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A Novel Methodology to Investigate the Impact of Electricity Market Reforms on Future Electricity Prices

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Abstract*— Electricity market reforms are essential to the United Kingdom (UK) government's plan to achieve net zero by 2035. However, the impact of these reforms on future electricity prices remains challenging due to the complex and intermittent nature of renewable energy sources. This research paper presents a novel methodology to investigate the impact of current electricity market reforms in the UK on future electricity prices. The methodology integrates advanced simulation techniques with a detailed analysis of market mechanisms, providing a comprehensive framework to assess the impacts of regulatory changes. Locational pricing is a proposed alternative to single wholesale market pricing in the recent Review of Electricity Markets Arrangements (REMA) consultation. To conduct the research, the study uses a 36-bus reduced version Great Britain (GB) transmission system using PowerFactory to calculate the prices in each zone based on the Future Energy Scenarios (FES). The findings of this study reveal that adopting locational pricing could result in significant geographical disparities in electricity prices across different zones.

***Keywords*— Electricity Ten Year Statement, Future Energy Scenarios, Locational Marginal Pricing, Optimal Power Flow, Power Factory.**

I. INTRODUCTION

Electricity markets reform through the REMA programme is crucial to the UK government's plan for a fully decarbonised electricity system by 2035 [1], subject to the security of supply. Existing market arrangements were established when fossil fuel-based generation was dominant. The goal of the previous electricity market reforms was to increase the amount of low-carbon renewable energy produced in a power system that was still primarily built for fossil fuel technology. This journey was accelerated by the introduction of new schemes such as Contracts for Difference (CfD) and Capacity Markets to ensure the security of supply. The purpose of the REMA programme is to create the market arrangements to complete this move to low-carbon technologies, managing a smooth and low-cost transition away from the remaining unabated fossil fuel generation capacity while maintaining security of supply.

Locational energy pricing is a proposed alternative to single wholesale market pricing in the recent REMA consultation [2]. It aims to provide locational market incentives by allowing prices to vary between network locations based on the local generation capacity, constraints of the network, and demand. Two models, zonal and locational marginal pricing (LMP), are possibilities. Zonal pricing separates the GB electricity system into broad zones based on network constraints. Each zone would have its own wholesale market and the supply and demand would be balanced within the zone and across the boundaries with neighbouring zones [3]. LMP pricing is a more granular regime where prices differ between 'nodes', such as the boundary between the transmission and distribution systems. LMP is often referred to as 'Nodal Pricing' and requires a shift from self-dispatch, where generators dispatch electricity that is then rebalanced by the System Operator (SO), to centralised dispatch where generators bid into a market and are then dispatched by the SO [3].

A recent study [4], investigates and evaluates the adoption of LMP in electricity markets using a six-bus network to model advanced market arrangements like the GB. Several reports [5], [6] including recent and ongoing work by the National Grid Electricity System Operator (NGESO) and Office of Gas and Electricity Markets (Ofgem) are assessing the potential benefits of moving the GB wholesale market from its current arrangement to a locational wholesale market. They contend that switching to a locational wholesale market would provide significant societal and GB consumer benefits relative to the current market design. Customers in each zone would benefit from a transition to a locational pricing design, although the size of these benefits would vary across GB. However, according to a study [7], a move to LMP may have important implications for investor cost of capital during any transition period. Ref [8] assesses the proposals for electricity market reform in the UK and identifies that locational pricing will impact heat pump running costs.

A study [9], proposes incorporating LMP pricing into future GB power market designs will be extremely beneficial in facilitating a smooth transition to a net zero grid. The report also intends to increase awareness of nodal pricing as the first best method for indicating locational value in an energy system that is more thoroughly decarbonised, decentralised, and digitalised. The main benefit of LMP pricing is that it encourages generators and flexible resource providers to position and run assets (such as production or storage) effectively while considering the network's actual physical restrictions. This should eventually result in additional resources being located more strategically and the network

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being expanded more effectively. It will encourage creativity and increase local flexibility. There is growing interest within the European Union (EU) for LMP as countries face similar challenges to the UK in relation to cost-efficiently integrating renewable energy sources [10]. Another study by [11] analyses the potential to transition the European internal electricity market to nodal pricing and concluded that LMP can be theoretically implemented in the current European market design.

The major objective of this paper is to propose a novel methodology to investigate the impact of electricity market reform on future electricity prices using the 36-zone reduced GB PowerFactory model enabling a detailed analysis based on the Future Energy Scenarios. The rest of the paper is as follows: Section II contains the GB Market model for current and future pricing, Section III presents the methodology, Section IV results and discussion while Section IV summarises the conclusions and future research.

II. Great Britain Market Model

In the GB Market, as illustrated in Fig.1, suppliers buy power at a wholesale price from generators, which represents the cost of producing electricity to meet demand from customers at any given time. Generators receive revenue for the electricity they generate from trades in the wholesale market, or through power purchase agreements or a Contract for Difference (CfD) [3]. Currently, national pricing is the system in place in GB [12]. This implies that there is a single wholesale electricity price for the entire nation at any one time. A number of variables affect the wholesale price of electricity, such as the amount of demand, carbon taxes, fuel prices, and the availability of renewable energy sources like the sun and wind. As a result, this price changes during the day, which may have an impact on the generators that are most competitive in the wholesale market.

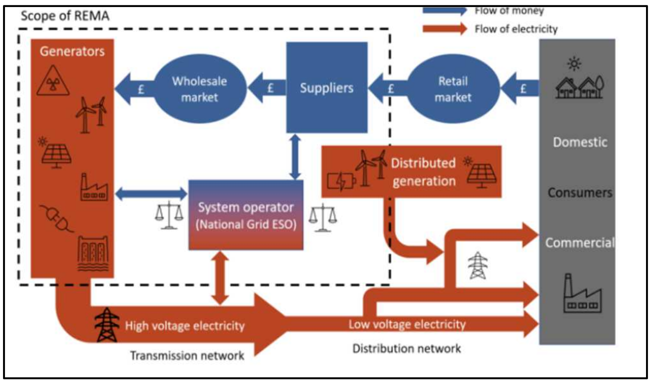

Figure 1. GB Market Model [3]

Locational pricing involves charging different electricity prices based on the user's location [8]. A recent assessment [13] focused on three different levels of locational granularity in the GB wholesale market as illustrated in Fig. 2, a base case representing the current national pricing market; a zonal pricing market design where GB is split into seven distinct price zones with the boundaries of the zones reflecting the expected incidence of bottlenecks on the transmission system; a LMP pricing market design in which prices are determined at all of the nodes in the network. The findings from this assessment are summarised in Table 1.

TABLE 1. Summary of Locational Pricing Benefits

Benefit	Zonal	Nodal
Societal Benefits	£6bn - £15bn	£13bn - £24bn
Consumer Benefits	£15bn - £31bn	£28bn - £51bn
CO_2 Emissions	65-100Mt CO_2	65-100Mt CO_2

The next section briefly describes the current and proposed future electricity pricing methods.

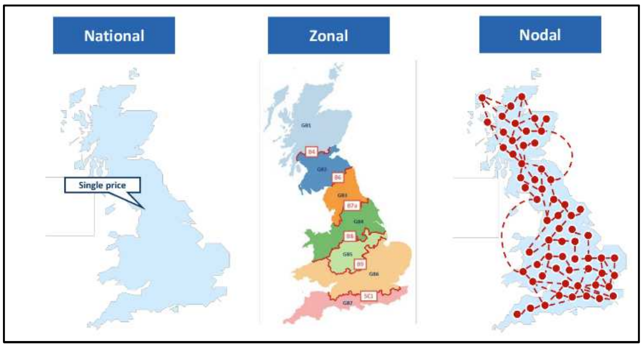

Figure 2 Great Britain Proposed Pricing Models [13]

A. National pricing

National pricing is currently used in GB. This means that the market consists of one ‘zone’ in which buyers and sellers are free to contract directly at a price agreed in private [12]. Wholesale trading within the GB zone does not account for network constraints when electricity cannot flow freely from where it is generated to where it is consumed. France, Germany, Poland and Greece also use the national pricing model.

B. Zonal pricing

The transmission network is divided into multiple pre-established zones, or geographic regions, for **zonal pricing**, also known as regional pricing. For instance, Italy has six price zones. In a zonal wholesale market, the wholesale price of energy clears as a single, consistent price for each zone at each settlement period [12], [14]. Generally, the wholesale price fluctuates in each zone during each trade period.

The borders between zones are typically drawn by countries at key transmission restrictions or the locations where congestion is most likely to occur on transmission cables. Zone boundaries designate the points at which each side of the boundary should have a separate wholesale power price. Zonal pricing is currently used in Australia and several EU countries, like Italy, Sweden, Norway and Denmark.

C. Locational Marginal Pricing

LMP is at the most granular end of the spectrum. It separates the country's network into hundreds or thousands of nodes, each with a different wholesale energy price [15]. Numerous factors, such as a nation's topography or network properties, affect how many nodes a country has. There are more than ten thousand nodes in California alone. Specific locations inside the system are linked to nodes. They may be the points at which demand depletes the grid or where generation enters the system. The price of each node reflects the expense of providing one more unit of energy at each location. For every trading period, the wholesale electricity

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price normally changes between each node. It is currently used in New Zealand, Singapore and several markets in the United States.

III. Methodology

A modified 36-bus reduced network of the GB transmission system as shown in Fig.3 modelled using PowerFactory was used for this research [16], [17]. The system is divided into 36 zones as shown in Figure 3. The reduced model of the GB transmission system was derived from the full system model by aggregating the Electricity Ten Year Statement (ETYS) zones into a reduced number of wider zones. Generators in each zone were categorised based on their fuel types and the demand was divided into active and reactive demand. Line impedances were also calculated to represent the electrical distance between the zones. Demand data was acquired from the FES regional breakdown 2023 specifically the Leading the Way scenario[18] provided by National Grid ESO and generator cost data provided by the Department of Energy Security and Net Zero (DESNZ) [19]. Power Factory was used to run a DC Optimal Power Flow (DCOPF) on the network with branch flow limits and active power limits as constraints to calculate the LMP at each zone.

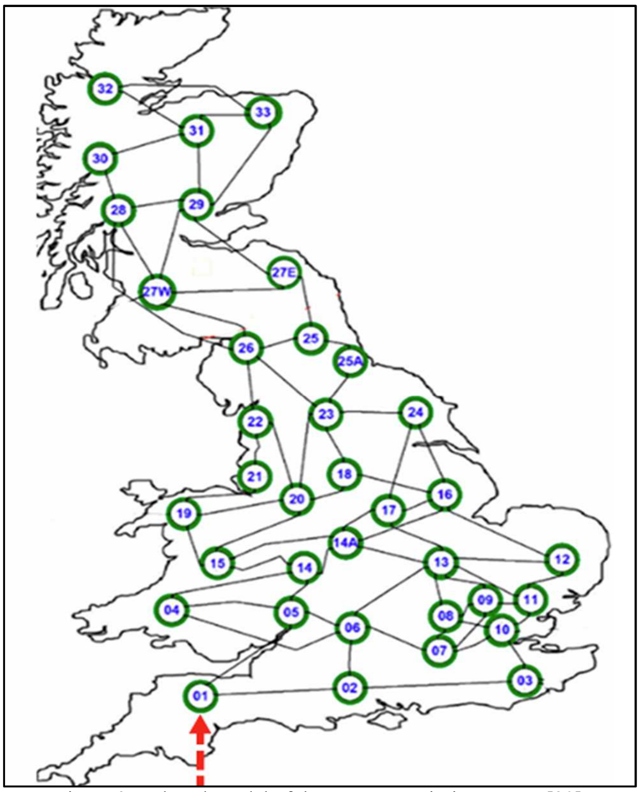

Figure 3 Reduced Model of the GB Transmission System[20]

DCOPF is a widely used optimisation technique in power systems that aims to determine the optimal operating point of a grid while considering various constraints such as power flows, line capacities, and generator limits. Linear programming (LP) is a mathematical approach often employed to solve DCOPF problems due to its efficiency and ability to handle linear constraints and objectives. PowerFactory uses a standard LP-solver (based on the simplex method and a branch-and-bound algorithm) which ascertains whether the solution is feasible. Table 2 gives a breakdown of the relationship between the reduced model and the full system zones as described in the ETYS, for instance, Zone 08 of the reduced model consists of ETYS zones A1, A4, and A7 of the full model and Zone 25 consists of zones Q5, Q6 and Q7 [20].

This research will focus on two key zones. Zone 8 represents the Greater London area due to its high demand and Zone 25 represents the Northeast of England and the border between England and Scotland which has excess wind generation.

Table 2. ETYS Zones

Reduced Model Zones	Full Model Zones
Zone 01	F6, E8, E7, E1, E6
Zone 02	B2, B1
Zone 03	C4, C7, C9
Zone 04	H1, H2, H6
Zone 05	G1, G5, G6, G7
Zone 06	B3, B4, D6
Zone 07	A8
Zone 08	A1, A4, A7
Zone 09	A3, A6, A9
Zone 10	C1, C2, C3
Zone 11	C5, C6, J8
Zone 12	J1, J2, J3, J5
Zone 13	D4, D5, J4, J6, J7, L8
Zone 14	L3
Zone 14A	L7
Zone 15	L2, L5
Zone 16	K1, K2, K4, K6
Zone 17	K5
Zone 18	P3
Zone 19	M4, M5, M6, M7, M8
Zone 20	N2, N4, N5, N6, N7, N8
Zone 21	N1, N3
Zone 22	R4, R5, R6
Zone 23	P1, P2, P4, P5, P6
Zone 24	P7, P8
Zone 25	Q5, Q6, Q7
Zone 25A	Q2, Q4
Zone 26	Q8
Zone 27 E	S1E
Zone 27 W	S1W
Zone 28	S2, S4, S6, S7
Zone 29	S3, S5
Zone 30	T3
Zone 31	T4
Zone 32	T1, T5
Zone 33	T2
Zone S9	S9

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A. Zone 8 Greater London

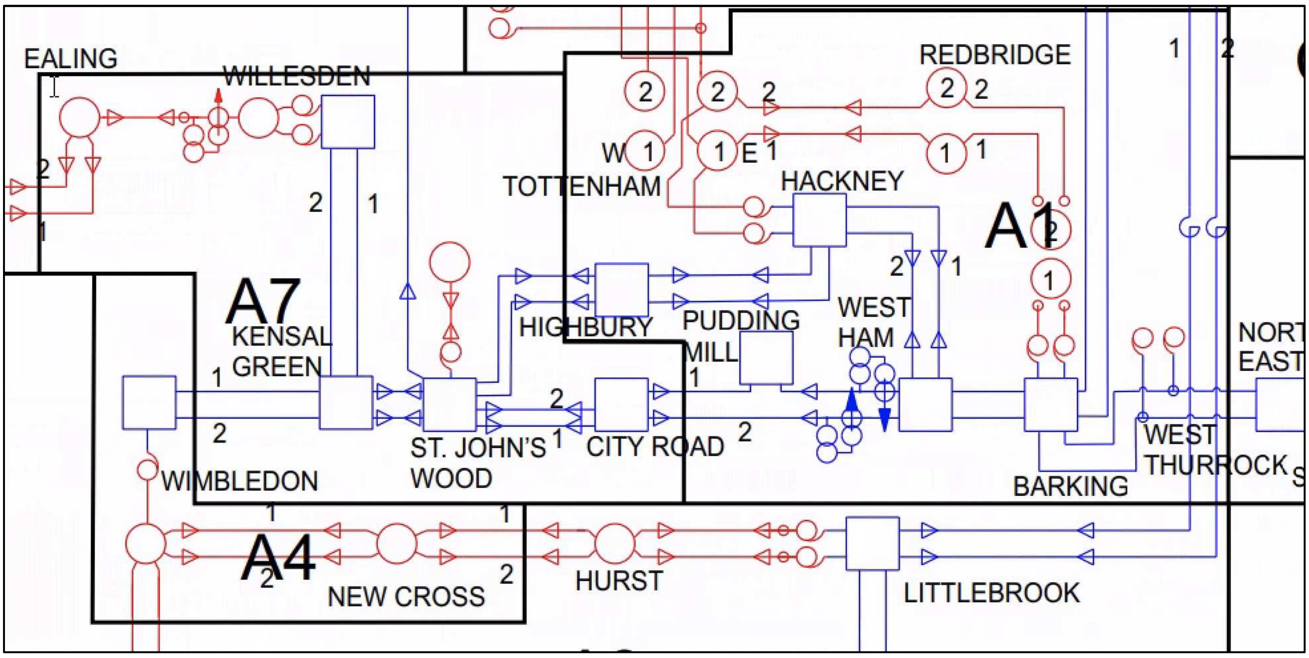

Figure 4 Greater London Area representing zones A1, A4 and A7 [21]

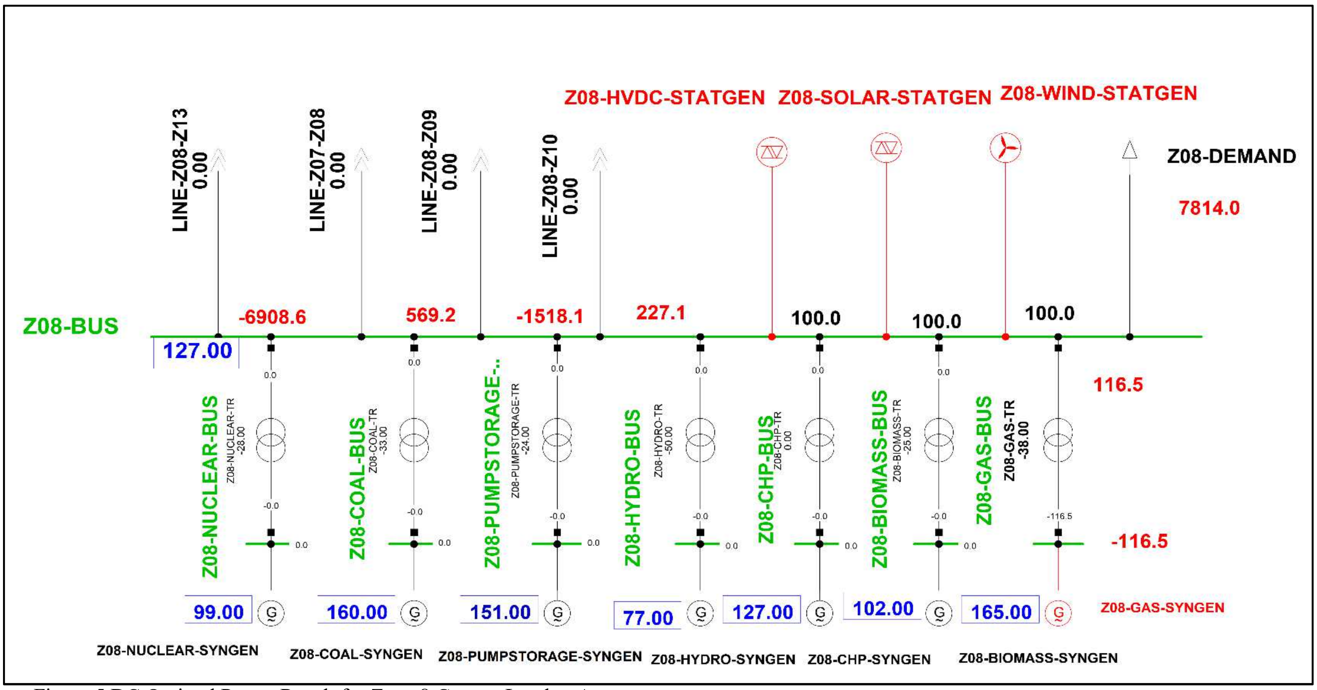

Figure 5 DC Optimal Power Result for Zone 8 Greater London Area

Figure 4 shows the map of Zone 8 with ETYS zones A1, A4 and A7 representing the Greater London area. This area, encompassing the capital city of the UK, exhibits unique and complex electricity demand characteristics driven by its dense population, diverse economic activities, and significant infrastructure. According to ETYS analysis [21], the London area has high voltage gain from cable circuits, particularly overnight when the demand is low, combined with reliance on local generation plants. The southeast coast of England faces low voltage issues due to high imports and high exports on interconnectors. PowerFactory was used to run a DC Linear OPF on the 36-bus reduced model of the GB transmission system.

The DC Optimisation (Linear Programming) is selected with the minimisation of costs as the objective function. The optimisation aims to supply the system at optimal operating costs. The result of the linear optimisation tool includes calculated results for control variables, such that all imposed constraints are fulfilled, and the objective function is optimised. The option Calculate Locational Marginal Prices (LMPs) is selected to calculate the LMPs in the network. Fig. 5 shows the results of DCOPF for Zone 8 using PowerFactory using data from the National Grid ESO's FES [18]. The Leading the Way scenario for 2035 was used as the basis for the data. The results show an LMP (figure in blue) of £127/MWh for Zone 8.

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B. Zone 25 North of England

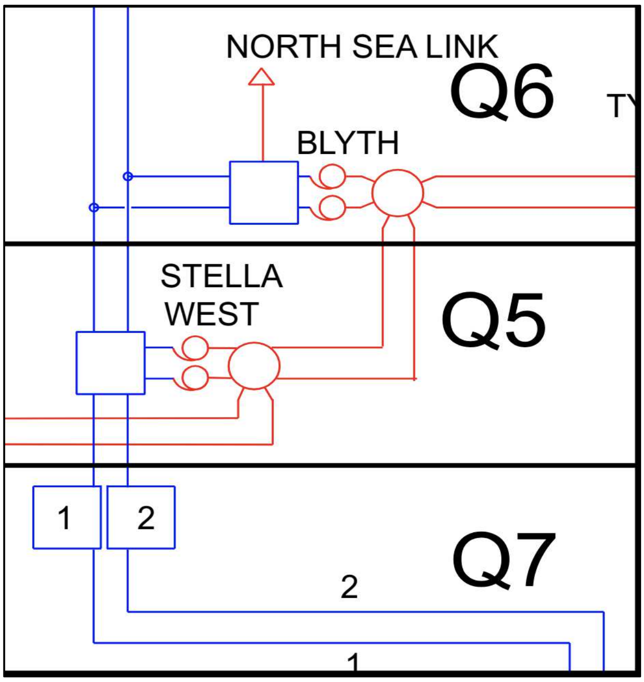

Figure 6 Zone 25 Northeast of England [21] representing Q5, Q6 and Q7

England, the Midlands and the South of England (often in industrial or densely populated areas) [22].

Figure 7 shows the results of DC Optimal Power Flow for Zone 25 using PowerFactory using data from the National Grid ESO's Future Energy Scenarios [18]. The Leading the Way scenario was used as the basis for the data.

IV. Results and Discussion

Analysis was undertaken using 2035 data to evaluate the impact of the electricity market reforms on future electricity prices in a net zero power system. Under Locational pricing, wholesale electricity prices differ across each zone due to varying constraints across the network. Lower prices are seen in Zone 25 the north of England while substantially higher costs are seen in the greater London area. In 2035 LMPs for Zone 8 and Zone 25 will be £127/MWh and £43/MWh respectively. The analysis of the electricity market using DCOPF in PowerFactory has provided valuable insights into the LMP across different zones in the UK. These results highlight significant regional disparities in electricity pricing, which can be attributed to various factors including demand patterns, generation capacity, and transmission constraints.

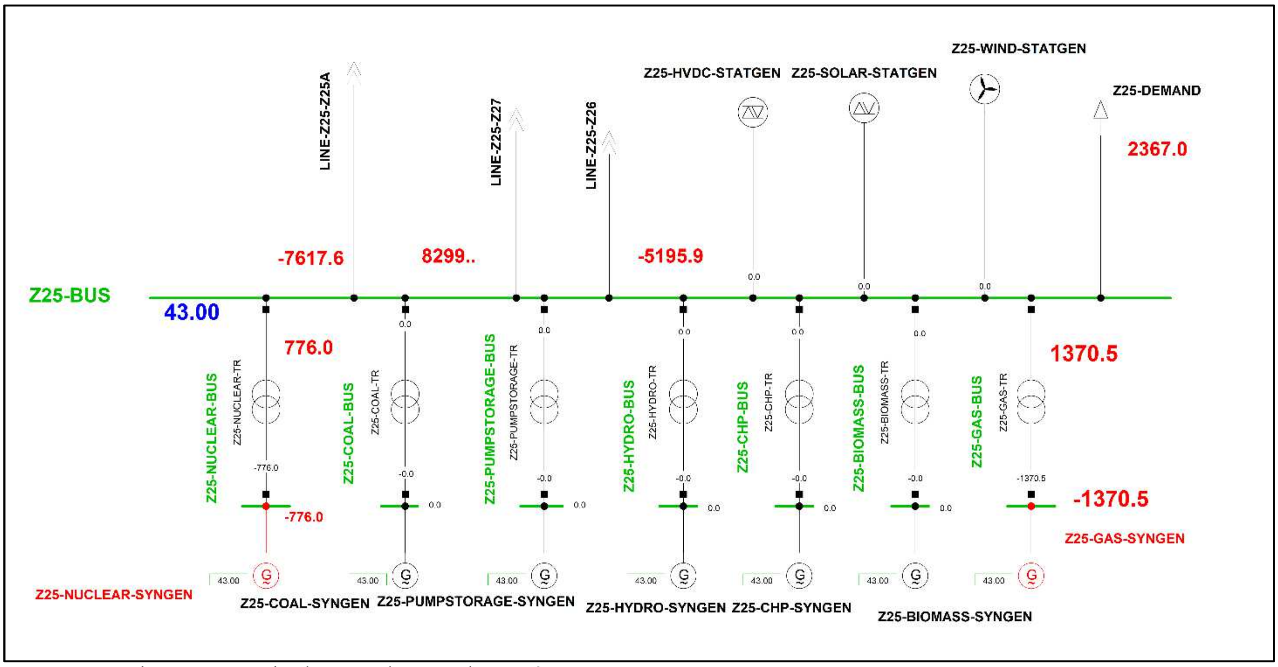

Figure 7 DC Optimal Power Flow Result Zone 25

Figure 6 shows the map of Zone 25 with ETYS zones Q5, Q6 and Q7 representing the Northeast of England area. This is an area between the borders of England and Scotland and has excess generation due to the high concentration of wind generation in Scotland. According to ETYS analysis [21] this region experiences high voltage due to generation closures and a combination of network changes that pose challenges to managing the voltage. During periods of high flows from Cumbria and Scotland, the Mersey region could experience low voltages. GB's future electricity network needs the capacity to transport clean, renewable electricity from generation centres in Scotland and parts of the North of England to demand centres elsewhere in the North of

In Zone 8, the LMP of £127/MWh is indicative of high electricity costs, which are primarily driven by the following factors, carbon tax, high demand, limited local generation and import constraints and reliance on peaking power plants.

Conversely, in Zone 25, the significantly lower LMP of £43/MWh can be attributed to abundant renewable generation, and lower demand relative to generation capacity. The contrast between the LMPs in Zones 8 and 25 underscores the impact of local conditions on electricity pricing. While Greater London struggles with high demand and limited local generation, the North of England benefits from its robust renewable energy output and effective infrastructure. These results clearly show how locational differences in generation capacity and demand patterns affect electricity pricing across regions. With 2024 average wholesale prices in the UK at £75/MWh [23], addressing these disparities through targeted policy and infrastructure investments can lead to more equitable electricity pricing and improved efficiency in the GB electricity market.

V. Conclusions and Future Research

The study has explored aspects of the potential impacts of current electricity market reforms on future electricity prices in the UK. Key findings reveal that locational pricing could result in significant geographical disparities in wholesale prices across different zones. Regions with high levels of renewable generation will have lower wholesale electricity prices. Conversely, regions with net electricity imports due to high demand will have high wholesale electricity prices.

This study contributes to the ongoing reforms in electricity market design by providing a robust analytical tool for evaluating the impact of proposed reforms. The results offer valuable insights for regulators, policymakers, and industry stakeholders aiming to optimise market structures for future energy systems. In future, an enhanced methodology will be used to conduct similar research with the 36-Bus GB Electricity Transmission Network Model provided by National Grid ESO.

VI. Acknowledgment

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