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# Thermal power plant operating regimes in future British power systems with increasing variable renewable penetration

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ABSTRACT

This work investigates the operational requirements of thermal power plants in a number of potential future British power systems with increasing variable renewable penetration. The PLEXOS Integrated Energy Model has been used to develop the market models, with PLEXOS employing mixed integer programming to solve the unit commitment and economic dispatch problem, subject to a number of constraints. Initially, a model of the British power system was developed and validated. Subsequently, a 2020 test model was developed to analyse a number of future system structures with differing fuel and carbon prices and generation mixes. The study has found that in three of the four scenarios considered, the utilisation of gas power plants will be relatively low, but remains fundamental to the security of supply. Also, gas plants will be subject to more intense ramping. The findings have consequent implications for energy policy as expensive government interventions may be required to prevent early decommissioning of gas capacity, should the prevailing market conditions not guarantee revenue adequacy.


## 1. Introduction

Power systems across the world will have to be decarbonised in order to satisfy legally binding emission reduction targets. In 2008 the UK government passed the Climate Change Act, legally committing the government to reduce GHG (greenhouse gas) emissions by 80% on 1990 levels by 2050 [1]. With electricity generation accounting for 27% of the GHG emissions in the UK, it is considered that in order to reduce emissions by 80% then the electricity system will have to be almost completely decarbonised [2,3]. Nations across the European Union are also bound to shorter-term emission reduction targets under European legislation [4]. Due to these targets and many other policies, such as the phase out of nuclear power in Germany, generation mixes in a number of countries are experiencing rapid changes. Due to the EU legislation, the UK has set an indicative target for 40% of electricity to be generated by low carbon technologies by 2020 [5].

While EU legislation beyond 2020 remains unclear, the UK is required to meet the targets set within the fourth carbon budget, namely a 50% emissions reduction on 1990 levels by 2025 [6]. The Climate Change Committee have stated that 30–40 GW's of low carbon capacity needs to be added to the power system through the period 2020–2030, in order to meet the fourth carbon budget and to prepare for the 2050 target [7]. In 2012, renewables (11.3%) and nuclear (19%) contributed 30.3% of the UK's electricity generation [8]. In order to meet the targets, it is expected that wind power will contribute between 50 and 90 TW h of electricity generation in the UK by 2020 [9].

The International Energy Agency [10] reports six properties that differentiate variable renewable generation technologies, notably wind and solar, from conventional thermal generation. Output from renewable generation is *uncertain*, in that it is difficult to predict accurately ahead of time, and *variable*, in that output varies significantly over time. These technologies can be described as *modular*, with unit outputs that are typically much lower than conventional thermal generators. As the availability of variable renewable generators is dictated by the resource, these technologies are described as *location constrained*. Variable renewable generators are often described as *non-synchronous* as they are typically connected to the grid via power electronics and thus lack the grid stabilisation capabilities of conventional units.[1] Finally, due to the low fuel costs, variable renewable generators have very *low short-run marginal costs* compared to conventional thermal generation.

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[1] The International Energy Agency [10] reports that variable renewable generators may be designed to emulate synchronous generators. However, there remain limits on the non-synchronous penetration in regions such as Ireland [31].

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Because of these properties, variable renewables can impact on the power system in a number of ways, including; reducing marginal prices, displacement of marginal power plants, reduced system stability, changing grid flows and increased requirement for balancing services. However, the impacts of variable generation will be highly dependent on a number of power system characteristics, including; balancing area size, the correlation between demand and variable renewable supply, demand growth and infrastructure retirement. Along with the technical characteristics of the power system, the market structure and dispatch arrangements will influence the impact of increased renewable generation. An effective market design should facilitate efficient operation and maximise value.

The costs associated with increasing variable renewable generation have been widely researched. Gross et al. [11] provide a review of the costs and impacts, covering over 200 articles. Research from IEA Task 25 on large penetrations of wind power in power systems has been updated frequently [12]. As Gross and Heptonstall [13] discuss, whole system analysis is required to assess the costs and impacts of increased variable generation. Connolly et al. [14] provide a review of tools that have been used to analyse the integration of renewable energy and conclude that the appropriate tool is highly dependent on the impact to be assessed. As impacts can occur over short time scales, such as the requirement for additional short term reserves, and over long term scales, such as the depression of average wholesale prices, the tool used will also be dependent on the resolution and detail required.

Literature concerning the impact of increased wind penetration on a number of system requirements, including balancing, security and reserves, has received much attention, particularly in Europe and the United States [15]. Also, many studies have looked at the requirements for additional flexibility in terms of energy storage and interconnections. Castillo and Gayme [16] review grid-scale energy storage applications for renewable energy integration, reporting on the technical benefits and the challenging economics under current regulatory frameworks. Becker et al. [17] report on the need for increased transmission capacity in a pan-European electricity system with increasing penetration of variable energy supply. Considering the British power system in the years 2020 and 2030, Edmunds et al. [18] report that increasing energy storage and interconnection capacity can increase the maximum technically feasible wind penetration, reduce curtailment and permit a reduction in systems emission intensity. However, the impact of increased renewable penetration on thermal power plants has received less focus in Great Britain (GB) and, therefore, is the focus of this study.

Denny and O'Malley [19] developed a PLEXOS model of the Irish Single Electricity Market (SEM) to analyse the impact of carbon prices on generation-cycling costs, finding that carbon prices significantly increase the cycling costs [19]. Troy et al. [20] use the WILMAR planning tool to assess the impact of increased wind penetration on the cycling of base load units in Ireland [20]. As wind penetration increases, the combined cycle gas turbine (CCGT) units experience rapid increases in start-stop cycling and a significant reduction in utilisation. Also, coal units are subject to increased part load operation and ramping. Forrest and Macgill [21] employ a range of econometric techniques to assess the impact of wind generation on wholesale prices and thermal plant dispatch in the Australian National Electricity Market (NEM), finding that wind output depresses market prices and displaces primarily flexible gas generation and to a lesser extent coal fired generation [21]. Other studies have considered the incentives to invest in thermal units in power systems with increasing renewable penetration. Traber and Kemfert [22] find that reducing market prices in Germany, due to increasing wind penetration, significantly diminishes the attractiveness of investment in natural gas fired units. Also, Di Cosmo and Valeri [23] determine that as wind penetration increases, profits for all base load plants are reduced. Significantly, because profits are reduced more for natural gas plants than less flexible coal plants, investment in flexible plant may be discouraged.

To assess the impacts of increased wind on power markets, mixed integer linear programming (MILP) can be used to solve the unit commitment and economic dispatch (UCED) problem, subject to a number of technical and economic constraints [24]. While there are a number of studies in the literature that have used this approach for many countries in Europe and Australia, there has been less focus in GB. Also, Deane et al. [25] report that a sub-hourly resolution gives a more realistic estimation of generation costs and that a higher resolution is beneficial when system flexibility is of interest.

The impact of increased renewable penetration on thermal power plants is of great importance as the transition to a low carbon power system will require dispatchable conventional generation to be maintained as variable renewables capture a greater market share [10]. Therefore, the aim of this paper is to develop a comprehensive power market model of the GB system and analyse the effect of increasing variable renewable penetration on thermal power plant operating regimes.

Multiple scenarios representing the years 2020 and 2023 will be analysed and plant operation data, including ramping intensity, capacity factors and cycling regimes, will be obtained. The modelling horizon has been chosen on the basis that variable penetration is forecast to increase markedly by 2020. Further, a greater understanding of the operational regimes of thermal plant during the transition to a lower carbon electricity system is required to inform longer term policy decisions. The structure of the paper is as follows; Section 2 provides the background and context, Section 3 describes the modelling approach and data acquisition, Section 4 contains the results and discussion and Section 5 provides the concluding remarks.

## 2. Background and context

Of the six properties of variable generation, low-short run marginal costs, variability and generation uncertainty will have the most profound effect on the dispatch of thermal plants [10]. This section provides more detail on these impacts and how they will affect the operation of thermal power plants in future power systems.

### 2.1. Revenue adequacy

As variable generation has very low short-run marginal costs, it is generally dispatched when it is available [26]. For this reason, the depression of average wholesale prices would be expected as wind penetration increases; this is demonstrated by studies covering Ireland [27], Australia [21], Spain [28] and Germany [22]. This process is often referred to as the merit order effect. The merit order effect will cause the displacement of generation with higher short run costs, thus leading to a reduced market share and a lower utilisation of these power plants. The reduction in utilisation of plant over time is termed the utilisation effect. This effect in the short term is referred to as the transitional utilisation effect and this describes the period in which variable penetration is increasing and the utilisation of mid-merit plant is reduced due to the reduction in average wholesale prices [10]. The transitional utilisation effect will not significantly reduce the use of base load power plants; however, revenues may be reduced as average prices decrease. This would challenge the long-term economics of these