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IoT-based intelligent source–load–storage coordination scheme for prosumer campus microgrids

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Electrical energy is very necessary for human life in the modern era. The rising energy prices, depletion of fossil fuels, and instability of the grid are alarming situations. So, it needs a smart solution to ensure the balance between pricing and saving natural resources. Some other issues like environmental change, limitations on installation of new transmission lines, reliability concerns, and considering the expansion in distributed energy generation technologies promise the implementation of distributed generation extensively. The integration of two or more energy supplies in a power system is known as distributed energy resource system. In this study, a university campus is taken as a case study to reduce the energy cost while considering the aforementioned issues. The intelligent source–load–storage coordination scheme is proposed to utilize the available renewable energy resources with storage systems. The proposed linear model is solved in MATLAB using the exact method technique considering the economic parameters. The campus microgrid analysis is not addressed considering the Internet-of-Thing (IoT)-based building, especially in the scenario of Pakistan. The results show the efficacy of the proposed model and can be implemented on the existing campus for source–load–storage coordination as an economical solution.

KEYWORDS

demand response, electric vehicle, distributed generation, energy management system, energy market, energy storage, campus microgrid

1 Introduction

The energy infrastructure experienced issues such as inflating demand cost, greenhouse gas (GHG) emission, and overburdening of the network Nonetheless, the traditional grid does not address such challenges; the new smart grid, comprising the electric delivery network fitted with distributed generators (DGs) and an energy storage system, can resolve such problems, considering power allocation by demand response (DR) systems (Raza and Malik, 2019). A microgrid (μG) is an integration of structured loads, on-site DGs, and storage devices with electrical limits defined in Guerrero et al. (2011) and Hirsch et al. (2018). The main characteristic of μG is its functioning either in a grid-tied mode or in an islanded mode (Marnay et al., 2008; Li et al., 2019; Javed et al., 2021). Based on the IoT system, the evolving grid is well controlled and has the main capability of μG such as self-healing and remote monitoring and its controlling techniques (Medina et al., 2010; El Rahi and El Rahi, 2017; El-hendawi et al., 2018). Similarly, μG offers different possibilities for the sustainability and utilization of renewable energy to prosumer μGs through the implementation of energy management systems (EMSs). It ensures the safe coordination between the prosumer and utility for smart control system operation (Shayeghi et al., 2019). The distribution grid comprises a μG array of individual distribution systems such as μGs of DGs, electrical energy storage, and demand response (DR) systems on location, which may play a crucial role in minimizing the expense of electricity (Iqbal et al., 2019; Shayeghi et al., 2019; Iqbal et al., 2021; Muhammad Shahab and Wang, 2021). The advantages of μGs with heavy loads are more prominent as compared to domestic loads. Institutional buildings are one of the high-load μGs that come into the structure of their loads. Such buildings can sell their excess power to a grid that functions as a prosumer, due to the availability of on-site generation resources (Hussain et al., 2017; Javed and Muqeet, 2021; Mehmood et al., 2021; Muqeet et al., 2021).

Additionally, when the local DGs and storages are inadequate to meet complete demand, they will import electricity from the grid under high-load conditions using advanced techniques such as Q-learning (Zia et al., 2018; Muqeet and Ahmad, 2020; Nasir et al., 2021a; Safraz, 2021). In addition to raising their operating energy prices, efficient involvement of these μGs in grid activities often benefits the distribution network. Grid operators also offer multiple additional benefits and value-based DR programs to attract such large-scale customers to actively participate in the electric power markets (Bazmohammadi et al., 2019). The power management policy with maximum allocation of usable energy satisfies their need at reduced rates and guarantees their successful participation in maintaining grid operations (Bazmohammadi et al., 2019; Muqeet et al., 2019; Hafiz Abdul Muqeet, 2020; Nasir et al., 2021b). The cost is the main concern in the energy management system, so most of the researchers focus on this aspect such as in Mehmood et al. (2021), Nasir et al. (2021b), and Muqeet and Ahmad, (2020). The authors proposed an energy management system (EMS) strategy for the institution which helps in reducing the operational cost with the help of using distributed generators (DGs). The operational cost was measured using DGs and without using DGs for comparison purposes and finally found the role of ESS in minimizing the combined load consumer class due to variable operational cost.

Similarly, in Marinakis et al. (2020), an energy management system (EMS) technique was used in an institution that helps in minimizing operational costs by using various DGs. The economic impact and environmental impact were compared by conducting different case studies, while the operational cost was evaluated using DGs and without using DGs. In Amaral et al. (2020), the authors presented a model that reduced the load for household appliances. Linear programming was used in MATLAB as an optimizing technique, considering different load-shedding hour scenarios while neglecting different DGs. In Husein and Chung, (2018), the authors devised the growth situation of the China's power storage industry. After confined studies, it was found that wind farms are assigned 53%, distributed microgrids are assigned 20%, transmission and distribution are assigned 7%, and other technologies are assigned 20%. In Xu et al. (2019), the authors gave his reviews on government, local, and energy regulations, which play a key role in microgrid upgradation in the United States. The US microgrid growth demonstrates a need for aggressive policy initiatives at various rates, financing schemes, and experimental projects to demonstrate technological and economic viability. In Leskarac et al. (2018), the authors performed an extensive research study on the activities and strategies implemented at university such as the expenditure criteria, payback, energy payback period, and minimizing usage that are used to overcome issues that show investment in strategic measures offers many advantages. In Leal Filho et al. (2019), the authors critically discussed P2P microgrids which are based on blockchain. The sandbox technique is used for discussing multi-dimensional systems, which demonstrates the importance of blockchain. In Sun et al. (2020), the authors presented an equivalent circuit showing the thermal framework of the Savona campus microgrid which elaborated its behavior. The findings showed the accuracy of the proposed model with an error of 3%. Moreover, a gap of only 6% was measured by performing a robustness test between two profiles. In Kumar et al. (2012), the authors presented a harmonic model for the Savona campus microgrid that was used in many controllers to remove harmonics.

Some authors also highlighted a new direction of making an efficient control system for future research. For example, in Reyasudin Basir Khan et al. (2018), the authors presented a model consisting of different renewable energy resources for the current network to evaluate the circuit for potential expansion. The case study showed that usage of the conventional generator was almost reduced to zero by utilizing different DGs with reduced (8–11%) active power loss. In Bozchalui and Sharma, (2012), the authors compared the consumption of the USTO campus and the production of the PV power plant. After analysis, it was shown that 1,845 PV panels were installed giving 452 kW on the output which did not meet the demand of campus, that is, 2,595 kWh. In Waqar et al. (2017), the authors presented a microgrid named ERESMA grid. However, generally, no criteria were identified for their formal description, and thus findings can be viewed with caution. In Rehman et al. (2019), the authors proposed a model in which a microgrid is connected to the main grid and can allow two-way power flow, which also allows purchasing and selling of electricity. ELM algorithm was used for forecasting power produced by DGs, while the fuzzy logic control (FLC) technique was applied to get a reasonable economic goal by decision-making.

In Gao et al. (2018), the authors proposed a big data framework that assists the production, growth, management, and optimization of smart energy resources. This framework helps in the minimization of carbon gasses, electricity cost, and energy utilization beyond 20 and 10% increment in the utilization of renewable DGs. In Vejdan and Grijalva, (2018), the authors evaluated the feasibility criteria for university microgrids. This microgrid development model involves all benefits including tax credits because they influence both the technical balance and financial viability of the project. In Zhang (2015), the authors proposed a micro-market system to enhance the participation behavior of decision-makers in a microgrid with extra-economic rewards. In this technique, nonlinear integer programming was used with all constraints, giving better results and solving the problem more effectively. In Vahedipour-dahraie et al. (2019), the authors presented a hybrid microgrid testbed that consists of DC and AC networks. Different tests were conducted to find the efficiency of the distribution network. This model introduced an advanced method of communication and control that enhanced its performance. In Mohiti et al., (2019), the authors investigated 50 education institutes for utilizing renewable energy resources and their types. For the future work, energy sustainability linked with academic research was suggested. In Sun et al. (2020), the authors introduced a power reduction technique for the second-use battery energy system, and power was optimized using the particle swarm optimization technique. Power and scheduling time were increased by using this method and verified by simulation which demonstrated that BESS remained under the working condition for 384 dispatches. In Kumar et al. (2012), the author proposed a method that evaluated the number of electric vehicles that can be supported by the transformer based on insulation loss of life. The microgrid has more impact on electric vehicles, and it was concluded that the number of electric vehicles with microgrids increased up to 33% as compared to that of several electric vehicles without microgrids. In Reyasudin Basir Khan et al. (2018), the authors implemented a microgrid on the campus consisting of PV and a battery storage system, and net present cost but its benefit was a higher rate of renewable energy penetration. A battery energy storage system is used in many applications such as stabilizing the microgrid, reduction of energy cost, and also beneficial for the intermittency of renewable energy resource mitigation. Table1 shows the comparison of various approaches, while Figure 1 presents the various functions of the smart grid power system.

Based on the aforementioned discussion and review of existing works, it seems that the development of an EMS for a prosumer μG having distributed generation, energy storage, and electric vehicles needs further improvement. In the energy management system, solar PV and energy storage are addressed, while battery degradation needs more consideration which is not addressed in the previous works. The demand response and EV are rarely investigated in the literature; therefore, in our proposed model, all the resources are considered and solved using the mixed-integer linear programming (MILP) for the source–load–storage coordination. The MILP is comparatively better due to its fast convergence and global exact solution.

Similarly, the proposed model is validated in various scenarios to analyze its efficacy of the model. The main contributions of the research work are as follows:

- In the proposed model, IoT-based intelligent source–load–storage coordination of the mobile and stationary energy storage system is analyzed.
- The campus microgrid is scheduled to reduce the operational cost, considering the storage degradation cost.
- The role and impact of electric vehicles on the energy consumption cost are also investigated in the proposed model.
- The proposed model will investigate GHG reduction by using environmentally friendly energy resources.
- Different scenarios are investigated considering the stability/sustainability and compared to the existing work to highlight the significance of the proposed model.

The remaining study is comprised of the following sections: Section 2 presents the general structure of the proposed system with its mathematical formulation. Results and discussion of the proposed model are addressed in Section 3, while Section 4 presents the conclusions of this study.

2 Proposed system architecture and formulation

The proposed system architecture is given in Figure 2 having the energy sources, load, and utility grid. The system is based on the IoT-based communication system among the various components. The problem formulation of the proposed model is presented in the next subsection.

TABLE 1 Comparison summary of approaches.

Reference	PV	ESS	ESS's optimal scheduling	Energy exchange with grid	Battery degradation	DR	EV
Li et al. (2019)	✓	✓	✓	_	_	_	_
Javed and Muqeet, (2021)	_	✓	✓	✓	_	✓	_
Bazmohammadi et al. (2019)	✓	✓	✓	✓	✓	_	_
Nasir et al. (2021b)	✓	✓	✓	✓	_	_	_
Nasir et al. (2019)	✓	✓	✓	_	_	_	✓
Li et al. (2015)	✓	✓	✓	_	_	_	✓
Feng et al. (2018)	✓	✓	✓	_	✓	_	✓
Amaral et al. (2020)	✓	✓	✓	_	_	_	✓
Ahl et al. (2019)	_	✓	_	✓	_	_	_
Barillari et al. (2015)	✓	✓	_	_	_	_	_
Labella et al. (2017)	✓	_	✓	_	_	✓	_
Saritha et al. (2017)	✓	✓	✓	_	✓	_	_
Bourahla et al. (2018)	_	✓	✓	_	_	_	_
De Simón-Martín et al. (2019)	✓	✓	✓	_	_	_	✓
El Bourakadi et al. (2020)	✓	✓	✓	✓	✓	_	_
Proposed model	✓	✓	✓	✓	✓	✓	✓

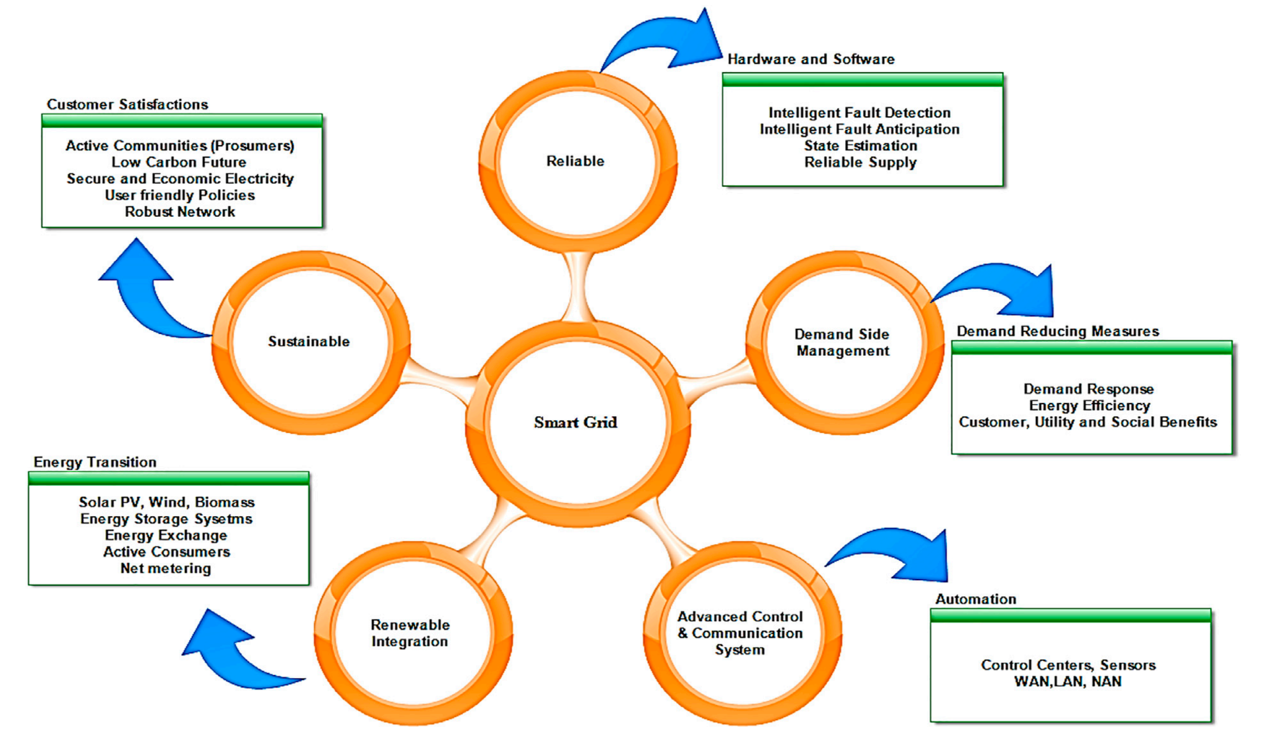

FIGURE 1
Smart grid functioning areas.

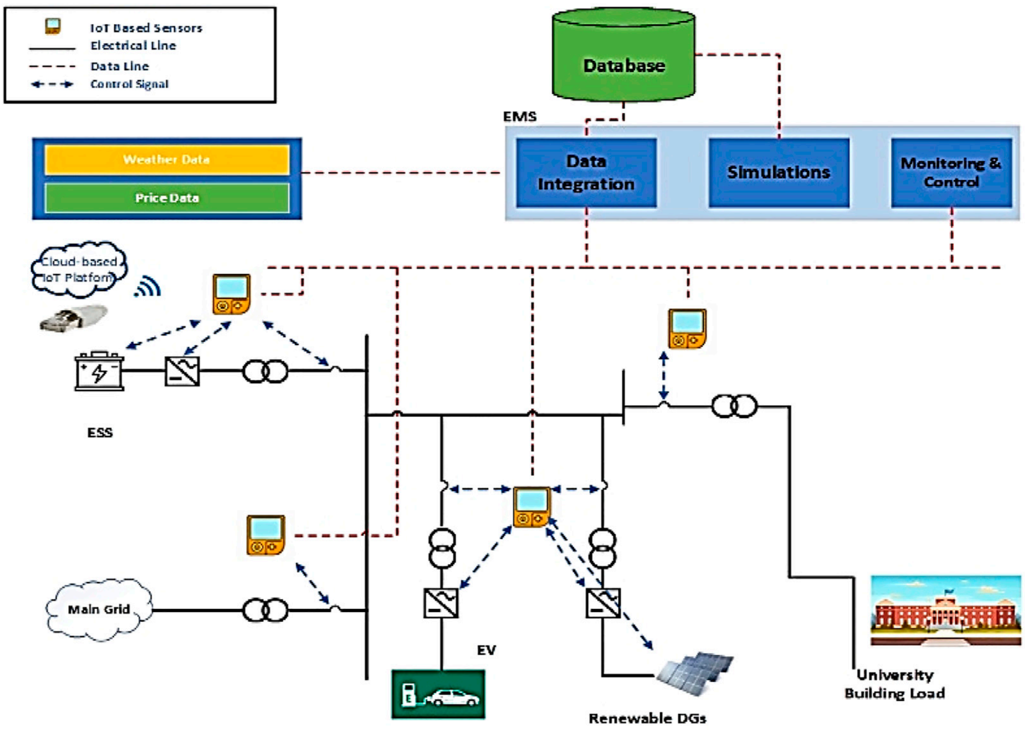

FIGURE 2
IoT-based system architecture.

2.1 Proposed model formulation

This formulation aims to reduce the operational cost of campus microgrids. The proposed system is comprised of solar PV, diesel generator, energy storage system, and electric vehicle.

2.2 Objective function

The objective function is comprised of various costs such as energy exchange with the grid, energy storage cost, and mobile energy storage as expressed in Eqs 1–5. The operational cost Equations 1–15 are shown as follows:

$$\mathbf{cost} = \mathbf{J} = \mathbf{min}\sum_{t=1}^{24}\left(C_t^e + C_t^{dg} + C_t^{es} + C_t^{EV}\right). \tag{1}$$

The aforementioned equations describe the system parameters. Here, $\mathbf{J}$ is the operational cost of the model. The operational cost J is the sum of four costs such as energy cost C_t^e with grid, diesel generator cost C_t^{dg}, energy storage cost C_t^{es}, and electric vehicle cost C_t^{EV}.

$$C_t^e = (p_t^g)\lambda_t \tag{2}$$

where p_t^g is the grid power, that is, exchanged with the grid and λ_t is expresses the per-unit cost of energy.

$$C_t^{dg} = \alpha T_G + \beta p_t^{dg} \tag{3}$$

The diesel generator cost is the sum of different constants and variables. Here, the term p_t^{dg} is the power of the diesel generator, T_G is the generation capacity, and α, β are slopes.

$$C_t^{es} = \left(\frac{\mathbf{capital_{cost}}}{\mathbf{No.\ of\ cycles \times total\ capacity \times 2}},\right) \tag{4}$$

$$p_t^{bat} = \eta_{ch} P_t^{ch} - \frac{P_t^{dch}}{\eta_{dch}} \left(\eta_{ch} P_t^{ch} + \frac{P_t^{dch}}{\eta_{dch}}.\right) \tag{5}$$

In Equation 5, the energy storage is expressed with different parameters such as charging power, discharging power, and efficiencies denoted as P_t^{ch}, P_t^{dch} ,η_{ch}, and η_{dch}, respectively.

$$p_t^{bat} = \eta_{ch} P_t^{ch} - \frac{p_t^{dch}}{\eta_{dch}} \tag{6}$$

2.3 Load balance constraint

Similarly, the balanced equation is the main constraint of energy management.

$$p_t^g + p_t^{pv} + p_t^{bat} + p_t^{dg} + p_t^{EV} = p_t^l \tag{7}$$

The sum of the energy sources should be equal to the energy demand as depicted in Eq. 6. The power exchanges with the utility grid are expressed as p_t^g. The solar PV output power is expressed as p_t^{pv}, while the storage output power is represented as p_t^{bat}.The diesel generator output power and electric vehicle are expressed as p_t^{dg} and p_t^{EV}, respectively. The right-hand side of Eq. 6 shows the energy demand load p_t^l.

2.4 ESS constraints

The battery energy storage is used as a backup energy source. Batteries are charged during the off-peak hours and discharged during peak hours also known as energy arbitrage as expressed in Eqs 7–15.

$$\frac{BSOC_{t-1} - BSOC_{max}}{100} C^{ES} \le p_t^{bat} \tag{8}$$

The storage state can be expressed as SOC, and capacity is expressed as C^{ES}.

$$p_t^{bat} \le \frac{BSOC_{t-1} - BSOC_{min}}{100} C^{ES} \tag{9}$$

The minimum and maximum states of charge show the threshold values of $BSOC_{max}$ and$BSOC_{min}$, respectively.

$$0 \le \eta_{ch} p_t^{ch} \le u_t^{ch} p_{ch,\max}^{bat} \tag{10}$$

The binary integer constants of charging and discharging are expressed as u_t^{ch} and u_t^{dch}, respectively.

$$0 \le \frac{p_t^{dch}}{\eta_{dch}} \le u_t^{dch} p_{dch,\max}^{bat} \tag{11}$$

$$u_t^{ch} + u_t^{dch} \le 1 \,\forall t \tag{12}$$

The sum of binary constants is less than or equal to 1 as shown in Eq. 11.

$$BSOC_t = BSOC_{t-1} - \frac{100 \times \eta_{dch} p_t^{dch}}{C^{ES}} - \frac{100 \times p_t^{dch}}{C^{ES} \eta_{dch}} \tag{13}$$

Eq. 13 expresses the various parameters of the storage elements.

$$\mathbf{BSOC_{min} \le BSOC_t \le BSOC_{max}} \tag{14}$$

The storage constraint of Eq. 14 expresses battery participation in the energy scenarios.

$$\mathbf{BSOC_T = BSOC_0} \tag{15}$$

The battery's initial and final stages will be equal due to the end of the day. So, the battery can participate at the start of the next day.

$$\left|\mathbf{p_t^{bat} - p_{t+1}^{bat}}\right| \le \Delta \mathbf{p^{bat}} \tag{16a}$$

The battery output power is lemmatized using Eqs 16a,b, so it can avoid the sudden charging and discharge of the battery. Δp^{bat} represents the battery output difference.

2.5 Electric vehicle energy storage

The energy stored in an electric vehicle can be used for grid support in a high-demand period. The energy-sharing limitations and their behavior are depicted in Eqs 16a–25. The operational cost of the electric vehicle is presented in Eqs 16a,b.

$$e_{mes,t} = (1 - \Phi_{mes}) e_{mes,t-1}\, \tau \left(P_{mes,t}^{chg} \eta_{mes}^{chg} - \frac{P_{mes,t}^{dch}}{\eta_{mes}^{dch}} \right) + E_{mes,t}^{conn} - E_{mes,t}^{disc} \tag{16b}$$

Here, $\mathbf{e}_{mes,t}$ is the energy state at time t, whereas the connected and disconnected energies are expressed as $\mathbf{E_{mes,t}^{conn}}$ and $\mathbf{E_{mes,t}^{disc}}$, respectively.

$$\underline{SOC}_{mes} = \bar{E}_{mes,t} \le e_{mes,t} \le \overline{SOC}_{mes} \bar{E}_{mes,t}. \tag{17}$$

The state of charge SOC represents the electric vehicle energy storage status.

$$\bar{E}_{mes,t} = \bar{E}_{mes,t-1} + \bar{E}_{mes,t}^{conn} - \bar{E}_{mes,t}^{disc}. \tag{18}$$

The connection energy and disconnection energy are represented as $\bar{E}_{mes,t}^{conn}$, $\bar{E}_{mes,t}^{disc}$.

The energy $\bar{\mathbf{E}}_{\mathbf{mes,t}}$ at time t and its previous time is expressed in Eq. 19.

$$\underline{E}_{mes,t} = \bar{E}_{mes,t-1} + \bar{E}_{mes,t}^{conn} - \bar{E}_{mes,t}^{disc}. \tag{19}$$

The charging–discharging integer variable is used to select the charging and discharging mode.

$$\mathbf{0 \le P_{mes,t}^{chg} \le u_{mes,t}^{chg} \bar{P}_{mes,t},} \tag{20}$$

$$\mathbf{0 \le P_{mes,t}^{dch} \le u_{mes,t}^{dch} \bar{P}_{mes,t},} \tag{21}$$

$$\mathbf{\bar{P}_{mes,t} = \bar{P}_{mes,t-1} + \bar{P}_{mes,t}^{conn} - \bar{P}_{mes,t}^{disc}.} \tag{22}$$

The power of the electric vehicle battery is expressed in Eq. 22 (Parhizi et al., 2018).

$$v_{ses,t}^{chg} \le u_{ses,t}^{chg} \le u_{ses,t-1}^{chg}. \tag{23}$$

Another integer variable used is $\mathbf{v}_{ses,t}^{chg}$ to express the charging and discharging conditions based on the demand.

$$\mathbf{v_{ses,t}^{dch} \le u_{ses,t}^{dch} \le u_{ses,t-1}^{dch}.} \tag{24}$$

The operation cost of the electric vehicle cost can be calculated using Eq 25.

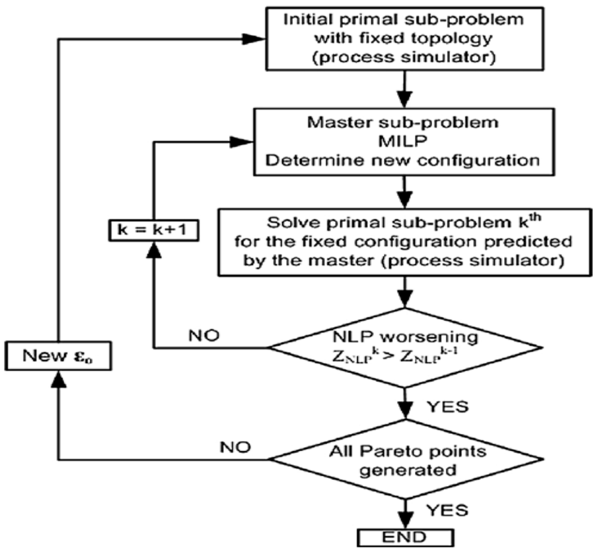

FIGURE 3
Flowchart of the proposed method.

$$\mathbf{C}^{EV}(\mathbf{t}) = \mathbf{C}^{dg}_{mes}\frac{1}{2}\left(\mathbf{v}^{chg}_{mes,t} + \mathbf{v}^{dch}_{mes,t}\right) + \mathbf{C}^{c}_{mes}\bar{\mathbf{E}}_{mes,t} + \frac{P^{dch}_{mes,t}}{\eta^{dch}_{mes}}\mathbf{C}^{s}_{mes,t} - \frac{P^{chg}_{mes,t}}{\eta^{chg}_{mes}}\mathbf{C}^{d}_{mes,t} \tag{25}$$

The summation of various costs is used to calculate the total EV operational cost.

The limitation on the grid power and a diesel generator is shown in Eqs 26, 27.

$$\mathbf{p}^{g}_{min} \leq \mathbf{p}^{g}_{t} \leq \mathbf{p}^{g}_{max}, \tag{26}$$

$$\mathbf{p}^{dg}_{min} \leq \mathbf{p}^{dg}_{t} \leq \mathbf{p}^{dg}_{max}. \tag{27}$$

Here, the grid p_t^g and diesel generator p_t^{dg} power can be lemmatized using Eq. 26.

The aforementioned relations are used to estimate the total optimal operational cost considering the system constraints. The flowchart in Figure 3 shows the procedural steps of solving the proposed model. It is comprised of subproblems and the main problem.

2.6 Solution methodology

As the objective function of the proposed system model and all the relevant constraints are linear, the mixed-integer linear programming is used to solve the proposed model. The general structure of MILP is described in Eqs 28, 29.

$$\min_{x} f^t x. \tag{28}$$

Subjecting

TABLE 2 Price of electricity.

Summer season	
Hour	**Unit price ($)**
0:00 to 19:00	0.091
19:00 to 23:00	0.134
23:00 to 24:00	0.091

$$\begin{cases} A.x \leq b, \\ A_{eq}.x = b_{eq}, \\ lb \leq x \leq ub, \end{cases} \tag{29}$$

where x (intcon) are integers.

The convex problem-based proposed model is solved in MATLAB using the “intlinprog” solver. In Eq. 28, it is the main functional expression of the MILP, while Eq. 29 presents the constraints of the proposed model. Table 2 shows the price of electricity used in the proposed model.

3 Results and discussion

The integration of renewable energy resources is analyzed using the MILP technique. The detailed results are described in the next subsection.

In this section, the case studies are discussed to analyze the different cases. Figure 4 shows the solution steps of the proposed methodology, while the monthly consumption cost of the campus is shown in Figure 5. Similarly, campus load and solar PV output are considered deterministic and are expressed in Figure 6. Table 3 shows the system parameters of our mathematical model, while Table 4 presents the profile of case studies.

Both the constants and limitation values such as maximum and minimum values are expressed in Table 3. The units of each parameter are also given to differentiate the related values such as kW and kWh that expressed the power and energy.

3.1 Scenario 1: grid only

In this scenario, the energy demand is supplied from the utility grid. The operation cost is observed at $950.4. All renewable and distributed generations are ignored. The peak hours of the utility grid are shown from 17:00 to 21:00 for 4 hours, and the results obtained are very high and reach $120000. Table 2 shows the prices that are comprised of peak

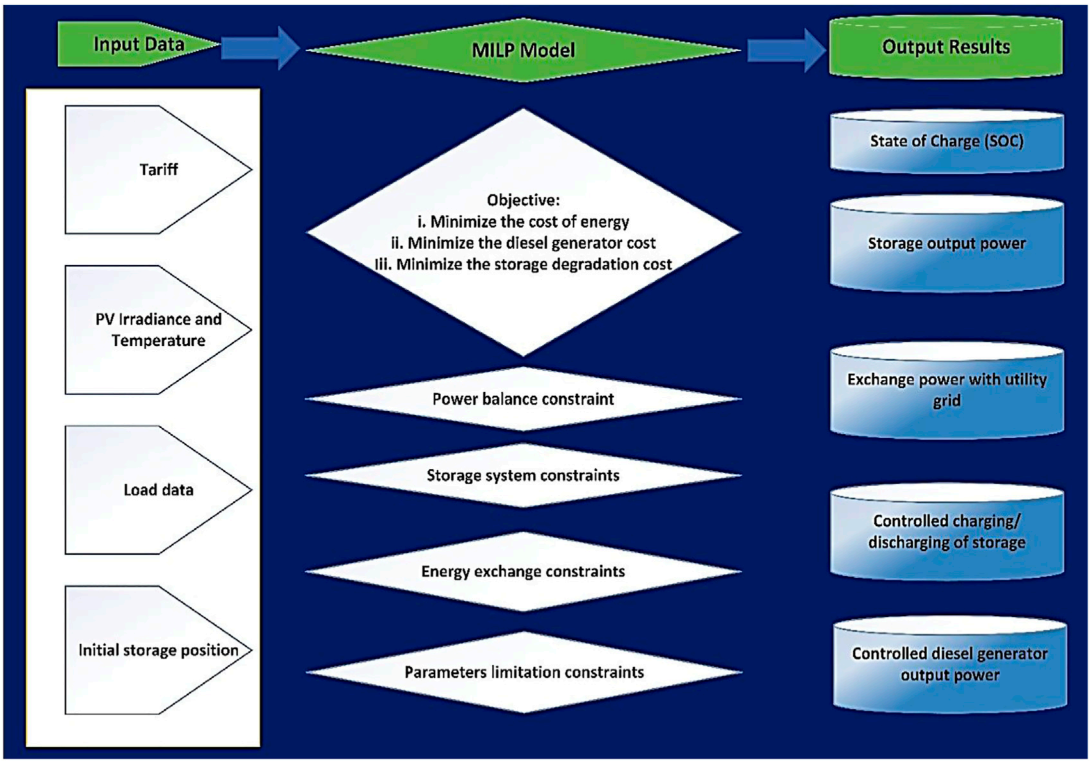

FIGURE 4
Steps of solution methodology variables.

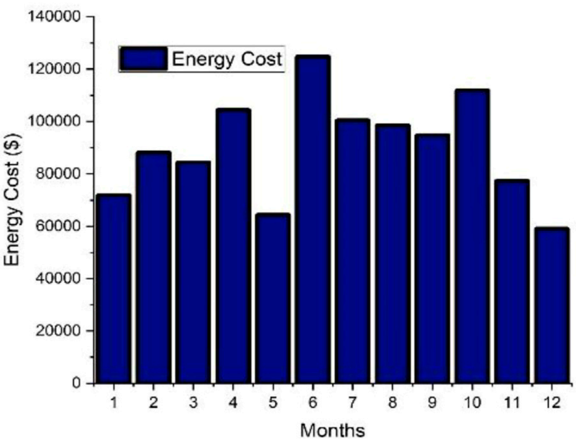

FIGURE 5
Monthly consumption cost of the campus.

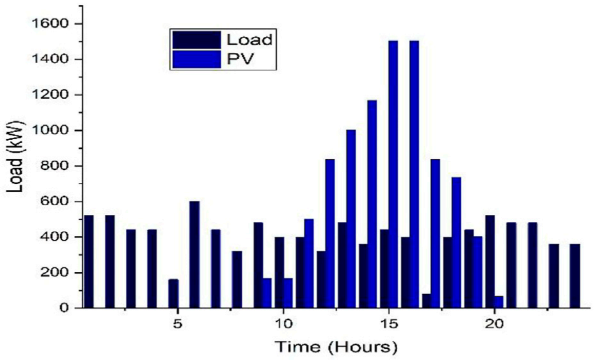

FIGURE 6
Solar PV output and energy demand of the building.

and off-peak hour tariffs. Table 2 shows the price of the summer season, while the winter season is quite different which is not addressed in our model.

3.2 Scenario 2: grid with solar PV

In this scenario, the solar PV is integrated and decreases energy costs. Solar PV energy is available usually during the day timing and can be stored. But in this case, only solar PV is analyzed without ESS. The surplus energy from solar PV is

TABLE 3 Proposed system parameters.

Parameter	Value	Parameter	Value
P^{PV}_{rated}	4,000 kW	C^{ES}	800 kWh
$P^{g}_{t,\max}$	2000 kW	$P^{g}_{t,\min}$	-1,000 kW
$P^{bat}_{t,\max}$	800 kW	$\mathrm{p}^{\mathrm{bat}}_{\mathrm{t,min}}$	-800 kW
$BSOC^{b}_{\max}$	90%	$\mathrm{BSOC}^{\mathrm{b}}_{\mathrm{min}}$	10%
$BSOC_0$	50%	$\mathrm{p}^{\mathrm{dg}}_{\mathrm{t}}$	600 kW

TABLE 4 Profile of case studies.

Case 01	Only national grid	Output power of solar PV	Battery storage	Diesel generator	EV integration	Power load
(a)	✓	✗	✗	✗	✗	Campus load
(b)	✓	✓	✗	✗	✗	
(c)	✓	✓	✓	✗	✗	
(d)	✓	✓	✓	✓	✗	
(e)	✓	✓	✓	✓	✓	

TABLE 5 Results of various scenarios.

Scenario	Only national grid	Output power of solar PV	Battery storage	Diesel generator	EV integration	Operational cost ($)	Observed saving
01	✓	✗	✗	✗	✗	950.4	-
02	✓	✓	✗	✗	✗	472.6	50.2
03	✓	✓	✓	✗	✗	440.5	53.6
04	✓	✓	✓	✓	✗	436.2	54.1
05	✓	✓	✓	✓	✓	434.3	54.3

available to exchange with the national grid using net metering. The cost observed in this case reduced from $950.4 to $472.6 as shown in Table 5.

3.3 Scenario 3: grid with solar PV and ESS

The optimal scheduling of the solar PV and energy storage system (ESS) is used to provide the supply. The ESS charges during the off-peak hours and discharges during the peak hours. So, the cost is also reduced as compared to scenario 1, but there is a little increase as compared to scenario 2. The cost is observed at $440.5 and is shown in Table 5. Figure 7 shows the energy exchange with the grid after installing the ESS.

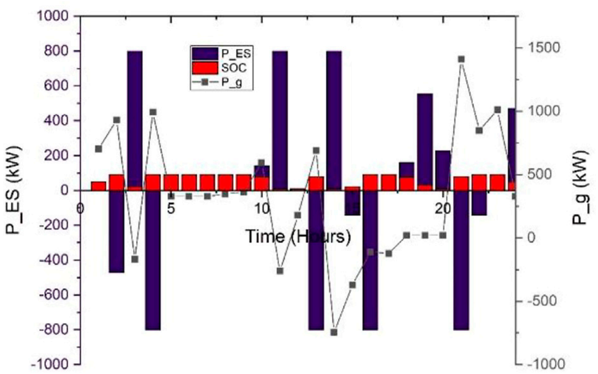

FIGURE 7
Optimal scheduling with solar PV and ESS.

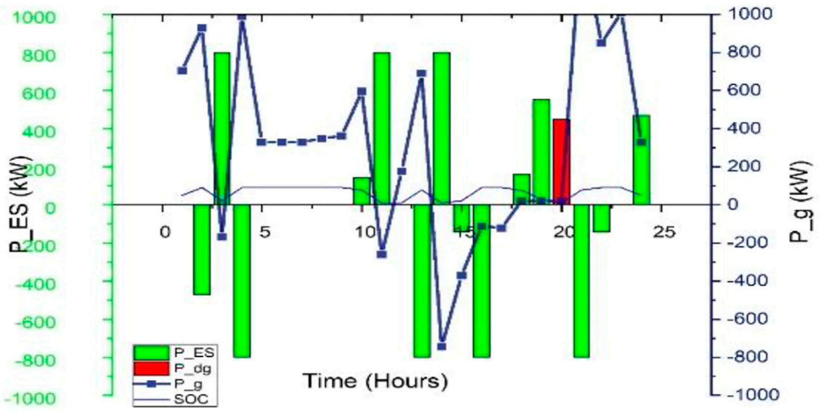

FIGURE 8
Energy exchange in the ESS scenario.

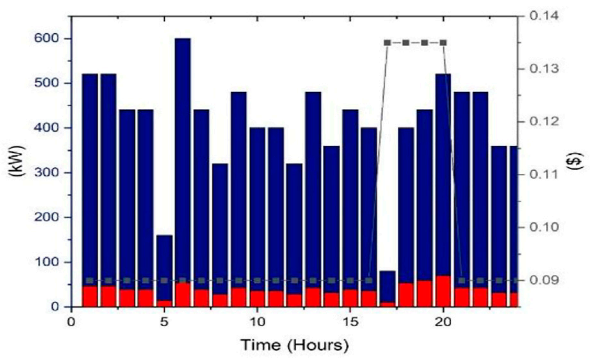

FIGURE 9
Optimal scheduling result without EV.

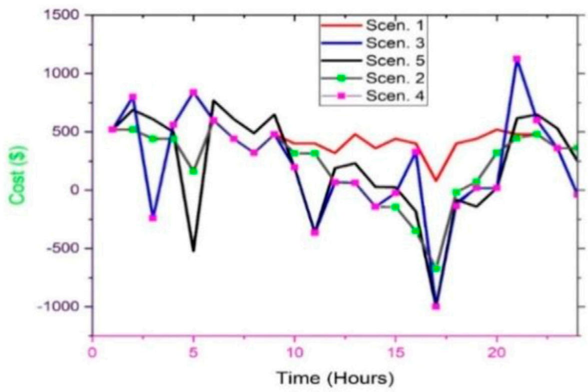

FIGURE 11
Cost comparison results.

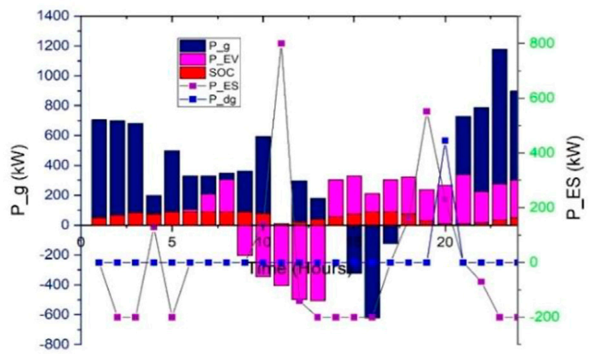

FIGURE 10
Grid with EV and all components.

3.4 Scenario 4: grid with the diesel generator without EV

In Scenario 4, a diesel generator is installed as a backup energy resource and operates during peak hours as shown in Figure 8. The cost is observed at about $436.2, and Figure 9 shows the different behaviors of the elements attached to the system.

3.5 Scenario 5: grid with EV and all components

In this scenario, all the distributed generation and storage systems are integrated along with the electric vehicle (EV). The electric vehicle is also considered and scheduled to reduce the

TABLE 6 Comparison of the proposed method with existing works.

Reference	Year	Used technique	Testbed system	Objective	Observed saving (%)
Sun et al. (2020)	2016	Ant colony optimization	Savona Campus μG	Minimize difference of various parameters	6%
Reyasudin Basir Khan et al. (2018)	2017	LP	Residential μG	Grid outage	16%
Gao et al. (2018)	2018	NA and conic technique	IEEE-15 bus system	Financial feasibility	3.3 %
Mohiti et al. (2019)	2017	BBSA	IEEE-14 bus system	Power losses and reliability	18.26%
Fazlalipour et al. (2019)	2012	Control algorithm	Nanyang Campus	Frequency regulation	7%
Marinakis et al. (2020)	2020	MILP	Campus μG	Self-consumption	35%
Proposed model	2022	MILP	Campus μG	Energy cost reduction	54.3%

energy demand by exchanging the surplus energy during the working of the day.

The energy exchange with the grid is shown in Figure 10. In this scenario, the optimal scheduling of all distributed generation is carried out and is solved using the MILP. The cost is reduced from $$436.2 to $434.3 which shows that EV integration reduces the operational cost as represented in Table 5. The last column of this table shows the operational cost of the proposed model. The highest cost is observed in the grid-only scenario. The lowest cost is observed using all resources and scheduled utilization. The scheduling of the available resources reduces the cost as compared to scenarios 1 and 2. Figure 11 shows the cost comparison of all scenarios. In Table 6, the various results are compared to show the significance of the proposed model. In the proposed model, the cost was reduced to 54% as compared to previous results. The main reason to reduce the cost is the scheduling of the EV considering the charging and discharging schedules.

4 Conclusion

The rise in energy prices and GHG emissions creates a problem for the smart grid stakeholders. The existing system cannot solve this problem due to some technical constraints. In this study, the campus microgrid and its actual load data are analyzed to reduce the energy cost of the campus. The smart grid environment can integrate renewable energy resources. The proposed model is solved by using the global optimization technique in MATLAB. Energy pricing of the prosumer campus is observed that decreases by the optimal scheduling of distributed generation. Electric vehicles are also considered and analyzed for their effect on the system. Different scenarios are analyzed and observed showing the effects of distributed generation on the operational cost. The cost is reduced significantly by integrating solar PV and ESS, considering the electric vehicle applications on the campus. All cases are compared with the base case to analyze the savings in the proposed model. The cost of the proposed model is reduced by 54% as compared to that of the base case from $950.4 to $434.3, which shows the efficacy of the proposed scheduling strategy. In the future, different types of energy storage and stochastic modeling of renewable energy resources will be analyzed for a more comprehensive campus model.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials; further inquiries can be directed to the corresponding author.

Author contributions

HA, MuS, MH, and ZA: conceptualization, methodology, software, and writing—original draft; RA, ZA, HA, MoS, and JA: writing—review and editing; ZA, RA, and MH: data curation; and MuS, JA, MoS, and HA: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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