost\ per\ Technology = LCOI + OPEX_{fix} + OPEX_{variable} + CO_2\ Cost$$

$$Cost\ avoided = \sum Annual\ Cost\ CCS\ Technologies - Annual\ Cost\ unabated\ Technologies$$

Across the scenarios selected the model shows CCS value pools are between −997 mGBP and 72 mGBP in 2030, −739 mGBP and 372 mBGP in 2040, and −14 mGBP to 1669 mGBP in 2050, summarised in Fig. 14. The costs are avoided through the equipment of fossil power plants with CCS systems and avoiding carbon prices. The ‘no progression’ scenario does not include any CCS power plants, accordingly the value pool is zero. The value pool is increasing over the review period due to increasing power specific carbon prices and improvement of the CCS technology leading to a higher efficiency and reduced CAPEX/OPEX. The span of the value pool increases over time due to the significantly different level of CCS capacity across the scenarios - Fig. 14.

4.2. Cumulative value pools across scenarios

Returning to the specific research question: “what is the magnitude of different value pools in the UK’s energy transition under a range of system scenarios?” Across the surveyed scenarios, the potential new revenues in the UK energy system are up to £12.8bn per year in 2050 (Fig. 15). The cost savings potential is up to £9.7bn per year in 2050 (Fig. 16). New revenues and cost savings are present to greater or lesser degrees across all scenarios analysed; there is no single base or reference case. The following results demonstrate the relative volatility/stability and magnitude of each value pool across the eight system futures.

Against the ‘No Progression’ scenario, each climate compatible scenario presents substantial new revenue pools. For avoided costs only the ‘DECC High RE more EE’, ‘High CCS more Bioenergy’, and ‘RTP market rules’ scenarios present substantially higher cost savings than the National Grid ‘No Progression’ scenario. The reason for those three scenarios achieving substantially higher savings is due to the composition of electricity generation fleets. While the DECC High RE has a large wind fleet which results in a large VP#4 the DECC High CCS has a very large CCS +Wind fleets which results in similarly large savings.

4.3. Sensitivity analysis

In addition to future system characteristics, the estimated size of the value pools is affected by cost inputs. To evaluate sensitivity to cost inputs, carbon pricing, fuel pricing, capital costs and discount rates were individually varied by −50% to +50% sensitivity. The results show that new revenue pools are less sensitive to cost input than the avoided cost pools. Thus, the availability and accessibility of these value pools is sensitive to the carbon price, and cost of capital as well as the investment and operational cost for the generation technologies. Following Newberry [17], the authors specifically focussed on the fuel and carbon price relations. Fig. 17 highlights that, by 2050, small variations in the carbon price can define if low carbon technology fleet can become cost competitive. In the National Grid Gone Green Scenario a carbon price of just −30% below the assumed value of 65.75 GBP_{2015}/t_{CO2} in 2050 can turn avoided costs into extra costs. The effect on VP4, large scale low carbon generation, showed that by 2050 carbon price sensitivity has more effect than fuel prices (Fig. 18), though fuel price sensitivities have more impact in earlier years, when the carbon price is lower.

For Value Pool #6, six out of the seven climate compatible scenarios render CCS a positive value pool (i.e. commercially attractive) by 2050. A 20% reduction in the carbon price would mean only three of the seven climate compatible scenarios render CCS as a cost saving value pool by 2050 (Fig. 19).

5. Discussion

These results show substantial variability across the six value pools identified in the UK electricity sector to 2050. There are five main points to draw out in discussion. The first is the importance of the carbon price. Without direct subsidy the main driver for firms to construct large scale low carbon generation (VP#4) are the cost differentials between these and conventional technologies. Carbon pricing and fuel price increase are the two factors likely to convert large scale low carbon generation from an extra cost to an avoided cost and hence an attractive firm investment. Across the scenarios analysed the carbon price only reaches a sufficiently high value to render these value pools positive in 2050. These points support previous analysis [17] in

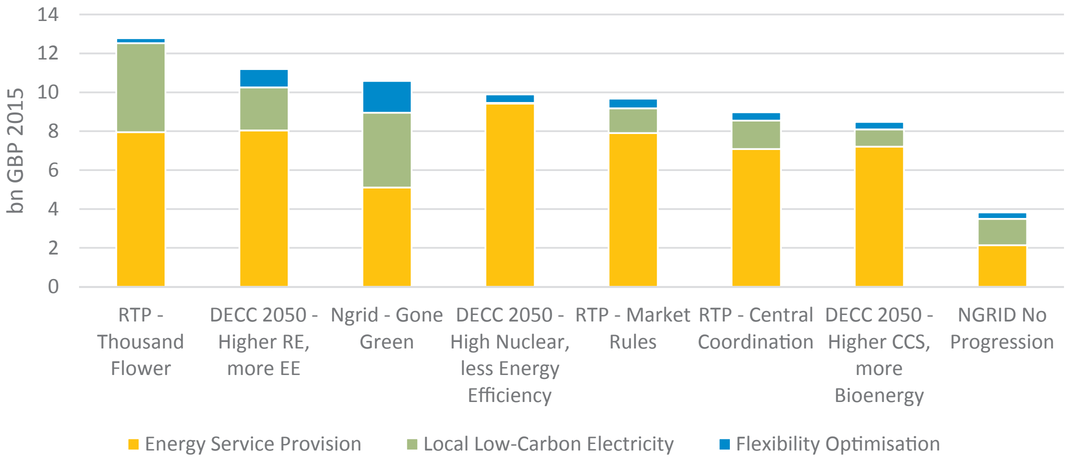

Fig. 15. Cumulative new revenues across system futures in 2050 by value pool.

suggesting that linked long term subsidy contracts of low carbon generation alongside carbon pricing will continue to be necessary to deliver required levels of large scale low carbon generation. Fossil fuel price volatility (particularly gas price) also affects this value pool, however, unlike carbon prices and subsidy levels, fossil fuel prices are not under the control of national governments. The authors add to this analysis by quantifying value pools across multiple scenarios to show how volatile the CCS and large low carbon generation markets are. They are both sensitive to the above variables and the scenario itself. This means that for utility firms seeking attractive markets, the CCS market in particular would present substantial risk and is likely to be selected as a firm strategy by very few actors. This may have the effect of reducing the competition to enter the industry due to high risks of asset stranding.

The second point is that the energy service provision value pool is robust across all scenarios, and the dominant driver of new revenue is the electric vehicle charging element. Across all climate compatible scenarios there is a substantial commercial opportunity available in electric vehicle service provision. Indeed electric vehicle services are the single biggest element of new revenues available across all assessed future energy scenarios including ‘no-progression’. In contrast to the more volatile value pools (i.e. VP’#6 CCS), energy firms may see the energy services for EVs as a more attractive option, particularly because it is an ‘asset light’ strategy dependent on branding and tariff innovation as opposed to incurring large CAPEX sunk costs [78].

The third point is that five of the six value pools analysed become either large value pools or are destroyed entirely depending on the energy system scenario. VP#3, local low carbon electricity, is robust across all scenarios tested (including no progression), apart from DECC High Nuclear less energy efficiency, where it is destroyed. This suggests firm strategy formed to pursue this value pool would be a low risk in

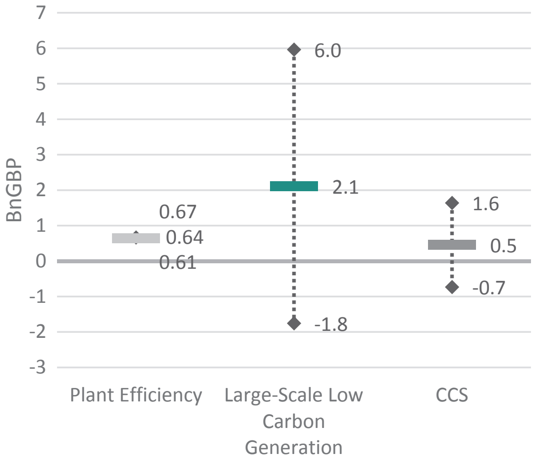

Fig. 17. Carbon price sensitivity: changes to avoided cost – value pools through variation of the carbon price by ± 50% in the NG gone green scenario in 2050.

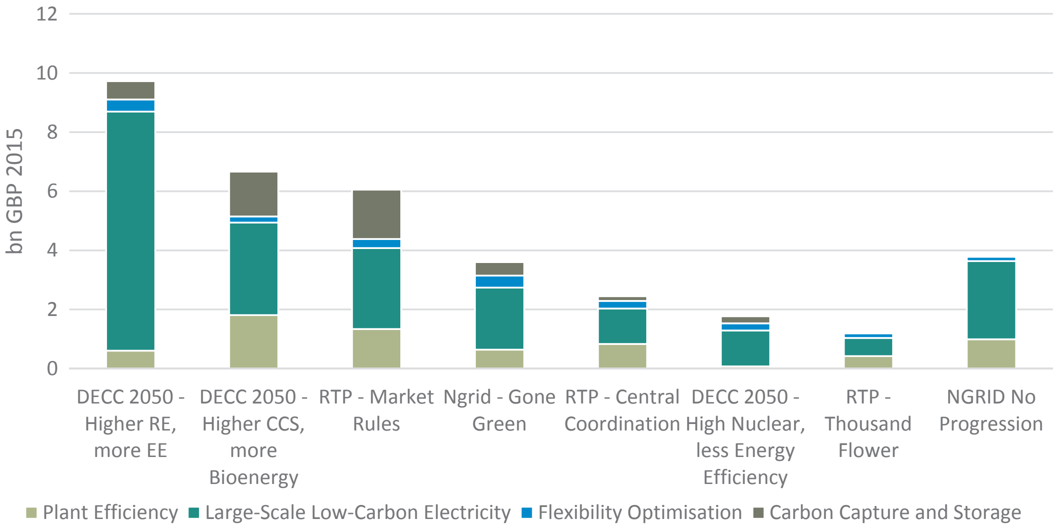

Fig. 16. Cumulative avoided costs across system futures in 2050 by value pool.

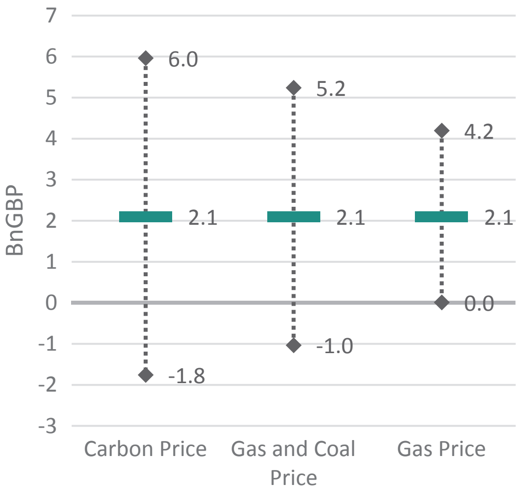

Fig. 18. Changes to VP#4 large-scale low carbon generation by varying carbon and fuel prices by ± 50% in the NG gone green scenario in 2050.

terms of complete asset stranding. In contrast, VP# 5 flexibility optimisation, and VP #6 CCS, are scenario sensitive and hence uncertain.

The fourth point is that the value pool method is compatible with the study objective, to understand how potential profit structures and market sizes over multiple future energy scenarios can be analysed. The identification and application of the value pool method across multiple system pathways enables assessment of 'industrial attractiveness' across uncertain futures. This is important for energy transitions in liberalised nations because the 'attractiveness' of industries such as energy service provision and flexibility will determine the risk perception of those sectors, the future levels of competition within them, and therefore the willingness of firms to allocate strategic resources to exploiting them. For example, the data above suggests that electric vehicle service provision is a robust value pool at low risk across multiple futures. The opposite is true for flexibility optimisation. All things being equal, the market pull for smart electric vehicle service would be much stronger than that for Demand Side Response or CCS, owing to the likely level of competition which will be created to acquire these new revenues. This demonstrates how the value pool method can bridge the gap between scenario modelling and investment decision-making under uncertainty, by using scenario outputs to determine potential market sizes across uncertain futures.

Returning to the resource based view of the firm and evolutionary firm theory, this would likely result in high competition and low profit margins in electric vehicle service provision, due to the relatively low costs of developing compatible financial, physical, human, organisational, informational and relational resources. These costs are low because servicing the electric vehicle value pool requires only tariff innovation, some smart metering, and tariff branding [78]. The combination of low barriers to entry (for incumbents) and a robust, sizeable value pool, suggests adapting utility business models to capture this revenue would be an attractive option. This may lead to strong 'market pull' and suggests innovation policy in this space need focus less on financial incentive, and more on securing an enabling regulatory environment. In contrast, one might expect low competition (or high firm failure rates) and higher relative profits for grid connected battery firms and CCS utilities. This is because it is a high risk strategy to acquire the financial, human, and other resources needed capture a new value pool that is so sensitive to both carbon pricing and future scenarios. This suggests low market pull, and may warrant innovation support including capital grants/subsidy. The flexibility optimisation value pool has low barriers to entry, however, the volatility of the sector may result in lower competition and higher profit margins for successful companies. Alternatively, flexibility companies may fail at increasing rates and render innovation support a critical component of energy policy.

The fifth and final point is that these data and the evolutionary, resource based view of the firm offer new and productive avenues of research that can link the energy systems modelling community to a more grounded and empirically realistic firm theory. This adds a new dimension to research on energy systems that can forge common ground between neo-classical models and more heterodox approaches [79]. Recent contributions [13,14] demonstrate that there are opportunities to deviate from perfect rationality within systems modelling and specifically demonstrate the ability of system models to vary capital costs/hurdle rates based on qualitative criteria [30]. An evolutionary

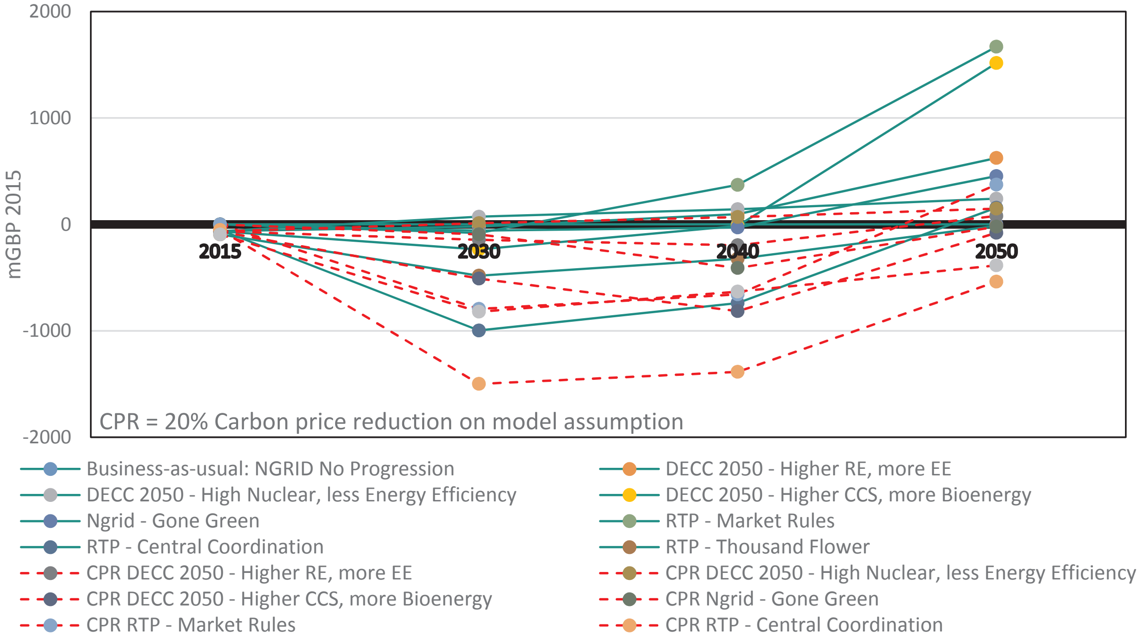

Fig. 19. The effect of a 20% reduction in carbon pricing on VP#6: CCS across scenarios.

resource advantage theory approach with a value pool method may be able to offer more realistic assumptions of firm dynamics, based on a more quantitative appreciation of future industry attractiveness and systemic market risks.

6. Conclusion

This research has demonstrated that the value pool approach, when combined with multiple future energy scenarios, is a valuable and insightful methodology to conduct a commercially focussed assessment of energy transitions. Cost optimisation or near optimisation models reporting in total investment costs are useful for energy and climate change policy making. Using the output of such models to investigate the creation and destruction of new values in energy transitions provides additional insight that could inform firm strategies, investor decision-making tools, and innovation policy. As contemporary energy systems in many developed nations comprise private firms seeking profits in competitive markets, this approach provides new insights applicable in a wide range of international and trans-national contexts, i.e. nations with liberalised or liberalising energy markets.

This analysis took the output of quantitative systems models to investigate how different value opportunities are created, re-scaled and destroyed by different energy futures. To address the ‘rational actor’ and ‘perfect foresight’ issues of current models, this value pool approach could be linked to provide inputs into firm behaviour, specifically by determining the levels of competition likely for each new opportunity created by energy transitions. A further extension of this work would be to investigate the business model innovations necessary to render future value propositions into revenue streams and ultimately firm profits.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.08.200.

References

[1] Mercure JF, Pollitt H, Chewpreecha U, Salas P, Foley AM, Holden PB, Edwards NR. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. Energy Policy 2014;73:686–700.
[2] Foxon TJ. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. Ecol Econ 2011;70(12):2258–67.
[3] Bolton R, Foxon TJ. A socio-technical perspective on low carbon investment challenges–insights for UK energy policy. Environ Innovation Societal Transitions 2015;14:165–81.
[4] Lempert RJ. A new decision sciences for complex systems. Proc Natl Acad Sci 2002;99:7309e7313. http://dx.doi.org/10.1073/pnas.082081699.
[5] Hughes N, Strachan N. Methodological review of UK and international low carbon scenarios. Energy Policy 2010;38(10):6056–65.
[6] Kannan R, Strachan N. Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches. Appl Energy 2009;86(4):416–28.
[7] Pfeiffer A, Millar R, Hepburn C, Beinhocker E. The ‘2 C capital stock’ for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Appl Energy 2016;179:1395–408.
[8] Caldecott B, McDaniels J. Stranded generation assets: Implications for European capacity mechanisms, energy markets and climate policy. Stranded Assets Programme, SSEE, University of Oxford; 2014. p. 1–62.
[9] Bolton R, Foxon TJ, Hall S. Energy transitions and uncertainty: Creating low carbon investment opportunities in the UK electricity sector. Environ Planning C: Government Policy 2016;34(8):1387–403.
[10] Watson J, Gross R, Ketsopoulou I, Winskel M. The impact of uncertainties on the UK’s medium-term climate change targets. Energy Policy 2015;87:685–95. http://dx.doi.org/10.1016/j.enpol.2015.02.030.
[11] Newbery DM. Towards a green energy economy? The EU Energy Union’s transition to a low-carbon zero subsidy electricity system–Lessons from the UK’s Electricity Market Reform. Appl Energy 2016;179:1321–30.
[12] Hall LM, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–28.
[13] Trutnevyte E. Does cost optimization approximate the real-world energy transition? Energy 2016;106:182–93.
[14] Li FG, Trutnevyte E. Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050. Appl Energy 2017;189:89–109.
[15] International energy agency. World energy outlook 2016, IEA, Paris; 2016.
[16] Strachan N, Pye S, Kannan R. The iterative contribution and relevance of modelling to UK energy policy. Energy Policy 2009;37. http://dx.doi.org/10.1016/j.enpol.2008.09.096.
[17] Newbery D. Policies for decarbonizing a liberalized power sector. Cambridge Working Papers in Economics 1614; 2016. https://doi.org/10.17863/CAM.5847.
[18] Reuter WH, Szolgayová J, Fuss S, Obersteiner M. Renewable energy investment: Policy and market impacts. Appl Energy 2012;97:249–54.
[19] Lam JCK, Woo CK, Kahrl F, Yu WK. What moves wind energy development in China? Show me the money!. Appl Energy 2013;105:423–9.
[20] Welkenhuysen K, Rupert J, Compernolle T, Ramirez A, Swennen R, Piessens K. Considering economic and geological uncertainty in the simulation of realistic investment decisions for CO 2-EOR projects in the North Sea. Appl Energy 2017;185:745–61.
[21] Ceseña EM, Mutale J, Rivas-Dávalos F. Real options theory applied to electricity generation projects: A review. Renew Sustain Energy Rev 2013;19:573–81.
[22] de Sisternes FJ, Jenkins JD, Botterud A. The value of energy storage in decarbonizing the electricity sector. Appl Energy 2016;175:368–79.
[23] Kitzing L, Juul N, Drud M, Boomsma TK. A real options approach to analyse wind energy investments under different support schemes. Appl Energy 2017;188:83–96.
[24] Kitapbayev Y, Moriarty J, Mancarella P. Stochastic control and real options valuation of thermal storage-enabled demand response from flexible district energy systems. Appl Energy 2015;137:823–31.
[25] Hernandez-Perdomo EA, Mun J. Active management in state-owned energy companies: Integrating a real options approach into multicriteria analysis to make companies sustainable. Appl Energy 2017;195:487–502.
[26] Helms T. Asset transformation and the challenges to servitize a utility business model. Energy Policy 2016;91:98–112.
[27] Nillesen P, Pollitt M. New business models for utilities to meet the challenge of the energy transition. Future of Utilities-Utilities of the Future: How Technological Innovations in Distributed Energy Resources Will Reshape the Electric Power Sector 2016:283.
[28] Grant RM. The resource-based theory of competitive advantage: implications for strategy formulation. California Manage Rev 1991;33(3):114–35.
[29] Porter ME. The five competitive forces that shape strategy. Harvard Business Rev 2008;86(1):25–40.
[30] Li FG. Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. Energy Strategy Rev 2017;15:57–71.
[31] Hunt SD. Resource-advantage theory: An evolutionary theory of competitive firm behavior? J Econ Issues 1997;31(1):59–78.
[32] Barney JB. Resource-based theories of competitive advantage: A ten-year retrospective on the resource-based view. J Manage 2001;27(6):643–50.
[33] Rothaermel FT. Complementary assets, strategic alliances, and the incumbent’s advantage: an empirical study of industry and firm effects in the biopharmaceutical industry. Res Policy 2001;30:1235–51.
[34] Unruh GC. Understanding carbon lock-in. Energy policy 2000;28(12):817–30.
[35] Hunt SD, Morgan RM. The resource-advantage theory of competition: dynamics, path dependencies, and evolutionary dimensions. J Marketing 1996:107–14.
[36] Kemp R, Schot J, Hoogma R. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol Anal Strategic Manage 1998;10(2):175–98.
[37] Geels FW. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ Innovation Societal Transitions 2011;1(1):24–40.
[38] Horbach J, Rammer C, Rennings K. Determinants of eco-innovations by type of environmental impact—The role of regulatory push/pull, technology push and market pull. Ecol Econ 2012;78:112–22.
[39] Foxon T, Gross R, Chase A, Howes J, Arnall A, Anderson D. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy Policy 2005;33:2123–37. http://dx.doi.org/10.1016/j.enpol.2004.04.011.
[40] Gadiesh O, Gilbert JL. Profit pools: a fresh look at strategy. Harvard Business Rev 1997;76(3):139–47.
[41] Mankins MC, Steele R. Turning great strategy into great performance. Harvard Business Rev 2005:2607.
[42] Eurelectric. Utilities: powerhouses of innovation - full report; 2013. Available at: http://www.eurelectric.org/media/79178/utilties_powerhouse_of_innovation_full_report_final-2013-104-0001-01-e.pdf.
[43] McKinsey. European electric power and natural gas: beyond the storm – value growth in the EU power sector. McKinsey & Company; 2014.
[44] van Beek M, Holst A, Keeble J. Low carbon, high stakes - do you have the power to transform? Accenture Strategy; 2015.
[45] Hall S, Roelich K. Business model innovation in electricity supply markets: The role of complex value in the United Kingdom. Energy Policy 2016;92:286–98.
[46] HM government, climate change act 2008. Available at: http://www.legislation.

gov.uk/ukpga/2008/27/contents.

[47] Foxon TJ. Transition pathways for a UK low carbon electricity future. Energy Policy 2013;52:10–24.

[48] National grid. Future energy scenarios 2016, national grid; 2016. Available at: http://fes.nationalgrid.com/fes-document/.

[49] Supplementary information 1: methodological data and scenario criteria.

[50] Supplementary information 2: full value pool model, data sources and assumptions.

[51] IEA. Energy technology perspectives 2014: harnessing electricity's potential. Paris: France; 2014.

[52] Department for business, energy and industrial strategy. Digest of UK energy statistics 2016, chapter 5, BEIS; 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/577712/DUKES_2016_FINAL.pdf.

[53] IEA. Transition to sustainable buildings: strategies and opportunities to 2050. Paris: International Energy Agency; 2013.

[54] Pye S, Usher W, Strachan N. The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Policy 2014;73:575–86.

[55] Laws ND, Epps BP, Peterson SO, Laser MS, Wanjiru GK. On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage. Appl Energy 2017;185:627–41.

[56] Competition and markets authority. Energy market investigation, final report, CMA, London; 2016.

[57] UK green building council, building places that work for everyone; industry insights into key government priorities February; 2017.

[58] Gouldson A, Kerr N, Millward-Hopkins J, Freeman MC, Topi C, Sullivan R. Innovative financing models for low carbon transitions: Exploring the case for revolving funds for domestic energy efficiency programmes. Energy Policy 2015;86:739–48.

[59] Quoilin S, Kavvadias K, Mercier A, Pappone I, Zucker A. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. Appl Energy 2016;182:58–67.

[60] PWC. Looking ahead: Future markets and business models, PWC, Accessed online March 2017; 2014. Available at: https://www.pwc.com/gx/en/utilities/publications/assets/pwc-future-utility-business-models.pdf.

[61] International energy agency. Tracking clean energy progress 2016, OECD/IEA Paris; 2016.

[62] Newbery DM. Towards a green energy economy? The EU Energy Union's transition to a low-carbon zero subsidy electricity system - lessons from the UK's electricity market reform. Appl Energy 2016. http://dx.doi.org/10.1016/j.apenergy.2016.01.046. in press.

[63] Laleman R, Albrecht J. Comparing push and pull measures for PV and wind in Europe. Renewable Energy 2014;61:33–7. http://dx.doi.org/10.1016/j.renene.2012.04.025.

[64] Department for business, energy, and industrial strategy. Electricity generation costs, November 2016; 2016. Accessed online, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/566567/BEIS_Electricity_Generation_Cost_Report.pdf.

[65] Ares E, Delebarre J. The carbon price floor, briefing paper number CBP05927, 23rd November 2016, House of Commons Library; 2016. Available at http://researchbriefings.files.parliament.uk/documents/SN05927/SN05927.pdf.

[66] Committee on climate change. Fifth carbon budget: the next step towards a low carbon economy. CCC; 2015. Available at https://www.theccc.org.uk/wp-content/uploads/2015/11/Committee-on-Climate-Change-Fifth-Carbon-Budget-Report.pdf.

[67] Wintour P, Vaughn A. Tories to end onshore windfarm subsidies in 2016. The Guardian, 18th June 2015; 2015.

[68] National grid. Keeping the electricity transmission system in balance. National grid; 2017. Accessed online May 2017 at: http://www2.nationalgrid.com/uk/services/balancing-services/.

[69] UK power networks. UK power networks (ed.). UKPN SNS WS4 - investment model template; 2013.

[70] Nord Pool AS. N2EX - Trading Rules; 2016. Available from: http://www.nordpoolspot.com/TAS/Rulebook-for-the-Physical-Markets/n2ex/ [accessed 30.03.2016].

[71] Frontier economics. Future potential for DSR in GB, a report prepared for DECC by frontier economics with support from LCP and sustainability first; 2015. Available at: https://www.gov.uk/government/publications/future-potential-for-demand-side-response-in-great-britain.

[72] Drysdale B, Wu J, Jenkins N. Flexible demand in the GB domestic electricity sector in 2030. Appl Energy 2015:139281–90.

[73] BEIS. Energy consumption in the UK; 2016. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/573269/ECUK_November_2016.pdf.

[74] Selosse S, Ricci O. Carbon capture and storage: Lessons from a storage potential and localization analysis. Appl Energy 2017;188:32–44.

[75] Schreiber A, Zapp P, Marx J. Meta-analysis of life cycle assessment studies on electricity generation with carbon capture and storage. J Ind Ecol 2012;16(s1):S155–68.

[76] DECC. 2050 pathways calculator with costs; 2012. Available at: https://www.gov.uk/guidance/2050-pathways-analysis.

[77] Hammond GP, Akwe O, Williams S. Techno-economic appraisal of fossil-fueled power generation systems with carbon dioxide capture and storage. Energy 2011;36(2):975–84.

[78] Hall S, Shepherd SP, Wadud Z. The innovation interface: business model innovation for electric vehicle futures. University of Leeds; 2017. Available at: http://eprints.whiterose.ac.uk/111115/1/11167_SEE_electrical_vehicles_report_WEB.pdf.

[79] Felder F. Why can't we all get along? a conceptual analysis combined with a case study. Energy Policy 2016;96:711–6.