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Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security

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HIGHLIGHTS

- We compare a large number of cost-optimal future power systems for Great Britain.
- Scenarios are assessed on cost, emissions reductions, and energy security.
- Up to 60% of variable renewable capacity is possible with little cost increase.
- Higher shares require storage, imports or dispatchable renewables such as tidal range.

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ABSTRACT

Mitigating climate change is driving the need to decarbonize the electricity sector, for which various possible technological options exist, alongside uncertainty over which options are preferable in terms of cost, emissions reductions, and energy security. To reduce this uncertainty, we here quantify two questions for the power system of Great Britain (England, Wales and Scotland): First, when compared within the same high-resolution modeling framework, how much do different combinations of technologies differ in these three respects? Second, how strongly does the cost and availability of grid-scale storage affect overall system cost, and would it favor some technology combinations above others? We compare three main possible generation technologies: (1) renewables, (2) nuclear, and (3) fossil fuels (with/without carbon capture and storage). Our results show that across a wide range of these combinations, the overall costs remain similar, implying that different configurations are equally feasible both technically and economically. However, the most economically favorable scenarios are not necessarily favorable in terms of emissions or energy security. The availability of grid-scale storage in scenarios with little dispatchable generation can reduce overall levelized electricity cost by up to 50%, depending on storage capacity costs. The UK can rely on its domestic wind and solar PV generation at lower renewable shares, with levelized costs only rising more than 10% above the mean of 0.084 GBP/kWh for shares of 50% and below at a 70% share, which is 35% higher. However, for more than an 80% renewable generation share to be economically feasible, large-scale storage, significantly more power imports, or domestic dispatchable renewables like tidal range must be available.

1. Introduction

There is wide agreement in the climate science community that global greenhouse gas emissions must be reduced by at least 80–90% by 2050 in order to avoid severe climate change [1]. The UK government has put into place ambitious legislation to reach this goal with the 2008 Climate Change Act, which stipulates an economy-wide 80% emissions reduction by 2050, relative to 1990. Much work has been conducted on possible configurations of the UK's energy system on that basis, and on cost-effective pathways to achieve such configurations (e.g. [2–4]). A common theme (mirrored by work for other countries, e.g. [5]) is that first, the electricity sector must be largely emissions-free, and second, significantly more electricity will be needed to help decarbonize other sectors (such as heating and road transportation). Renewable energy is seen as one key source of low-carbon energy, and policies are therefore in place to support its deployment. While there is some recent uncertainty around the strength of policy

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commitments in the wake of the European Union's 2030 renewables target, which is binding only at an EU level [6], the deployment of renewable power generation has been steadily advancing, and this trend is likely to continue both in the UK and globally [7].

The deployment of renewable energy in the UK can be seen in the light of climate change mitigation, but also as part of a desire to balance affordability with energy security [8]. To achieve these goals, energy system models are crucial tools to produce high-level scenarios, providing broad guidance on what mix of technologies is more desirable or cost-effective under a given set of assumptions and policy choices. A recent example for the UK is the UK Energy Research Center (UKERC) scenarios for the 2050 energy system [4]. However, large-scale energy system models do not incorporate the necessary degree of spatial and temporal detail to examine different ways in which different mixes of renewables with existing technologies could be achieved [9]. There has therefore been increasing interest in using spatially and temporally explicit models to examine systems with higher shares of renewables in greater detail (e.g. [10]). While energy system models are one approach to generating scenarios, there are two main approaches for managing them: one where a small set of (often narrative) scenarios are carefully crafted [11], and the other, where a large number of scenarios are generated computationally and analyzed for salient features. Examples of the latter approach are the Modeling to Generate Alternatives method [12] or the scenario discovery methods developed at RAND [13].

Here, we investigate the three contrasting objectives for the future UK energy system: within a common model framework, how well does a future power system based on different combinations of technologies work in terms if its total system cost, its greenhouse gas emissions, and its energy security? A particular focus is on systems with high shares of wind and solar PV, and approaches, such as storage, to improve the cost and reliability of such systems. This investigation is performed by combining a newly developed cost-optimizing model with high resolution in space and time with the ability to generate and analyze a large number of scenarios. Generation technologies are grouped into three classes: renewables, fossil fuels, and nuclear. The scenarios are grouped by a key narrative (e.g., "deployment of carbon capture and store (CCS)" or "large-scale solar imports"), and within each of these groups, a number of different combinations of the three technology classes are explored. The approach used here improves on existing large-scale energy system models in three ways. First, it goes beyond single representative time slices to a full year of data. Second, it disaggregates the GB power system into 20 zones and considers transmission between the zones. This means that possible transmission bottlenecks as well as the spatial correlation of wind and solar power can be considered. Third, it can run and analyze a large number of models while varying one or a few key parameters, in order to explore the solution space.

The paper proceeds as follows. A literature review section discusses other work with similar aims or methods. It is followed by the description of methods (for more detail on these, also refer to the Supplementary material), and the results. The next section discusses sensitivity analyses as well as weaknesses of and possible improvements to the approach taken here, and is followed by a concluding discussion on the significance of the results obtained.

2. Literature review

The analysis presented here builds on three classes of existing work. The first class consists of large-scale scenarios of the entire energy system, often derived from optimization models, which attempt to describe various feasible energy system transition scenarios under a range of different assumptions. In the UK, the MARKAL model has been for many large-scale modeling exercises in support of the policy process [14], superseded more recently by the TIMES model [4]. These models depict the entire energy system and assess scenarios based on high-level constraints, such as the costs of technologies, or the expected deployment speed and potential. Large-scale scenario models, even when assessing futures with high shares of renewable energy, also must take simplifications to deal with computational tractability and data availability. A common simplification is to match output with demand annually or for a small set of time slices rather than for real (e.g. hourly) time series [15].

The second class is work that models 100% renewable energy systems (but often focusing on electricity only), attempting to complement large-scale analyses from the first class with more detailed considerations of renewable energy's technical feasibility (sometimes leaving aside economic considerations). For example, Connolly et al. [16] shows that a 100% renewable Ireland is technically possible using 1-hourly simulation with the EnergyPLAN model, but does not discuss the costs of this. Likewise, Heide et al. [17] discuss requirements for storage if Europe were to be powered with renewables, using detailed renewable resource data and modeling, but also leaving aside transmission network and economic considerations. Lund and Mathiesen [18] show similarly that a 100% renewable Denmark is physically possible with several caveats, including the necessity of a widely coordinated approach and requiring either large-scale biomass or hydrogen deployment. Costs for an intermediate target in 2030 are considered, but not the 2050 endpoint.

Scenarios from these first two groups of studies disagree significantly on the importance and feasibility of key technology groups such as nuclear power or fossil fuels with CCS. These disagreements are partially driven by differing levels of detail on technical feasibility and partially by how strongly economic considerations are included (e.g. via cost minimization) [19]. The third and final class consists of more recent attempts to synthesize approaches from both previous groups, combining (1) more spatial and temporal detail based on measured or modeled renewable resource data, and (2) modeling these constraints in the context of economic capacity planning.

One of the ways for renewables integration is large-scale storage, and as this is only possible with sufficient temporal detail, it has served as a driver for more detailed models. Budischak et al. [20] evaluate cost-minimal combinations of wind, solar and grid-scale storage for the northeastern United States, which can be considered a similar scale as a single European country. They find that with grid-scale storage of between 9–72 h and 50–60 GW throughput (which is about double the average demand in the studied system), and with renewables generating three times as much as actual demand, it is possible to meet demand 99.9% of the time at costs comparable to today (with assumptions for 2030 technology costs). A different modeling approach is to link different models, taken for example by [21], who discuss a framework which iteratively solves the TIMES long-term optimization model followed the EnergyPLAN short-term operational model to better consider the influence of fluctuating renewables on capacity planning. Using average daily renewable capacity factors and demand data for Portugal, they show that in cases with low storage availability, combining both models led to substantially different installed capacities compared to TIMES on its own. An alternative to storage is increased interconnection to balance meteorological conditions across space. Haller et al. [22] assess a high renewables future by modeling 19 zones across Europe and the possibility for interconnection and storage using a selection of 49 six-hourly time slices, finding that adequately deployed grid extensions and storage technologies enable renewables shares up to about 60% at an