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The value of electricity and reserve services in low carbon electricity systems

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HIGHLIGHTS

- A power dispatch model is used to simulate electricity and reserve prices.
- Good agreement is observed between modelled and historic prices in 2015.
- Higher renewables and CCS with lower fossil fuels leads to lower electricity prices.
- Contrary to expectation, gone green scenario leads to lowest increase in reserve price.
- Flexible aggregated demand response likely to offer significant economic benefits.

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ABSTRACT

Decarbonising electricity systems is essential for mitigating climate change. Future systems will likely incorporate higher penetrations of intermittent renewable and inflexible nuclear power. This will significantly impact on system operations, particularly the requirements for flexibility in terms of reserves and the cost of such services. This paper estimates the interrelated changes in wholesale electricity and reserve prices using two novel methods. Firstly, it simulates the short run marginal cost of generation using a unit commitment model with post-processing to achieve realistic prices. It also introduces a new reserve price model, which mimics actual operation by first calculating the day ahead schedules and then letting deviations from schedule drive reserve prices. The UK is used as a case study to compare these models with traditional methods from the literature. The model gives good agreement with and historic prices in 2015. In a 2035 scenario, increased renewables penetration reduces mean electricity prices, and leads to price spikes due to expensive plants being brought online briefly to cope with net load variations. Contrary to views previously held in literature, a renewable intensive scenario does not lead to a higher reserve price than a fossil fuel intensive scenario. Demand response technology is shown to offer sizeable economic benefits when maintaining system balance. More broadly, this framework can be used to evaluate the economics of providing reserve services by aggregating decentralised energy resources such as heat pumps, micro-CHP and electric vehicles.

1. Introduction

Climate change is a physical and economic hazard that threatens to alter the course of human development if left unchecked [1]. As such, a global agreement to mitigate climate change is a high priority for governments worldwide to avoid the most severe impacts [2]. The UK is a leading country in terms of energy policy in this regard. The 2008 Climate Change Act constitutes legally binding legislation that requires the UK to reduce its greenhouse gas emissions by 80% by 2050 in comparison to 1990 [3]. The Climate Change Act also set up the Committee on Climate Change to advise the government on decisions and progress related to its targets. This committee established a series of carbon budgets to define the intermediate emission targets. The most recent Fifth carbon budget pertains to the period 2028–2032, and sets the target at 57% below the levels seen in 1990 [4].

The literature shows a consensus that decarbonisation of electricity systems is fundamental in the global transitions [1,5,6]. In scenarios that consider the possible make-up of future electricity

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Nomenclature

Sets

J	set of all generators $j \in J$
T	set of all time periods $t \in T$

Parameters

$\Pi_{j,t}$	feasible operating region of generator j in period t
Γ_t	feasible operating region of pumped storage in period t
D_t	electricity demand in period t (MW)
I_t	value of system electricity imbalance in period t (MW)
$P_{j,t}^{DA}$	electricity generation for unit j in period t from day-ahead model (MW)
$Q_t^{p,DA}, Q_t^{g,DA}$	pumped storage consumption (p) or generation (g) in period t from day-ahead model (MW)

Continuous variables

$\Delta p_{j,t}$	deviation of power schedule from day-ahead dispatch for unit j in period t (MW)
$\Delta q_t^p, \Delta q_t^g$	deviation in pumping schedule (p) or generation schedule (g) from day-ahead dispatch for pumped storage in period t (MW)
b_t	electricity consumed by a hypothetical demand-responsive end-use technology in period t (MW)
$c_{j,t}^{carbon}$	carbon cost for unit j at period t (£)
$c_{j,t}^{fuel}$	fuel cost for unit j at period t (£)
$c_{j,t}^{startup}$	start-up cost for unit j in period t (£)
$p_{j,k}$	electricity generated by unit j at period t (MW)
p_t^{solar}	electricity injected from solar sources in period t (MW)
p_t^{wind}	electricity injected from wind sources in period t (MW)
q_t	electricity released or consumed by pumped storage in generating mode in period t (MW)

systems, decarbonisation is typically achieved via a combination of nuclear power, carbon capture and storage (CCS), and renewables such as bioenergy, wind, solar, and marine sources [7].

Electricity systems dominated by low carbon generation differ greatly from most present-day systems. Particularly, they impose to two new characteristics: inflexibility (relatively constant output from nuclear, or predictable but uncontrollable output from marine energy) and intermittency (fluctuating output from wind and solar). As the penetration of these sources increases, market price dynamics can change significantly, as evidenced by the emergence of occasional negative electricity prices in several countries [8]. It is widely expected that the cost of providing reserve services to ensure supply-demand balance will also increase, due to changing plant operation strategy and investment choices. Ultimately changes will influence the overall energy mix and electricity system greenhouse gas emissions [9,10]. Given the importance of prices for long-term investment decisions, and on a vast array of end-use technologies and decentralised energy resources, there is a pressing need for technically-grounded analytical tools to understand the complex relations between future electricity system design and the prices it will yield.

1.1. Structure of the unbundled electricity market in the UK

The British electricity system had around 358 TWh annual and 52 GW peak demand; supplied by 80% fossil and 16% renewables in the year 2015 [11]. The structure of a typical unbundled electricity market consists of four segments: generation, transmission, distribution and retail. In the British market, the first and the last segments are competitive with many players competing for market share. Transmission and distribution are natural monopolies, and as such are often regulated or state-owned and operated.

Simplistically, trade of electricity between generators and retailers mainly consists of bilateral agreements and over the counter (OTC) trades, power exchange trades and the balancing mechanism [12]. Bilateral trades can happen years in advance. Power exchange trades happen days or hours in advance, up to the point of 'gate closure' which is one hour before delivery in the British market [13]. The spot market operates in half-hourly segments.

Electricity contracts are frozen one hour before physical delivery. Trading parties can no longer make any changes to their contracted positions (i.e. level of generation). The contracted positions at this point are known as Final Physical Notifications (FPN). The balancing mechanism primarily operates in the period between gate closure and the end of the settlement period, and is intended to fine-tune generation such that it is equal to demand at any moment. The trading parties must only deviate from their contracted positions at the instruction of the System Operator (National Grid) where they are participating in the balancing mechanism, or otherwise face penalty charges known as imbalance pricing [14].

1.2. Literature survey

1.2.1. Low carbon technologies and policy

When it comes to low carbon policy support, the UK has experimented with numerous policy instruments and offers a wealth of lessons for countries aiming to decarbonise their electricity system [15]. Long term studies of low carbon futures make use of energy system models to determine capital investment decisions that minimise the carbon emission intensity while achieving security of supply. Such studies can focus on the power sector [16] or span over different sectors [17–19]. Decarbonisation studies show that when faced with high emission reduction targets, energy savings and efficiency measures play an important role, without which high mitigation costs are encountered [20]. Results show that international action rather than fragmented effort is required to reduce global emission level [21]. Emission reduction pathways tend to point movement towards renewables, nuclear and CCS [22]. These developments underscore the increasing importance of the models described in this article.

1.2.2. Effect of renewable penetration

Previous work related to electricity prices outside the forecasting space is related to the change in electricity prices due to the in-feed of renewable energy generation. The merit-order effect, whereby conventional generation is displaced by zero marginal cost renewable electricity, is well documented in Germany [23–25], Denmark [26], Italy [27], Spain [28] and Britain [29]. In essence, these studies show that renewable penetration often allows demand to be met by lower marginal cost units and hence generally reduces the price of electricity. The literature can be broadly split into simulation and empirical methods. Simulation methods use technically rigorous descriptions to emulate market conditions through the use of optimization [25] or agent based models [30] to calculate the change in electricity price due to renewable penetration. Empirical methods [23,24,26–29] use