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Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050

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HIGHLIGHTS

- 800 future transition pathways for the UK power sector explored under uncertainty.
- Analysis combines Monte Carlo simulation and Modelling-to-Generate-Alternatives (MGA).
- Many technologically diverse pathways are found to incur similar overall costs.
- Meeting climate targets may require an additional 25–70 GW of power capacity.
- Achieving climate targets may require additional investments of £35bn–£80bn.

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ABSTRACT

Deep decarbonisation of the electricity sector is central to achieving the United Kingdom's (UK) climate policy targets for 2050 and meeting its international commitments under the Paris Agreement. While the overall strategy for decarbonising the energy system has been well established in previous studies, there remain deep uncertainties around the total investment cost requirements for the power system. The future of the power system is of critical importance because low carbon electricity may create significant opportunities for emissions reduction in buildings and transport. A key policy application of quantitative analysis using models is to explore how much investment needs to be mobilised for the energy transition. However, past estimates of energy transition costs for the UK power sector have focused only on 2030 rather than 2050 and consider a relatively narrow range of uncertainties. This paper addresses this important research gap. The UK government's main whole system energy economy model is linked to a power system model that employs an advanced approach to uncertainty analysis, combining Monte Carlo simulation with Modelling-to-Generate Alternatives (MGA), producing 800 different scenario pathways. These pathways simultaneously consider uncertainties in policy, technology and costs. The results show that with *No Climate Policy*, installed generation capacities in 2050 are found in the range 60–75 GW, while under an *80% Reduction in GHG Emissions*, between 100 GW and 130 GW of plant are required. Meeting climate targets for 2050 is also found to increase the investment requirements for new electricity generation. The interquartile range for cumulative investments in new generation under the *No Climate Policy* scenario ranges from £60bn to £75bn, while under an *80% Reduction in GHG Emissions*, investment requirements approximately double to £110bn - £140bn. The exercise demonstrates the importance of uncertainty analysis to policy evaluation, yielding insights for future research practice both in the UK and internationally.

1. Introduction: investment needs and the key uncertainties facing the UK electricity sector

The Paris Agreement commits signatories from 175 states to limiting anthropogenic global warming below 2 °C above pre-industrial levels [1]. Achieving this objective will require large-scale decarbonisation of the global energy system through actions taken at the level of individual countries. Under Article 4, more developed countries are expected to take a leading role. Examples of deep decarbonisation analysis can be found for multiple countries, including China [2,3], the United States [4], Germany [5], Denmark [6], Ireland [7], Switzerland [8], Portugal [9], and the United Kingdom [10,11]. The United Kingdom (UK) is one example

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of an advanced economy which is already committed to ambitious long-term decarbonisation targets. These targets are enshrined in law under the Climate Change Act 2008 [12], and are implemented as a series of carbon budgets subject to monitoring by an independent regulator [13].

Whole system analyses of long-term climate mitigation strategies for the UK that simultaneously evaluate options for buildings, industry, transport and energy supply have shown the critical role of decarbonising the UK electricity sector [14,15]. Most modelled UK low-carbon pathways that achieve climate targets for 2050 rely on the rapid decarbonisation of electricity generation before the 2030s in order to later electrify large fractions of building heating and road transport [16]. Model-based insights have led to the decarbonisation of the power sector and the electrification of heating and transport becoming key pillars of the UK government's greenhouse gas (GHG) emissions reduction strategy [17–19]. However, while the strategic direction of travel is clear, the level of investment costs required to mobilise the energy transition remains an important unresolved area for policymakers.

Previous analyses have evaluated the investment costs associated with a handful of potential electricity sector pathways out to the 2030s [20,21]. However, these pathways accounted for only a limited set of uncertainties and did not include an outlook to 2050 (Section 3). The willingness of investors to finance new low-carbon generation remains a major uncertainty [22]. The 2008 financial crisis left many traditional financing sources, such as banks, in a weakened state and recent "Electricity Market Reform" measures have been designed to attract investment from a wider range of financial institutions [23]. However, empirical research suggests that institutional investors are currently deterred from placing funds into low-carbon infrastructures because of the perceived high risks caused by the Government's uncertain strategic intentions [24]. It remains to be seen whether the UK's current institutional and governance arrangements will be fit for purpose and deliver the required investment levels, or whether other alternatives may need to be pursued. Research has explored market-, state- and civic-led pathways for the electricity sector [25], but it remains far from clear what the most effective governance arrangements could be to drive the desired transition.

Another key uncertainty is the timing for the commercial availability and deployment of key low-carbon generation technologies and their future costs in the period to 2050 [22,26]. For example, new nuclear power has received significant policy support in the UK, but attracting investment for the first new plant, Hinkley Point C, has been an extremely challenging process [27]. The UK has historically been a strong proponent of nuclear power despite vociferous opposition from various political and civil society groups [28]. Nuclear power is not the only low-carbon power technology that potentially faces deep uncertainties and an uphill struggle. Fossil-fuelled plants fitted with Carbon Capture and Storage (CCS) have been identified as key to enabling an affordable transition towards UK climate targets [13,14,29]. Although pilot and demonstration projects are essential for the eventual commercialisation of CCS [30,31], in 2016 the UK Government cancelled its support for a CCS demonstration programme for the second time in 5 years [32]. This again increases uncertainties about the future costs and availability of CCS in the UK.

Other key uncertainties highlighted in both expert elicitations and model-based analyses include the influence of economic growth, population demographics [26], and long-term shifts in energy demand resulting from changes to behaviour and lifestyles [33]. The costs of fossil fuels, for which the UK is a net importer, are uncertain and could be highly significant for the future transition [15,26,34]. The future availability of bioenergy resources is another widely-acknowledged uncertainty [35–37]. Bioenergy may be central for decarbonising many UK economic sectors such as industry, heating and transport. It could also be particularly important in electricity generation, especially when used in conjunction with CCS technology to achieve negative emissions [15]; though this is considered by many to be a controversial strategy [38].

Finally, there are large uncertainties associated with the socio-political dimension to energy policy [22]. The UK Climate Change Act enjoyed broad cross-party political support when it was implemented in 2008, but the political appetite to strive for extremely challenging climate targets has yet to be seriously tested [39]. The new administration which came into power in July 2016 has taken the step of abolishing the UK Department of Energy and Climate Change (DECC), potentially signalling that environmental issues are falling down the policy priority scale. It remains to be seen whether an electorate that can vote out unpopular governments will be willing to bear the increased and sustained costs of any future energy transition [40].

2. Study objectives

Deep decarbonisation of the electricity system is central to achieving the UK's climate targets for 2050. While the critical role of the power sector in enabling emissions reductions has become broadly accepted in the energy policy community, critical details for implementing this strategy such as understanding the total costs involved remain underexplored. The costs of meeting the decarbonisation challenge are subject to multiple uncertainties that make investment appraisals difficult. This study aims to review past investment analyses (Section 3), evaluate the current state-of-the-art in energy modelling and uncertainty analysis (Section 4), and conduct an original UK electricity sector investment appraisal for the period 2010–2050 under a broad spectrum of policy, technology and cost uncertainties (Sections 5 and 6). Finally, the implications for UK and international energy policy and research into energy systems decarbonisation using quantitative models is explored (Sections 7 and 8).

3. Review of existing estimates of the UK electricity sector investment requirements

Before presenting our own analysis in Sections 5 and 6, we first present a review of past estimates of the investment costs required to transform the UK electricity sector. In line with earlier overviews by Blyth et al. [41] and Trutnevyte et al. [20], a range of first-order estimates for investment costs from a variety of sources is shown in Fig. 1. To enable cross-comparison across different time horizons, investment costs are expressed in terms of annual capital expenditure.

Historically, after the UK energy market liberalisation of the 1990s, investment into the power sector averaged around £3-4bn [20], with this rising to an average of £11bn from 2010 to 2013 [50]. Fig. 1 shows that there is significant variation in the estimates of future investment requirements. This variation not only arises from the different time horizons considered, but also from differing assumptions with respect to technology-specific investment costs, electricity demand, and the future electricity generation mix. Despite the relatively large number of published estimates (Fig. 1), understanding the scale of the investment challenge remains difficult. The spread of estimates is wide and it is not immediately clear where the differences come from. A cross-comparison of existing estimates is a useful starting point for discussion but does not begin to unpick the complex web of uncertainties affecting the future investment requirements. To assess these uncertainties, some of the core assumptions are compared in Table 1.