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RESEARCH

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Maximizing the cost effectiveness of electric power generation through the integration of distributed generators: wind, hydro and solar power

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Abstract

Background The transition towards renewable energy sources has become an imperative step to mitigate climate change, reduce carbon emissions and improve energy security and economic prosperity in a sustainable manner. Maximizing the cost effectiveness of electric power generation is crucial to making renewable energy sources viable and attractive options for clean energy production. The strategic allocation of wind, hydro and solar power systems is essential to achieving this goal. This paper attempts to demonstrate how the cost effectiveness of electrical power system could be maximized through the integration of wind, solar and hydropower systems and comparison at different penetration levels of 0, 25, 50, 75 and 100% on cost effectiveness of electric power generation. The different generator technologies were designed based on their electrical output attributions.

Results The cost of electric generation for the integration of each generator at the various buses were calculated at different penetration level for fair comparison. The results indicate that the minimum money loss for the integration of solar power was $743.90 at bus 4 and at 50% penetration level, the minimum money loss for the integration of wind power was $999.00 at bus 4 and at 25% penetration level while the minimum amount loss for the integration of hydropower was $546.50 at bus 4 and at 75% penetration level.

Conclusions The magnitude to which the integration of the different generator affects the cost effectiveness of power production hinges on the type of generator, the penetration level and the location of the generator in the grid.

Keywords Cost effectiveness, Electric power generation, Distributed generators, Wind, Hydro, Solar power

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Background

Renewable energy sources, notably wind, hydro, and solar power, are pivotal in advancing cost-effective power generation (Ang et al. 2022). These sources, being replenishable, do not emit harmful greenhouse gases during generation and usage, making them environmentally favorable options for nations aiming to diminish their carbon footprint and address climate change (Pan et al. 2022). In the long run, they can be more cost-effective due to lower operational and maintenance costs compared to traditional power generation methods (Rasul et al. 2022). There is an escalating interest in optimizing the utilization of these renewable energy sources through strategic allocation and integration within existing power infrastructures, a move crucial for enhancing cost-effectiveness and mitigating environmental impacts (Abolarin et al. 2015; Akçaba and Eminer 2022; Bilgili et al. 2023). However, the improper placement of these installations can lead to decreased energy output and heightened maintenance costs, adversely affecting local ecosystems and communities (Abolarin et al. 2022; Mokarram et al. 2022).

For instance, wind turbines should be located in areas with stable and technically suitable wind patterns to maximize energy production. Hydroelectric plants require sites with consistent mechanical energy and adequate water flow for efficient electricity generation, avoiding areas with fluctuating mechanical energy to prevent reduced energy output and increased maintenance costs (Homa et al. 2022). Furthermore, the siting of solar power systems should consider minimal shading and visual impact on the surrounding landscape, while hydro plants should prioritize locations with lesser impacts on local water bodies and wildlife habitats. This strategic placement is vital in maximizing the cost-effectiveness of renewable energy sources and minimizing their environmental and community impacts (Al-Thani et al. 2022; Attia et al. 2022).

This research aims to emphasize the escalating importance of renewable energy sources in achieving cost-effective and environmentally friendly power generation. Furthermore, it seeks to explore the long-term economic benefits of these sources, including lower operational and maintenance costs compared to traditional energy sources. Lastly, it focuses on the critical role of proper placement of renewable installations in optimizing energy output.

Wind power

Wind power is a form of renewable energy that converts the kinetic energy of wind into electricity (Bhowon 2023). Wind power is generated by using wind turbines, which are tall structures with large turbine blades that rotate when the wind surrounding the turbine blades are energized. The rotation of the turbine blades drives a generator, which harnesses the rotational energy of the blade to generate electricity (Rehman et al. 2023) in accordance with the first law of thermodynamics. The electricity generated by the wind turbine are then available to be used immediately, directly, stored in batteries, or fed into the power grid (Deevela et al. 2023) to activate productive economic activities. Wind turbines are typically sited in areas with suitable wind speeds corresponding to the manufacturers' specifications, such as on hilltops, in open fields, or offshore in coastal areas (Veers et al. 2023). Wind speeds are affected by a variety of factors, including topography, vegetation, and weather patterns (Veers et al. 2023). Therefore, the strategic location of wind turbines is critical to ensuring optimal energy production. Wind power has many advantages over traditional fossil fuel-based power generation, including its renewable nature, low carbon emissions, and potential cost-effectiveness (Veers et al. 2023). However, wind power also has some limitations (Husby and Pearson 2022), such as its dependence on wind speeds, noise pollution, and potential impacts on wildlife and local communities. In general, wind power offers a variety of advantages in cost-effective power generation, including low operational costs, renewable nature, low emissions, modular design, and long-term energy security.

Hydropower

Hydropower is a form of renewable energy that uses the power of falling or flowing water to generate electricity (Ugwu et al. 2022) in the form of mechanical energy. This is done by using a hydraulic turbine, which transforms the flow energy, kinetic energy and potential energy of flowing water into mechanical energy that powers a generator to produce electricity (Kumar et al. 2023). Hydropower plants are typically located near natural water sources, such as rivers, waterfalls, or dams (Ewim et al. 2023; Soukhaphon et al. 2021). The water is directed through a turbine, which is connected to a generator. As the water flows through the turbine, it causes the blades to rotate, which in turn drives the generator, producing electricity. The two main types of hydropower plants are run-of-river plants and storage plants (Pal and Khan 2021). Run-of-river plants use the natural flow of a river or stream to generate electricity, while storage plants employ a reservoir with dam to accumulate. The water is subsequently released as required to generate electricity (Pal and Khan 2021). Hydropower offers several benefits compared to conventional fossil fuel-based power generation which include: its renewable nature, low operating costs, and potential cost-effectiveness (Farghali et al. 2023). However, it also has some limitations, such as its dependence on water availability and potential environmental impacts on local ecosystems and communities (Kuriqi et al. 2021).

Solar power

Solar power is a form of renewable energy that converts sunlight into electricity (Rahman et al. 2022). It works by using photovoltaic cells. The cells consist of semiconductor materials, such as silicon, arranged in layers, which convert sunlight into electricity. When the surface of a photovoltaic (PV) cell is exposed to sunlight, the electrons within the semiconductor material are excited, resulting in their movement, thereby generating a direct current (DC) of electricity (Zheng et al. 2021). The DC electricity produced by the PV cells is then converted into alternating current (AC) electricity by an inverter (Riskiono et al. 2021), which is the type of electricity that is used in homes and businesses. The production capacity of a solar panel is contingent on various factors including panel's size, the level of sunlight it receives and the efficiency of its photovoltaic cells (Jathar et al. 2023). Solar panels can be installed on rooftops, on the ground, or in large solar farms. In addition to PV cells, there is another type of solar power called concentrated solar power (CSP), it employs mirrors or lenses to focus sunlight onto a limited area, generating heat which can be utilized for electricity generation (Mohammad et al. 2023). CSP systems are typically used in large-scale solar power plants. In general, solar power represents a clean and renewable energy source that has the potential to mitigate greenhouse gas emission and reduce reliance on fossil fuels (Kandpal and Singh 2022). With the advancement of technology and decreasing costs, solar power is becoming more accessible and cost-effective for homeowners and businesses alike.

Pioneering strategies and innovations in renewable energy integration

Germany and Denmark have been leaders in the integration of renewable energy, with Germany making substantial investments in wind, solar, and biomass and implementing the "Energiewende" policy to transition towards a more sustainable energy system (Oteman et al. 2014). Germany's well-developed grid infrastructure is pivotal in managing the integration of variable renewable energy. Meanwhile, Denmark has focused extensively on integrating wind power, setting ambitious targets for carbon neutrality, and implementing advanced grid management systems and interconnections with neighboring countries to balance supply and demand effectively, showcasing a commitment to pioneering sustainable energy solutions.

China, Spain, and Sweden have also made significant strides in renewable energy integration. China, being a global leader in solar panel production, has been integrating various forms of renewable energy to meet its growing energy demands and reduce reliance on coal (Yang et al. 2010). Spain has developed extensive renewable energy projects, focusing on wind and solar power, and has implemented conducive policies and incentives to promote renewable energy adoption. Sweden aims to achieve 100% renewable electricity production by 2040, integrating primarily hydropower and wind energy through various policies, incentives, and technological innovations, demonstrating a holistic approach to renewable energy integration.

Methods

This research is focused on four grid types namely: the traditional bulk power grid, the bulk power grid with wind power decentralized generation (DG) integrated to it, the bulk power grid with solar power DG connected to it and the bulk power grid with hydropower DG connected to it. The power losses of these grid systems are calculated using the Newton–Raphson load flow method and the amounts of money loss as a result of the power losses in the grid are calculated. The Newton–Raphson load flow method is a computational technique used in power systems to determine the optimal set points for generators while adhering to physical constraints. It involves the linearization of the nonlinear power flow problem and solving the resulting linear equation, often requiring the calculation and manipulation of a Jacobian matrix (Xia et al. 2020; Thurner et al. 2018).

Traditional bulk power grid

Within the conventional bulk power grid, the processes of electric power generation and distribution are straightforward. Users have limited options and can solely acquire their power supply from the bulk power generator. The traditional bulk power grid in this research is represented by the IEEE 14 bus test system (Fig. 1). The IEEE 14-bus test case serves as a simplified representation of the American Electric Power system from February 1962. It consists of 14 buses, 5 generators, and 11 loads. Figure 1 provides a visual depiction of the IEEE 14 bus test system (Bouchiba and Kaddouri 2023).

The base load

In the realm of an electric power system, the base load delineates the consistent minimum level of electricity demand observed over a specific timeframe, usually spanning a day or a year (Haviv et al. 2020). This perpetual demand is catered to power stations that function incessantly, ensuring a stable and dependable supply of electricity. Traditionally, these stations have been powered by energy sources such as coal, nuclear, or hydroelectric power, which are capable of generating electricity at a uniform rate. The infrastructure of base load power plants is crafted to operate with high efficiency, avoiding frequent fluctuations in power output. The incorporation of alternative power generation avenues, including renewable energy sources, into the base load can augment cost-effectiveness by potentially diminishing fuel expenses and mitigating adverse environmental repercussions (Haviv et al. 2020).

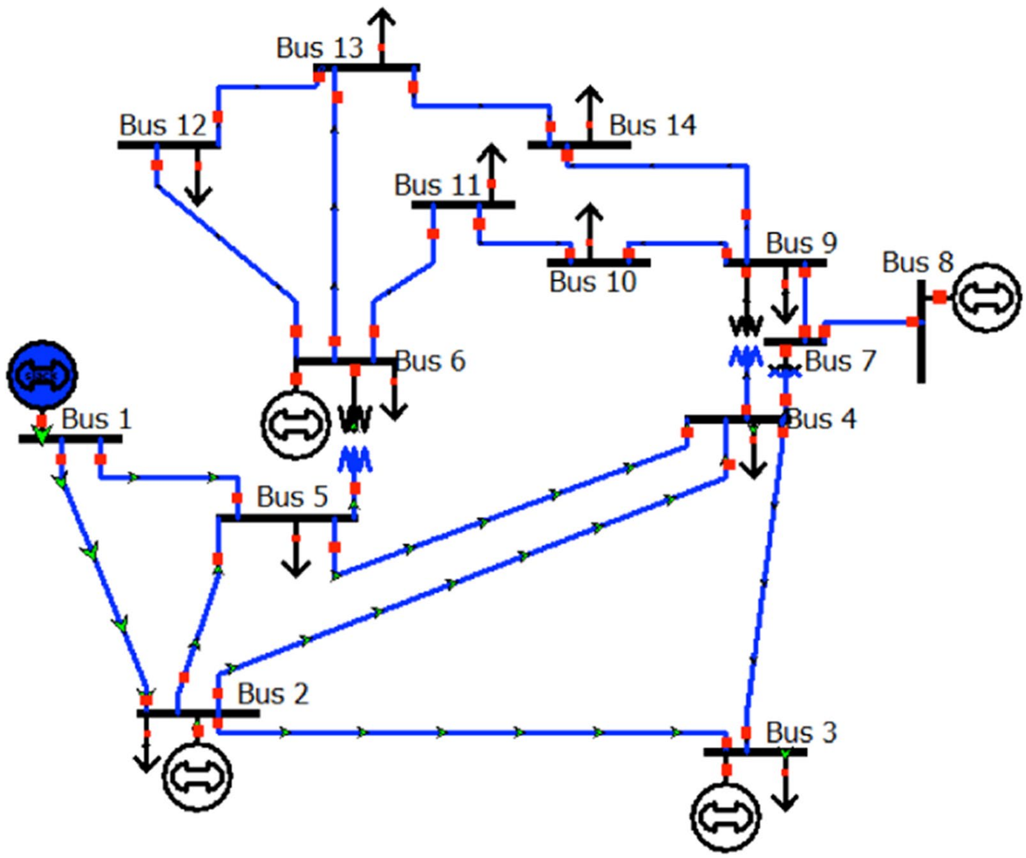

Fig. 1 The IEEE 14-bus test case

Integrating diverse forms of power generation, notably renewable energy sources, into the base load of an electric power system can significantly enhance cost-effectiveness. Firstly, renewable energy sources such as solar and wind power are inexhaustible, thus potentially reducing the reliance on finite and often expensive fossil fuels (Haviv et al. 2020). This transition not only curtails fuel costs but also minimizes the operational and maintenance costs associated with conventional power plants. Moreover, renewable energy sources have the added advantage of being environmentally friendly, as they do not emit greenhouse gases or other pollutants during energy production. This aspect is crucial in mitigating the adverse environmental impacts commonly associated with traditional energy generation methods, thereby fostering a sustainable energy landscape (Haviv et al. 2020).

Furthermore, the integration of renewable energy sources into the base load can enhance the resilience and reliability of the power system. By diversifying the energy mix, the system becomes less vulnerable to disruptions in supply, which can be caused by geopolitical tensions or fluctuations in fuel prices. Consequently, a more stable and reliable energy supply can be maintained, which is vital for sustaining economic growth and development (Haviv et al. 2020).

The load flow equations for the traditional bulk power grid (Ghimire et al. 2020) are given as:

Equation (1) provides the expression for the complex power, S_i injected by the generating source into the ith bus.

$$S_i = P_i + jQ_i = V_i I_i^* \quad i = 1, 2, \ldots, n \tag{1}$$

where V_i is the voltage at the ith bus with respect to ground and I_i^* is the complex conjugate of source current I_i injected into the bus, P_i is the real power and jQ_i is the reactive power.

It is easy to manage load flow problem by utilizing I_i instead of I_i^*. Therefore, by computing the complex conjugate of Eq. (1), we obtain Eq. (2).

$$S_i = P_i + jQ_i = V_i I_i^*; \quad n = 1, 2, 3, \ldots, n \tag{2}$$

Substituting Eq. (3) into Eq. (2) to obtain the complex power in terms of line admittance as shown in Eq. (4)

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \quad (3)$$

$$S_i^* = P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k; \quad i = 1, 2, 3, \ldots, n \quad (4)$$

From Eq. (4), the real power is expressed as shown in Eq. (5) and the reactive power in Eq. (6), respectively.

$$P_i = R_e \left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} \quad (5)$$

$$Q_i = I_m \left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} \quad (6)$$

V_i and Y_{ik} are expressed in polar form in order to rewrite the real power and the reactive power as shown in Eqs. (7) and (8), respectively, as:

$$V_i = V_i < \delta_i . V_i^* = V_i < -\delta_i \quad (7)$$

$$Y_{ik} = Y_{ik} < \theta_{ik} \quad (8)$$

The real and reactive powers are expressed in polar form by Eqs. (9) and (10), respectively.

$$P_i = V_i \sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_i) \quad (9)$$

$$Q_i = -V_i \sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_i) \quad (10)$$

Newton–Raphson method was employed in solving the power flow equations for the IEEE 14-bus system. A MATLAB code was written to this effect because of the number of buses and equations involved.

Distributed generators

There are three types of distributed generation technology based on their electrical output characteristics (Ayodele et al. 2015) as shown in Table 1. They include the synchronous technology generators, the induction technology generators and the asynchronous generator technology. Synchronous generator technologies (SGTs) regulate their terminal voltage by adjusting the level of reactive power they produce, thereby ensuring a consistent voltage at the output. Consequently, they can function at variable power factors. For induction generator technologies (IGTs), the magnetization of their rotors requires reactive power. This reactive power can be provided by either the grid or capacitor banks.

In contrast to the other two technologies, asynchronous generator-based technologies (AGTs) employ power electronic devices as an interface with the grid. These devices convert the power generated by the AGT into a form that poses minimal or no difficulties for the grid to transmit. The asynchronous generators rely on power electronic devices to convert the generated DC power into AC power at the necessary grid frequency and voltage.

Real power of the distributed generators

The real powers of the generators are the same for respective penetration levels. The difference in the generator is the reactive power which is dependent on the model of the generator technology. The real power of the generators are modeled using the penetration level Eq. (11) provided in the work of (Ayodele et al. 2015) as follows:

$$P_L = \frac{P_{DG}}{P_{Load}} \times 100\% \quad (11)$$

Making the power generated the subject of the formula in Eq. (11), we have Eq. (12)

$$P_{DG} = \frac{P_L}{100} \times P_{load} \quad (12)$$

Table 1 Distributed generation technology classes (Ayodele et al. 2015)

DG technology	Type of model	Physical examples
Synchronous generator	Variable reactive power	Reciprocating engine, combustion turbine, small hydro turbines
Induction generator	Reactive power consumption model	Squirrel cage induction generators (i.e. wind generators)
Asynchronous generator	Constant power factor model	Solar PV, fuel cells

where $P_{\text{load}} = 259$ MW (Total load of the IEEE 14-bus network.), $P_{\text{L}} =$ penetration level, $P_{\text{DG}} =$ power of the distributed generator, and $P_{\text{load}} =$ total load of the IEEE 14 bus test case. The generators real powers were calculated for 0, 25, 50, 75 and 100% penetration levels.

The wind power model

The wind power was modeled after synchronous generator technology. The wind generator was represented by generators that maintain a consistent terminal voltage, with known limits on real power and reactive power. In order to maintain a constant terminal voltage, the reactive power generated can fluctuate within the predetermined limits. In this work, the (González-Longatt et al. 2007) and Constant Voltage Model of Teng (2008) were used.

The model presented by Ogunjuyigbe et al. (2016) allows the reactive power Q_{SGT} to vary while keeping the real power P_{SGT} and terminal voltage V_{SGT}, constant. The model is given as

$$-0.75P_{\text{SGT}} \leq Q_{\text{SGT}} \leq 0.75P_{\text{SGT}} \tag{13}$$

Choosing the value of the reactive power to be:

$$Q_{\text{SGT}} = 0.7P_{\text{SGT}} \tag{14}$$

The hydropower model

The hydropower was modeled after the induction generator technology. The reactive power required for the rotor magnetization of the induction generator, sourced from either the grid or capacitor banks, is determined by the equivalent circuit of an induction generator as described in the works of Ayodele et al. (2015) and (Pidre et al. 2003):

$$\begin{aligned} Q =& V^2\frac{X_{\text{c}} - X_{\text{m}}}{X_{\text{c}}X_{\text{m}}} + X\frac{V^2 + 2RP}{2\left(R^2 + X^2\right)} \\ &- X\frac{\sqrt{\left(V^2 + 2RP\right)^2 - 4P^2\left(R^2 + X^2\right)}}{2\left(R^2 + X^2\right)} \end{aligned} \tag{15}$$

$$Q = -Q_0 - Q_1P - Q_2P^2 \tag{16}$$

where Q = reactive power drawn by the induction generator from the grid or capacitor bank, V = bus voltage, X_{m} = magnetizing reactance, X_{c} = reactance of the capacitor bank, X = sum of the rotor and stator reactance, R = sum of the rotor and stator resistances, P = real power generated.

By focusing solely on the first two derivatives of the McLaurin approximation and disregarding the resistance R, the reactive power consumed by an IGT was estimated using Eq. (17) as:

Table 2 Machine data for the induction generator model

Parameter	Value
Stator reactance	0.01 p.u
Rotor reactance	0.01 p.u
Magnetizing reactance (X_{m})	3.0 p.u

$$Q_{\text{IGT}} \approx V^2\frac{X_{\text{c}} - X_{\text{m}}}{X_{\text{c}}X_{\text{m}}} + \frac{X}{V^2}P^2 \tag{17}$$

Consequently, for a specific generated real power P and machine parameters (X_{c}, X_{m}, and X), the reactive power utilized by induction-based generator technologies can be determined. The induction generator parameters employed in this investigation are provided in Table 2.

The capacitive bank reactance was selected as $X_{\text{c}} = 0.4$ p.u.

$$X = 0.01 + 0.01 = 0.02 \text{ p.u.}$$
$$V = 1.0132 \text{ p.u.}$$

Substituting values of X_{c}, X and V into Eq. (17) gives Eqs. (18) and (19)

$$Q_{\text{IGT}} = 1.0132^2\frac{0.4 - 3.0}{(0.4)(3.0)} + \frac{0.02}{1.0132^2}P^2 \tag{18}$$

$$Q_{\text{IGT}} = 0.08554785333 + 0.01948227339P^2 \tag{19}$$

Modeling of the distributed solar power generation

The distributed solar power generation was model after asynchronous generator technology. For a real power P_{AGT} generated by the asynchronous generator, the reactive power generated is expressed as:

$$Q_{\text{AGT}} = \pm\sqrt{P_{\text{AGT}}^2\left(\frac{1}{\cos^2\emptyset} - 1\right)} \tag{20}$$

$\cos\emptyset \geq 0$, $Q_{\text{AGT}} \geq 0$, otherwise $Q_{\text{AGT}} < 0$.

where $\cos\emptyset$ = power factor of the asynchronous generator, $P_{\text{AGT}} =$ real power generated by the asynchronous generator, and $Q_{\text{AGT}} =$ reactive power generated by the asynchronous generator.

The asynchronous generators were modeled following the correlation in the work of Ayodele et al. (2015) as negative loads at the bus, operating with a constant power factor.

For triggering angle of 50°, $\cos\emptyset = 0.64$

$$Q_{\mathrm{AGT}} = \pm\sqrt{P_{\mathrm{AGT}}^{2}\left(\frac{1}{\cos^{2} 50} - 1\right)} \tag{21}$$

$$Q_{\mathrm{AGT}} = \pm 1.192 P_{\mathrm{AGT}} \tag{22}$$

Integration of the distributed generators

Each of the distributed generators was integrated to the grid system through 8 buses namely bus 4, bus 5, bus 9, bus 10, bus 11, bus 12, bus 13 and bus 14 at 0, 25, 50 75, and 100% penetration levels and the load flow of the grid system in each case was calculated using the Newton–Raphson method just as in the bulk power system. The power loss in each case is calculated as follows:

$$P_{\mathrm{Loss}} = P_{\mathrm{G}} - P_{\mathrm{R}} \tag{23}$$

P_{G} = total power generated,
P_{R} = total power delivered to the load,
P_{Loss} = total power loss in the line.

The cost of electric power loss in the grid system

The cost of electric power loss in the grid when distributed generators are integrated is given as:

$$A_{\mathrm{L}} = (C_{\mathrm{BG}} + C_{\mathrm{DG}}) - S_{\mathrm{R}} \tag{24}$$

When no distributed generator is connected to the grid, the value of C_{DG} becomes zero and the equation becomes:

$$A_{\mathrm{L}} = C_{\mathrm{BG}} - S_{\mathrm{R}} \tag{25}$$

where A_{L} = total money lost as a result of power loss in the system, C_{BG} = cost of bulk power generation, C_{DG} = cost of distributed power generation, S_{R} = total amount of money from selling to customers.

$$C_{\mathrm{BG}} = \text{Bulk power generated} \times \text{unit cost of bulk power generated}$$
$$C_{\mathrm{DG}} = \text{distributed power generated} \times \text{unit cost of distributed power generated}$$
$$S_{\mathrm{R}} = \text{total power sold} \times \text{unit price of power}$$

The unit cost of bulk power generated is given as $150/MWh. The unit cost of wind, solar and hydropower generation is $115/MWh, $68/MWh and $47/MWh according to international renewable energy agency (IRENA 2021).

A MATLAB code was written to calculate the electric power loss cost when distributed generators are integrated into the grid and when they are not integrated into the grid for proper analysis.

Results

Discussion

Effect of integrating solar power on the electric power system

Solar power-based distributed generator was connected to 8 buses namely bus 4, bus 5, bus 9, bus 10, bus 11, bus 12, bus 13 and bus 14 at 0, 25, 50, 75, and 100% penetration levels. The results for amount of money loss due to power loss on the grid at each penetration level are shown in Fig. 1 and Table 3. The minimum amount of money lost because of power loss for the integration of solar power was $743.9 at bus 4 at 50% penetration level as shown in Table 3. This shows that integrating solar power at 50% penetration level is most profiting for solar power integration.

Table 3 shows the total amount of money lost in the grid for integration of solar power. The amount of money lost was the same for all the buses at 0% penetration level. At 25% penetration level, integration at bus 4 has the least amount of money loss of $992.40 while integration at bus 12 has the highest loss of $1769.40. At 50% penetration level, the least money lost was $743.90 which occurred at integration at bus 4 while the maximum loss was $3202.20 which occurred upon integration at bus 12. At 75% penetration level, integration at bus 4 produced the lowest amount of money loss of $743.90 while integration at bus 12 produced the highest loss of money of $5490.30. At 100% penetration, integration at bus 4 also has the least amount of money loss of $1323.00 and integration at bus 12 has the highest amount of money loss of $1323.00.

Table 3 Representation of total amount ($) loss in the grid for solar power integration

Penetration level	$P_{4\mathrm{solarL}}$	$P_{5\mathrm{solarL}}$	$P_{9\mathrm{solarL}}$	$P_{10\mathrm{solarL}}$	$P_{11\mathrm{solarL}}$	$P_{12\mathrm{solarL}}$	$P_{13\mathrm{solarL}}$	$P_{14\mathrm{solarL}}$
0	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5
25	992.4	1080.8	1005.5	1173.3	1405.3	1769.4	1327.2	1433.3
50	743.9	887.8	865.9	1478.9	2085.8	3202.2	1977.9	2421.6
75	865.0	1003.3	1096.3	2298.8	3426.0	5490.3	3363.1	4143.2
100	1323.0	1353.3	1641.0	3503.6	5255.5	8382.2	5310.3	6344.8

Table 3 also shows that for integration of solar power at buses 4, 5 and 9, the amount of money lost in the grid reduced as the penetration level increased from 0% through to 50% and then increased as the penetration level increased from 50% through to 100%. Buses 10, 11, 13 and 14 shows dissimilar trend from the previous buses mentioned. The amount of money loss for these buses reduced as the penetration level increased from 0 to 25% and then increased as the penetration level increased from 25% through to 100%. The amount of money loss in the grid is different for integration of solar at bus 12. The amount of money increased as the penetration level increased from 0% through to 100%. More so Table 3 shows that bus 4 has the lowest amount of money lost at all penetration levels while bus 12 has the highest.

Figure 2 above is a multiple bar chart showing the amount of money lost for the integration of solar power at increasing penetration level at buses 4, 5, 9, 10, 11, 12, 13 and 14. At 0% penetration level, the amount of money loss for the different buses are the same. At penetration levels other than 0%, bus 12 has the highest loss. Next to bus 12 is bus 14, bus 11 and bus 13, respectively. The chart also shows that bus 4 has the lowest amount of money loss at all penetration level other than 0%. This is followed by buses 5, 9 and 10, respectively.

Effect of integrating wind power on the electric power system

The solar power-based distributed generator was replaced with the wind power and the effect on cost was again simulated for each of the eight selected buses namely bus 4, bus 5, bus 9, bus 10, bus 11, bus 12, bus 13 and bus 14 at 0, 25, 50, 75, and 100% penetration level. The results are presented in Table 4 and Fig. 2. It was observed that the minimum amount of money lost as a result of power loss was $999 at bus 4 at 25% penetration level. This also shows that in order to integrate wind power to the power system and incur the least cost, wind power should be integrated at bus 4 at 25% penetration level.

Table 4 shows the total amount of money loss in the grid for integration of wind power. The amount of money loss was the same for all the buses at 0% penetration level. At 25% penetration level, integration at bus 4 has the least amount of money loss of $999 while integration at bus 12 has the highest loss of $1818. At 50% penetration

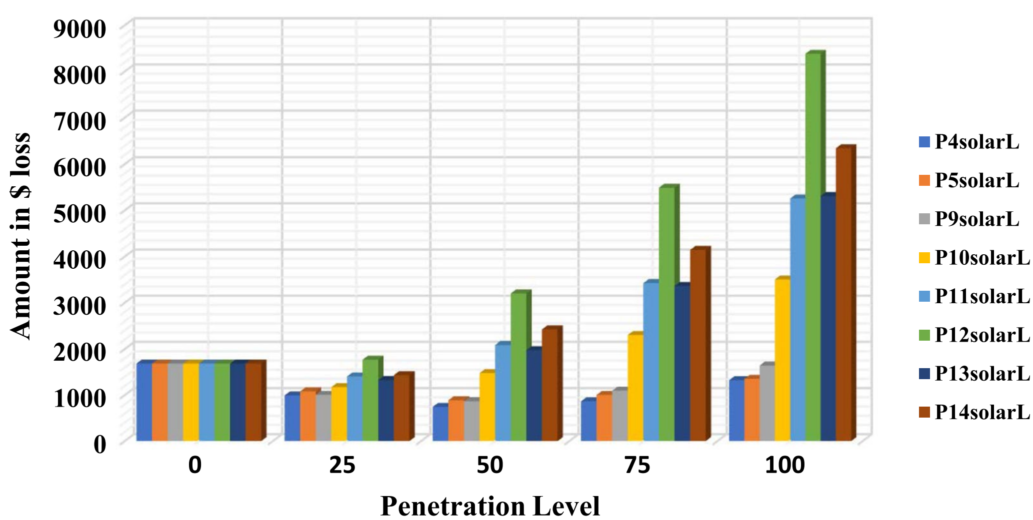

Fig. 2 Representation of total amount ($) loss for solar power integration

Table 4 Representation of total amount ($) lost for the grid for wind power integration

Penetration level	P_{4windL}	P_{5windL}	P_{9windL}	$P_{10windL}$	$P_{11windL}$	$P_{12windL}$	$P_{13windL}$	$P_{14windL}$
0	1685	1685	1685	1685	1685	1685	1685	1685
25	999	1086	1013	1192	1433	1818	1353	1472
50	1588	1538	1694	3245	4577	6993	4410	5665
75	4626	4204	4885	9734	13,934	21,587	14,233	17,029
100	11,264	10,004	11,088	21,626	31,200	50,548	33,542	37,326

level, the least money loss was $1538 which occurred at integration at bus 5 while the maximum loss was $6993 which occurred upon integration at bus 12. At 75% penetration level, integration at bus 5 produced the lowest amount of money loss of $4204 while integration at bus 12 produced the highest loss of money of $21,587. At 100% penetration, integration at bus 5 also has the least amount of money loss of $10,004 and integration at bus 12 has the highest amount of money loss of $50,548.

Table 4 also shows that for integration of solar power at buses 4, 5, 9, 10, 11, 13 and 14 the amount of money loss in the grid reduced as the penetration level increased from 0% through to 25% and then increased as the penetration level increased from 25% through to 100%. The amount of money loss in the grid was different for integration of solar at bus 12. The amount of money increased as the penetration level increased from 0% through to 100%. More so Table 4 shows that bus 4 has the lowest amount of money loss between 0 and 25% penetration levels and bus 5 have the least amount of money loss from 50 to 100% penetration level. More so bus 12 is found to have the highest amount of money loss in the transmission line at all penetration levels.

Figure 3 above is a multiple bar chart showing the amount of money loss for the integration of wind power at increasing penetration level at buses 4, 5, 9, 10, 11, 12, 13 and 14. At 0% penetration level, the amount of money loss for the different buses are the same. At 25% penetration level, integration at bus 4 has the least amount of money loss of $999 while integration at bus 12 has the highest loss of $1818. At 50% penetration level, the least money loss was $1538 which occurred at integration at bus 5 while the maximum loss was $6993 which occurred upon integration at bus 12. At 75% penetration level, integration at bus 5 produced the lowest amount of money loss of $4204 while integration at bus 12 produced the highest loss of money of $21,587. At 100% penetration, integration at bus 5 also has the least amount of money loss of $10,004 and integration at bus 12 has the highest amount of money loss of $50,548. Figure 3 also shows that for integration of solar power at buses 4, 5, 9, 10, 11, 13 and 14 the amount of money loss in the grid reduced as the penetration level increased from 0% through to 25% and then increased as the penetration level increased from 25% through to 100%. The case is different for bus 12. The amount of money increased as the penetration level increased from 0% through to 100%.

Effect of integrating hydropower on the electric power system

The wind power-based distributed generator is replaced with hydroelectric power and simulation for each of the eight selected buses namely bus 4, bus 5, bus 9, bus 10, bus 11, bus 12, bus 13 and bus 14 at 0, 25, 50, 75, and 100% penetration level was performed. The minimum amount of money loss as a result of power loss for the integration of hydropower was $546.50 at bus 4 at 75% penetration level as shown in Table 5. This shows that integrating hydropower at 75% penetration level is most profiting for solar power integration as it will incur the least cost.

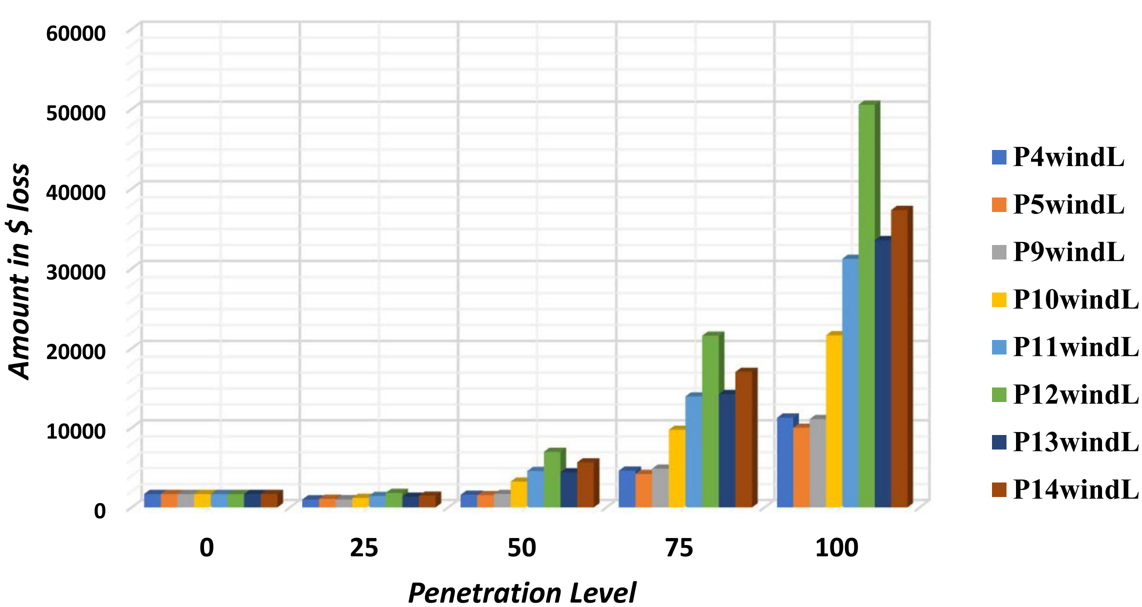

Fig. 3 Representation of total amount ($) loss for wind power integration

Table 5 shows the total amount of money loss in the grid for integration of hydropower. The amount of money loss was the same for all the buses at 0% penetration level. At 25% penetration level, integration at bus 4 has the least amount of money loss of $957.40 while integration at bus 12 has the highest loss of $1506.60. At 50% penetration level, the least money loss was $598.30 which occurred at integration at bus 4 while the maximum loss was $2399.40 which occurred upon integration at bus 12. At 75% penetration level, integration at bus 4 produced the lowest amount of money loss of $546.50 while integration at bus 12 produced the highest loss of money of $4054.20. At 100% penetration, integration at bus 4 also has the least amount of money loss of $756.6 and integration at bus 12 has the highest amount of money loss of $6280.70.

Table 5 also shows that for integration of solar power at buses 4 and 5 the amount of money loss in the grid reduced as the penetration level increased from 0% through to 75% and then increased as the penetration level increased from 75% through to 100%. For integration at bus 9, the amount of money loss in the grid reduced as the penetration level increased from 0% through to 50% and then increased as the penetration level increased from 50% through to 100%. For integration of hydropower at buses 10, 11, 12, 13 and 14 the amount of money loss in the grid reduced as the penetration level increased from 0% through to 25% and then increased as the penetration level increased from 25% through to 100%.

Figure 4 shows the total amount of money loss in the grid for integration of hydropower. The amount of money loss was the same for all the buses at 0% penetration level. At 25% penetration level, integration at bus 4 has the least amount of money loss, $957.40 while integration at bus 12 has the highest loss, $1506.60. At 50% penetration level, the least money loss was $598.30 which occurred at integration at bus 4 while the maximum loss was $2399.40 which occurred upon integration at bus 12. At 75% penetration level, integration at bus 4 produced

Table 5 Representation of total amount ($) loss for the grid for hydropower integration

Penetration level	$P_{4hydroL}$	$P_{5hydroL}$	$P_{9hydroL}$	$P_{10hydroL}$	$P_{11hydroL}$	$P_{12hydroL}$	$P_{13hydroL}$	$P_{14hydroL}$
0	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5	1685.5
25	957.4	1060.0	980.7	1088.3	1252.9	1506.6	1187.5	1210.0
50	598.3	773.0	722.1	1119.6	1577.5	2399.4	1490.1	1743.8
75	546.5	754.5	831.0	1635.4	2471.2	4054.2	2418.1	2924.0
100	756.6	963.4	1189.3	2505.5	3825.2	6280.7	3862.4	4606.8

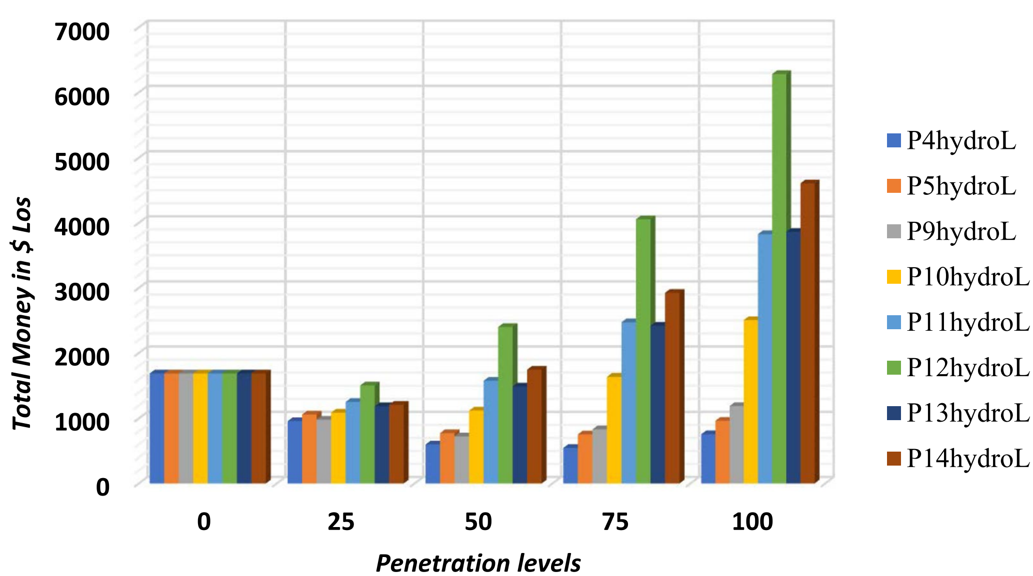

Fig. 4 Representation of total money ($) loss for the grid for hydropower integration

the lowest amount of money loss of $546.50 while integration at bus 12 produced the highest loss of money of $4054.20. At 100% penetration, integration at bus 4 also has the least amount of money loss of $756.60 and integration at bus 12 has the highest amount of money loss of $6280.70. Figure 4 also shows that for integration of solar power at buses 4 and 5 the amount of money loss in the grid decreased as the penetration level increased from 0% through to 75% and then increased as the penetration level increased from 75% through to 100%. For integration at bus 9, the amount of money loss in the grid decreased as the penetration level increased from 0% through to 50% and then increased as the penetration level increased from 50% through to 100%. For integration of hydropower at buses 10, 11, 12, 13 and 14 the amount of money loss in the grid decreased as the penetration level increased from 0% through to 25% and then increased as the penetration level increased from 25% through to 100%.

Comparison of the three distributed generators

To gain understanding of how various distributed generation technologies may impact the electric power system, simulations were conducted. Each distributed generator was connected to eight specific buses: bus 4, bus 5, bus 9, bus 10, bus 11, bus 12, bus 13, and bus 14. The simulations covered different penetration levels, namely 0%, 25%, 50%, 75%, and 100%. The results are presented in Figs. 5, 6 and 7. For cost of electric power, Figs. 5, 6 and 7 generally revealed that the cost effectiveness of the power system can be improved by integrating distributed generator into the power system.

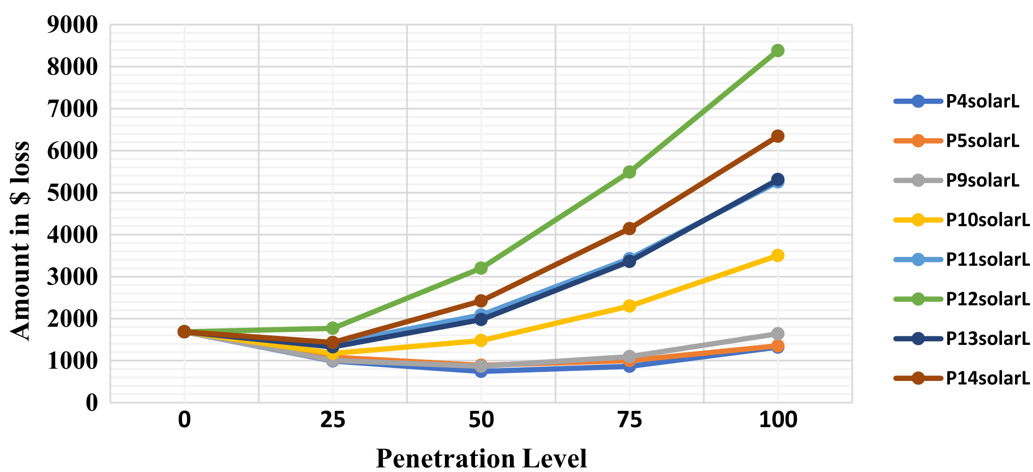

Fig. 5 Representation of total amount ($) loss for solar power integration

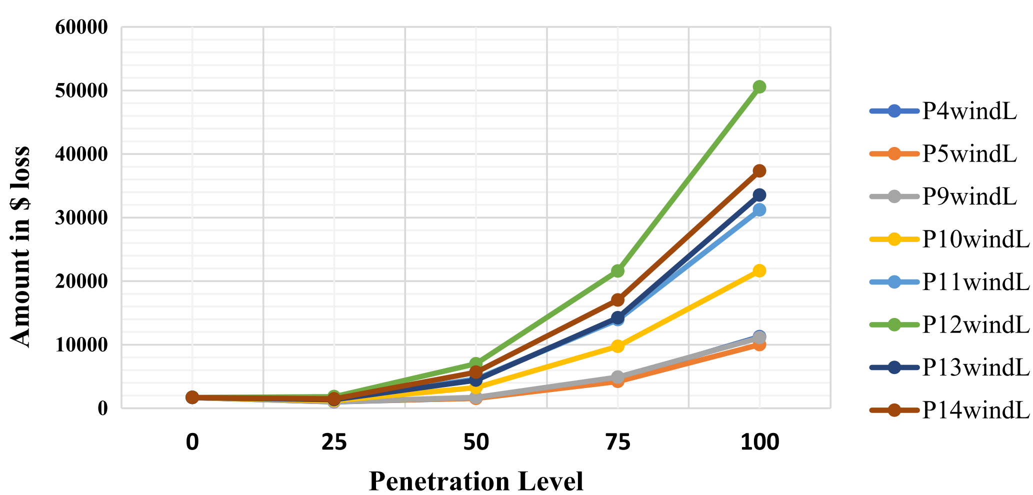

Fig. 6 Representation of total amount ($) loss for wind power integration

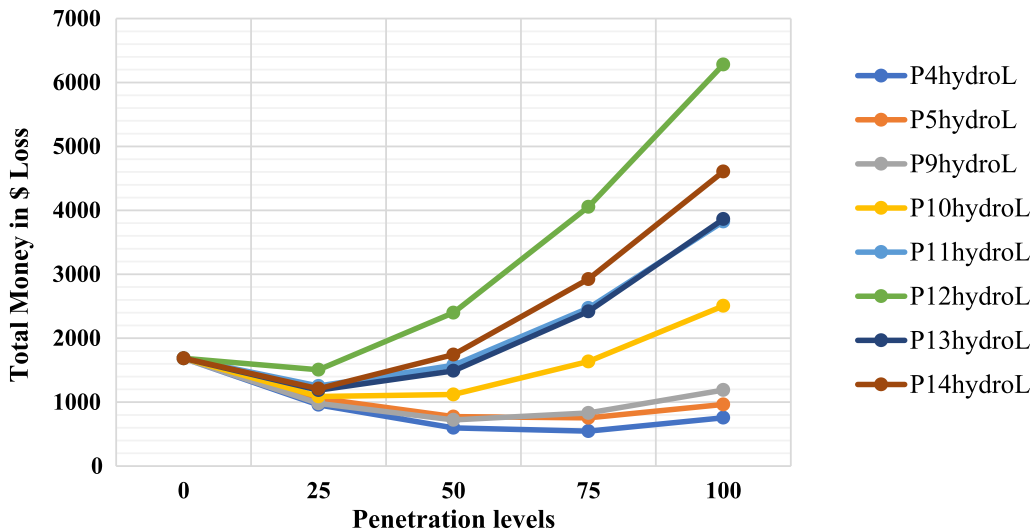

Fig. 7 Representation of total money ($) loss for the grid for hydropower integration

Figures 5, 6 and 7 also show that similar amount of money is loss for hydro and solar power due to the loss of electric power in the system however wind power distributed generator shows greater loss of money than the two distributed generators due to power loss in the system.

Conclusions

The integration of distributed generators, such as wind, hydro, and solar power, offers a host of advantages that enhance the cost effectiveness of electric power generation. The decreasing costs of renewable energy technologies are making them increasingly competitive with traditional fossil fuel-based methods, leading to price parity with conventional sources due to economies of scale and technological advancements.

Furthermore, incorporating distributed generators aids in diversifying the energy mix, reducing reliance on fossil fuels, and mitigating the environmental impact of power generation. Renewable energy sources produce minimal greenhouse gas emissions, making a significant contribution to the global fight against climate change and alleviating air pollution. This shift to clean energy aligns with worldwide sustainability objectives and fosters a more robust and sustainable energy infrastructure.

For money lost in the grid due to the integration of solar power, At 25%, bus 4 had the lowest loss of $992.40, while bus 12 had the highest loss of $1769.40. At 50%, bus 4 again had the least loss ($743.90), and bus 12 had the highest ($3202.20). At 75%, bus 4 had the least loss ($743.90), and bus 12 had the highest loss of $5490.30. At 100%, bus 4 had the lowest loss ($1323.00), and bus 12 had the highest loss ($1323.00). There were different trends among buses: buses 4, 5, and 9 saw decreasing losses up to 50% penetration, then increasing; buses 10, 11, 13, and 14 had losses decreasing until 25% and then increasing; bus 12's loss consistently increased with higher penetration. Bus 4 consistently had the lowest losses, while bus 12 had the highest. For money loss from integrating wind power, At 25%, bus 4 had the lowest loss ($999.00), and bus 12 had the highest ($1818.00). At 50%, bus 5 had the least loss ($1538), and bus 12 had the highest ($6993.00). At 75%, bus 5 had the lowest loss ($4204.00), and bus 12 had the highest ($21,587.00). At 100%, bus 5 had the least loss ($10,004.00), and bus 12 had the highest ($50,548.00). Trends were similar to solar power integration for certain buses, with bus 12 consistently having the highest losses. For money loss from hydropower integration, At 25%, bus 4 had the lowest loss ($957.40), and bus 12 had the highest ($1506.60). At 50%, bus 4 had the least loss ($598.30), and bus 12 had the highest ($2399.40). At 75%, bus 4 had the lowest loss ($546.50), and bus 12 had the highest ($4054.20). At 100%, bus 4 had the least loss ($756.60), and bus 12 had the highest ($6280.70). Similar to previous solar and wind power integration, bus 4 consistently had the lowest losses, while bus 12 had the highest. Trends in money loss fluctuated differently for different buses based on penetration levels. The analysis suggests that optimizing the penetration level of the renewable energy for different buses is crucial in minimizing losses and improving the efficiency of the power integration.

To fully harness the cost effectiveness of integrating distributed generators, meticulous planning, coordination, and policy support are imperative. By implementing efficient grid management systems and energy storage technologies, the utilization of renewable energy can be optimized, ensuring a stable power supply. Additionally, supportive regulatory frameworks, incentives, and financial mechanisms play a crucial role in encouraging investments in distributed generation projects and facilitating their seamless integration into the existing power grid.

Finally, by combining wind, hydro, and solar power within a distributed generation framework, we can maximize the cost effectiveness of electric power generation. This approach not only delivers economic benefits but also advances environmental sustainability and fosters energy resilience, paving the way for a cleaner, more efficient, and economically viable energy future.

List of symbols

A_L	Total money lost as a result of power loss in the system ($)
C_{BG}	Cost of bulk power generation ($/MWh)
C_{DG}	Cost of distributed power generation ($/MWh)
i	Bus number
I_i^*	Complex conjugate of source current I_i injected into the bus (A)
P	Real power generated (MW)
P_{AGT}	Real power generated by the asynchronous generator (MW)
P_{DG}	Power of the distributed generator (MW)
P_G	Total power generated (MW)
P_i	Real power (MW)
P_L	Penetration level (%)
P_{Load}	Total load of the IEEE 14-bus network (MW)
P_{Loss}	Total power loss in the line (MW)
P_R	Total power delivered to the load (MW)
P_{SGT}	Real power of the synchronous generator technology (MW)
Q	Reactive power drawn by the induction generator from the grid or capacitor bank (MVAR)
Q_{AGT}	Reactive power generated by the asynchronous generator (MVAR)
Q_{IGT}	Reactive power of the induction generator-based technology (MVAR)
Q_i	Reactive power at bus i (MVAR)
Q_{SGT}	Reactive power of the synchronous generator technology (MVAR)
S_i	Complex power injected (MVA)
S_R	Total amount of money from selling power to customers ($)
V	Bus voltage (V)
V_i	Voltage at bus i (V)
V_{SGT}	Terminal voltage of the synchronous generator technology (V)
X	Sum of the rotor and stator reactance (Ω)
X_C	Capacitive bank reactance (Ω)
X_m	Magnetizing reactance (Ω)
Y_{ik}	Line admittance between buses i and k (S)
δ_i	Phase angle of voltage at bus i (°)
δ_k	Phase angle of voltage at bus kS (°)
θ_{ik}	Phase angle of admittance between buses i and k (°)
Ø	Power angle of the asynchronous generator (°)

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Author contributions
IPI: Conceptualization, writing the introduction, methods, results, discussion, editing and reviewing, writing first draft of background and literature survey. TRA: Conceptualization, supervision, writing first draft of the background/literature, editing, reviewing, results, discussion, editing and reviewing. SMA: Conceptualization, co-supervision, writing first draft of the background/literature, editing, reviewing, results, discussion, editing and reviewing, adherence to the journal's formatting and citation guidelines. DREE: Conceptualization, co-supervision, writing the introduction, methods, results, discussion, editing and reviewing, adherence to the journal's formatting and citation guidelines. All authors have read and approved the manuscript.

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