V. International Conference on Electrical, Computer and Energy Technologies (ICECET 2025)
3-6 July 2025, Paris-France

Advanced Energy Management and Planning Strategies for the IEEE 33-Bus System: Integration of EV Penetration, INVELOX Turbines, and Bifacial PV Panels

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***Abstract*—The rapid urbanization and growing population in cities present significant challenges in energy management. Smart cities aim to address these challenges by leveraging advanced technologies to optimize energy production, distribution, and consumption. This paper explores advanced energy management and planning strategies for the IEEE 33-Bus system through the synergistic integration of Electric Vehicle (EV) penetration, INVELOX turbines (IWT), and bifacial photovoltaic (BPV) panels. These innovative technologies offer substantial potential for enhancing power distribution systems' efficiency, reliability, and sustainability. The integration of these elements is examined to understand their combined impact on energy management, system stability, and overall grid performance. The findings provide a comprehensive understanding of how these technologies can be harnessed to optimize energy management in modern power systems. Multi-objective functions, including total cost and emission, are considered, which should be minimized simultaneously. The study models a mixed integer quadratic linear programming (MIQCP) in GAMS software and solves it using CPLEX. Furthermore, the weighted sum approach is used to solve this problem. The final results show the efficiency and accuracy of responses and the operator's planning in addressing the distribution network (DN) issues.**

Keywords*—Bi-facial PV (BPV), Energy management system (EMS), Electric Vehicles (EV), INVELOX wind turbines (IWT), Optimization, Renewable energy resources (RERs).

I. Introduction

A. General overview of the proposed issue

Greenhouse gas (GHG) emissions, largely driven by human activities, play a major role in global climate change. Gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) act like a thermal blanket around the Earth, trapping heat and intensifying the greenhouse effect. This process fuels global warming, disrupting ecosystems, weather patterns, and the balance of our planet's climate.[1]. This phenomenon has profound consequences, from rising sea levels and more frequent extreme weather events to the disruption of ecosystems. However, emerging renewable technologies provide a promising path forward. By reducing GHG emissions and shifting towards a more sustainable energy system, these innovations offer a tangible way to curb climate change and protect the planet for future generations [2]. The impact of GHG emissions is both profound and far-reaching. Rising global temperatures disrupt weather patterns, fueling more frequent and intense hurricanes, droughts, and floods. These shifts endanger human health and safety and threaten biodiversity as many species struggle to adapt to rapidly changing environments. To counter these harmful effects, transitioning to renewable energy sources is not just an option—it is an urgent necessity for a more sustainable and resilient future [3]. Cutting-edge renewable technologies—such as solar photovoltaics (PV), wind turbines, advanced bioenergy, and emerging solutions like tidal and wave energy—are leading the transition toward a cleaner and more sustainable energy future. By harnessing natural processes to generate power without emitting greenhouse gases, these innovations provide a viable alternative to fossil fuels. However, the modern power grid must navigate several challenges, including growing energy demand, seamless renewable integration, and the need for improved reliability and efficiency. Overcoming these obstacles is essential to building a resilient and sustainable energy infrastructure [4]. The development of electric vehicles (EVs) dates back to the early 19th century, but only in recent decades have advancements in energy storage and management systems made them a practical alternative to internal combustion engines (ICEs). Today's EVs offer up to ten times lower transportation costs and deliver full power across the entire RPM range, making them an increasingly attractive choice for consumers and policymakers. At the heart of EV performance is the Energy Management System (EMS), which seamlessly coordinates electrical, thermal, and safety operations. A well-designed EMS optimizes charging and discharging efficiency, regulates temperature for peak performance, and ensures safety through real-time monitoring and control [5]. Centralized systems like the CAN Bus play a critical role in diagnosing and managing these complex processes. Among various EMS strategies, hybrid energy storage systems (HESS), which integrate batteries with supercapacitors, have demonstrated significant potential. Supercapacitors offer high power

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density, alleviating battery stress, thereby extending battery lifespan and enhancing overall efficiency. Effective EMS strategies also employ advanced control algorithms, such as fuzzy logic and dynamic programming, to dynamically adjust to changing driving conditions and optimize energy consumption. Despite these advancements, challenges persist in making EVs more economically viable and environmentally sustainable. High initial costs, insufficient charging infrastructure, and the environmental impact of battery production remain key barriers. However, continuous innovation in EMS and energy storage technologies is essential for overcoming these obstacles and accelerating the widespread adoption of EVs [6]. Researchers have evaluated many aspects of energy management in the past years by considering different approaches, energy resources, and various schematics.

B. *Investigation and review of the recent studies*

Rimpas et al. [7] reviewed various energy management systems (EMS) and storage strategies in electric vehicles (EVs). It highlighted the increasing market share of EVs and the need for effective EMS to improve efficiency, reduce costs, and extend battery life. The paper classified EMS into three layers: hardware low-level control, component control, and software-based high-level supervisory control. Various strategies such as fuzzy logic, rule-based strategies, dynamic programming, and genetic algorithms were reviewed for their effectiveness in managing energy and extending battery life. Majeed et al. [8] explored the potential of renewable energy sources, such as solar, biomass, wind, and geothermal energy, for energy management in agriculture. It discussed the benefits, challenges, and opportunities of adopting these technologies to enhance sustainability, reduce greenhouse gas emissions, and improve energy efficiency in the agricultural sector. Pandiyan et al. [9] reviewed and examined the technological advancements toward smart energy management in smart cities. It categorized advancements by applications such as smart grids, smart buildings, and smart transportation, discussing benefits like increased efficiency, reduced costs, and sustainability. The paper included case studies and explored emerging technologies and research areas, emphasizing the importance of these advancements for future smart cities. Engelhardt et al. [10] presented a novel energy management system (EMS) for hybrid fast charging stations with battery storage and local renewable energy generation. It focused on a multi-battery design that connects directly to other DC components via a bus bar matrix, eliminating the need for power converters. The EMS had two main functions: allocating battery strings to different DC microgrid components (PV system, EV fast chargers, grid-tie inverter) and managing energy exchanges with the local grid. The study compared basic droop control with an enhanced control incorporating PV forecasts. Extensive Monte Carlo simulations using real EV charging data from various seasons in Denmark show that the enhanced control improves self-sufficiency and reduces battery cycles, though it may accelerate battery aging due to higher average charge levels. This research highlights the potential of integrating local renewable generation to support low-carbon EV charging while mitigating grid impact. Ammari et al. [11] presented a comprehensive literature review of hybrid renewable energy systems (HRES). It analyzed recent studies in four key areas: sizing, optimization, control, and energy management. The review highlighted sizing methods: Comparison between commercial software and traditional methods, noting the advantages and limitations of each. Optimization techniques: examining classical, artificial, and hybrid optimization methods, discussing their efficiency, accuracy, and complexity. Control Strategies: analysis of centralized, distributed, and hybrid control methods, emphasizing their effectiveness and challenges. Energy Management: Focused on techno-economic objectives, using various algorithms and software to optimize system performance and cost. The paper concluded by discussing the role of HRES in grid supply, energy saving, emission reduction, and cost reduction, summarizing the advantages and drawbacks of different methods and providing insights into effective HRES design and management. Mostafa et.al [12] addressed the benefits and challenges of applying big data analytics (BDA) to renewable energy power stations and smart grids. A framework for implementing BDA in smart grids and renewable energy utilities was developed. The research proposed a five-step approach for predicting smart grid stability using machine learning methods. Data from a decentralized smart grid system, consisting of 60,000 instances and 12 attributes, was used. The accuracy of various machine learning models was evaluated: the penalized linear regression model achieved 96% accuracy, the random forest model 84%, the decision tree model 78%, and both the convolutional neural network and gradient-boosted decision tree models 87%. The primary limitation noted was the relatively small dataset for big data analytics, though the use of cloud computing and real-time event analysis demonstrated the suitability of the BDA framework. The study concludes that while the dataset is relatively small, the proposed BDA framework and machine learning models effectively predict smart grid stability, showcasing the potential for future enhancements with larger datasets. Hadi et al. [13] explored the use of the gray wolf optimization (GWO) algorithm and the whale optimization algorithm (WOA) to determine the optimal number of grid-connected bifacial photovoltaic (PV) systems in Babylon Hilla. Factors such as available space, desired energy production, radiation, dihedral factor, budget constraints, and grid connectivity requirements were considered. The mathematical formulation of the problem and the implementation details of both algorithms were provided. Two case studies were conducted: one for a residential area and another for a single house. The results show that efficiency and effectiveness of both GWO and WOA algorithms in finding optimal solutions for PV system sizing are good. Moreover, the WOA surpassed the GWO in meeting optimization criteria. Conversely, results illustrate that proper selection of PV systems resulted in higher power generation, lower costs, and improved energy management. The WOA showed notable economic benefits, while the GWO excelled in energy management. The study confirmed the increased energy efficiency and cost-effectiveness of the optimized systems. Furthermore, the paper highlighted the potential of these optimization techniques in supporting sustainable solar energy solutions. Further research suggests integrating real-time data and dynamic factors like weather and grid demand fluctuations to enhance optimization accuracy and effectiveness. Alilou et al. utilized a new multi-objective scheduling method for energy management in smart homes within a residential microgrid. This method combined the multi-objective dragonfly algorithm with the analytical hierarchy process to optimize the operational schedule of home appliances, rooftop photovoltaic (PV) panels, and plug-in hybrid electric vehicles (PHEVs). The study considered uncertainties in PV and PHEV operations and used a real-time pricing tariff as part of a demand response program. The proposed method demonstrates a significant reduction in electricity bills and peak demand in a smart microgrid with 20 smart homes. Moreover, by optimizing the operational schedule, the consumption patterns are better aligned with the generation curve. Furthermore, the performance of smart homes and the smart microgrid is improved by more than 30% in terms of technical and economic indices. The availability of PV panels positively affected technical, economic, and environmental indices, showing an 86% improvement during peak solar times. PHEVs participate in demand side management by supplying part of the demand in discharge mode while primarily functioning as consumption devices. The study confirms the effectiveness of the proposed energy management method in enhancing the efficiency and consumer satisfaction of smart homes by optimizing the use of home appliances, PHEVs, and PV panels.

C. *Novelty and innovation of the presented study*

While many papers have addressed energy management issues and considered bi-facial PV panels separately, a few assumed these items together. Moreover, investigating these units is an issue that has not yet been addressed. This paper examines energy management systems in the real case of the IEEE 33 Bus system by considering novel RER technologies such as INVELOX wind turbines and bi-facial PV panels and the integration of electric vehicles. This combination helps predict and solve congestion issues related to the high penetration of EVs. Briefly, the innovation of this study is the INVELOX wind turbine consideration in a real IEEE standard 33 bus system regarding the bi-facial PV panels and high penetration of EVs. Therefore, this research investigates advanced strategies for energy management and planning in the IEEE 33-Bus system by integrating Electric Vehicle (EV) penetration, INVELOX wind turbines (IWT), and bifacial photovoltaic (BPV) panels. The study focuses on how the combination of these technologies affects energy management, system stability, and grid performance. Multi-objective functions, such as minimizing total cost and emissions, are considered. The problem is formulated as a Mixed Integer Quadratic Constrained Programming (MIQCP) model in GAMS software and solved using the CPLEX solver. Furthermore, the weighted sum approach addresses the multi-objective optimization problem.

D. *Arrangement of various sections of the proposed study*

Section II expresses the explanation of these novel RERs. Section III explains the proposed IEEE 33 bus test system and optimization approach. Section IV describes the objective functions. Section V brings the results, and eventually, section VI is dedicated to the conclusion.

II. RENEWABLE ENERGY RESOURCES

A. *INVELOX wind turbine (IWT)*

NVELOX turbines are wind energy technology designed to capture and accelerate wind flow through a funnel-like structure before directing it to the turbine, thereby increasing efficiency. This method allows power generation at lower wind speeds than traditional wind turbines. The wind is captured at the top of the tower, funneled through a narrowing passage, and then accelerated before reaching the turbine generator. This design enhances the energy output and reduces noise and visual impact, making it suitable for urban and rural installations. The technology is particularly effective in areas with variable wind conditions, as it maximizes the use of available wind resources to generate a stable and reliable power supply. Maintaining the Integrity of the Specifications [14]. The output power of such systems is obtained from Eq. (1). Moreover, the general schematic of these turbines is illustrated in Fig. (1).

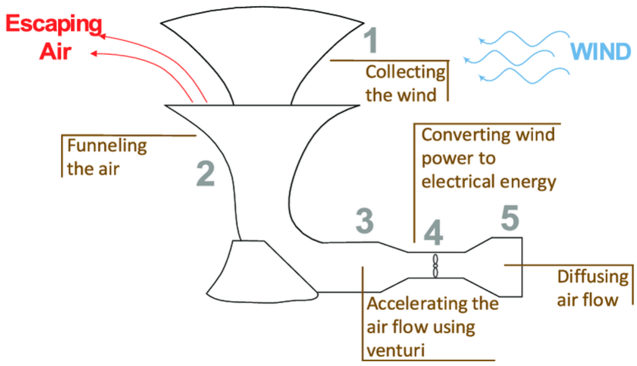

Fig. 1. The overall structure of the INVELOX turbine [15].

$$P_{IWT}(t)=\begin{cases} 0 & \forall t: V^{Cut-in-IWT} \geq V_t \\ 0 & and \;\; V^{Cut-out-IWT} \leq V_t \\ \left(0.5\cdot\rho_{IWT}\times A_{IWT}\times \eta^{IWT}\times K_p\times(V_t\times S_R)^3\right) & \forall t: V^{Cut-in-IWT} \leq V_t \\ & V_t \leq V^{Cut-out-IWT} \end{cases} \quad (1)$$

B. *Bi-facial PV panels (BPV)*

Bifacial photovoltaic (BPV) panels are designed to capture sunlight on both their front and rear surfaces, allowing for increased energy generation compared to traditional mono-facial panels. Light is absorbed from direct sunlight on the front side and reflected light from the ground or surrounding surfaces on the rear side. This dual-sided exposure enhances overall energy efficiency and output, especially in environments with high albedo surfaces like snow, sand, or white rooftops. Bifacial PV panels maximize energy production within the same installation footprint, contributing to more effective and sustainable solar power systems. Their implementation can lead to a higher return on investment by utilizing both direct and diffuse light to generate additional electricity [16]. The equation related to the extra radiation and surplus power generated by BPV are shown in Eqs. (2) and (3).

$$G = G_{front} + \lambda \times G_{rear} \quad (2)$$

$$P_{BPV}(t) = P_{PV}(t) + \left(C \times P_{PV}(t)\right) \quad (3)$$

III. IEEE 33 BUS STANDARD SYSTEM AND OPTIMIZATION METHOD

A. IEEE 33 bus test case

The IEEE 33-bus system is commonly utilized as a benchmark for evaluating the performance of power distribution networks. This test system, comprising 33 buses and 32 branches, is modeled to represent a real-world distribution network, providing a standard for academic and industrial research. Fig. (2) illustrates the configuration of the IEEE 33-bus test system, including the connections between buses and branches and the locations of various loads. All related information is brought in [17] for further consideration. Furthermore, the candidate buses for installing wind turbines are 13 and 30, and for photovoltaic panels are 7, 10, 24, and 27. All needed information is presented in [18] for interested readers.

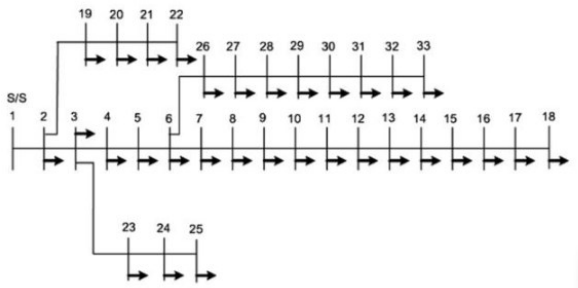

Fig. 2. The overall structure of the IEEE standards test system.

B. Weighted optimization approach

The weighted sum approach is used in multi-objective optimization to combine multiple objectives into a single composite objective function. This approach is particularly useful when dealing with two objective functions, as it simplifies the optimization process by transforming it into a single-objective problem. Each objective function is assigned a weight that reflects its relative importance in this method. The weighted sum of these objective functions is then minimized (or maximized). Mathematically, if f1(x) and f2(x) are the two objective functions to be minimized, the weighted sum approach can be expressed as Eq. (4):

$$Z\left(x\right)=W_1\times f_1(x)+W_2\times f_2(x) \tag{4}$$

where w1 and w2 are the weights assigned to the objective functions f1(x) and f2(x), respectively. The weights are typically chosen such that w1+w2=1 ensures that the combined objective function appropriately balances the original objectives. The optimization process involves adjusting the decision variables x to find the minimum value of the composite objective function Z(x). By varying the weights w1 and w2, different trade-offs between the two objectives can be explored, providing a set of optimal solutions known as the Pareto front. It should be mentioned that each objective function is assumed to have an equal value, meaning that, in this work, they are considered to have an equal impact on the proposed planning.

IV. OBJECTIVE FUNCTIONS

The most important objective functions and weighted sum approach expression are explained as follows, in which Eq. (5) demonstrates the amount of pollution emission. Moreover, Eq. (6) shows the total summation of various costs, including distributed generation cost, loss cost related to the transmission lines, and total energy cost related to the amount of buying power from the main grid. Finally, Eq. (7) illustrates the coefficient of the weighted sum approach method for optimization of the dual presented problem.

$$EM=\frac{365\times\sum_{s,t}\left(P_s(s)\times P_g(T,s)\times\left(CO_2+SO_2+NO_X+PM_{10}\right)\right)}{1000} \tag{5}$$

$$\text{Total Cost}=\left(\text{Cost}_{\text{DG}}+\left(2\times\text{Cost}_{\text{power loss}}\right)+\text{Cost}_{\text{Energy}}\right) \tag{6}$$

$$Z=\omega_1\times\text{Cost}t+\omega_2\times EM \tag{7}$$

V. NUMERICAL RESULTS

A. Nominal scenario (Scene 1: without BPV & IWT)

This section provides the results of the multi-objective optimization problem without participating in any distributed generation resources. The results of this section are shown below. As can be seen, the total cost and pollution for this scenario have been calculated as $ 2,019,066.902 and 15,661.704 tons. The voltage magnitude of various buses of the assumed scenario is depicted in Fig. (3). Furthermore, the weaker areas can be reachable by looking at Fig. (4). It is worth noting that the electric vehicles have been added to the grid between time intervals 6 to 10 and 13 to 17. As can be understood from the figures, the voltage magnitudes in most time intervals have been below 0.95 pu. In other words, Adding EVs to the grid caused a voltage drop in the mentioned time intervals, especially affecting the buses far from the main grid. In other scenarios, DGs are added to this grid to improve performance and enhance the network's voltage magnitude and power quality.

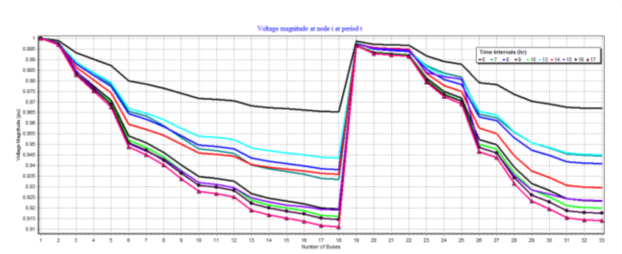

Fig. 3. The voltage magnitude of various buses in different time intervals for the IEEE standard system for the first scenario.

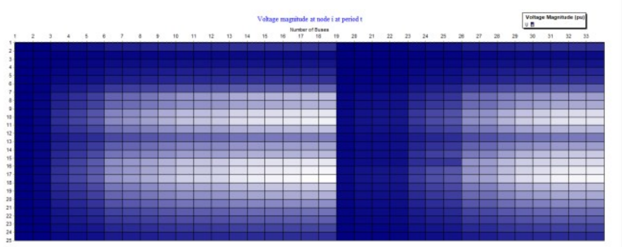

Fig. 4. The voltage magnitude of various buses in different time intervals for the IEEE standard system in grid aspect view for the first scenario.

B. *With distributed generation (Scene 2: Typical WT & PV)*

The typical wind turbine and photovoltaic panels are added to the IEEE 33 bus test system to evaluate its performance in this scenario. For this scenario, the total cost and pollution values have been calculated as $ 3,801,075.106 and 874.208 tons, respectively. As can be seen, compared to the previous scenario, the total cost has increased due to the usage of several renewable energy resources. This increase has positively affected total pollution and decreased it by about 94 %, a significant percentage. However, the total cost has also increased. In other words, this reduction in environmental pollution has resulted from increased investment in renewable-generation units. It should be noted that the life year of an RER is considered to be about 20 years. As can be seen from Fig. (5), although adding RERs has increased the total cost, it has had many advantages, such as improving the voltage magnitude for all buses in the time intervals that consumers connected their EVs to the grid. The voltage of various buses has been kept at 0.95 pu.
Furthermore, as mentioned, the emission has also been reduced to an appropriate value. However, based on Fig. (6), RERs have tried to provide uniform voltage in all buses. This scenario's power loss has increased from 1.988 MW to 3.438 MW. This has occurred due to the congestion in lines due to generated power by RERs, which increases the total loss.

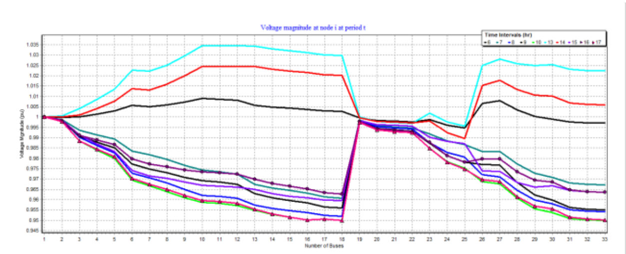

Fig. 5. The voltage magnitude of various buses in different time intervals for the IEEE standard system for the second scenario.

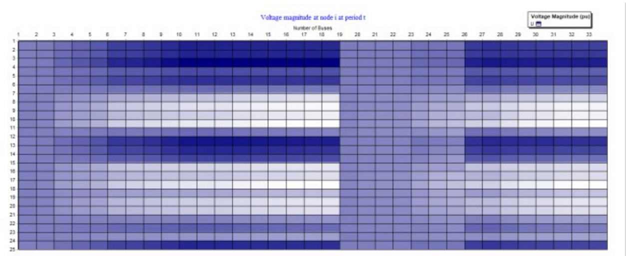

Fig. 6. The voltage magnitude of various buses in different time intervals for the IEEE standard system for the second scenario.

C. *With distributed generation (Scene 3: IWT & BPV)*

In this scenario, the impact of INVELOX and Bi-facial PV panels has been evaluated. This scenario's total cost and pollution are $ 2,561,295.060 and 7,150.610 tons. The amount of power loss for this scenario has been 2.099 MW. Compared to the previous scenario, it can be understood that the total cost has decreased; however, compared to the second scenario, the pollution has increased. This increment has been due to the surplus power of IWT and BPV. By using such units, the power purchased from the upstream network has been reduced, which has led to a reduction in power loss. It should be noted that the life year of an RER is considered to be about 30 years. Moreover, based on Figures (7) and (8), the voltage magnitudes have been kept in a suitable condition. Furthermore, using such units strengthens the weaker areas and enhances the quality and reliability of various buses. By using these elements, the voltage magnitude has been more uniform compared to other scenarios.

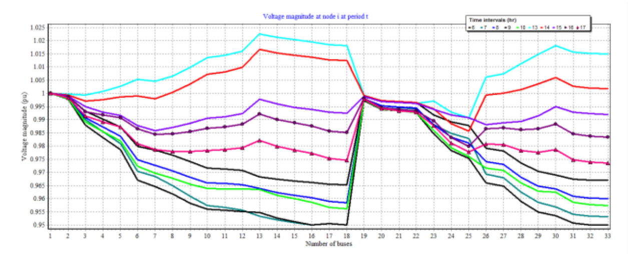

Fig. 7. The voltage magnitude of various buses in different time intervals for the IEEE standard system for the third scenario.

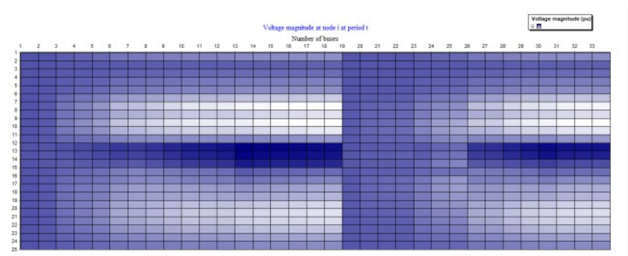

Fig. 8. The voltage magnitude of various buses in different time intervals for the IEEE standard system for the third scenario.

VI. Conclusion

This study successfully demonstrates the potential of integrating Electric Vehicle (EV) penetration, INVELOX turbines (IWT), and bifacial photovoltaic (BPV) panels into the IEEE 33-Bus system to enhance energy management and grid performance in smart cities. By employing advanced energy management and planning strategies, the combined impact of these technologies on energy optimization, system stability, and overall grid performance was comprehensively analyzed. Utilizing Mixed Integer Quadratic Constrained Programming (MIQCP) in GAMS software and solving with CPLEX, the study effectively minimized multi-objective functions, including total cost and emissions, using the weighted sum approach. The INVELOX and Bi-facial PV panels successfully reduced the total cost and power loss by about 32.62 % and 38.95% compared to the typical renewable energy units. The increment of total costs due to Bi-facial PV panels was neutralized by the significant reduction in the cost of INVELOX turbines instead of typical wind turbines. The pollution was reduced from 15,661.704 tons to 7,150.61 tons, compared to the first scenario, because of the presence of INVELOX and Bi-PV. The final results confirm the efficiency and accuracy of the proposed methods in addressing various distribution network issues.

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