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Low carbon electricity systems for Great Britain in 2050: An energy-land-water perspective

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HIGHLIGHTS

- We assess how land and water constraints shape Great Britain's 2050 power system.
- We consider restrictions on nuclear/renewables siting and water for cooling.
- Combined these lead to an up to 25% more costly electricity system.
- Such constraints impact the system design both spatially and technologically.
- The cost optimal share of renewable generation is found to be at least 50%.

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ABSTRACT

The decarbonisation of the power sector is key to achieving the Paris Agreement goal of limiting global mean surface temperature rise to well below 2 °C. This will require rapid, national level transitions to low carbon electricity generation, such as variable renewables (VRE), nuclear and fossil fuels with carbon capture and storage, across the world. At the same time it is essential that future power systems are sustainable in the wider sense and thus respect social, environmental and technical limitations. Here we develop an energy-land-water nexus modelling framework and use it to perform a scenario analysis with the aim of understanding the planning and operational implications of these constraints on Great Britain's (GB) power system in 2050. We consider plausible scenarios for limits on installed nuclear capacity, siting restrictions that shape VRE deployment and water use for thermal power station cooling. We find that these factors combined can lead to up to a 25% increase in the system's levelised cost of electricity (LCOE). VRE siting restrictions can result in an up to 13% increase in system LCOE as the deployment of onshore wind is limited while nuclear capacity restrictions can drive an up to 17% greater LCOE. We also show that such real-world limitations can cause substantial changes in system design both in terms of the spatial pattern of where generators are located and the capacity mix of the system. Thus we demonstrate the large impact simultaneously considering a set of nexus factors can have on future GB power systems. Finally, given our plausible assumptions about key energy-land-water restrictions and emission limits effecting the GB power system in 2050, the cost optimal penetration of VREs is found to be at least 50%.

1. Introduction

Limiting global mean surface temperature rise to well below 2 °C above pre-industrial levels, the headline goal of the UNFCCC Paris Agreement, will require large scale changes to energy systems across the world, transitioning from carbon intensive today to 'net-zero' emissions before 2100 [1]. At the same time as achieving deep cuts in greenhouse gas (GHG) emissions, these national level energy system transitions must simultaneously address the other two pillars of the so-called energy trilemma by keeping overall costs as low as possible and enhancing and maintaining energy security. In this context, energy system optimisation models (ESOM), which capture a simplified representation of this complex problem, are often used to support and guide national and international policy making. These stylised models optimise the planning and operation of the energy system over a particular time horizon by minimising total costs under technology, emissions and policy constraints.

Long time horizon national whole energy system models such as the

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National Energy Modeling System [2] and UK TIMES (UKTM; [3]) are used to conduct scenario analyses which explore possible decarbonisation pathways to meet policy objectives and are particularly relevant given the bottom-up, Nationally Determined Contribution framing of The Paris Agreement. A common theme emerging from such scenarios (e.g. see Fais et al. [4]) is that the electricity sector will lead the decarbonisation charge, as it is already beginning to do, owing to its comparatively low marginal abate costs and that, in conjunction with the electrification of heat and transport, demand for electricity will grow in future, despite an overall increase in system efficiency. At present, key low carbon generation technologies that can support such a transition take three main forms: variable renewables (VRE) such as solar photovoltaics (PV) and wind, nuclear power and fossil generation with carbon capture and storage (CCS), which is considerably less proven at scale and thus has a more uncertain role going forward. It is this sector and these technology classes that will be the focus of this study.

While the aforementioned trilemma encapsulates three of the principle objectives of energy system transitions, these are by no means the only factors that guide the design of future low carbon energy infrastructure. With this in mind, for some time now a need has been identified to move beyond the trilemma to consider how the planning and operation of such systems will likely have implications for the wider coupled social, economic and environmental system in terms of a nexus of energy, land and water [5–7]. This natural resource viewpoint helps to add context to low carbon transitions and allows an assessment of their broader feasibility and impacts. For instance, future power systems could feature substantial amounts of fossil generation with CCS which rely on water for their cooling and have abstraction requirements significantly beyond that of their none CCS counter parts. If this extra abstraction is to be met by freshwater it must be considered simultaneously with increasing pressure from population growth and climate change [8]. Furthermore, solar and wind have seen substantial cost reductions globally in recent decades making them attractive options going forward, yet their scale, visibility, and infrastructure requirements mean that specific projects often face significant opposition due to a range of social, environmental and technical factors. For example, Höltinger et al. [9] found that Austria's physical onshore wind resource potential is reduced by over 95% when taking into account the multi-aspect criteria which can inhibit its deployment. Indeed, nuclear too can experience multifaceted issues around its siting for various, often quite different, reasons [10]. Therefore, all three of the key generation technology classes considered here have non-cost restrictions that will very likely shape their deployment in future and as a result could have a sizable impact on system costs and design.

To understand this complex problem, studies have taken various modelling approaches (for a full review of methods and tools see Dai et al. [11]). Some teams have brought together and integrated a number of models to form a nexus focused modelling framework with examples including the Climate, Land, Energy and Water Systems (CLEWS) framework [12,13] or the PRIMA model [14]. Other studies have integrated water directly into a sub-national [15], national [16] or regional [17] ESOM, thus forming a hard-link and allowing them to optimise the electricity system and its usage of water at the same time. On the land side, efforts have concentrated on bioenergy production and its interaction with the food system (e.g. [18,19]) while other papers have included siting limitations during the calculation of wind energy potentials [9,20,21] and both solar and wind in an ESOM [22]. From a UK perspective, studies investigating restrictions on water resources have typically taken pre-existing energy/electricity system scenarios and sought to estimate their footprints in terms of cooling [23–27]. Only very recently has cooling water availability been integrated into an ESOM and allowed to endogenously influence power system design Murrant et al. [28]. UK modelling studies addressing land-energy interactions have looked at bioenergy (e.g. [18,29]) and included constraints on the siting of wind turbines [30]. Work which has captured both resources (e.g. [25]) has focused on an analysis of pre-existing scenarios. None of these studies have simultaneously considered the implications of land and water availability, and its geographic detail, on the design of future low carbon electricity systems while at the same time modelling both key VREs, i.e. solar PV and wind, at a high spatiotemporal resolution.

Unlike conventional sources of generation, VREs possess significant spatiotemporal variability because of their dependence on weather. Studies have demonstrated the impact that low temporal [31] and spatial resolution [32] can have on results from ESOMs when modelling systems with significant renewable shares. To capture how important renewable sources such as solar and wind interact with the rest of the electricity system, e.g. dispatchable generation, electricity storage and the transmission network, studies have resorted to three key approaches. Firstly, efforts have been made to increase their temporal and spatial resolution (e.g. [32–34]). Secondly, separate system planning (capacity expansion) and detailed operational dispatch models have been integrated together, either in the form of a uni-directional (e.g. [35]) or bi-directional, iterative (e.g. [36]) link. Thirdly, recently a number of studies have used hybrid high spatial and temporal resolution ESOMs that simultaneously make investment and hourly operational decisions for a single "snapshot" year at a time (e.g. [22,37,38]). A key advantage of hybrid models is that both planning and dispatch decisions are made in the same high resolution whole electricity system framework. In addition, their spatiotemporal disaggregation allows them to simultaneously examine the system benefits of different contemporaneous weather conditions in different locations (spatial diversification) and different production profiles for different VRE technologies (technological diversification).

In this paper, and to the best of our knowledge for the first time, we simultaneously consider how constraints on both land-use and water for cooling impact the spatially detailed planning and high resolution operation of low carbon electricity systems consisting of the three key technology classes outlined above. We specifically focus on the cost and system design implications of restrictions on both resources at the same time. To do this we bring together two ESOMs, the high spatial and temporal resolution electricity system model (highRES) and the long time horizon ESOM UKTM, and a nexus tool, Foreseer,[1] and present a case study of potential future configurations of Great Britain's (GB) power system in 2050 taking into account land and water resource limitations. The system is further constrained by the UK's Climate Change Act which mandates an economy wide GHG emissions reduction of 80% relative to 1990 levels by 2050. We frame our land and water resource analysis in the context of the three technology classes outlined above and aim to represent some of the key restrictions that shape the deployment of each technology, i.e. water availability for power station cooling and limitations on the siting of VRE and nuclear. We use UKTM to provide 2050 electricity system boundaries to highRES, a nexus-aware hybrid power system model. A uni-directional soft-link of this kind ensures that the latter model designs scenarios that are consistent with the rest of the energy system, i.e. in terms of the demand met and emissions produced by the electricity system. The land and water constraints in the hybrid model are formulated by integrating methods and data from the nexus tool directly into it. Into this framework we feed a set of scenarios that are intended to span the plausible range of key restrictions that shape the deployment of the three technology classes we consider with the aim of quantifying the potential cost and system design impacts of these constraints.

This paper is structured as follows: in Section 2 we describe the models and methodology used here in more detail, Section 3 provides a thorough discussion of the results and Section 4 summaries the insights emerging from this study.

[1] https://www.foreseer.group.cam.ac.uk/.