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UNICROSS JOURNAL OF SCIENCE AND TECHNOLOGY, UJOST

RESEARCH ARTICLE VOL. 3(4) DECEMBER, 2024 ISSN:2814-2233

Date Approved December 31, 2024 Pages 41 –52

DEMAND-SIDE MANAGEMENT IN WIND POWER SYSTEM: AN ECONOMIC ANALYSIS

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Abstract

Sustainable energy infrastructure management pervades the interdisciplinary engineering, economics and other fields respecting systems and subsystems. Extant researchers' information provides for the need to employ a sustainable management approach regarding energy resources (energy mix) as a novel concept for mitigating this crisis. The drive to decarbonise the electricity system has led to a large penetration of intermittent energy resources such as wind. This situation has changed the known unilateral distribution network to a multidirectional distribution network hence the need for sustainable network management. This paper shows the application of demand-side management in a system with a large penetration of wind generation. Basic economic analysis tools such as the annual annuity payment (AAP) model are used to determine the optimal investment and capacity of wind power generation. The load and generation data used in this study were obtained from the SDG UK network and tested on a simple 5 bus network shown in Appendix. AAP considers the economic benefits examination of investment in wind farm infrastructure and the potential return-on-investment (ROI). Outcomes from this investigation demonstrate that the ROI is not directly proportional to the amount of wind energy produced as estimated. Also, demand-side management can lead to better network management.

Key Words: Distribution network, Demand response, Renewable energy, Sustainability, wind energy

1.0 Introduction

In recent years, the world has witnessed a huge utilization of renewable energy resources, with wind having a greater percentage in the energy mix of approximately 8.6% capacity, which doubles the capacity in 2017 (International Energy Agency [IEA], 2024). This increase in wind energy deployment is linked to its economic importance and sustainable nature, which attracts many investments from the private, public and cooperative sectors (Global Wind and Energy Council [GWEC], 2021). Wind energy, if properly harnessed within the built environment, will play a vital role in the achievement of a low carbon economy (IEA, 2022 and GWEC, 2021). Progressively, researchers' efforts have been tailored in the direction of effective management of this natural resource, given that, there are many innovative models that could help to achieve optimal exploitation of these wind energy resources (Mansouri et al., 2022; Asl et al., 2021). It is imperative to evaluate the investment costs likely to yield a reasonable Return Of Investment (ROI) given a certain percentage level of wind generation. Experience has shown that most wind farm projects are located far from the main load, leading to high investment costs (Girleanu et al., 2021; Porchetta et al., 2021). The bulk of this cost is related to the connectivity of the wind farm to the load centers using transmission lines or distribution lines (Xiang et al., 2021; Haddadi et al., 2022). Therefore, for an effective evaluation of a wind farm investment, factors such as operating and maintenance costs, investment/capital cost, interest rate, and fuel cost, among others, need to be considered (Thyssen, 2015; OWPB, 2016; Santhakumar et al., 2022; Bathrololoum et al., 2024). Proper evaluation of these factors will allow potential investors to decide whether to invest in the wind farm.

In this work, economic analysis to determine the optimum wind generation capacity suitable for investment using a simple economic AAP model (Masters, (2013) is performed on a simple distribution network test case. In this case, the ROI is not linearly related to the wind generation capacity invested. In recent times, the distribution network has witnessed huge penetration of intermittent generation, especially wind and solar energy resources (Aziz et al., 2010; Impram et al., 2020; Iweh et al., 2021). This has affected the historical operational philosophy of the distribution network, changing it from a unidirectional system to a multidirectional system (Karimi et al., 2016; Panigrahi et al., 2020).

Hence, the existing literature has revealed that the traditional operation of the distribution network has become inadequate following the high penetration of distributed generation (DG). For sustainability reasons, most of these DGs are in the form of renewable energy such as wind, solar, and tidal, among others. Discussion from (Zubo et al., 2017) shows that the uncertainty about the reliability of distribution systems (DS) has increased because of the violation of the voltage constraint specifically in the case of intermittent generation. This problem thus limits the amount of variable generation that can be connected to the DS typically during the period of maximum generation-minimum demand. Also, this drawback in the deployment of intermittent generation (wind and solar) can be associated with violation of the DS thermal constraints and reverse power flow just to mention but a few ((Masters, (2013). The traditional way of addressing this issue will involve the reinforcement of the distribution network which is considered uneconomical to the distribution network operators (DNOs) (Celli et al., 2013; Ceseña, E. A. M., & Mancarella, P., 2014).

This study generally focuses on providing active control of the DS using a price-based demand response as a control option. In this study also, the approach provides evidence that more wind generation can be accommodated on the DS through the applied model. In addition, through this method, the reliability of the system can be maintained thus guaranteeing the security of supply to meet the world's energy demand. Also, the main contribution of this work is using demand side management (price-based demand response) as an active network management tool to compute the optimal wind energy investment capacity.

2.0 Methodology

The methodology used in this investigation involves literature review, modelling, and load flow simulation with Matlab software. The 132/33KV five-bus distribution test system was used along with the wind and load profiles obtained from the UK Generic Distribution System (UKGDS) for Sustainable Energy and Distributed Generation (SEDG) (UKGDS & SEDG, 2016). This load profile (domestic economy, industrial and commercial) considers the consumers' behaviour, classes of consumers and all other factors which could affect the load in a typical distribution network. Two scenario approaches which are passive network management (PNM) and active network management (ANM) were adopted during this investigation. The PNM was used as the base-case scenario to determine the amount of wind generation that can be accommodated on the network. On the other hand, the PBDR model was applied to the DS to increase the amount of wind generation that can be connected to the distribution network. This model helps to ensure that the distribution network bus's nominal voltage range of ± 6% is maintained.

The techniques used in this study are literature review, data collection (wind energy and demand profiles) from the UK sustainable electricity and distributed generation (SEDG) source available in the public domain (UKGDS & SEDG, 2016). Using the half-hourly loads and wind generation profile obtained from (UKGDS & SEDG, 2016), a time series analysis for a year-round (8760 h x 0.5hr) period was conducted on the 132/33KV distribution test system. This helped to determine the different levels of cost parameters at different wind penetration as well as the optimum capacity for investment. The cost parameters include net revenue, generation cost, and the profit derived at different wind MW penetration. In this paper, linear programming is adopted to solve the optimization problem. The objective function is given in (1) which minimises the total operating cost and the investment cost of wind generation with the incorporation of a simple annuity model denoted by T. The objective function is subject to the power flow constraints represented by Kirchhoff's Voltage Law (KVL) and power balance constraints by Kirchhoff's Current Law (KCL) given in (2) and (3). Constraints (4) and (5) represent the limits of the generator and the lines, while the bus voltage is limited by constraint (6). Equation (7) provides an elaboration of the term T in (1). The positivity limits of investment decisions are enforced by Constraint (8).

$$\min = w_t \sum_{g \in N_g} C_g P_{g,t} + T \sum_{g \in N_g} K_g I_g \quad (1)$$

$$P_{l,t} = \frac{(\theta_{s(l),t} - \theta_{r(l),t})}{R} = 0 \quad (2)$$

$$\sum_{\forall g \in N_g} P_{g,t} + \sum_{\forall l \in N_l} P_{l,t} = \sum_{\forall d \in N_d} P_d \quad (3)$$

$$P_g^{\min} \le P_{g,t} \le P_g^{\max} \tag{4}$$

$$P_l^{\min} \le P_{l,t} \le P_l^{\max} \tag{5}$$

$$V^{\min} \le V_{i,t} \le V^{\max} \tag{6}$$

$$T = \frac{PV}{\frac{1}{i}\left(1 - \frac{1}{(1+i)^T}\right)} \tag{7}$$

$$I_g \ge 0, \forall_g \tag{8}$$

$$n(E_{cv} \cap E_{nv} \cap S_{ov} = n(S_{uv}) \tag{9}$$

$$e = \frac{\%\Delta D}{\%\Delta P} \tag{10}$$

$$P_{wg}^{\max} \le \frac{V_s^{\max} - V_{source}}{R} \tag{11}$$

Where,

N_g	Set of generators
N_d	Set of demands
N_l	Set of lines
PV	Present value of loan
i	Interest rate
w_t	Weighting factor of hours
I_g	Invested capacity of Wind technology g (MW)
K_g	Investment cost of generation technology g (£/MW/year)
T	Payment period
E_{cv}	Economic values

E_{nv}	Environmental values
S_{ov}	Social values
S_{uv}	Sustainability Values
n	Number
$P_{wg}^{\max}$	Maximum real power injection
e	Elasticity of demand
$\%\Delta D$	Percentage change in demand
$\%\Delta P$	Percentage change in electricity nodal price
R	resistance of the R network
P_{wg}	Real power from wind generation
$V_s^{\max}$	Voltage at bus 5 (DG connection point)
V_{source}	The voltage at bus 2

Therefore, sustainability within this context can only be achieved through the application of (9). In (9), the associated economic value of wind energy is economically cheaper than conventional energy sources. The Environmental value is related to the benefit of decarbonising the electricity supply system while the social value relates to the overall welfare of all participants in the system (generators, distribution owner/operator, and consumers). Finally, sustainability values simply encompass the overall benefit of renewable energy deployment in the electricity energy mix. The AAP model given in (7) as used in the study assumes that the wind farm project is financed with capital secured from a financial institution. The loan of £800 per kW of electrical power (£0.8m/MW/yr) is payable for 20 years at an interest rate of 7%. Increasingly, for a typical wind farm project, the operation and maintenance (OM) cost increases as the turbine ages. Then, considering the study at hand, it is therefore assumed that the installation is new, and as such the OM is relatively low at about 2% of the investment cost. The observation of this study reveals that the investment cost has a great impact on the profit derived by the wind farm operator.

3.0 Results and Discussion

Figure 1 shows the correlation between the electricity generation cost and the corresponding revenue likely to be derived from an investment made in a particular wind farm capacity. From the plot, it can be observed that the revenue increases linearly up to about 15MW wind generation capacity and then begins to level up at about 20MW. Imperatively, the generation cost as shown on the graph increases as the wind generation capacity increases thus reducing the revenue derived from the investment. Further analysis in Figure 2 shows the profit derived from the wind farm investment under investigation. This analysis reveals that wind farm investment is profitable up to 20MW wind generation capacity with 15MW yielding the greatest profit. This illustrates that any investment made beyond 20MW will result in negative profits or losses to the wind farm operator(s). From a technical perspective, the network if actively controlled may accommodate more than 20MW wind generation capacity but at the expense of the profits derived from the investment. Based on these facts, a proper financial analysis should be considered while planning for a wind farm project. Equation (9) shows the concept of elasticity of demand, where the variation in price causes a corresponding change in demand with some degree of elasticity. Typically, (9) as applied in this study means that the electricity price increases in periods when generation is zero and decreases when the upper limits of the voltage are violated

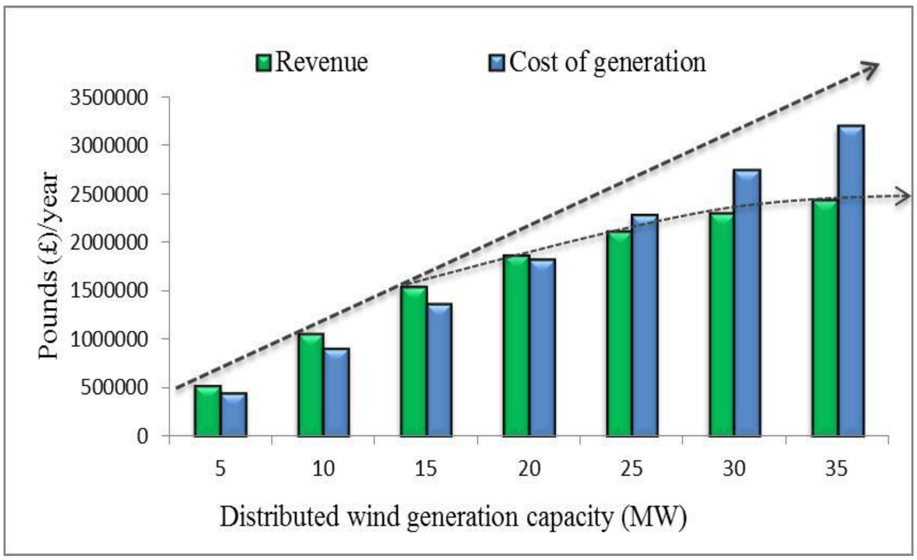

Figure 1: Net wind farm revenue and generation cost.

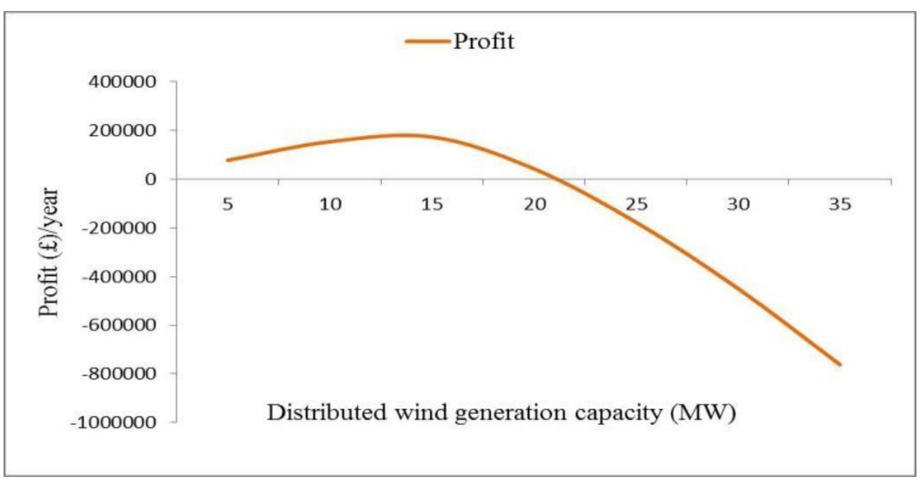

Figure 2: Profit from various wind generation capacities.

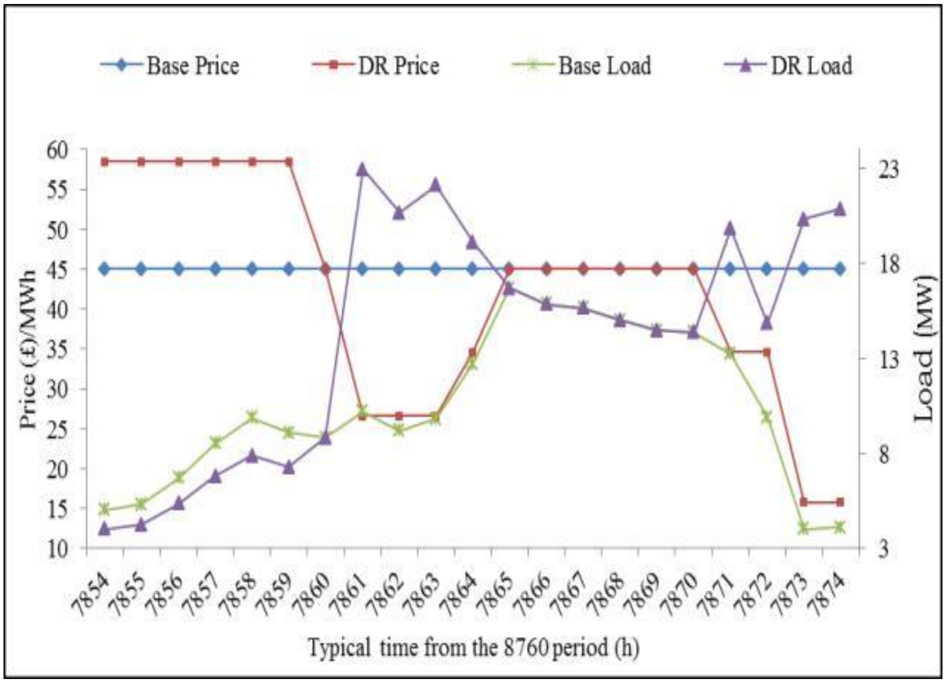

Figure 3: Application of PBDR as a control option.

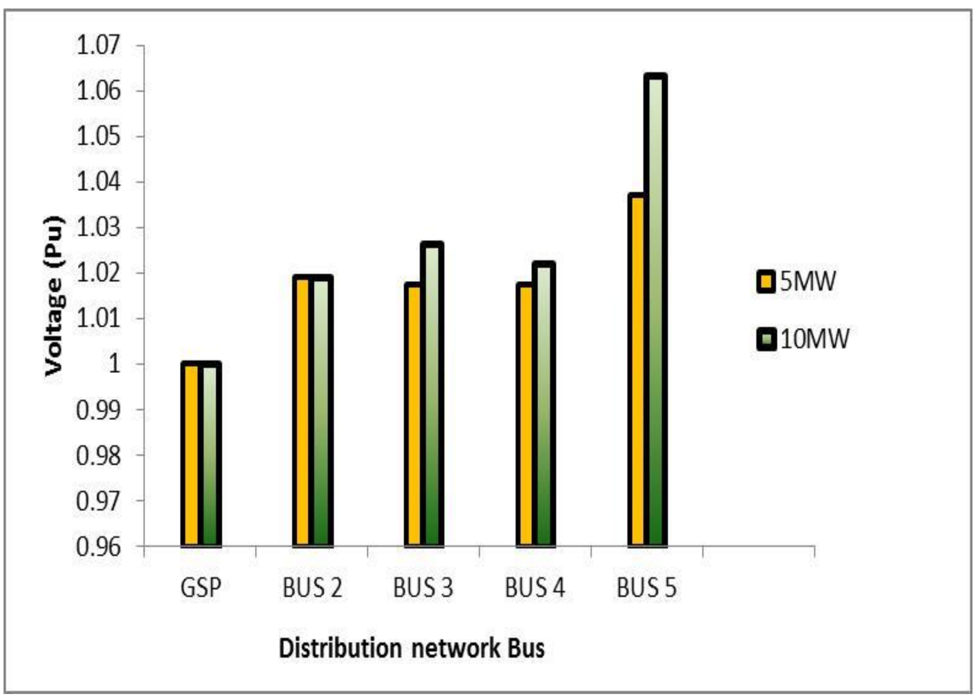

Figure 4: System voltage profile without PBDR.

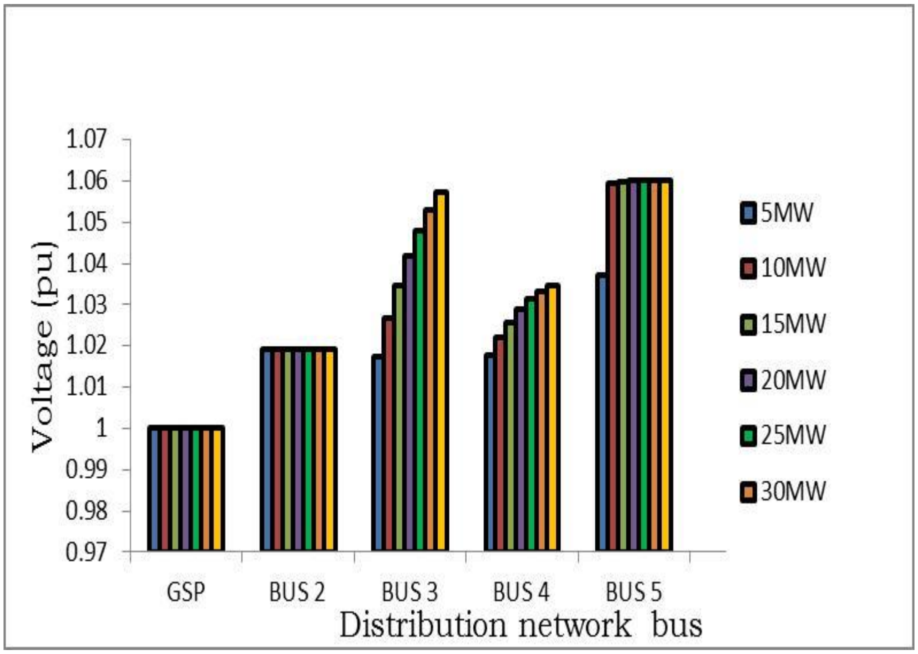

Figure 5: Effect of PBDR on the voltage profile.

Similarly, from (11), it can be deduced that the real power injection P_{wg}^{max} is dependent on the voltage rise at bus-5, where the wind generator is connected, and the resistance of the network. Figure 3 denotes typical periods with an electricity base price of £45/MWh extracted from the simulation where the PBDR control was applied. From this graph, it is established that at some periods when the wind output was zero, the price was increased to about £58.5/MWh hence, resulting in a corresponding decrease in the load (DR load) from the baseload. Indeed, during periods of voltage rise, the electricity nodal price decreases, leading to an equivalent increase in load. This increase in load will assist in creating a balance between the demand and generation, therefore, resolving the voltage issue. But this assumes that as long as the thermal constraint of the network is not violated; demand is always available. Increasingly, Figure 4 demonstrates the effect of the conventional method (PNM) of operating the distribution network. Given that the voltage at the grid supply point (GSP) is maintained at 1pu, Figure 4 shows that at 10MW wind generation capacity, the voltage at bus-5 has risen above the acceptable voltage limit of 1.06 pu. On the contrary, Figure 5 illustrates the benefit of an ANM of the distribution network. Using the PBDR model, the voltage was maintained within the acceptable range (0.94 V - 1.06) in all buses and the optimum wind generation capacity was increased from 5MW to 30MW, Figure 5. The application of the PBDR model in this study has offered a huge advantage in ensuring that the integrity of the distribution network is not jeopardised, thus supporting the penetration of wind generation cost-effectively.

4.0 Conclusion

Outcomes from this study are evident that for optimum utilization of wind energy resources, financial analysis is crucial. Although several technical models have been developed to maximize the deployment of wind energy resources, the result obtained from this study shows that the ROI needs to be determined. This is intended to justify the investment for the various stakeholders. Furthermore, these results will provide the investors with the knowledge that the revenue derived from wind farm investment is not linearly related to the capacity invested. Indeed, the results are very reasonable, as they point toward the infrastructure services pattern, in this case, over their life cycle. Also, a balance in this analysis is centered on (3) for the attainment of sustainability goals. Incorporating this model will promote healthy and greener energy for future generations. Although the results presented in this study appears promising and informative, it is interesting to note that the results shown are system specific.

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Appendix

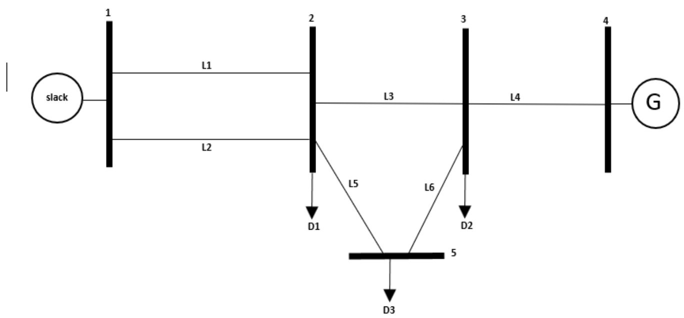

Figure 1: 5 bus Test System

Table 1: Generation Information

Generator ID	Generator Capacity (MW)	Generator Location
G1	50MW	1
G2	40MW	4

Table 2: Load information

Load ID	Load Location	Load Capacity (MW)
L1	Bus 2	20
L2	Bus 3	12
L3	Bus 4	14

Table 3: Line information

Line ID	Bus Origin	Bus Destination	Max Capacity (MW)
L1	1	2	30
L2	1	2	30
L3	2	3	30

L4	3	4	30
L5	2	5	30
L6	3	5	30

Table 4: Load data

Load ID	Load capacity (MW)
D1	20
D2	12
D3	14