# OPTIMISING INTEGRATION OF RENEWABLE ENERGY SOURCES TO ACHIEVE NET ZERO

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## Abstract

This research paper develops a novel data-driven method to optimise the connection and integration of renewable energy resources (RES) in the United Kingdom (UK), aiming to address the ambitious target to achieve net-zero greenhouse gas emissions in the UK by 2050, according to 2019 legislation. This commitment has led to a major transition from using fossil fuels to high penetration of RES. A future transition to clean energy is achievable through a combination of RES, their optimal location, and the reform of existing market arrangements. Firstly, the paper aims to establish locations with optimal weather conditions for deploying photovoltaic (PV) and wind power generation using the k-means clustering technique. The datasets used for this research were collected from available weather data stations located across the UK. The power generation of PV installations heavily depends on solar irradiance, whereas onshore wind generators require stable and strong wind conditions. However, the choice of location is crucial for the connection of such RES. The strategic placement of these energy sources can play a major role in relieving congestion and enhancing grid efficiency. The research as presented in this paper suggests locations with favourable weather conditions for the integration of RES. Secondly, the paper uses a 36-zone reduced model of the Great Britain transmission system to conduct direct current power flow studies across the network to determine areas with network constraints. The findings of this study have implications for policymakers and investors as they provide the necessary signals for the optimal integration of RES to achieve net-zero

## 1 Introduction

The United Kingdom (UK) is legally committed to achieving a net-zero target by 2050. This ambitious goal requires a transformative shift from reliance on fossil fuels, such as coal or gas, to a substantial integration of renewable energy resources (RES). At present, photovoltaic (PV) installations and wind turbines (WT) have emerged as the main players in the RES market [1]. The effective power generation using RES is highly dependent on specific geographic and meteorological conditions. PV power generation, for instance, requires areas with high solar irradiance [2], while WT power generation is most effective in regions with strong and stable wind patterns [3]. Therefore, allocating these energy sources to areas with favourable weather conditions leads to maximum power production and optimal RES efficiency. Furthermore, the integration of these RES into the existing network always requires grid management improvements due to existing constraints and leads to significant changes in overall market pricing. In this context, data-driven approaches are highly valuable. Leveraging advanced analytical techniques and comprehensive datasets can provide insights into the most suitable locations for renewable energy installations and the potential impacts on the existing grid infrastructure. These methodologies enable a more informed and strategic planning process, facilitating the efficient and cost-effective integration of RES.

Accordingly, this research paper contributes to innovative solutions for strategic planning by presenting a novel method to optimise the deployment and integration of RES, thereby supporting the UK's transition to a sustainable and resilient energy future. Based on an integrated method combining k-means clustering and direct current (DC) power flow analysis, this paper describes areas that are limited by the network.

The remaining paper is structured as follows: The review of the state-of-the-art section highlights the topicality of the proposed research and reviews the recently published research papers. The methodology section provides insights into the clustering techniques, system analysis, and data background utilised for the research. The results section discusses the findings obtained. Finally, the conclusion section sums up the key outcomes and their implications, offering recommendations for future research.

## 2. Review of the State-of-the-art

This research paper presents a comprehensive overview of current research papers and analyses their topicality using the Scopus database. Firstly, the search query "integration and renewable and energy" employed in the Scopus database confirms the growing number of papers published in the final decade of 2013-2023. This study involved the investigation of approximately twenty-five thousand research papers. Fig. 1 presents the results.

Furthermore, the abstracts and keywords extracted from the Scopus-indexed research papers were used for the generation of the Word Cloud Diagram. This allowed the further assessment of research relevance. The results were obtained by utilising the Text Analytics Toolbox from MATLAB and presented in Fig. 2. The core elements of most of the research papers are investigations around renewable systems energy or power. The analysis also confirms that the topical research on the RES integration topic includes the studies related to the two main technologies of renewable energy generation—solar and wind—and research is also concentrated across analysing, optimisation, and simulation. However, there are a lot of topics representing the core elements involved in the integration of RES that are not represented in this study, e.g., storage elements, voltage control, etc.

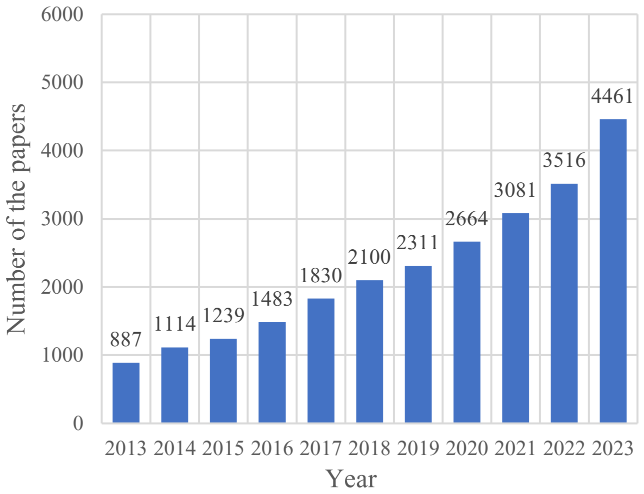


Fig. 1 Dynamics analysis of the recently published research papers indexed by the Scopus database in 2013-2023

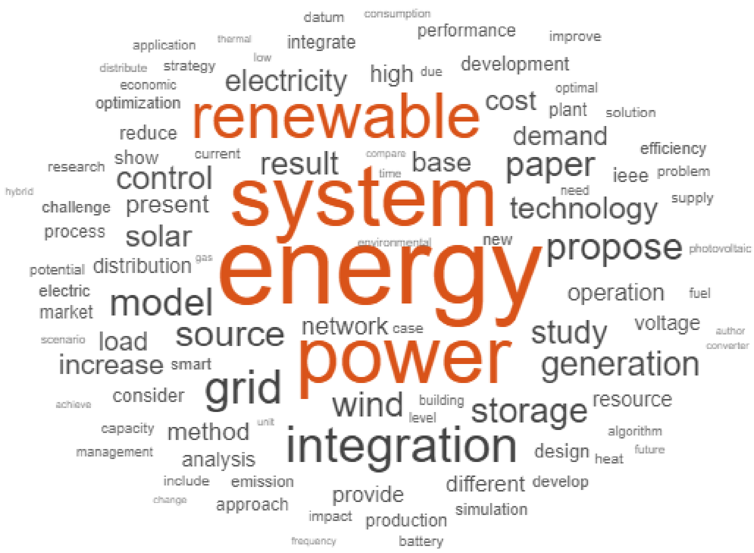


Fig. 2 Word Cloud Diagram involving abstracts and keywords of the research papers indexed in the Scopus database in 2013-2023 on the topic of the RES integration

Subsequently, the paper analyses some of the recent sources received from the query to identify papers related to the presented one.

Accordingly, [4] examines integration strategies for hybrid RES. It investigates combining solar, wind, hydro, biomass, and other RES with energy storage solutions. The study researches technological, economic, and regulatory aspects, analysing critical parameters for successful deployment. Overall, the paper provides valuable insights for policymakers, researchers, and industry stakeholders aiming to accelerate RES adoption.

Paper [5] investigates the feasibility of achieving net zero in the UK by 2050. It emphasises the need for a transition combined with the dramatic energy shift and elimination of all emissions sources. According to the paper key components, such as RES generation and electric vehicles, are well-developed, but challenges remain. The study highlights the importance of maintaining employment, economic growth, and reduced inequality while decarbonising the economy.

Ref [6] employs a comprehensive review methodology to examine the challenges and opportunities related to the integration of RES into smart grids. The study focuses on the technical aspects of grid integration, including power quality, voltage stability, and frequency regulation. The authors use case studies and simulations to analyse the impact of high RES penetration on grid stability, particularly emphasising the role of advanced control systems and demand-side management. The results indicate that while smart grid technologies can enhance the integration of RES, significant challenges remain, particularly in maintaining grid reliability and stability under high RES penetration.

Paper [7] proposes an optimisation-based approach to enhance the capacity of existing power grids for integrating RES. The authors develop a mathematical model that considers grid constraints such as voltage limits, thermal limits, and power flow equations. The model is implemented using mixed-integer linear programming to identify optimal grid configurations that maximise RES integration while minimising infrastructure upgrades. The study uses simulations based on real-world grid data to test the effectiveness of the proposed method. The results demonstrate that the approach can significantly increase the grid's capacity to accommodate renewable energy, reducing the need for costly grid expansions.

In terms of k-means utilisation for the power systems, ref [8] highlights several key applications of this algorithm. Specifically, by analysing 440 research papers published in 2022, they identified the focus role of k-means in analysing and optimising modern power systems, load forecasting, fault detection, power quality analysis, and system security assessment.

There are examples of the application of k-means for the identification of spatial patterns related to renewable energy potential for the European Union countries [9]. However, the utilisation of k-means is mostly dedicated to finding cross-border similarities in the distribution of renewable energy potential based on the RES potential and socioeconomic and geographical data. This research does not consider power system constraints or characteristics.

Lastly, DC optimal power flow (DCOPF) is widely applied for the assessment and modelling of the power system performance in terms of RES development and integration [10].

Accordingly, this research paper contributes to the RES integration methodology by employing novel approaches to advance the transition and leverage progressive software tools. While k-means clustering and DCOPF are separately established methods, our paper presents a combination of these techniques to identify favourable renewable energy locations and assess network constraints strategically. This integrated framework offers new insights into how meteorological conditions and network congestion can be co-optimised for renewable integration, which is rarely explored in sequence.

## 3. Methodology

This research paper presents a comprehensive multi-stage investigation. Initially, k-means clustering is utilised to identify regions with weak, moderate, and favourable conditions for developing PV installations and WT. Subsequently, a DC power flow assessment is conducted to determine zones with congestions. In the context of this paper, optimal refers to locations that maximise the technical, economic, and operational feasibility of RES deployment. The subsequent methodology sub-sections detail the specifics of each applied method and the datasets used.

### *3.1 K-means Clustering*

This research uses K-means, an unsupervised machine-learning algorithm, to identify clusters with different weather conditions for the development of different types of RES. K-means clustering separates the data on the predefined number of clusters and iteratively evaluates them using the Euclidean distance formula between data points and centroids. The algorithm determines the cluster number for each observation once it obtains stable, consistent results. The clustering assessment employs the following mathematical equation (1):

$$d_{ij} = \sqrt{\sum_{k=1}^{n}(x_{ik} - x_{jk})^2} \quad (1)$$

where $d_{ij}$ is Euclidean distance, $n$ is the number of observations, and $k$ is the observed data point, $x_{ik}$ is the coordinates of the observed data point, $x_{jk}$ is the coordinate for the centroid [11].

K-means requires the user to predefine the number of clusters and can be sensitive to the initial positions of the centroids. This study suggests using the 3-cluster approach to identify locations with weak, moderate, and strong weather conditions for the development of RES. Statistical analysis was used to further assess the received clusters.

In power systems analysis, K-means clustering can be particularly useful for spatially categorising weather conditions that impact the potential for RES development. By clustering data from weather stations across different regions, the algorithm groups areas with similar meteorological profiles, such as wind speed, solar irradiance, or temperature. This classification is essential for optimising the allocation of renewable technologies. Combining k-means with other data-driven methods, such as power systems analysis and simulations, can help develop energy transmission, distribution, and storage strategies.

### *3.2 Network Constraint Analysis*

A 36-bus reduced network of the Great Britain (GB) transmission system, as shown in Fig. 3, modelled using PowerFactory, was used to run a DCOPF on the network with branch flow limits and active power limits as constraints to identify the congested areas in the network. It 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 [12].

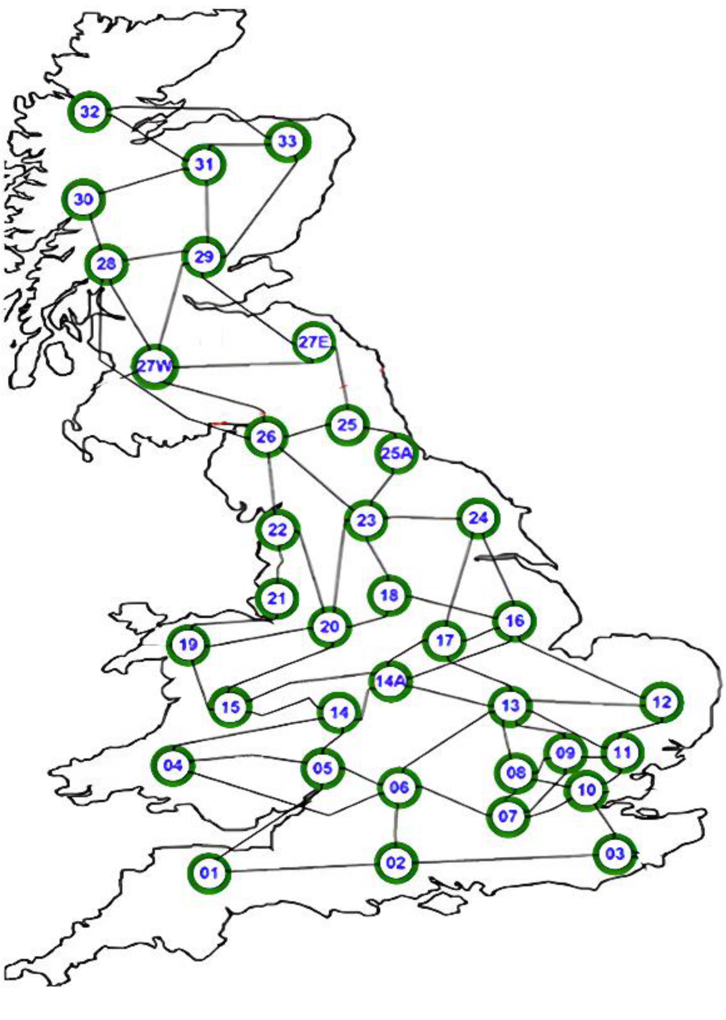


Fig. 3 Representation of the reduced GB model [13]

The goal is to optimise power distribution across the grid, ensuring that energy generation and consumption are balanced while adhering to the grid's operational limits. By highlighting congested areas, the paper confirms system reliability with the subsequent target of developing RES.

### *3.3 Data Used for the Research*

Data from 285 weather stations across the GB was used to identify locations with optimal weather conditions for deploying RES. This was collected from the Visual Crossing platform [14] and contains different daily weather statistics for 2023. Subsequent works will incorporate longer-term datasets to validate and generalize findings, but the use of large amounts of data presents several challenges, such as computational complexity and data access costs. Section 1 clearly demonstrated the significant dependence of PV installations on solar irradiance and WT under robust wind conditions. For the RES development assessment, this paper uses corresponding datasets with the measured solar irradiance in W/m² and average wind speed in miles per hour (mph) [15] for the PV installations and WT, respectively. Both datasets processed have dimensions of 265x365 and contain around 97,000 cells each. The dataset used for the PV installation investigation is represented in Table 1, and the WT research used a similar one with correspondingly changed values for the average wind speed in mph.

Table 1 The representation of the solar irradiance dataset used for the PV installation development assessment

| Number of the weather station | Location coordinates (longitude, latitude) | Value of solar irradiance on 01/01/23, W/m² | … | Value of solar irradiance on 31/12/23, W/m² |
|---|---|---|---|---|
| Station 1 | 49.92, -6.30 | 16.1 | … | 22.4 |
| Station 2 | 50.87, -2.94 | 11.5 | … | 15.2 |
| … | … | … | … | … |
| … | … | … | … | … |
| … | … | … | … | … |
| Station 264 | 58.95, -2.90 | 4.9 | … | 6.1 |
| Station 265 | 59.00, -3.30 | 12.8 | … | 14.5 |

## 4 Results

Application of the k-means to the proposed datasets has led to the clustering results presented in Fig. 4. This paper uses statistical approaches to assess the received cluster and highlights locations with different weather conditions for RES development. The results of each cluster assessment are in Table 2. The minimum values across the table can be explained as the possible weather conditions where there is a 100% cloud cover and accordingly solar irradiance is missing or there is no wind.

As previously discussed, PV installations are proportionally dependent on solar irradiance. Therefore, properly installed PV generates more power with higher maximum and average values. Cluster analysis shows that the optimal locations for PV installations are in England and Wales. Moving north to Scotland directly leads to reduced weather conditions for PV development. Therefore, the general recommendation for PV installation location is to position these generators within the green highlighted areas on the map in Fig. 4.

Table 2 Assessment of the clustering received

| Cluster number | Solar irradiance for PV installations, W/m² | | | Average wind speed for WT, mph | | |
|---|---|---|---|---|---|---|
| | Min | Max | Average | Min | Max | Average |
| Weak conditions | 0.0 | 387.4 | 60.9 | 0.0 | 183.6 | 22.9 |
| Moderate conditions | 0.0 | 444.2 | 95.3 | 0.0 | 126.0 | 28.7 |
| Strong conditions | 0.0 | 721.0 | 110.3 | 0.0 | 123.9 | 31.4 |

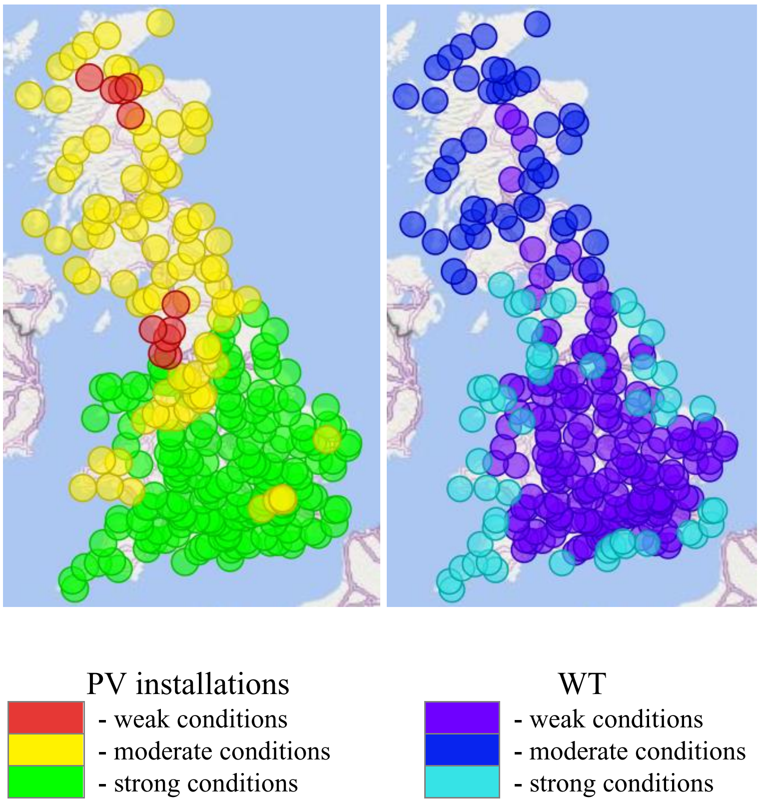


Fig. 4 Results of k-means clustering for the optimal development of RES

The wind clustering revealed an unexpected trend in the average maximum wind speed. As the maximum wind speed decreases, an increase in average wind speed is observed. However, robust winds are preferable for WT, as such conditions allow the prediction of power output more accurately, reduce mechanical stress for wind generators, and optimize energy capture.




The copy of record is available at https://doi.org/10.1049/icp.2024.4585

The results for WT display the best conditions for development in the seashore areas of England and Wales and are close to the optimal meteorological situation across the mainland of Scotland.

The integration of RES into the GB electricity network is pivotal in achieving the net-zero targets. However, network constraints present significant challenges that must be addressed to optimise this integration effectively.

The results from a simple DCOPF across the reduced GB model are displayed in Figs. 5 and 6. Constraints appear on the lines around the B6 boundary areas between Scotland and England and in the northeast of England. Furthermore, the southeast of England features lines that reach their maximum between Zone 3 and Zone 10. Table 3 illustrates a summary of the congested lines across the GB network.

Table 3 Summary of congested lines across the GB network

| S/No | Congested lines | Region |
|---|---|---|
| 1 | Zone 3 - Zone 10 | Southeast England |
| 2 | Zone 12 - Zone 13 | East England |
| 3 | Zone 27W - Zone 26 | Scotland |
| 4 | Zone 27E - Zone 25 | Scotland to England |
| 5 | Zone 25A - Zone 23 | Northeast England |
| 6 | Zone 26 - Zone 22 | Northwest England |

These congested lines across different regions of the GB network highlight key areas where strategic planning and optimal placement of RES could alleviate congestion. According to the overall results, deploying RES in regions where weather conditions are most favourable, PV in areas with high solar irradiance (e.g., southeast England), and WT in regions with high wind speeds (Scotland and northeast England) will maximise generation and grid efficiency.

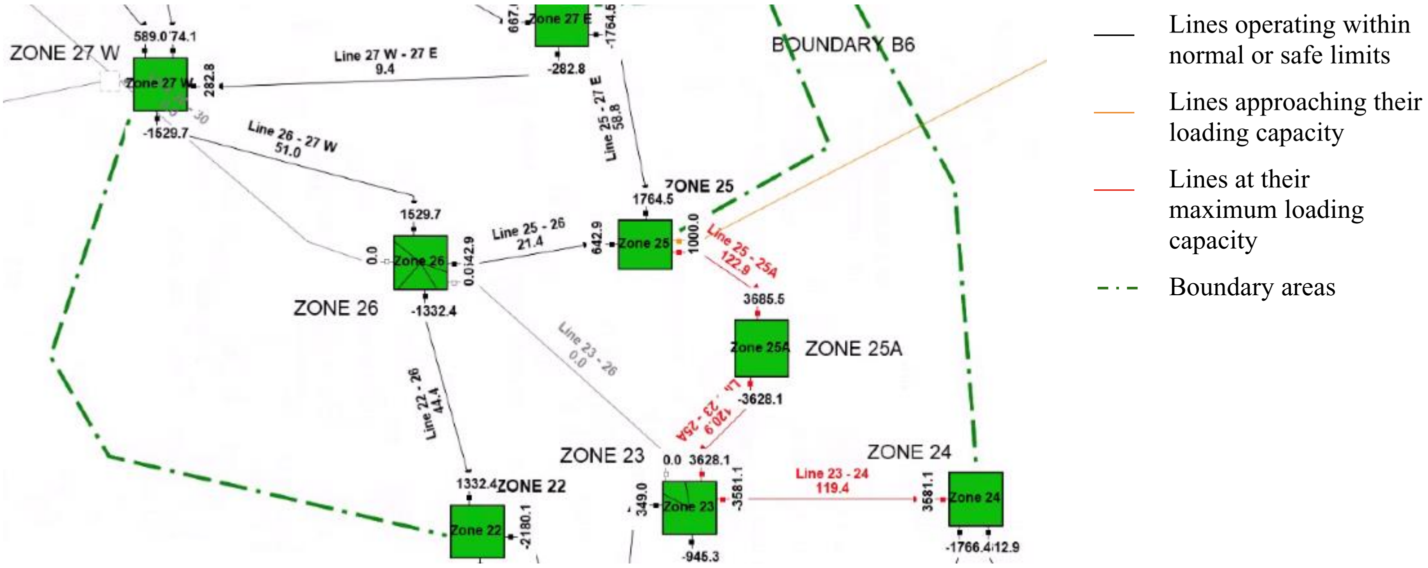


Fig. 5 The results of the executed DCOPF around the B6 Boundary

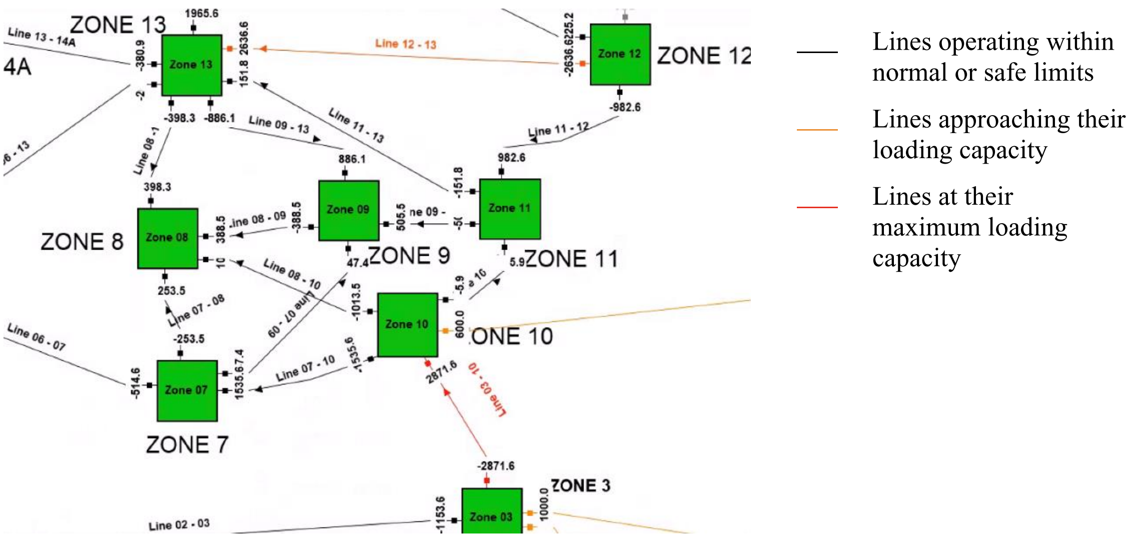


Fig. 6 The results of the executed DCOPF for the lines between Zone 3 and Zone 10

## 5 Conclusions

This paper has introduced a novel data-driven framework aimed at optimising the integration of RES within the GB electricity network, a critical contribution to achieving the UK's 2050 net-zero target. This integrated approach, which employs k-means clustering to determine optimal locations for PV and WT installations and conducts DCOPF analysis to assess network constraints, offers new insights into the joint optimisation of meteorological conditions and network congestion to support the effective integration of RES. The results underscore the importance of strategically positioning renewable installations to maximise efficiency, with regions such as Southeast England showing favourable conditions for PV and coastal Scotland for wind. Additionally, by identifying key congestion points, such as the B6 boundary between Scotland and England, the study offers valuable guidance for mitigating grid bottlenecks.

The research establishes a robust, data-driven foundation for policymakers, enabling them to align renewable energy goals with grid capacity and stability considerations. This ensures that future investments in generation, storage, and grid infrastructure are economically sound and technically optimised to meet Net-Zero objectives.

While this study focused on select case studies within the GB power system, the proposed approach is highly scalable, making it applicable to a broader range of locations and scenarios. Future research will expand this methodology to a wider array of contexts, optimising RES placement across the entire network and further supporting the UK's transition to a sustainable energy system.

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