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Research paper

Reinforcement of smart campus grid infrastructure for sustainable energy management in buildings across horizon 2030

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ABSTRACT

Electricity consumption expenses take a significant amount of an educational institution's budget. A major part of utility production in Pakistan depends on non-renewable sources of energy, which have a bad impact on the environment, while their production cost is very high. To mitigate these problems at an institutional level, Renewable Energy (RE) should be promoted; this research provides a detailed plan for improving the NUST grid structure for sustainable energy management by 2030. The study improves the location of RE sources, especially solar PV systems, and includes a central Diesel generator (DG) to replace dispersed generators. The research provides a new strategy for the development of the National University of Science and Technology (NUST) grid infrastructure to support sustainable energy management by 2030. It combines central utility-scale solar photovoltaic (PV) systems and distributed generation (DG) systems, unlike the current literature that largely consists of distributed renewable power systems. This research evaluates grid performance by creating a 75-bus distribution network model in MATLAB/Simulink and implementing variations to various scenarios to optimize operational costs at 38.24 % and decrease CO_2 emissions by 46.05 %. This, together with the use of the HOMER software for both cost and environmental analysis, avails a good model that other institutions experiencing similar characteristics in the power sector can emulate when in pursuit of the optimal, efficient integration of sustainable energy solutions.

1. Introduction

The need for energy has grown because of rising living standards and world population. Our main sources of energy are conventional, but they are not sustainable because of their limited availability and are bad for the environment because they release greenhouse gases (GHG) [1]. Also, their power-generating capacities are affected by the price of fuel. Renewable Energy (RE) sources are the best way to satisfy the growing demand for energy while avoiding problems with sustainability and harmful byproducts [2]. The energy sector has played an important part in driving growth in the economy, marked by a significant rise in electricity use. Several factors contributed to the rising energy usage [3]. Due to population growth, reliable and efficient electrical systems are essential for delivering uninterrupted energy supply to consumers [4]. Power Distribution Network (DN) may face limitations in handling substantial power transfers because of capacity limits, even if the generation is sufficient to meet the load demand [5]. BP Outlook 2035 has estimated that global energy consumption is likely to rise by almost 50 per cent from 1995 level to 2035, as depicted in Fig. 1.

Until the end of 2023, slow progress in the sector has been observed, and the renewable energy share is approximately 5 % to 6 % of the total installed power generation capacity, belonging to hydro, wind and solar power resources only. The government is outlining ambitious goals of raising this share greatly in the future and putting it at 30 % by 2030. Regarding campus energy costs, energy costs in education institutions of Pakistan remain significantly high, with the average rates drifting in the vicinity of PKR 15 to PKR 25 per kWh, subject to the geographical location and supplier. Currently, NUST has 5.96 MW of power, and the average demand has been 2.71 MW for the whole year, making it very important to apply effective power management strategies in a bid to reduce the high cost of operation and use of fossil fuels.

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Nomenclature

η_{DG}	Efficiency of DG
η_{PV}	Efficiency of PV panel
$A_{PV}(t)$	Area of the PV panel
DG	Diesel Generator
DN	Distribution Networks
$E_{DG}(t)$	Energy generated by DG
$E_{Grid}(t)$	Energy imported from grid at time t
$E_{Grid}(t)$	Energy imported from grid at time t
$E_{PV}(t)$	Energy generated at time t by PV
G(t)	Solar irradiance at time t
GHG	Green House Gas
H	Hydro
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
MG	Microgrid
NPC	Net Present Cost
PBP	Pay Back period
$P_{DG}(t)$	Power output of DG at time t
$P_{DG}(t)$	Power output of DG at time t
$P_{Grid}(t)$	Load demand at time t
PV	Photovoltaic
RE	Renewable Energy
ROI	Return on Investment
SDG	Sustainable Development Goals
W	Wind

1.1. Campus microgrid systems

Institutional buildings are considered high-load consumers because of the mixed nature of their loads, falling under the category of diverse load consumers. These buildings may send surplus energy to the grid as they contain on-site power generation resources, which makes them consumers [7]. During peak demand times, they can meet their energy needs by utilizing power from the grid if their on-site generators and energy storage facilities are insufficient. Most educational institutions have what is needed to turn their power systems into Micro Grids (MGs) for the whole campus. The first university in Pakistan, NUST, intends to include a 4 MW PV system in its distribution network [8].

The current campus grid infrastructure of NUST does not have an effective system for energy management that can optimize energy usage in response to growing demand and handle challenges like scheduling multiple DG's during outage situations, including load shedding or faults [9]. The current electrical grid system on the NUST campus utilizes a DG and only has a very small mode solar PV system. Although this kind of structure has been adequate to provide energy to the institution up to this year, its consequences imply operation costs such as high fuel consumption, large volumes of GHG emissions, and power failures. Due to growing energy demand towards 2030, the currently available grid system is unable to support sustainable and reliable control of energy [10].

Every building on campus has its own set of loads and producing units and a centralized controller keeping a check on their operations [11]. This research's main purpose is to investigate campus MGs that integrate several resources, including traditional power sources, solar & DGs [12]. Analysis of campus MGs involves evaluating optimization techniques, functional objectives, and modelling methodologies. Various options are offered in the present study to manage several campus MGs [13]. Fig. 2 of the campus MG reveals that the electrical load for 24 h of the day is not constant because it rises in the mid-morning to mid-afternoon (12:00 – 14:00) because of academic activities and congestion. In the evening, the use of energy is lower because the academic and administrative facilities of a university are less busy.

A wide range of universities across the globe are facing issues, including increased energy prices, outdated facilities, and the shift towards green energy. For instance, the University of California and the University of Arizona are among the universities that have incorporated solar PV systems on large to curb high operation costs and greenhouse gas emissions. These universities have revealed that their investments in renewable energy have led to cost reduction and increased energy reliability.

On the other hand, challenges faced by NUST include its dependency on fossil fuels for power generation and having a dated grid system that cannot meet the burgeoning power requirements. Despite the global

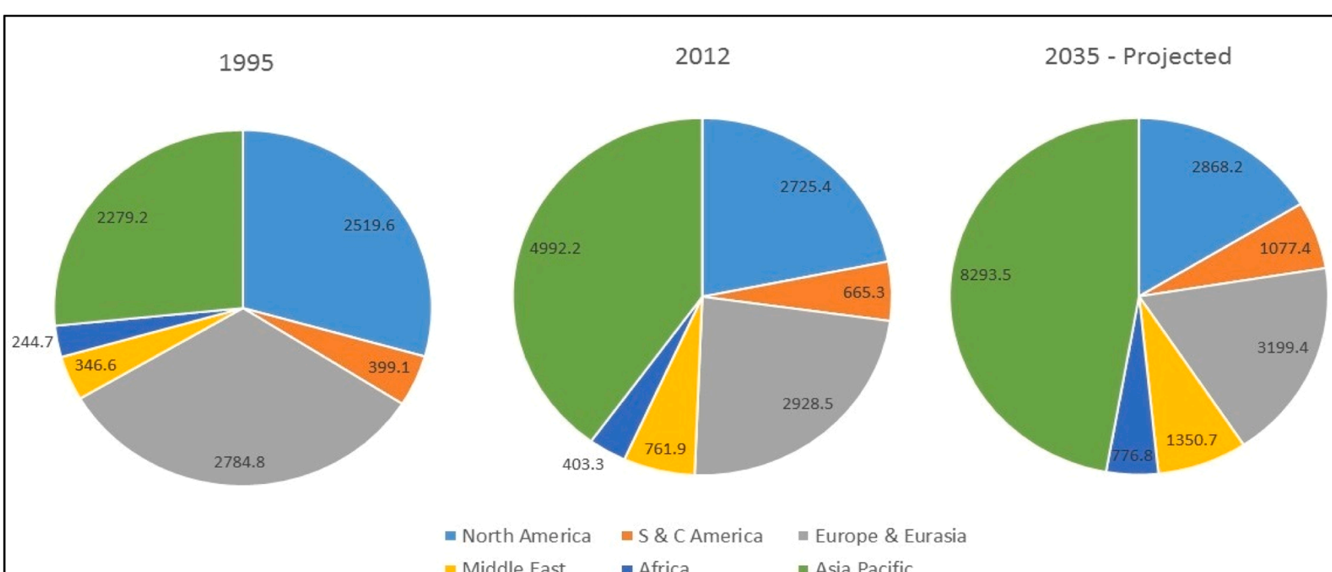

Fig. 1. Energy Consumption worldwide from 1995 to 2035 by region [6].

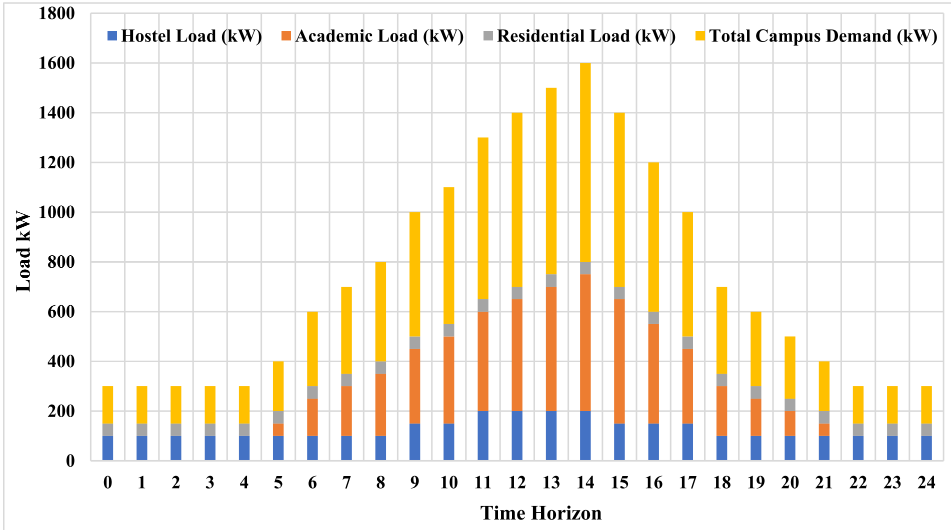

Fig. 2. Average load distribution of campus electricity [22].

shift towards the use of renewable energy, for instance, in Germany, where renewable sources in recent years were above 40 %, Pakistan's renewable energy mix is still very limited and stands at roughly 5–6 %. This contradiction underlines the need for NUST to implement sustainable and efficient energy management practices that conform with international trends.

In the study [14], concerning the stable integration and optimal operation of microgrids, the authors presented the investigation of increasing energy efficiency based on EV charging strategies. The methodology includes the study of different optimisation approaches for deploying EVs to ensure the optimal supply and demand of energy in the microgrids. Conclusions based on findings are that integration of EV charging can benefit energy control and minimise energy costs and environmental effects. The background gives an insight into how microgrids and Extension Vehicles will play an important role in achieving sustainable energy. In a study [15], the author introduces the design optimisation of a stand-alone green energy system for the campus of a university by using the algorithms of Jaya-Harmony Search and Ant Colony Optimization. In comparing these algorithms, the study examines the costs and benefits of how these algorithms make use of renewable energy sources such as solar and wind power. Analyses show that the use of the proposed hybrid optimisation approach has a positive effect on the system performance, offering a solution with fewer costs and environmental effects. In a study [16], the author assesses metaheuristic algorithms to determine the power management of hybrid energy systems for isolated rural locales with a focus on utilising hydrogen storage. The research reviews the efficiency of several approaches in estimating such systems' dimensions and considers the economic and environmental aspects as primary key performance indicators. Some findings demonstrate that the use of these algorithms improves the sustainability and dependability of the system. The outcomes assist in the effective development of energy solutions for off-grid communities. The connection of Renewable Energy (RE) sources to the electric utility grid is considered attractive due to emerging sustainable power supplies. Signs point to the fact that distributed generation (DG), most especially solar photovoltaic (PV), can improve the reliability and reliability of electrical power systems. For instance, the real scale-up of solar systems has been addressed in large facilities such as the University of Arizona and California State University, which resulted in a significant amount of reduced operating cost and lower CO_2 emission levels [17] Nevertheless, technical issues arising from the integration of Distributed Generation (DG) into the existing power distribution networks include voltage stability, modified protection systems, and economic costs [18] Research indicates that while technical solutions exist, the economic and regulatory frameworks necessary for widespread adoption remain underdeveloped [19]. In educational settings, particularly in developing countries, institutions like the National University of Science and Technology (NUST) face unique challenges. The current reliance on fossil fuels for energy generation leads to high operational costs and significant carbon emissions. Existing literature highlights that many universities have yet to transition from decentralised energy systems to more integrated approaches that leverage RE sources effectively [20]. While some educational institutions have embraced small-scale projects to harness power from the sun or other renewable energy sources, there is still a shortage of copious approaches that will give the grid-connection infrastructure its best shot. The majority of papers that consider smart energy management at scale are oblivious to the real operational requirements of campuses that have varying energy profiles [21].

Despite the available and abundant literature on the need to incorporate RE into campus energy systems, few extensive approaches have been formulated to enhance the grid system, particularly for educational institutions with distinctive managerial constraints. Additionally, only a limited number of papers have focused on evaluating, both in terms of cost and sustainability, the changes in going from decentralized energy systems to those centralized within such settings. This research seeks to fill these gaps by presenting an improved approach to integrating centralized diesel and solar PV systems to supplement the NUST grid infrastructure. Through an analytical 75-bus DN model created with MATLAB/Simulink, this paper assesses the feasibility of EM in different circumstances to minimise costs and GHG emissions. The research findings will seek to give solutions that call for sustainable usage of energy in educational institutions concerning the SDGs.

The addition of DG into the power system enhances efficiency by providing power close to the load end and serving as a backup to reduce transmission and distribution network stress [23]. Renewable comprising of DG integrates various renewable resources, including Wind (W), solar and Hydro (H) power. Costs associated with fuel prices for DGs make the use of RE sources possible, which reduces GHG emissions and, thus, global warming [24]. There are many DGs present throughout the campus, and there are several more under construction to make the environment better for work and to provide quick responses to the customers. However, power outages often cause a loss of income because the use of backup generators entails rather high costs [25].

Larger generators with low demand tend to be highly uneconomic at anything <50 % of their generating capacity [26]. The average load distribution of campus electricity is illustrated in Fig. 2. Table 1 below shows the approximation of different parameters of DG's based on a literature review [1,4,12,17,20].

From Table 1, it is evident that the DG should be selected considering the parameters like its capital cost, operating cost and maintenance cost. The literature review is shown in Table 2.

This research aims to achieve specific objectives necessary for the replacement of the existing power system of NUST Islamabad with an advanced and efficient one. The main contributions of this research include:

- Developed and modelled a complete 75-bus DN network for NUST with the help of MATLAB/SIMULINK to synthesize the current state of the NUST grid as well as various enhancement scenarios such as upgrade of solar PV, optimization of generator placement and the addition of RE.
- To model and analyze the defined grid scenarios with the help of enhanced optimizing algorithms and check the impact of the outcomes in terms of operation cost, carbon footprint, power loss, and reliability of the grid.
- To enable the comparison of the performance of the simulated scenarios against the identified performance metrics and conduct of sensitivity analysis to verify the soundness and validity of the chosen grid configuration.
- The objectives of the study are to determine the most economical, environmentally friendly and efficient for the grid to adopt and to recommend the best strategy for implementing this configuration in the NUST.
- To evaluate the environmental and economic consequences of the desired grid formation based on the comparison of the expected GHG emissions, the development costs and possible cost savings, as well as to check the correspondence to the SDG by the year 2030.
- To give the best suggestion for the measure of the chosen grid structure and to recommend further research ways to improve NUST grid infrastructure.

Here is the layout of the paper: In Section 2, the details of the NUST grid infrastructure are presented, while research methodology and the 75-Bus DN model are in Section 3 of the paper, whereas the NUST model will be explained in Section 2 of the paper. The distribution of results is in figures, with discussion in Section 4. Section 5 presents a summary of findings, recommendations, and limitations of the study, followed by References: and Appendix

2. CAMPUS electrical grid infrastructure

University campuses typically have large structures that contribute to substantial energy use [20] Universities are currently dealing with the challenges arising from decreased funding and rising energy costs. The pressures act as a significant motivator to implement energy-conservation programs and embrace the significant depletion of RE resources [45]. This improves the MG's ability to withstand the most extreme disruption of renewable resources.

Table 1
Expenses of a DG.

Parameter	Value
Capital cost ($)	56,000
Operation and maintenance cost ($/h)	0.277
Replacement cost ($)	40,000
Minimum load ratio (%)	30
Lifetime (h)	90,000

2.1. NUST grid infrastructure

NUST has a dedicated 132 kV electrical grid system, which is managed by IESCO, and an 11-kV DN that is administered by the institution. The current approved power capacity of the campus is 5.96 MW, with the potential to be increased to 16 MW in the future if needed. The maximum load reached at its highest point is approximately 4.8 MW, while the average load remains at roughly 2.71 MW throughout the year. NUST possesses a specialized solar power system that is connected to the electrical grid and is distributed throughout the campus, producing a total of 1.08 MW of electricity. Additionally, NUST has a total of 43 generators that run on diesel fuel, with a combined capacity of 8.262 MW. The generator's details are included in Appendix A section A.2. NUST has abundant resources available for grid strengthening, along with all the necessary prerequisites.

2.2. Details of campus connected load

Fig. 3 shows the average load profiles of individual loads inside the NUST campus. These loads are of 10 individual buildings. Buildings are linked to the feeders via the 11 KV / 400 V delta wye transformers have their active and reactive loads. The peak loads measured at certain time intervals during a day are shown in Appendix A section A.3. The load ranges from 0.043 MW to 0.920 MW, with NICE having the highest building load at 0.920 MW and RAZI - 1 having the lowest load of 0.043 MW. NICE and RAZI are the names of the buildings in NUST.

2.3. NUST solar pv details

NUST installed a 1.08 MW solar PV system to reduce their electricity expenses. The overall load of NUST had been augmented by 1.2 MW because of the inclusion of NSTP & SINES and the construction of 36 additional residential apartments. Table 3 shows the available solar power on different points with the values mentioned in the specified location. The maximum power demand of NUST in the 2018–19 period, before the COVID-19 pandemic, was 4.5 MW.

3. Methodology

It can be said that MATLAB/Simulink, tools for electrical systems modelling, has rather a long history, which is evidenced by the number of publications. As evidenced by the work in [46] and [20], it is a convenient tool for emulating power system behaviors and incorporating renewable power plants. HOMER is one of the most popular tools in the optimization of microgrid designs, and according to count [47] and [46], different studies have validated the tool by providing accuracy in evaluating economic and environmental performance indicators. For more robustness, the study should also compare the result from the simulation with real data from existing microgrids or case studies following the assumptions made in terms of load, generation from renewable energy sources and operation costs.

Fig. 4 shows the flow diagram of the procedure adopted to make the current campus grid into a smart grid. The first step is the collection of reference data, and the load data needed for this research has been collected from the NUST Project Management Office and through surveys. The next stage is then the modelling of the detailed infrastructure of the grid using MATLAB Simulink, and different scenarios are considered. To compare the performance of each configuration, simulations are carried out. Cost, environmental aspects, and grid reliability indicators are the points of focus in this comparison. Another form of analysis that is carried out is the sensitivity analysis, where the model checks for the sustainability of the configuration selected when conditions change. The most optimal grid configuration is thus chosen, and the advancements and effectiveness of the implemented solution are reviewed all the time to assess whether it achieves the goals of the research. This methodology is to help NUST grid infrastructure towards

Table 2
Summary of literature.

Ref	Year Published	Tool	Analysis Type			Technologies			Objective Function			Explicitly Considered Parameters		FM	SA	Findings
			T	E	E	PV	DG	G	NPC	LCOE	IRR	ROI	PBP			
[27]	2021	PVsol	✓	✓	×	✓	×	✓	✓	✓	✓	✓	×	×	Yes	The PV model can produce 3196.53 kWh of solar energy, adding up to 3784.56 kWh, resulting in a feasible yearly LCOE reduction of $4483.56. The paper uses a simulation-based methodology to design a prosumer microgrid for MNS UET Multan Campus, focusing on renewable energy integration and cost optimization. Results show reduced energy costs and improved sustainability, with findings emphasizing the potential for energy self-sufficiency in campus settings. However, the lack of real-world validation and scalability analysis highlights the need for field implementation and advanced energy storage studies in future research.
[28]	2023	MATLAB	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	Yes	The optimized policies are more practical in protecting MGs' privacy, they provide outcomes equivalent to standard model strategies. The methodology employs RL to optimize energy distribution and cost efficiency dynamically across interconnected MGs. Results demonstrate improved energy utilization and cost savings compared to traditional methods. However, the critical analysis reveals that while RL provides adaptability, challenges in scalability, convergence, and real-world deployment require further investigation for broader applications.
[29]	2022	MATLAB	✓	✓	×	✓	×	✓	✓	✓	×	×	×	×	No	The Annual operational LCOE reduced from $140,497/year to $126,644/year and System's operational cost reduced by 67.91 % per day by integrating W, PV, ESS, and grid energy. The study employs simulation models to optimize energy efficiency, integrate renewables, and enhance grid reliability. Results indicate significant improvements in energy sustainability and system performance. However, the methods lack real-world validation and detailed cost analyses, suggesting future research should prioritize field implementation and explore economic feasibility alongside technological advancements.
[30]	2023	HOMER, MATLAB/ Simulink	✓	✓	✓	✓	×	×	✓	✓	×	×	×	×	Yes	A 94 % reduction in carbon emissions is achieved by using the recommended PV/ Battery system. The study uses simulation and cost-benefit analysis to evaluate system performance, highlighting significant reductions in operational costs and carbon emissions. While the methodology effectively combines technical and economic aspects, the analysis could benefit from a more detailed examination of system scalability and region-specific regulatory impacts to enhance future applicability.
[31]	2021	CPLEX solver	✓	✓	✓	✓	×	✓	✓	✓	×	×	×	×	Yes	Constant power techniques reduced LCOE by 62.8 % and GHG emissions by 63.3 %. The study demonstrates enhanced performance and adaptability of the MG design across various scenarios. While the approach is comprehensive, future work should focus on real-world deployment and integration with advanced technologies such as AI-based predictive management for further optimization.
[32]	2023	GAMS	✓	✓	×	✓	×	✓	✓	✓	×	×	×	×	Yes	The strategy effectively decreases LCOE by 58.67 %, allowing the community to operate independently from the electricity grid. The methodology optimizes energy utilization, cost, and environmental impact through

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Table 2 (*continued*)

Ref	Year Published	Tool	Analysis Type			Technologies			Objective Function			Explicitly Considered Parameters		FM	SA	Findings
			T	E	E	PV	DG	G	NPC	LCOE	IRR	ROI	PBP			
																simulation-based modeling. Results highlight improved energy efficiency and reduced emissions. However, the approach lacks real-world validation and scalability analysis, suggesting future studies should explore large-scale implementation and long-term system stability.
[33]	2021	CPLEX	✓	✓	✓	✓	×	×	✓	✓	×	×	×	×	No	Compared with the case without demand response, the LCOE & NPC decreased by 14.7 %, going from $296.64 to $245.10. The study uses a stochastic optimization framework to balance cost, energy efficiency, and user comfort. Results demonstrate enhanced scheduling performance and adaptability under variable conditions. However, the method could benefit from real-world testing and integration of advanced predictive algorithms to further improve robustness and scalability for diverse operational scenarios.
[34]	2020	MATLAB	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	Yes	Implementing prosumer batteries to store energy cut LCOE by 35 % in the summer and 29 % in the winter. The study uses an optimization model to balance energy consumption, cost reduction, and system stability while considering real-time pricing. Results show significant cost savings and improved energy management. However, the method could be enhanced by including more dynamic factors, such as grid fluctuations and long-term forecasting, to increase its applicability in real-world, large-scale campus settings.
[35]	2023	CPLEX Solver	✓	✓	×	✓	✓	×	✓	✓	×	×	×	×	No	Decrease demand at peak times by 1.17 MW, improvement of 20.83 % in GHG Emissions. The study optimizes energy distribution, cost, and system reliability while considering flexibility in demand response. Results show improvements in system efficiency and cost savings. However, the approach could be further enhanced by including real-world validation and a more detailed analysis of scalability, particularly in complex, diverse environments with variable demand profiles.
[36]	2022	MATLAB	✓	✓	×	✓	✓	×	✓	✓	×	×	×	×	Yes	Decreased CO_2 emissions by 213.23 kg; total system costs decreased by $0.728 million. The study uses simulation models to optimize the operation of V2 G and battery storage, focusing on cost reduction and environmental benefits. Results indicate that the integration can significantly lower energy costs and reduce carbon emissions. However, the methodology could be improved by including real-world implementation data and a deeper exploration of the challenges related to V2 G system adoption and grid stability.
[37]	2023	HOMER	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	No	The ideal configuration includes a 33-kW converter, an 84-kWh battery bank, a 20-kW biofuel generator, and 47 kW solar PV arrays which is reducing LCOE by 30 %. The study employs the GWO algorithm to optimize the hybrid system's performance, considering factors like energy efficiency, cost, and social impact. Results indicate significant potential for sustainable energy generation, cost reduction, and enhanced energy access in remote areas. However, the study could benefit from further analysis of long-term system viability and real-world operational challenges in similar regions.
[38]	2022	HOMER Pro	✓	✓	×	✓	×	✓	✓	✓	×	×	×	×	Yes	Using automated systems with several criteria for managing the energy sector resulted in a 10 % to 60 % improvement in NPC. The study uses decision-making tools to evaluate and

(*continued on next page*)

Table 2 (*continued*)

Ref	Year Published	Tool	Analysis Type			Technologies			Objective Function			Explicitly Considered Parameters		FM	SA	Findings
			T	E	E	PV	DG	G	NPC	LCOE	IRR	ROI	PBP			
																prioritize different design options and management strategies for the RE community. Results show that the approach enhances overall sustainability and community resilience. However, the methodology could be strengthened by incorporating more detailed real-world case studies to better understand the practical challenges and scalability of such systems.
[39]	2023	HOMER, MATLAB	✓	✓	×	✓	×	✓	✓	✓	×	×	×	×	Yes	The multi-objective optimization strategy decreases operating costs by around 20 % and CO_2 emissions by 25 %. The review highlights advancements in energy storage, forecasting, and optimization techniques. However, it suggests that future research should focus on real-world implementation, system scalability, and addressing challenges related to intermittency and grid integration to ensure the long-term viability of solar MGs.
[40]	2022	HOMER	✓	✓	✓	×	×	✓	✓	✓	×	×	✓	×	No	Energy management technologies were proposed that are sustainable and help solar MGs operate smoothly to cutdown the overall CO2 emissions by 43 %. The study uses a data-driven approach to optimize the size and configuration of PV and battery storage systems for EV charging, focusing on maximizing energy efficiency and cost savings. Results show that the proposed framework enhances the system's performance by reducing operational costs and improving energy management. However, further validation through real-world case studies and consideration of dynamic charging patterns could strengthen the findings and applicability of the model.
[41]	2021	MATLAB	✓	✓	×	✓	×	×	✓	✓	×	×	×	×	No	A techno-economic study of grid-connected hybrid systems included electricity costs for PV/Diesel/Battery combinations which was found to be 20 % less than usual. The study uses simulations to evaluate system performance, focusing on cost, efficiency, and reliability under various scenarios. Results demonstrate that the hybrid system provides a reliable and cost-effective solution for energy access in remote areas, with significant reductions in fuel consumption and emissions. However, the study could benefit from a more in-depth exploration of the long-term maintenance costs and the scalability of the system in diverse geographic regions.
[42]	2022	CPLEX 12.8	✓	✓	✓	✓	×	×	✓	✓	×	×	✓	×	No	The proposed SP method results in a 3.12 % decrease in operating cost per day and a 4.85 % decrease in monthly average cost. The study employs a stochastic optimization approach to minimize costs and ensure reliability over different time scales. Results show that the method effectively enhances the robustness of energy management by accounting for variability in renewable energy generation and load fluctuations. However, the study could be improved by incorporating real-time data integration and testing its scalability in larger, more complex MG systems to address operational challenges.
[43]	2024	MATLAB	✓	✓	×	✓	×	×	✓	✓	×	×	×	×	No	Electric power generation in Koh Samui: a cost-benefit analysis of HRES with 89 % solar PV power. The study uses advanced optimization techniques to balance power generation, storage, and grid interactions to minimize costs and enhance system reliability. Results demonstrate significant improvements in energy management efficiency and cost

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Table 2 (*continued*)

Ref	Year Published	Tool	Analysis Type			Technologies			Objective Function			Explicitly Considered Parameters		FM	SA	Findings
			T	E	E	PV	DG	G	NPC	LCOE	IRR	ROI	PBP			
																reduction. However, the methodology could benefit from further analysis of long-term system performance, scalability, and integration challenges in real-world applications, particularly in regions with highly variable renewable resources.
[44]	2022	HOMER Pro	✓	✓	×	✓	×	✓	✓	✓	✓	✓	✓	✓	No	According to the techno-economic study, approach results in a 58 % reduction in LCOE. The study evaluates the performance, cost-effectiveness, and environmental impact of combining various renewable energy sources such as solar, wind, and storage for a campus setting. Results show that the hybrid system offers a cost-effective and sustainable energy solution with reduced environmental footprints. However, the study could be strengthened by including a more detailed risk analysis and considering real-world operational conditions in the optimization process.
[P]	2023	MATLAB, HOMER	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Yes	The proposed model will reduce the total fuel consumption by 65 % using one big DG and the connected solar will reduce the overall bill by to 8 %. The seamless integration of additional 2MW PV will reduce the bill further by 30 %

***Note:** T: Technical, E: Economical, E: Environmental, PV: Photovoltaic, G: Grid, DG: DG, NPC: NPC, LCOE: Levelized Cost of Energy, IRR: Internal Rate of Return, ROI: Return on Investment, PBP: PBP SA: Sensitivity Analysis, FM: Financial Mechanism.

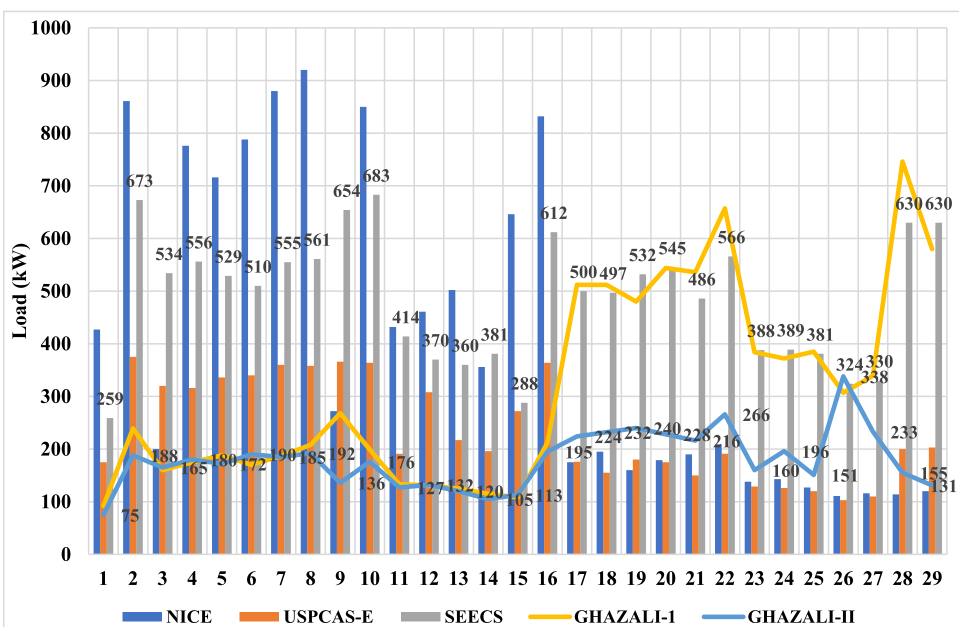

Fig. 3. Monthly Consumption trends of NUST.

Table 3
Solar installed with rated power capacity on different locations.

S No.	Location	kW
1	USPCASE	100
2	SEECS	150
3	NICE	250
4	Boys Hostel	200
5	NSTP	153.7
6	Central Library	147
7	Swimming Pool	81

sustainable energy management, considering not only economic feasibility but environmental sustainability and efficiency.

Fig. 5 shows the single-line diagram of the model that has been proposed in this study. It consists of 75 buses, including loads and sources. In the current system of NUST, DGs are placed near load ends, and a total no of 43 generators are placed on different locations. But, in the proposed design, a single unit DG consisting of accumulative power is installed on a substation rather than remote locations, and the solar systems are kept the same. Using the cost optimization technique, the optimal placement of RE resources is confirmed. Initially, the actual

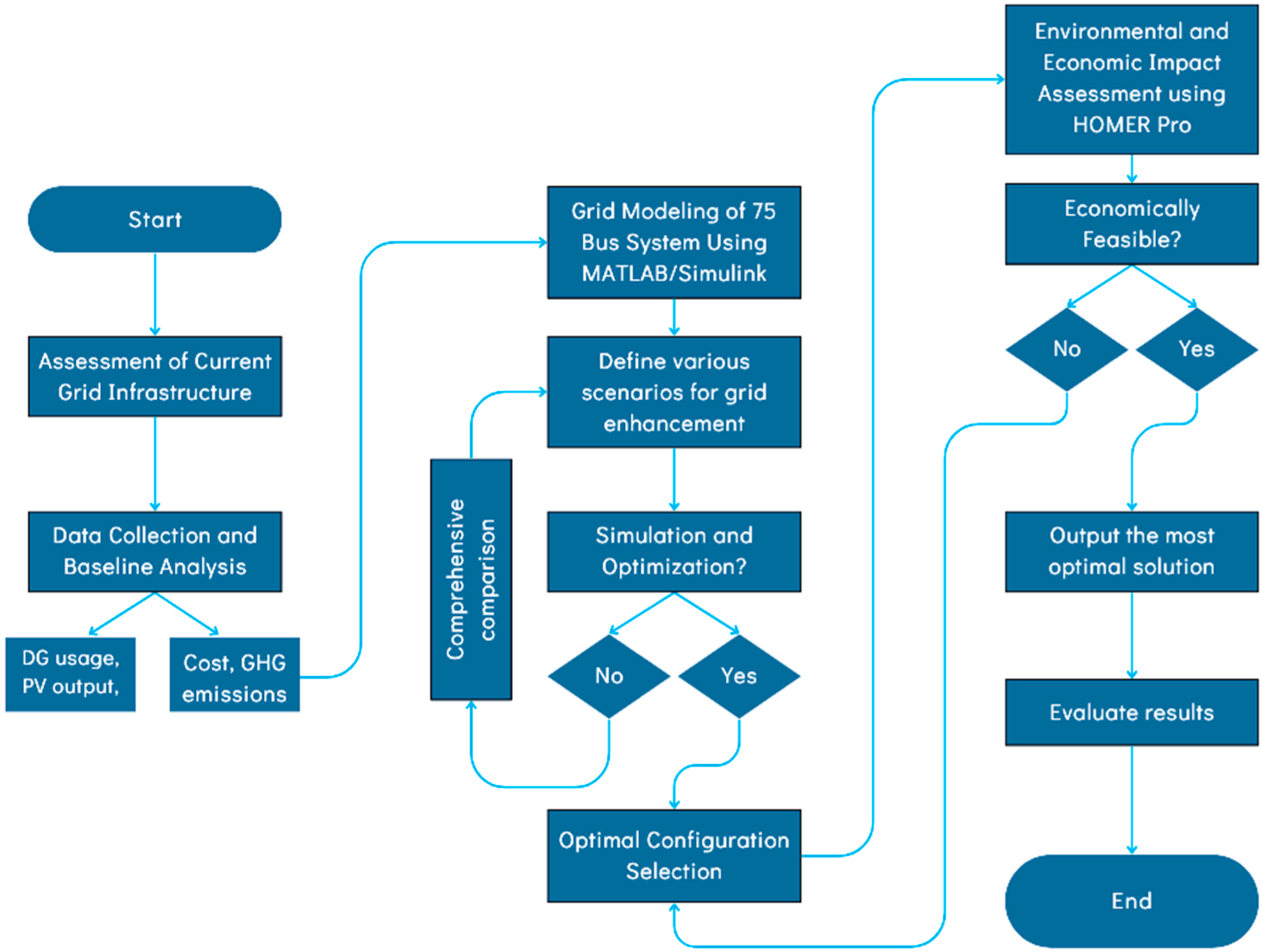

Fig. 4. Flow Chart of Proposed Strategy.

system is developed in MATLAB, and its Load flow analysis is performed after that, the changes are made according to the adopted technique and simulated the results. Some cases, including worst-case scenarios, are made and compared with the base case. Cost optimization SDGs are ensured. Moreover, a 2 MW future extension is also added to the design.

The analyzed 75-bus DN model effectively presents the electrical grid infrastructure of the National University of Science and Technology (NUST). Currently, its major function is used in determining the ability of the grid to operate under different conditions, such as load growth and incorporation of RES, namely solar PV. It enables the assessment of consumed energy from DG, PV systems, as well as the grid and the optimal management of energy distribution.

In parallel, the DN contains 75 buses of the electrical network where power is either demanded or supplied. These buses are linked to each other by feeders, which supply the campus with electric power. The load profiles for the buses are assigned as actual consumption figures obtained from different buildings in the campus show. This encompasses classrooms, lecture theatres, students' hostels, directors' offices, and laboratories which show a variation in energy usage. The application of distributed power generation, which comprises a central DG unit along with various DG units such as solar PV, can be included. It provides bidirectional power flow, utilizing which any unused power produced by PV systems can be transferred to the grid. Closed-loop control strategies are used to regulate DG units and control the energy flow according to load requirements and DG sizes.

Through the integration of DG and RES, the DN results in increased reliability by distributing power generation and load close to the consumers, hence increasing system reliability against outages. The optimization of the distribution of energy brings down the cost of operation in a very big way. For example, some of the findings show an initial estimate of cost savings estimated at 38.24 % based on sound management of DG and RES. The integration of solar PV systems also leads to actual emissions reduction and reducing greenhouse gas emissions with estimates of the emission of 46.05 % less CO2 than conventional fossil fuel generation. This characteristic of being broken down into 75 buses can then allow for increasing the size of the model in the future to cater for higher loads or more renewables in the future as NUST develops. The model supports net metering practices, allowing excess energy generated by solar PV systems to be credited back to the university's account, further enhancing financial viability.

The campus infrastructure consists of a radial distribution feeder network for the 75 bus MV, with 33 buildings connected to the feeder by an 11 kV / 400 V Delta Wye transformer. Fig. 6 below shows the model diagram of the NUST Grid system implemented in MATLAB. It depicts the 11-kV feeder, which is linked to the 132-kV grid via a 4 MVA power transformer. Every building's electrical load is tied to an 11 kV feeder using an 11 kV / 400 V Delta Wye transformer. A 10mm^2 conductor size is utilized with a current carrying capability of 81 As for a feeder length of 5 km.

A 75-bus distribution network (DN) model is used as an electrical model for the NUST because of the complexity and size of the NUST campus. This model size enables a detailed evaluation of power flows

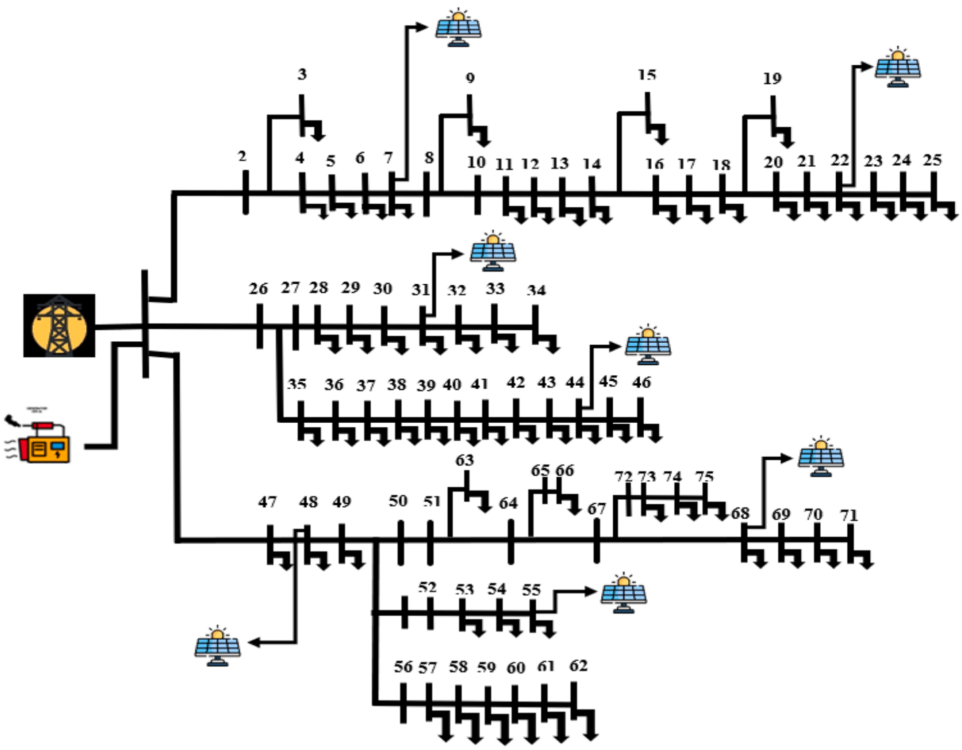

Fig. 5. NUST Electrical Grid with Solar PV and DG.

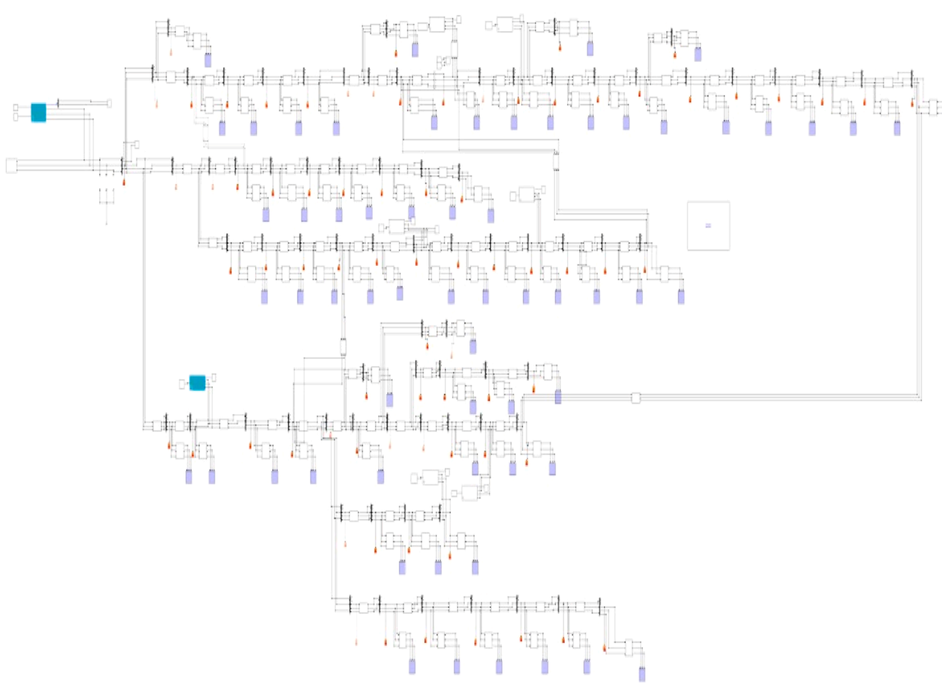

Fig. 6. One Line Diagram of NUST in Simulink.

between loads in various categories as well as other generation sources, critical given their different energy requirements among academic, residential, and administrative facilities. Also, the 75-bus system allows evaluation of different operating conditions, such as load increase and the addition of renewable power generation, so that specific improvement measures can be applied to power system stability and performance. This scale is most important for designing the required energy management systems that will be able to respond to the current conditions as well as future energy demands for the NUST.

This article examines the effect of distributed PV power generation on different locations on the voltage profiles as well as the contribution of the PV to cost minimization. Load flow analysis has been employed in MATLAB Simulink to examine the voltage at every bus within the network. Grid-tied solar PV inverters equipped with reactive power control are utilized for feeding the generated electricity into the grid. These distributed PVs are installed to control the voltage at different buses and keep them within the limit of 5 per cent. The NUST is rich in solar irradiance geographically, so a PV source can be the best option for RE at this location. In this region, throughout the year, solar irradiance is available in abundant.

Battery systems play a very critical role in acting as energy storage, where excess energy is produced at some times of the day and can be used at other times when demand is high. This capability improves the stability and reliability of the grid, which makes them suitable for use in accommodating renewable resources such as solar PV. Lithium-ion batteries, lead-acid batteries, and flow batteries are types of batteries, each offering specific benefits. Lithium-ion batteries are preferred for their compact size, energy density, and response time, and lead-acid batteries are suited for large-scale deployment due to their low cost. Unlike standard 'rocking-chair' rechargeable batteries, flow batteries are more scalable and can deliver power for longer durations, which makes them ideal for use in larger-scale applications.

On the other hand, DG systems involve distributed power generation technologies that are installed near the load point, as in the case of solar PV systems, wind power systems and microturbines. These systems minimize transmission losses since electricity is produced where it is most required, and they improve reliability by providing backup electricity during power blackouts. The incorporation of DG into the campus energy management system is conducive not only to local generation but also to the environment when renewable energy sources are used.

Besides battery systems and DG, other types of energy storage should be considered as well. Pumped hydro storage involves using electricity to pump water up to a higher reservoir and then using the gravitational force to generate electricity in the evening, but it is restricted in some areas. CAES is an energy storage method that involves the compression of air in underground structures such as hydrogen and natural gas storage caverns to generate electricity. Flywheel energy storage systems utilize a rotary mass for storing kinetic energy and have fast response capabilities for applications requiring a short cycle time. Thermal energy storage operates by storing excess electricity in the form of heat that can later be used in heating or power production.

3.1. Energy resources in campus mg

The energy resources installed at NUST include PV systems, DG and the main power supply or utility supply. All sources help to take the load demand, and effective management of these sources influences the cost environment and stability of the system significantly. We used MATLAB 2021a/Simulink for all our simulations.

3.1.1. Solar pv in campus MGs

This research used MATLAB/Simulink for the simulation of different cases in which the PV array of model SunPower SPR-238E-WHT-D is employed with 1.08MW capacity, with 18 % panel efficiency. There is no peak power point tracking mechanism in the system, and the PV panels are positioned horizontally at a 30-degree tilt. The energy output of a PV system, considering the area of the panel and solar irradiance, can be calculated by Eq (1):

$$\boldsymbol{E_{PV}(t) = A_{PV}.\eta_{PV}.G(t)} \tag{1}$$

Where $E_{PV}(t)$ is the energy generated at time t, A_{PV} is the area of the PV panel, η_{PV} is the efficiency of the PV panel, and $G(t)$ is the solar irradiance at time t.

3.1.2. DG in campus MGs

The energy generated by DGs is the gross of their power rating and efficiency, while the cost of DGs comprises fuel costs and other expenses. For this research, we used a single DG of capacity 8.262MW at the substation side instead of 43 DGs as in the actual model of NUST. The operating and maintenance (O&M) cost is USD 0.15/kWh, and the efficiency is 35 %. The energy output of a DG considering the power output and efficiency can be calculated by Eq (2)

$$E_{DG}(t) = P_{DG}(t).\eta_{DG} \tag{2}$$

Where $E_{DG}(t)$ is the energy generated at time t, $P_{DG}(t)$ is the power output of DG at time t, and η_{DG} is the efficiency of DG installed.

3.1.3. Grid power in campus MGs

The energy imported from the grid is expected by load demand and the non-renewable capacities connected by PV systems and DGs. In this research, we have used an independent grid that is receiving electricity from IESCO at a voltage of 132KV. With step-down transformers, the NUST grid reduces the voltage from 132KV to 11KV. The NUST DN delivers electricity to the loads via the grid. The grid is modelled in Simulink using three-phase supply blocks. The energy imported from the grid can be calculated by Eq (3):

$$E_{Grid}(t) = P_{Load}(t) - (E_{PV}(t) + E_{DG}(t)) \tag{3}$$

Where $E_{Grid}(t)$ is the energy imported from the grid at time t, $P_{Load}(t)$ is the load demand at time t,$E_{PV}(t)$ is the energy generated by PV at time t and $E_{DG}(t)$ is the energy of DG at time t. The details of the parameters considered for the components used in this study are given in Table 4.

$E_{Grid}(t)$Multiple benefits are available with hybrid renewable energy systems and include combined wind turbines and the solar PV system, the fluctuation of energy generation can be managed. Solar power generation can be well integrated with wind power generation since during some hours of the day or sometimes days or weeks, the wind is not favourable while the sun is still shining. The potential is that this combined solution generates a more reliable, strengthened and diversified power network system which is less depending on fossil resources.

In hybrid systems, battery storage also assumes an important place while it is charged during periods of excess generating capacity and supplied during periods of high demand. This capability does not only meet the real-time demands for supply and demand but also can act as a backup power supply for the campus energy system, increasing its reliability. For example, the use of a battery storage system connected to a solar PV array enables the NUST to draw energy from the battery each time generation is low or inadequate and hence avoid high demand charges that may result from peak power usage.

Table 4
Details or parameters used in the model.

PV system		Grid		DG	
Parameters	Value	Parameter	Value	Parameters	Value
Panel Efficiency	18 %	**Maximum Import Capacity**	100MW	**Fuel type**	Diesel
Panel area	12,000 m^2	**Tariff**	Variable ($0.10-$0.20/kwh)	**Fuel consumption rate**	0.45/ltr
Irradiance	1000 Wm^2	**Voltage Level**	11Kv	**Efficiency**	35 %
Temperature	25 °C	**Frequency**	50Hz	**Emission factor (CO_2)**	2.68kg/ltr
Efficiency of inverter	95 %	**Power Factor**	0.98	**Operational cost**	0.15/kwh
Tilt angle	30°	**Reliability**	99 %	**Maintenance Interval hours**	500 h
Orientation	South-facing	**Demand Charges**	$100/ month per MW	**Start-up Time**	5 min
				Shutdown time	5 min

Furthermore, the integration of these alternative solutions is in line with global tendencies in renewable energy utilization, traditionally described as using hybrid systems as a means of increasing energy security and stability on the global level. Since many universities and colleges around the world use similar approaches to tackle the issue of escalating energy costs and the deterioration of the conditions in the environment, NUST can learn from these hybrid configurations.

3.2. Sensitivity analysis

Sensitivity analysis is a useful technique used in the analysis of the variations in the behavior of a certain dependent variable relative to a set of assumptions under varied values of the independent variables. Every grid solution shall undertake sensitivity analysis to analyze the impact of variation of major assumptions on the reliability of the analysis. This study will evaluate the stability and performance of the proposed grid structures considering the variation in the key factors, which are the load increase (1 % to 5 % annual increase), fuel prices (20 % decrease to a 50 % increase) and the level of integration of RE resources (20 % to 80 % of the total energy mix). This will help in the establishment of robust configurations of the grid, which will be relevant in future situations.

Weekly and daily fluctuations of the load are dependent on the academic calendar, usually peak at mid-morning to mid-afternoon business hours due to class activities and register lower energy usage during the evening and on weekends. Customer behavior is also incredibly crucial, with consumption habits changing with weather conditions that define heating or cooling requirements.

The inclusion of these variabilities into the study will help in the enhancement of such understanding in a way that the grid can be used to provide for the variabilities, as noted below. For example, during periods of high load density, such as the academic year, the use of Distributed generation (DG) systems and renewable energy like solar PV systems can support the utility and bring balance to the system. On the other hand, while during periods of low consumption, the generated renewable energy can remain unused, batteries for storage help to store the excess energy for use later.

This analysis assumes a certain rate of load growth based on consumption data from NUST and expected future trends in load because of increased enrolments and power consumption on the expanded campus. This assumption is important for making forecasts of future energy demands and subsequently proving that the proposed grid topology can effectively handle higher loads without strain. These results include forecasts of fuel costs, especially for diesel for distributed generation systems.

These are projections derived from past data on the business and marketing information acquired from the business arena. Assumptions about fuel prices are important as they form the basis of many calculations of costs per unit of electricity generated, as well as the cost-effectiveness of incorporating renewable energy sources as opposed to conventional fossil fuels. The study also factors in the degradation rates of solar PV, which averagely lie between 0.5–1 % per year. This assumption is very important when forecasting the future performance of the grid and the rate of energy produced by the solar PV systems installed. It is only possible to assess the sustainability and feasibility of investing in solar energy if we know how degradations impact the generation time constantly.

4. Results & discussions

This Section will discuss the results briefly. The 75 Bus proposed model system shown in Fig. 6 is simulated against different scenarios using MATLAB/Simulink 2021a.

4.1. Comprehensive comparison

In this section, we made a comparative analysis of the performance of the proposed NUST grid infrastructure model with other models in terms of cost, consumption of CO_2 emissions, power quality, and reliability. The comparisons are made with the current grid configuration as a reference or the Base Case and other possibilities incorporating the use of more than one DG, incorporation of other types of renewables in the existing system and a composite system with several forms of energy feeds.

- **Base Case**: Current NUST Grid Setup

The existing grid structure in NUST largely depends on a decentralized system of DGs, with an installed capacity of 8.262 MW distributed across the whole campus.

- **Model A**: Multiples DGs

In this case, we analyze the use of many small DGs placed at various locations on the campus, as was the case in the base case but evaluated for efficiency improvements.

- **Model B**: Increased Solar PV integration

This case doubles the capacity of the solar PV system; thus, the need for DGs is decreased.

- **Model C**: Hybrid system with W and solar

As for the configuration of the W energy system, in this case, it is integrated with the current existing solar PV system.

- **Proposed Model**: Single Large DG with Solar PV

Model A, with a centralized solar PV system in parallel with the diesel, has reduced operational costs and optimized energy supply. This configuration gets higher solar capacity and load efficiency and reduces its operation and maintenance cost by 38.24 % and CO_2 emission by 46.05 %. This central hub-based system reduces transmission losses and optimizes the use of renewable energy at the time of maximum sunlight production.

On the other hand, the proposed Model B, with the integration of additional wind generation, may continue to face performance issues and challenges associated with dealing with a combination of different energy types and the fluctuating nature of wind energy. They may also result in higher system expenses and difficulties in controlling the grid at times when there is little or no wind power output.

- In terms of sustainability and cost, model C, which is configured with only diesel generation and no renewable integration, is found to be most suboptimal and has reduced operational costs. This configuration benefits from a higher solar capacity and efficient load management, leading to a 38.24 % reduction in operational costs and a 46.05 % decrease in CO2 emissions. The centralized approach minimizes transmission losses and maximizes the use of renewable energy during peak sunlight hours.
- Conversely, Model B, which incorporates a hybrid solution with additional wind generation, may experience performance limitations due to the intermittency of wind energy and the complexity of managing multiple energy sources. This can lead to increased operational costs and challenges in maintaining grid stability during periods of low wind generation. Model C, focused solely on diesel generation without renewable integration, performs poorly in terms of sustainability and cost-effectiveness. While it may assure a steady

power supply, the fuel consumption is high, meaning high operation costs and high emission of greenhouse gases.

The presented SC configuration of the proposed solution of solar PV and diesel generation system unambiguously outperforms hybrid configurations that involve other REs like wind or batteries. Although hybrid systems can improve energy resilience, the cost of the proposed system cuts 38.24 % of the operational costs and CO2 emissions were reduced by 46.05 %Thus, the proposed system has a significant economic and environmental gain.

Measured values suggest that by eliminating decentralized energy production, it is possible to provide consumers with efficient energy distribution with less reliance on fossil fuels while preserving the stability of the grid. However, hybrid systems have some issues following integration difficulty and high fixed costs compared with integrated systems. Analyzing the key characteristics of the proposed model, its ability to collect all distributed generation into a single point at the substation enhances the efficiency of compared configurations if one or several energy sources are used, which can complicate the operation of the system several times.

According to a comparison made in Table 5, the proposed model is 38.24 % cost-effective and 46.05 % less harmful to the environment. While comparing all three models, Model C (Hybrid) has the lowest CO2 emissions and operational cost however, the proposed model is very suitable with the required simplicity and efficiency to provide offshore reinforcement of the NUST grid infrastructure. The model proposed here takes and optimizes resources and minimizes the environmental footprint as much as possible. The use of one big DG makes it smooth, and hence, the effort of cutting down costs by saving on fuel is achieved. An additional feature of solar PV, which lowers the level of CO_2 emission and power loss, makes this model ideal for sustainable energy management. Fig. 7 shows the comparison of different scenarios.

4.2. Detailed cost-benefit analysis

4.2.1. Long-Term financial savings

Diesel generation, which is currently scattered throughout the region, along with better integration of new renewable generations, also presents substantial cost savings in the long-term grid structure. Having multiple distributed generators, as in the base case, results in high operating costs due to wastage of fuel and frequent maintenance. The proposed approach may help NUST save about 200 million PKR for 10 years, with less fuel consumption and lower maintenance charges.

4.2.2. Payback period

The cost to implement the first strategy, namely, grid optimization (for example, replacing one large DG with many small ones and increasing the use of RE sources), is expected to be 50 million PKR. By achieving operational savings of about 20 million PKR annually, the PBP of this investment is roughly 2.5 years. Within this perspective, the relatively short payback time for the proposed grid infrastructure means that not only is it an investment economically feasible, but it is quite economically appealing due to its high rates of return. Table 6 shows the details of the cost analysis and illustrated in Fig. 8.

4.3. Cost efficiency analysis

In this section, the cost efficiencies of various grid connection schemes, such as the DGs and PV(PV) systems, will be discussed. These are the base case configuration in which DGs are installed at multiple points in the electrical grid and the proposed configuration in which two DGs are connected in parallel at the substation level. Also, we estimate the effect of the rise in the capacity of PV on the cost-effectiveness of the total power system. Table 7 shows the summary of the results for different scenarios. The detailed calculations are presented in Appendix A Section A.4. To provide a clear comparison of the cost savings across the different scenarios, we present the following pie chart in Fig. 9.

The comparative evaluation of the three cases indicates that there are enhanced aspects of the cost considerations and the environmental impact. The improvement in operational cost when moving from the base case of multiple distributed DGs to the proposed centralized DG is approximately 22 % when, in terms of maintenance, the optimal configuration has approximately 25 % lower requirements than multiple distributed DGs. Furthermore, when PV capacity is increased in the given scenario, all these benefits are amplified – totaling a decrease in operational costs to a percentage of about 39 % less than the base case. Also, this scenario cuts fuel use by roughly 40 % as well as an approximate 45 % cut in CO_2 emissions, pointing out the significant environmental gains that result from incorporating more of the RE systems into the grid networks.

4.4. Technical analysis

Technical and Economic analysis is performed to find out the optimal placement and the number of DGs to use. Through this practice, it is found that the proposed model in which if parallel (rather than a single unit) DGs are placed on the substation side, their cost of operation is less as compared to the single unit on the substation side and multiple units installed separately on different load ends. Another aspect of DGs about load shedding is also considered. In this scenario, load shedding of 10 hrs., 150 hrs. and 250 hrs. are considered for the base case and proposed case.

For this analysis, the diesel fuel costs and maintenance rates were determined using specific sources to ensure accuracy and relevance. The cost of diesel fuel was obtained from Google, an online market data which updates the current prices of diesel fuel in Pakistan. In this research, we assumed an average cost of about $0.80 per litre, which was consistent with the prevailing market prices at the time this analysis was done. The rates of maintenance for the diesel generators were considered based on information from the NUST PMO office. These costs are current and are broken down into industry-standard annual maintenance costs for each generator in use on campus, which we estimated as 5 % of the initial capital cost per year. This figure is within acceptable maintenance standard practice for such equipment in educational institutions.

Base case details given in Table 8 include the current Grid infrastructure of NUST, and the proposed case details given in Table 9 include a cost analysis of the proposed approach for grid infrastructure

If the comparison of these two cases is made, the proposed approach

Table 5
Comprehensive Comparison of Grid Infrastructure.

Metrics	Base Case (Current Grid)	Model A (Optimized DGs)	Model B (Increased Solar PV)	Model C (Hybrid System)	Proposed Model
Total DG Capacity (MW)	8.262	8.262	8.262	5	8.262
Solar PV Capacity (MW)	1.08	1.08	2.16	2.16	2.16
W Capacity (MW)	–	–	–	3	–
Operational Cost (PKR/hr.)	360,000	280,000	280,000	250,000	280,000
CO_2 Emissions (kg/hr.)	9852	9000	4068	3000	4068
Power Loss	High	Moderate	Low	Very Low	Low
Grid Reliability	Medium	Medium	High	Very High	High

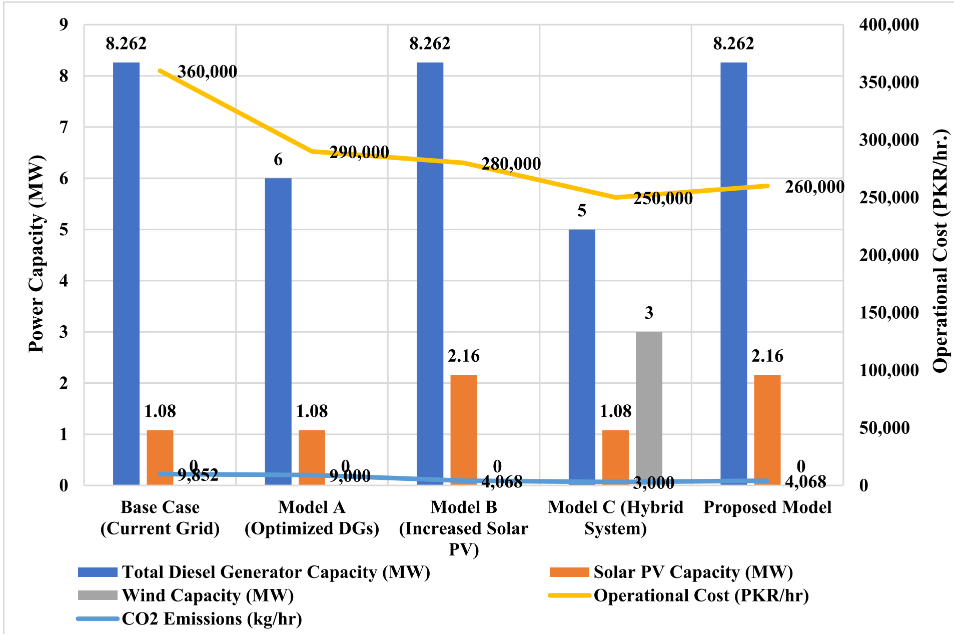

Fig. 7. Comparison of different cases of comparative analysis.

Table 6
Long-Term Financial Savings and PBP.

Item	Base Case	Proposed Case	Savings
Operational Cost (10 years)	800 million PKR	600 million PKR	200 million PKR
Maintenance Cost (10 years)	100 million PKR	60 million PKR	40 million PKR
Total Cost (10 years)	900 million PKR	660 million PKR	240 million PKR
Initial Investment	–	50 million PKR	–
PBP	–	2.5 years	–

of grid infrastructure has too many benefits according to the cost point of view. This comparison of cost between the base case and the proposed case is shown graphically in Fig. 10, from where it is evident that almost 24.86 % of the operational cost of DGs is reduced due to the use of the proposed technique. The detailed mathematical calculations are included in Appendix A section A.5.

Table 7
Summary of Cost and Load Analysis.

Scenario	DG Load (MW)	Total Sanctioned Load (MW)	PV Capacity (MW)	Cost per Hour (PKR/hr.)
Scenario 1: Base Case	8.262	5.96	1.08	360,000
Scenario 2: Proposed Case	8.262	5.96	1.08	280,000
Scenario 3: Increased PV	8.262	5.96	2.162	220,000

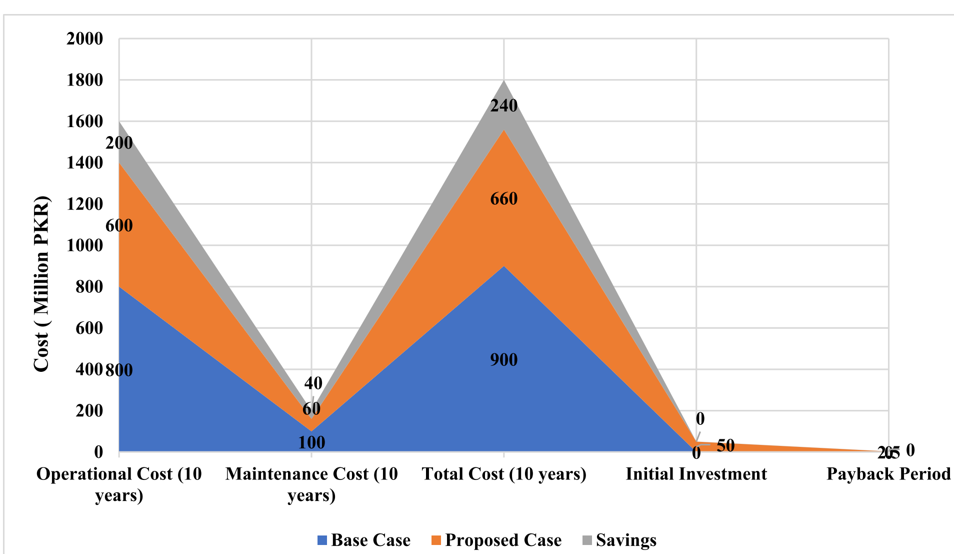

Fig. 8. Cost benefit Comparison of actual and proposed model.

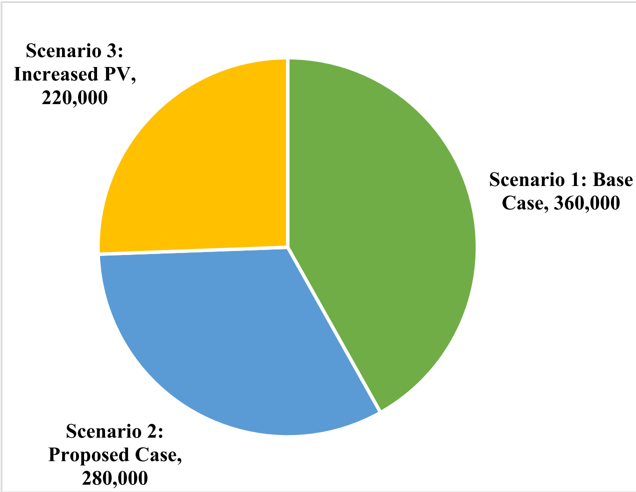

Fig. 9. Comparative Cost for Different Scenarios.

Table 8
Details of Load Shedding Scenario of Actual Case.

Other Parameters					
Generation capacity		Average fuel consumption per hr.		Rate of the Fuel (Diesel)	
8.262 MW (43 Generators)		45 Liters / hr.		279 Rs / Liters	
10 hr. load shedding		150 hr. load shedding		250 hr. load shedding	
Parameters	***Value***	***Parameters***	***Value***	***Parameters***	***Value***
Total cost of fuel	5.39 m PKR	Total cost of fuel	80.97 m PKR	Total cost of fuel	134.97 m PKR
NUST PV shutdown cost	0.2016 m PKR	NUST PV shutdown cost	0.324 m PKR	NUST PV shutdown cost	0.547 m PKR

Table 9
Details of Load Shedding Scenario of Proposed Case.

Other Parameters					
Generation capacity		Average fuel consumption per hr.		Rate of the Fuel (Diesel)	
8.262 MW (01 Generator)		45 Liters / hr.		279 Rs / Liters	
10 hr. load shedding		150 hr. load shedding		250 hr. load shedding	
Parameters	***Value***	***Parameters***	***Value***	***Parameters***	***Value***
Total cost of fuel	0.12555 m PKR	Total cost of fuel	1.883 m PKR	Total cost of fuel	0.324 m PKR
NUST PV shutdown cost	0.0216 m PKR	NUST PV shutdown cost	0.324 m PKR	NUST PV shutdown cost	0.547 m PKR

4.5. *Voltage stability and power loss analysis*

This section discusses the results of the voltage stability and power loss calculations carried out for the NUST grid. This study assesses the effect of load growth and the inclusion of RE on the performance of the grid by examining the voltage profile and amount of energy loss.

4.5.1. *Voltage stability analysis*

The voltage profile of the network was studied under various load conditions, which include a load of 5MW, 10 MW and 15 MW with 2MW of PV system integrated into the grid. According to the obtained figures, the proposed grid configuration improves voltage stability since it concentrates DG at the substation and offers more PV energy. In this way, the voltage levels across the nodes are reasonably controlled during high-load operation, and steady voltage quality and very low voltage sag or surge probabilities are maintained. Fig. 11 shows the comparison of the voltage values for all three cases.

From this voltage profile figure, the magnitude of voltage on all buses and nodes close to the buildings remains within a defined tolerance of 5 % by the utility. In the 5 MW load scenario, the voltage remains very stable in the range of 0.99 and 1. 00pu. Thus, the maximum levels of efficiency are achieved for the electric power system. At 10MW, there are small fluctuations to 0.988p.u. Found the structure, especially at 64 nodes, slightly less stable under greater loads. The 15MW version shows more frequent drops to 0.9775pu at nodes 63 and 64, which shows that there is a need for improving the voltage profile. The main goal involves reducing fluctuations and ensuring that voltage levels remain close to 0 when a 2 MW PV system has been incorporated 0.99 to 1.00p.u. Indicating the advantage of the RE resources in voltage control and stability at different load conditions.

Voltage stability is critical for grid performance, and simulations reveal distinct behaviours under increasing load scenarios. The results reveal that, at large, the overall voltage improvements are realised by the enhancement of the PV integration. From the results presented in the high voltage context of the grid, acceptable voltage stability near 1.00 pu for 10 MW PV integration is valid for all the nodes, proving that RE solutions are efficient in mitigating voltage sags.

4.5.1.1. Impact of increased pv penetration on voltage profiles. To assess the feasibility of the system and determine whether the voltage profile would remain stable under various PV penetration levels, we conducted simulations by integrating 5MW and 10MW PV systems across all the load conditions we considered (5MW, 10MW, and 15MW loads). By analyzing the results, we aimed to evaluate how increasing PV capacity impacts voltage stability across different load scenarios, ensuring that the system operates efficiently and reliably even under increased RE integration.

From Fig. 12, it can be seen from the voltage plot that with the 5MW load and the PV integration of 5MW, the voltage does not deviate much from 1.00pu, with only slight variation. When the penetration level is adjusted to 10MW for PV, as displayed in Fig. 13, voltage follows a similar level, and it increases further, proving that the system can accommodate more RE integration but with minimal fluctuations.

As we can see in Fig. 14, in the case of the 15MW load, the voltage spread tends to be lower and drops under 0.98 p. u., with an additional increase with a high PV penetration level. This implies that the system is stable at lower loading levels, but at higher loading levels, more effort must be exercised to keep the voltage stable. These findings fully support that incorporating PV capacities beyond the current limit of 2MW, like 10MW, assists in keeping voltage stability, especially during periods of raised loads. Nevertheless, as load levels increase, voltage stability is not easily controlled, thus, a need for additional measures towards grid stabilization.

4.5.2. *Power loss analysis*

This section seeks to calculate energy losses for the same cases discussed above. The studied approach of the power loss calculation compared active and reactive power loss under the same loading conditions. In the case of multi-DG, the base case shows that the grid itself suffers from higher losses in the form of distribution and transmission losses. On the other hand, the new configuration, which enhances the placement of DG and increases the PV rating, offered a considerably low amount of these losses. Fig. 15 shows the comparison of active losses, while Fig. 16 shows the comparison of reactive losses as a result of different load conditions and solar capacity. The details of these losses are presented in Table 15 and Table 16 in Appendix A Section A.6.

According to the result, the scenario with the highest active power losses has been obtained with a 15MW load, and the other scenarios of 10MW load, 2MW PV and 5MW load have also been listed in decreasing order. From this trend, it is inferred that as the load increases, the active

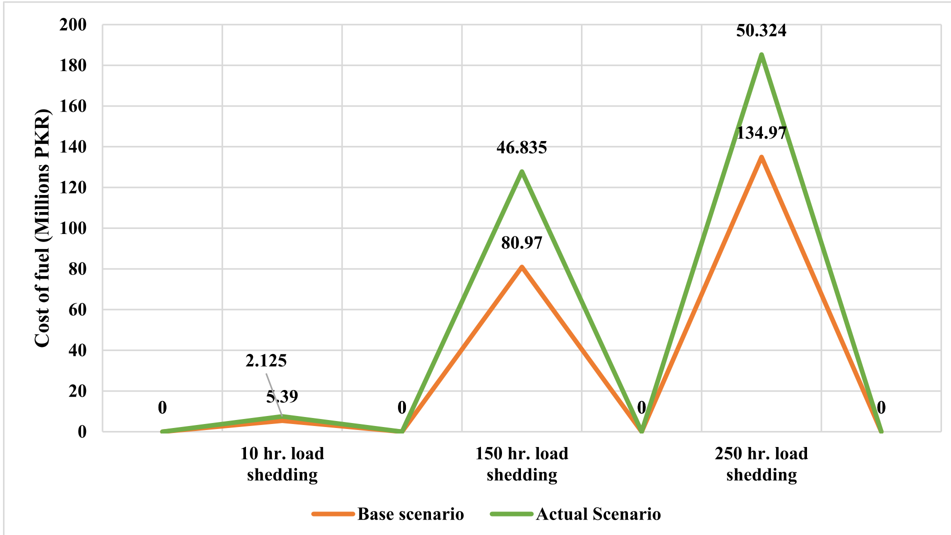

Fig. 10. Cost Comparison of Base case and proposed case.

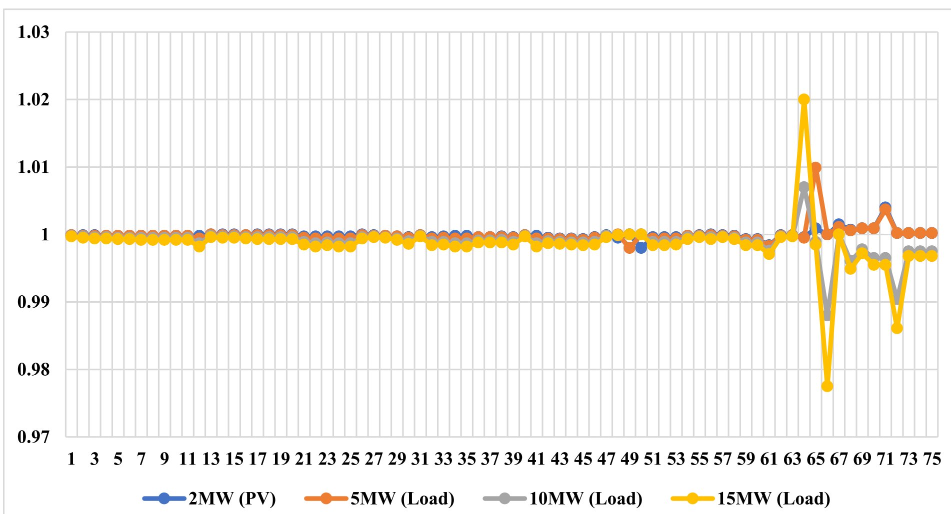

Fig. 11. Comparison of Voltage magnitude.

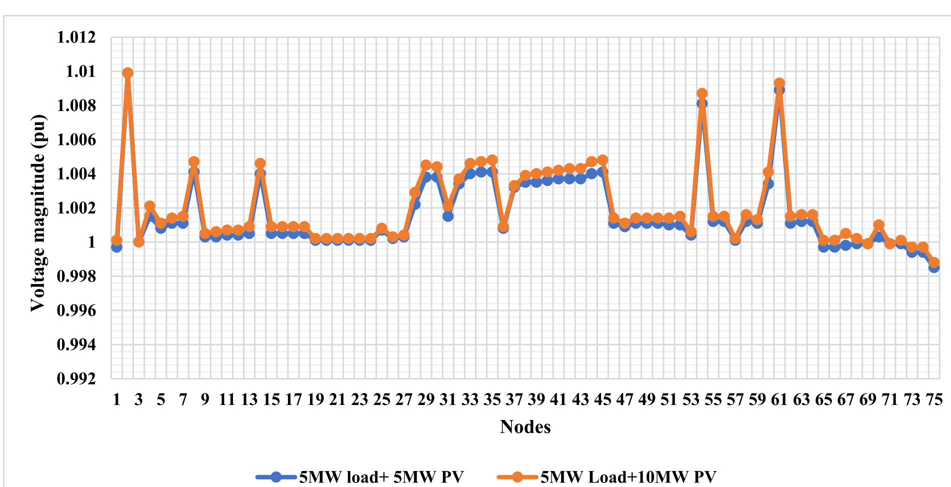

Fig. 12. Voltage profile for 5MW load with 5MW and 10MW PV penetration.

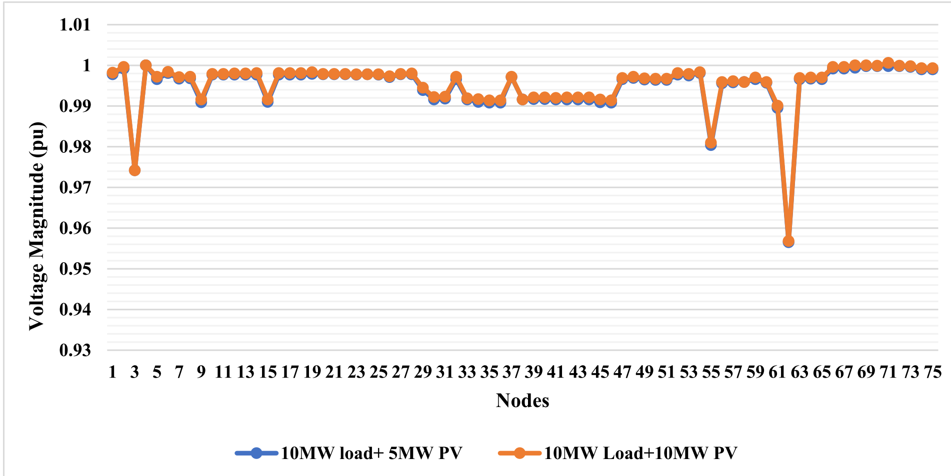

Fig. 13. Voltage profile for 10 MW load with 5MW and 10MW PV penetration.

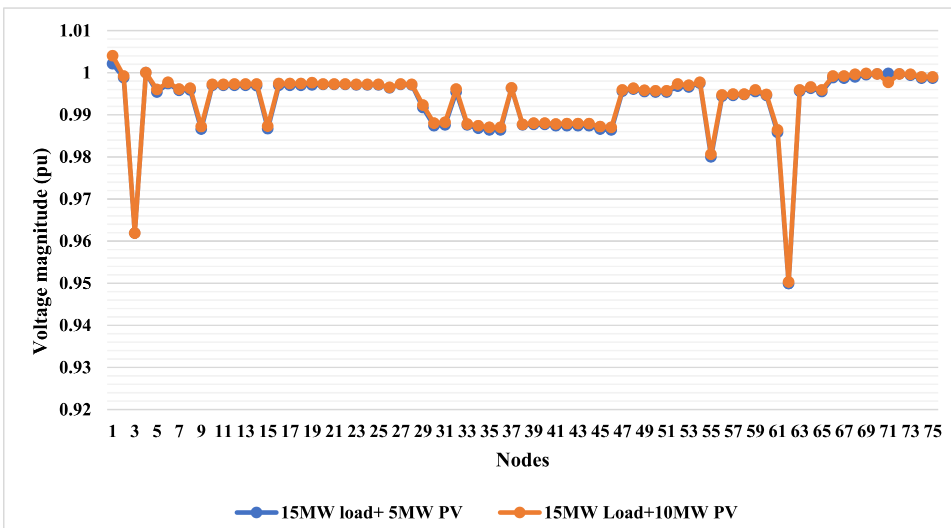

Fig. 14. Voltage profile for 15MW load with 5MW and 10MW PV penetration.

power losses also rise drastically. Reactive losses also have similar trends, as seen in the first figure; the highest Q losses are obtained at a 15MW load.

The real active power loss and the reactive power loss are both very valuable parameters for grid performance analysis. Active Power losses are also a function of load and vary from 5 MW (66.87 kW) to 15 MW (281.67 kW). Far greater penetration of PVs results in much fewer losses, with beneficial effects being most marked in the 10 MW PV case. While with Reactive Power Losses, similar trends are observed, the losses are from 133.18 kVAR or 5MW to 500.53kVAR or 15MW. These losses are, however, lowered by higher integration of RE, which also improves the efficiency of the grid.

4.5.3. *Combined impact on grid efficiency*

The evaluation of the voltage stability and the losses which have been provided collectively show that the proposed grid has a very significant potential to improve the general efficiency of the grid. Thus, centralizing DGs along with more and more PV units results in better voltage control and reduced energy losses of the grid to make it more balanced. Indeed, it has been testified by this study that these two enhancements are significant for realizing robust and efficient energy management at NUST in terms of economic and environmental return.

The integration of centralized DGs and higher PV capacities offers significant enhancements to grid performance stability, which is improved in all modes, including when the load levels are high and voltage variation is reduced. Substantial Active & Reactive loss mitigation, as well as the consequential improvement of Organisational efficiency and decrease in overhead costs. The advancement of increased integration of RE delivers diverse energy sources and has positive consequences on the idea of sustainable development. The proposed system categorizes more centralized DGs due to more PV capacity to provide a relevant, grid, competent, effectual, and eco-friendly to cater to emerging energy requirements.

4.6. *Sensitivity analysis*

In this research, to assess the proposed grid configuration, the sensitivity analysis is implemented properly to consider various conditions. The analysis focused on three key parameters: load growth, fuel price variations and penetration of RE. First, the deviation range of each parameter was specified; the yearly energy demand increase was set at 1 %, 3 %, and 5 %; the diesel fuel prices, in turn, were decreased by 20 % and increased to 50 %; the RE portion varied within a range of 20 % to 80 % of the total energy consumption. In MATLAB/Simulink, all the grid configurations were subjected to these different conditions to get a full understanding and analysis of the performance of the grids. Costs of

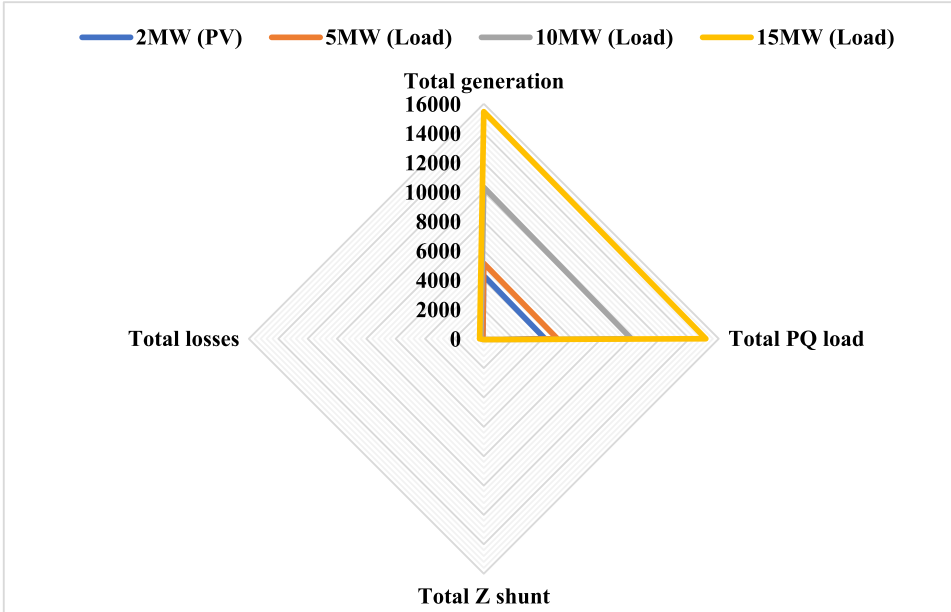

Fig. 15. Comparison of active losses for different loads and PV cases.

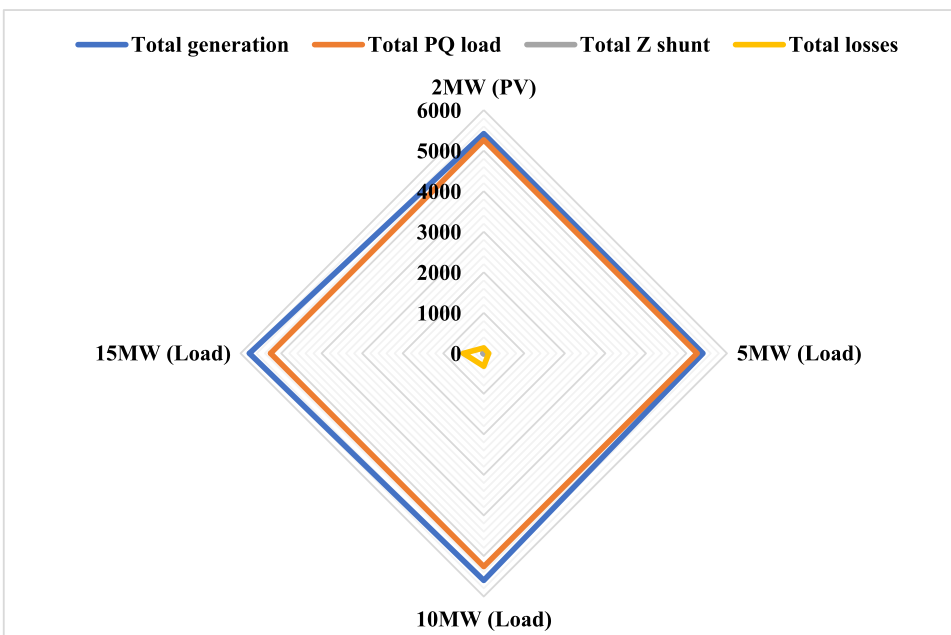

Fig. 16. Comparison of reactive losses for different loads and PV cases.

operation, CO_2 emission data, and grid reliability of all the scenarios were then compared. Using this approach, it was easy to determine which of the configurations was most suitable in terms of cost, sustainability and reliability, especially under these conditions as described below, to give insight into the best grid structure to support sustainable energy management at NUST by 2030. The base demand for the case was 5 MW.

4.6.1. *Case 1: load growth*

In this case, energy demand increases by 1 % per year from the base demand of 5 MW. All three cases are simulated in MATLAB/Simulink. Table 10 shows the impact of load growth on operational cost, CO_2 emissions and reliability.

Table 10
Results of Load Growth.

Load Growth Rate	Energy Demand (MW)	Operational Cost (PKR/hr.)	CO_2 Emissions (kg/hr.)	Grid Reliability (%)
1 % per year	5.52	460,000	5300	98
3 % per year	6.47	520,000	6200	95
5 % per year	7.69	600,000	7500	92

Table 11
Results of fuel price variations.

Fuel Price Variation	Diesel Cost (PKR/liter)	Operational Cost (PKR/hr.)	CO_2 Emissions (kg/hr.)	Grid Reliability (%)
−20 %	223	430,000	5000	98
0 % (No Change)	279	520,000	5300	98
50 %	418	650,000	5600	97

4.6.2. Case 2: fuel price variation

In this case, the base rate for the computation of operational cost is based on PKR 279 per litre in different conditions with proposed −20 %, no change and +50 % variations in diesel fuel rates. Table 11 shows the impact of fuel prices on operational cost, CO_2 emissions and reliability.

4.6.3. Case 3: re penetration

In this case, the contribution of RE sources (solar and W) varied from 20 % to 80 % of the total energy mix, with a base demand of 5 MW. Table 12 shows the impact of ER penetration on operational cost, CO_2 emissions and reliability of the grid. The results of sensitivity Analysis is represented in a summary Table 13.

It is evident from the sensitivity analysis that for a future energy configuration of 80 % renewable source integration, a grid configuration is the most effective for NUST. This configuration had the lowest response to load growth and changes in fuel price among all the cases analysed; the operational cost increased by 10 %, and CO_2 emissions increased by 20 % under the 5 % annual growth of load. Furthermore, even with a 50-cent increase in diesel prices, the operational cost of this configuration has been seen to rise by only 15 %, which is a smaller rise in comparison to the 25 % seen in some more diesel-oriented configurations. However, when the share of renewables was increased to 80 %, the total operational cost was reduced by 27 %. Besides, the reduction in CO_2 emissions was even higher, accounting for 64 % as compared to the base case, which has only 20 % penetration of renewables. The analysis also showed that there was increased grid reliability by 9 %, and therefore, this positions this configuration as the most sustainable way of reinforcing the NUST grid infrastructure by 2030 in terms of cost and resilience. Fig. 17 shows the comparison of all scenarios based on three parameters (Cost, CO_2 Emission and Reliability). Graphs of individual parameters are displayed in Appendix A section A.5.

As in our study, a 75-bus distribution network system model was built in MATLAB/Simulink to evaluate different operating conditions. Since we have not performed simulations specifically for the generator failures or severe weather events, we can, however, use the inherent characteristics of the system based on our findings depicted in the sensitivity analysis above. The efficient centralized diesel and solar PV systems outlined here are to be more reliable. Regarding the cases of failure of the primary generator in the system, the centralized structure can offer quick reallocation of load on the remaining generators and renewables. The results show that connecting distributed generation (DG) systems can act as a barrier against such failure. For example, if, during the peak demand, the diesel generator is offline, the remaining solar PV capability can help to keep voltage levels across certain nodes stable.

While the detailed simulation of severe weather was not performed, our model includes factors that influence the amplitude of renewable energy generation. The integration of solar PV systems is most beneficial in this respect as it can also decentralize distributed generation systems so that some of the devastating effects of disruptions because of severe weather may be absorbed. Accordingly, this paper shows that beyond unfavourable conditions, solar-based generation may not be stable, but having a diversified source of power, such as diesel generators, helps improve the reliability of the electrical grid.

Table 12
Results of RE Penetration.

RE Penetration (%)	Renewable Capacity (MW)	Operational Cost (PKR/hr.)	CO_2 Emissions (kg/hr.)	Grid Reliability (%)
20 %	1	540,000	7000	90
50 %	2.5	440,000	4800	95
80 %	4	380,000	2500	99

Table 13
Summary of Sensitivity Analysis.

Scenario	Operational Cost (PKR/hr.)	CO_2 Emissions (kg/hr.)	Grid Reliability (%)
1 % Load Growth	460,000	5300	98
3 % Load Growth	520,000	6200	95
5 % Load Growth	600,000	7500	92
−20 % Fuel Price	430,000	5000	98
0 % Fuel Price (No Change)	520,000	5300	98
+50 % Fuel Price	650,000	5600	97
20 % RE Penetration	540,000	7000	90
50 % RE Penetration	440,000	4800	95
80 % RE Penetration	380,000	2500	99

First, even though our current work did not incorporate specific simulations of generator failures or other extreme weather conditions, the results indicate that the proposed design of a centralized grid, by default, enhances the level of protective actions against these breakdowns. Future work may include extending these cases into a more refined sensitivity analysis to achieve a better picture of grid stability in worse-case states.

4.7. Financial mechanisms analysis

This section would be a quantitative analysis where HOMER software would be used to determine the LCOE, NPC, ROI, IRR and PBP of the system for a 5MW, 10MW and 15MW load demands and with the PV system installed with a capacity of 2MW. These aspects will be useful in evaluating potential and sustainable economic performance and returns of the first energy configurations. All four configurations are separately simulated in HOMER software. Fig. 18 shows the schematic diagram of them.

The results of the scenarios simulated in HOMER software are presented in Table 14 to make a comparison.

The HOMER software financial analysis presented in Fig. 19 shows that the evaluated 2 MW PV system is the cheapest with a low LCOE of 0. 93$/kWh, the lowest NPC at $2. 5 million but considering the low PBP of 2 years makes the 5 MW Load scenario with 1.08MW PV as the most beneficial because it offers the best cost to income ratio and almost twice the return on investment (ROI) within the space of 2.1 years and a terrific IRR of 34 %. That is why the 5 MW Load scenario can be considered very appealing for investors desiring to get more of a payback time while keeping a reasonable return rate.

4.8. GHG emissions

The proposed method also helps in the reduction of total GHG Emissions. It will be easy to maintain the single unit DG rather than 43 units and will allow it to control its carbon gas exhaust. All four configurations are separately simulated in HOMER software. The schematics are already displayed in the previous section.

Table 15 includes the results of the carbon footprints of future loads combined with solar power. Carbon emission is calculated along with the currently available solar power and for the future extension of solar power, due to the use of PV system and the single unit DG carbon

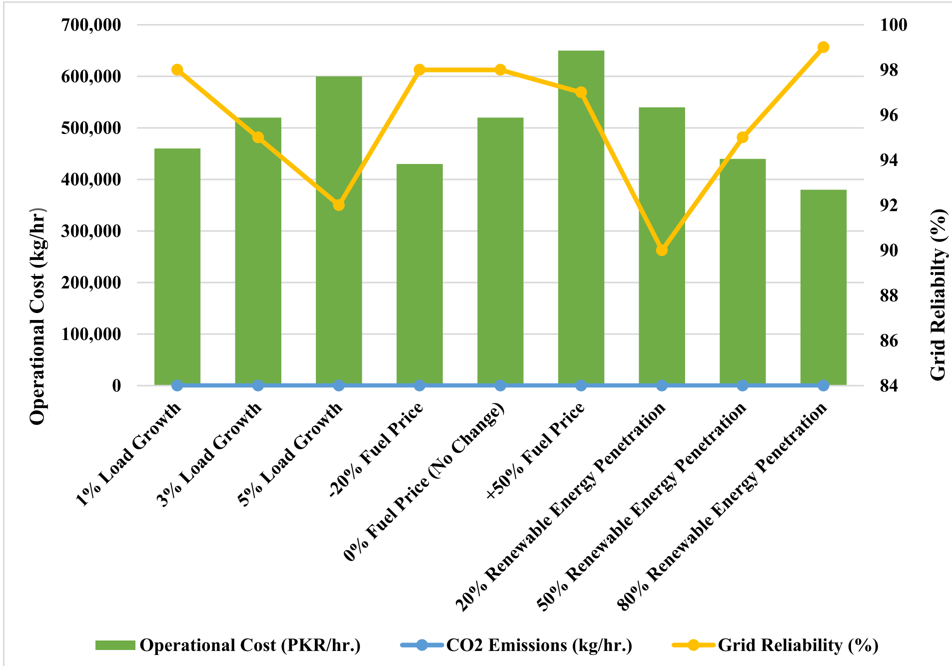

Fig. 17. Results of sensitivity analysis for all scenarios.

footprints reduced by a significant amount.

It can be seen in Fig. 20 that as the load increases from 5MW to 15MW with 1.8 MW PV capacity, the levels of all the gases (SO_2, NO_x, CO_2, and CO) are noticeably higher. This is due to higher energy use, and most of its energy is from those sources that contribute to environmental degrading factors such as greenhouse gases. While increasing the PV capacity from 1.08MW to 2MW and 5 MW load, a reduction of 58.66 % to 58.81 % therefore contributes to the minimization of emission of the various pollutants. The results also show that total GHG emissions are significantly reduced when the installed PV capacity is increased significantly, highlighting the benefits of RE systems.

4.9. Feasibility analysis for the placement of solar pv

NUST in Islamabad has planned to enhance its performance with an effective energy management system by incorporating RE resources. In this regard, a strategic plan has also been laid down for the proper placement of a 2MW solar power system for upcoming load demands that have been predicted to be a maximum of 16MW. The locations that have been proposed as suitable for the installation of solar facilities are described in detail, along with the rationale for each location of its significance in the macro as well as micro context because of energy conservation and efficiency. It is noted that the introduction of the 2MW solar power system is a significant development in the institution's efforts towards the substitution and gradual elimination of the use of fossil fuels and, consequently, the emission of carbon. Therefore, through harnessing solar energy, NUST seeks to reduce electricity expenses, ensure a steady power source, and likewise improve the campus' resource efficiency. The several areas that have been selected for the installation of the proposed solar systems are within the NUST Islamabad (H-12 Sector) campus.

4.9.1. Solar location and capacity

According to the data in Table 16 below, the strategic positioning of feeders guarantees the identification of places that are ideal for control of the selected feeders that are critical for solar power generation and interconnection with the existing power grid. All the sites have been drawn by their distance from the grid, exposure to the south direction and space for installation. The scalable locations for future expansion are indicated. The defined execution is consistent with NUST's objective to strengthen its grid infrastructure with renewable power, whereby the utility will respond to its planned load requirements of as much as 16MW.

The specific location of a 2MW solar power system at NUST based on the given data will cover the current power requirement of the university and the future power demands as well. The fifteen locations presented in the table above are ideal for the placement of future solar. This process will strengthen the energy management in the institution, cut expenses and encourage the use of RE, hence making the institution environment friendly.

4.10. Proposed future solar installation

Due to the rising energy requirement and the call for utilizing sustainable energy resources, NUST-Islamabad (H-12 Sector) has recommended the establishment of a 2MW Solar Power Generation System. The load demand is expected to grow in the future hence, this initiative seeks to be prepared to handle this aspect in advance to create additional load of up to 16MW. Fig. 21 shows the graphical presentation of the narratives of the actual area of car parking as well as the roofs where installations of solar systems are proposed with a capacity to be fitted in both car parking and rooftops.

4.10.1. Feasibility of wind power and batteries (should be heading)

The level of wind integration at NUST, therefore, depends on the local wind resource potential. Anemometric data for feasibility studies: Average wind speed and seasonal wind distribution for the adequate selection of certain types and configurations of the turbines. Renewable energy storage can be used hand in hand with wind power because the excess energy produced due to high windy conditions can be stored and used during conditions of low wind generation. Determining the feasibility and the level of advance of battery systems, including lithium-ion or flow batteries, is important for enough storage capacity.

4.10.2. Potential challenges

Wind power is an intermittent source of energy, as with solar PV

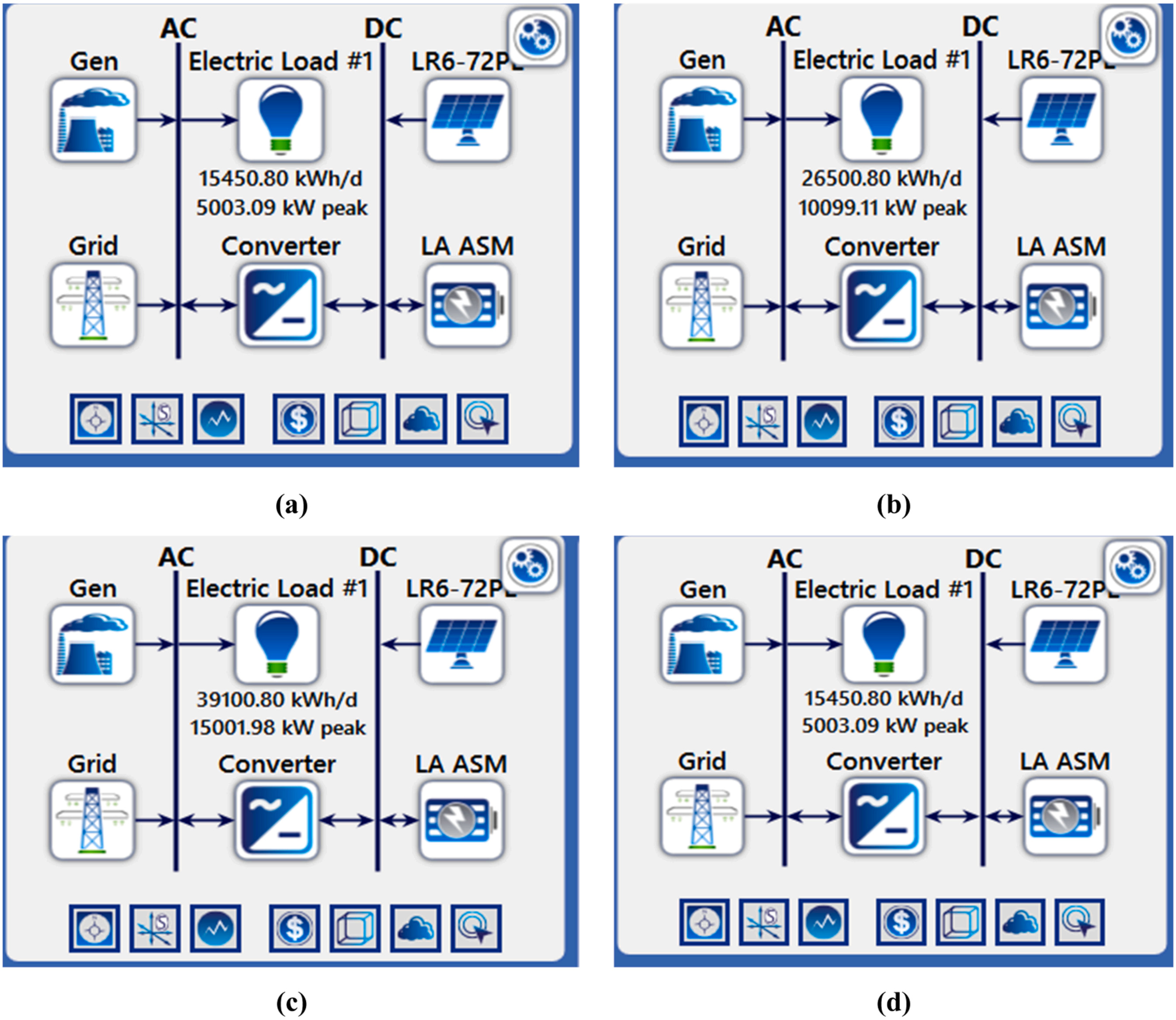

Fig. 18. Schematic of different cases a) 5MW Load b) 10MW Load c) 15MW Load d)2MW PV.

Table 14
HOMER results of FM parameters.

Scenario	LCOE ($/kWh)	NPC (Million $)	ROI (%)	IRR (%)	PBP (years)
5 MW Load	0.219	2.58	44 %	34 %	2.1
10 MW Load	0.212	3.87	42 %	31 %	2.3
15 MW Load	0.309	5.2	39 %	28 %	2.5
2 MW PV	0207	2.5	45 %	33 %	2.2

power. It causes fluctuation in the stability of power, and strong energy management systems become essential for the stabilization of supply and demand forces. Depending on the design of the integrated system of wind turbines and energy storage, there may be changes to the electrical system that may include modification of the current distribution system for bi-directional power flow to maintain stability in the grid. Monetary planning also proves complex while dealing with the regulations regarding the integration of renewable energy sources; another challenge is the funding of the first investments in wind turbines and storage systems.

4.10.3. *Integration strategies*

To support reliability, it is possible to create a form of a mixture of renewable energy systems like solar PV and wind power with battery storage capacity. That is why this design of integration is useful, as solar generation is in large part during the day, while wind generation may occur at night or in certain months. Implementing smart grids and control problems helps control energy flow at specific times from various sources. This includes better forecasting techniques for energy generation, especially based on meteorological conditions, which enhances the decision-making of the energy dispatch. Using demand response programs often enables control of load during peak periods by

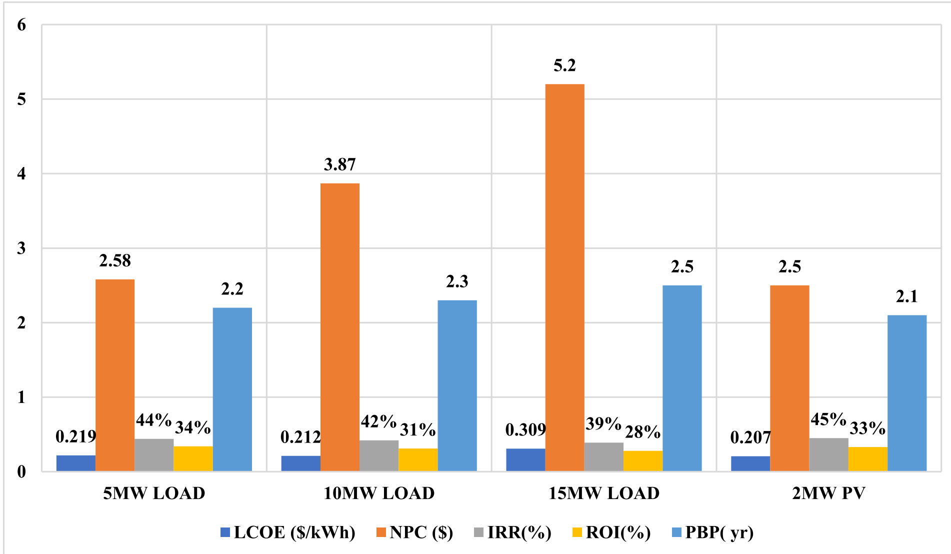

Fig. 19. Comparison of Financial Parameters.

Table 15
Carbon footprint details of the proposed system.

Case 1	5 MW Load with 1.08 MW PV capacity	Quantity	Value (kg/hr.)
		Carbon Dioxide	9852
		Carbon Monoxide	62.1
		Unburned Carbons	2.71
		Particulate Matter	0.376
		Sulfur Dioxide	24.1
		Nitrogen Oxides	58.3
Case 2	10 MW Load with 1.08 MW PV capacity	**Quantity**	**Value (kg/hr.)**
		Carbon Dioxide	14,278
		Carbon Monoxide	90
		Unburned Carbons	3.93
		Particulate Matter	0.545
		Sulfur Dioxide	35
		Nitrogen Oxides	84.5
Case 3	15 MW Load with 1.08 MW PV capacity	**Quantity**	**Value (kg/hr.)**
		Carbon Dioxide	26,143
		Carbon Monoxide	165
		Unburned Carbons	7.19
		Particulate Matter	0.999
		Sulfur Dioxide	64.0
		Nitrogen Oxides	155
Case 4	5 MW Load with 2 MW PV capacity	**Quantity**	**Value (kg/hr.)**
		Carbon Dioxide	4068
		Carbon Monoxide	25.6
		Unburned Carbons	1.12
		Particulate Matter	0.155
		Sulfur Dioxide	9.96
		Nitrogen Oxides	24.1

rewarding consumers for curtailing load or shifting load demands to periods of high renewable generation.

5. Conclusion

In conclusion, the findings of this study highlight the need to efficiently regulate energy usage within educational institutions such as NUST to reduce finances. The purpose of this research was to improve NUST's grid infrastructure with a special concentration on the sustainable management of energy by the year 2030. MATLAB/Simulink for technical analysis was employed, supported by the HOMER software for financial and emission analysis. In performing the analysis, various grid configurations were tested concerning load scenarios and integration of RE sources, especially solar PV systems. In the proposed grid design, there is a recommended transition from many separate DGs to a single large DG, which will be in the center of the grid. In this way, there is a considerable enhancement of operating profitability through simplifying the management procedures of many small power stations, decreasing maintenance expenditures, and increasing the fuel utilization rate properly. The generator centralized at the substation is also advantageous since the control of energy provision of different regions can be well coordinated, therefore providing a stable electrical supply to the regions of the campus. The financial analysis pointed to the lowest load scenario as the most advantageous, to be supported by the centralized DG and an extended solar PV system. This scenario provides a PBP of only 2.1 years, the least time taken in any of the scenarios, an ROI of 44 % and is complimented by an IRR of 34 %. Environmentally, DG is centralized, and when it is augmented with the increased solar PV

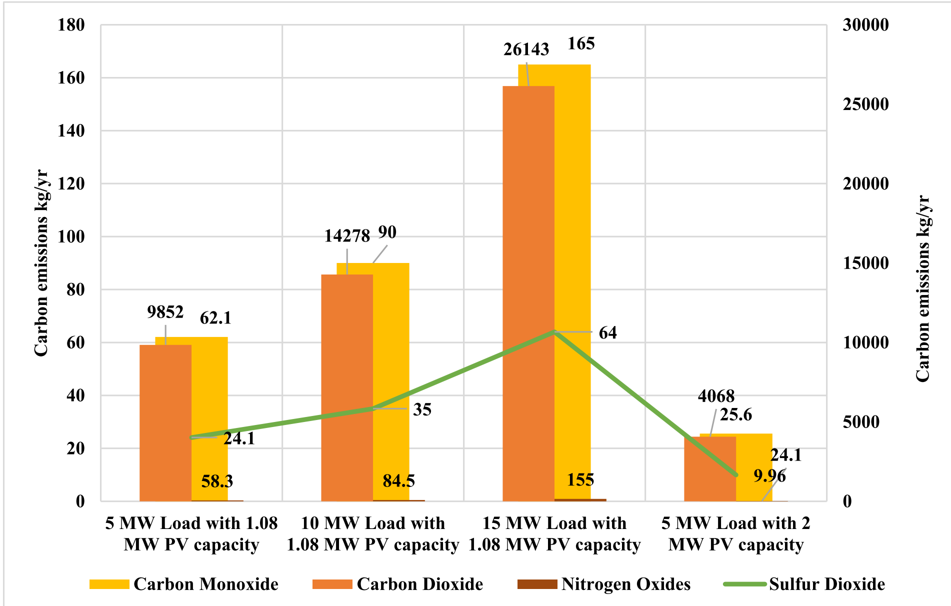

Fig. 20. GHG emissions of the proposed models.

Table 16
Optimal placement of solar for all feeders.

Sr No	Location	South availability	Proximity to Grid	Area availability	Scaling ability
FEEDER 1					
1	SCME	✓	✓	✓	✓
2	Adm Office	✓	✓	✓	✓
3	NIT/Hajvari & Zakria Hostel	✓	✓	✓	✓
4	SNS Building	✓	✓	✓	✓
FEEDER 2					
1	Fatima Hostel	✓	✓	✓	✓
2	Central Library	✓	✓	✓	✓
3	SEECS	✓	✓	✓	✓
4	SEECS	✓	✓	✓	✓
5	ASAB	✓	✓	✓	✓
6	SADA	✓	✓	✓	✓
FEEDER 3			✓		✓
1	Iqra Apartments / Guest House	✓	✓	✓	✓
2	NSTP / NICHE	✓	✓	✓	✓
3	NSTP / NICHE	✓	✓	✓	✓
4	NSTP	✓	✓	✓	✓
5	Swimming Pool / Sports Complex	✓	✓	✓	✓

capacity, it is responsible for minimizing greenhouse gas emissions. This transformation from a decentralized to a centralized system not only reduces CO_2 emissions but also reduces other pollutants, which a good deal assists NUST in its quest to achieve a sustainable environment. The sensitivity analysis was effectively used to validate the analysis under the conditions of a 5MW Load scenario with a centralized generator where the growth of load, fuel prices and level of renewables were varied. Most notable in this area is the centralized DGs, where stable and cost-efficient operations were recorded to keep the grid strong and flexible to future demands.

For our research on the improvement of the smart campus grid infrastructure, the ARENA report was reviewed to support our arguments and approaches at the National University of Science and Technology (NUST). The information available in the ARENA report covers all aspects of the sustainability of the grids when incorporating renewable energy sources. This report is quite important to our study since it comes with details on best practices together with real-life case studies that will show us how different educational institutions were able to adopt renewable technologies of energy efficiency and low carbon emissions. Many of the ARENA findings were instrumental in developing our approaches for the combination of solar PV systems and concentrated central diesel generators; our proposed model post-EDP aligns with recognised approaches used in the realm of grid stability. The link for the report is: https://arena.gov.au/

5.1. Limitations and future studies

To summarize, this study highlights that transitioning to a centralized DG, alongside more effective integration of solar PV, is a tactical upgrade of the grid on NUST. This configuration not only guarantees the appropriate regulation of energy but also offers a great economic and environmental return. In the future, we can study the configurations by seeking out other feasible types of RE, like W power or batteries for storage for NUST to improve its energy management. The efficient use of energy could also be achieved using smart grid technologies and demands side management of energy. Such future initiatives shall confirm that NUST will set the pace in the desirable changes in energy management, with positive economic as well as environmental impacts.

We acknowledge the importance of statistical validation in assessing the robustness of our findings. However, due to data limitations and methodological constraints, we were unable to perform the necessary statistical tests. Although we were unable to perform statistical validation, our findings are grounded in theoretical and conceptual foundations. Moreover, our results are consistent with comparative analysis amongst the cases, which provides confidence in the validity of our conclusions.

In future research, we will prioritize statistical validation to confirm the robustness of our findings. Potential avenues for future research include machine learning across multi-year data with sound statistical backgrounds. It will include confidence intervals and significance tests that will justify the robustness of cost and emission reductions across a certain planning, scheduling and operation horizon in an integrated approach.

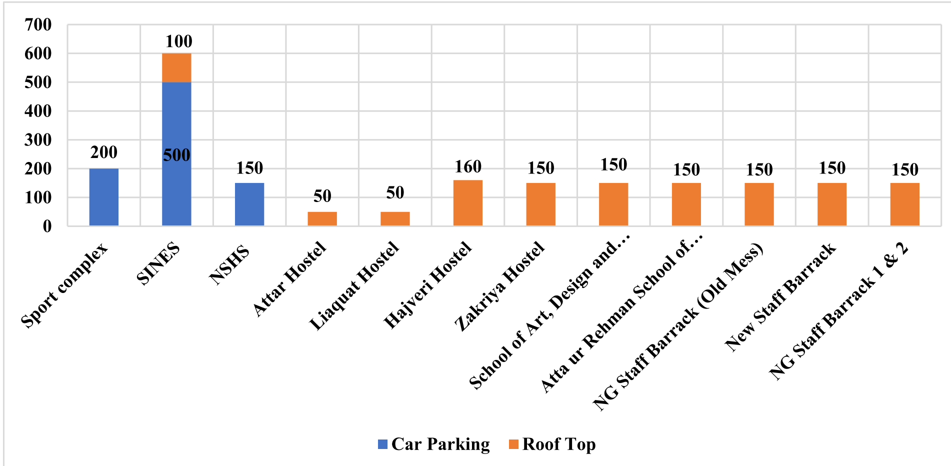

Fig. 21. Location and capacity of future solar system.

CRediT authorship contribution statement

Mahnoor Abbasi: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Syed Ali Abbas Kazmi:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Muhammad Zubair Iftikhar:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Mustafa Anwar:** Writing – original draft, Validation, Resources, Project administration, Formal analysis. **Muhammad Hassan:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Thamer A.H. Alghamdi:** Validation, Supervision, Resources, Project administration, Funding acquisition. **Mohammed Alenezi:** Writing – review & editing, Visualization, Project administration, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

A. Appendix

A.1. Mathematical Formulation

A.1.1. Total NPC

The present value of all the costs the system incurs over its lifetime minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, and fuel costs. NPC can be calculated using the Eq (4):

$$\boldsymbol{D_{NPC}} = \frac{\boldsymbol{D_{ann,total}}}{\boldsymbol{CRF}(\boldsymbol{j},\ \boldsymbol{L_{proj}})} \tag{4}$$

Where $D_{ann,total}$ Is the total annualized cost ($/y), j is the annual real interest rate (%) (discount rate), L_{proj} is the project lifespan (yr.), and $CRF(j,\ N)$ is the capital recovery factor with j expressed as a % of the interest rate"

A.1.2. Cost of energy

The COE is the Average cost per kWh of useful electrical energy produced by the system, measured in $/kW and is given by Eq (5):

$$\boldsymbol{COE} = \frac{\boldsymbol{D_{ann,total}}}{\boldsymbol{E_{ls}} + \boldsymbol{E_{grid}}} \tag{5}$$

Where E_{ls} is the electrical energy in kilowatts per hour supplied by the MG system E_{grid} is the power in kilowatts sold by the MG to the grid.

A.1.3. IRR

The yearly cost savings relative to the initial investment. It is given as by Eq (6):

$$\boldsymbol{NPV} = \sum_{n=0}^{N} \frac{\boldsymbol{C_n}}{(1 + \boldsymbol{IRR})^{n}} \tag{6}$$

A.1.4. ROI

The rate at which the total project investment is returned in terms of revenue. The formula is given by Eq (7):

$$ROI = \frac{Total\ benefit - Total\ cost}{Total\ cost} \times 100 \tag{7}$$

A.1.5. PBP

Indicates the number of years required to recover the initial capital cost of the system. The formula for PBP is given by Eq (8):

$$PBP = \frac{Initial\ investment}{Cash\ flow\ per\ year} \tag{8}$$

A.2. Details of DGs installed at the NUST campus

Fig. 22, Fig. 23, Fig. 24, Fig. 25, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22

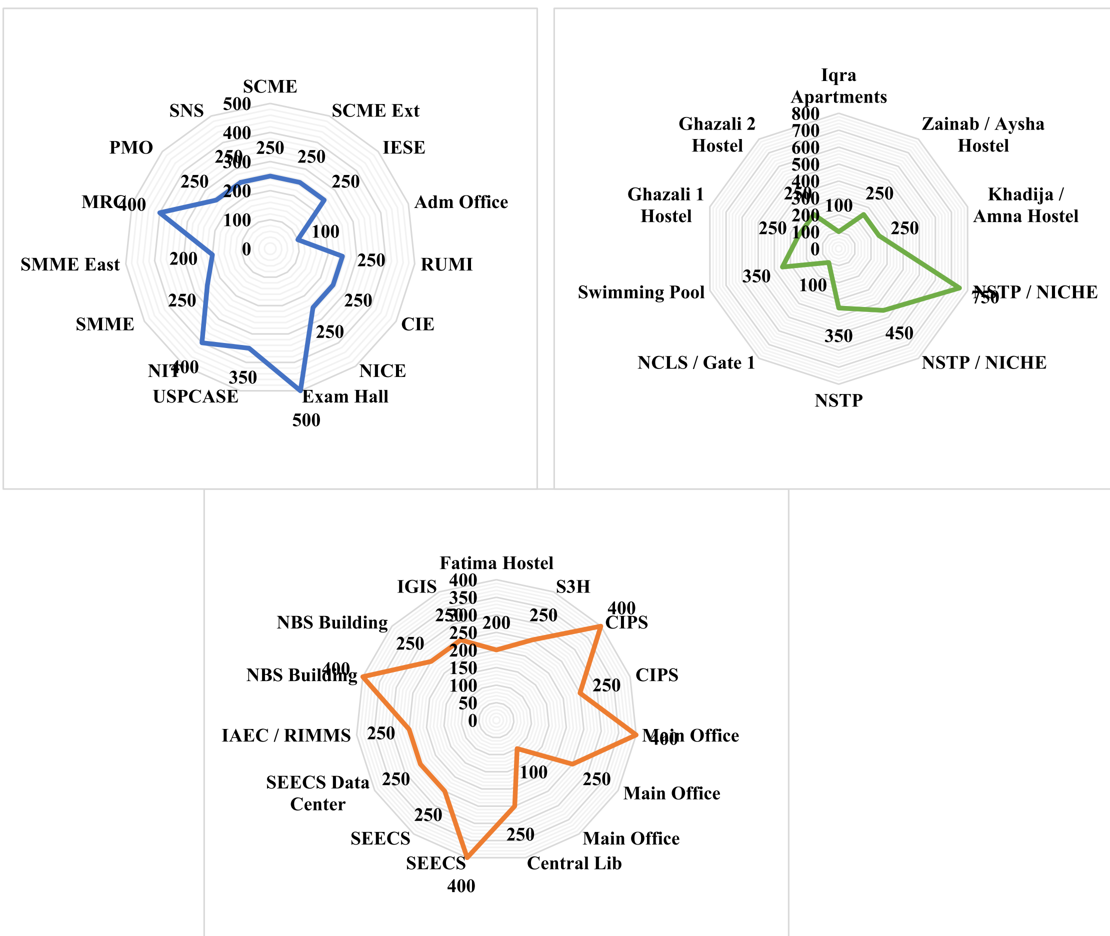

Fig. 22. DGs connected to electrical Grid of NUST (a) Feeder 1 (b) Feeder 2 (c) Feeder 3.

A.3. Monthly consumption of NUST

Table 17
Monthly Consumption Patterns of NUST.

NICE	USPCAS-E	SEECS	GHAZALI-1	GHAZALI-II
427	175	259	92	75
861	375	673	239	188
200	320	534	160	165

(continued on next page)

Table 17 (*continued*)

NICE	USPCAS-E	SEECS	GHAZALI-1	GHAZALI-II
776	316	556	175	180
716	336	529	188	172
788	340	510	170	190
880	360	555	187	185
920	358	561	208	192
272	366	654	268	136
850	364	683	199	176
432	191	414	133	127
461	308	370	131	132
502	217	360	125	120
356	196	381	115	105
646	272	288	108	113
832	364	612	212	195
175	176	500	512	224
195	155	497	512	232
160	180	532	480	240
179	175	545	544	228
190	150	486	536	216
209	191	566	657	266
138	129	388	384	160
143	126	389	372	196
127	120	381	385	151
111	103	324	307	338
116	110	330	339	233
114	200	630	746	155
120	203	630	580	131

A.4. Cost efficiency analysis

Table 18
Results of different case Scenarios.

Base Case:	
DG used at Substation	8.3 MW (single unit)
7 PVs placed	1.08 MW Accumulative Power on different locations
Cost Per hour	36,000 Rs
Load on DG	.96 - 1.08 = 4.88 MW
Total sanctioned Load	5.96 MW
Case 1: Parallel DGs	
2 Parallel DGs used at Substation	2.5 MW each (5 MW Total)
7 PVs placed	1.08 MW Accumulative Power on different locations
Cost Per hour	28,000 Rs
Load on DG	5.96 - 1.08 = 4.88 MW
Total sanctioned Load	5.96 MW
Case 2: Double the PV Capacity	
DG used at Substation	8.3 MW (single unit)
7 PVs placed	2.162 MW Accumulative Power on different locations
Cost Per hour	22,000 Rs
Load on DG	5MW
Total sanctioned Load	5.96W

A.5. Technical analysis

Table 19
Details of Load Shedding Scenario of Base Case.

Base Case (Actual Scenario):	
With 10 H Load Shedding:	
Total load shedding hours in one year	10 hrs.
Total generators capacity in NUST	8.262 MW (43 Generators)
Average fuel consumption per hour for each generator	45 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 10 × 45 × 43 = 5.39 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 05 / 24 × 24 = 0.0216 Million PKR
With 150 H Load shedding:	
Total load shedding hours in one year	150 hrs.

(*continued on next page*)

Table 19 (*continued*)

Base Case (Actual Scenario):	
Total generators capacity in NUST	8.262 MW (43 Generators)
Average fuel consumption per hour for each generator	45 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 150 × 45 × 43 = 80.97 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 75 / 24 × 24 = 0.324 Million PKR
With 250 H Load shedding:	
Total load shedding hours in one year	250 hrs.
Total generators capacity in NUST	8.262 MW (43 Generators)
Average fuel consumption per hour for each generator	45 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 250 × 45 × 43 = 134.97 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 125 / 24 × 24 = 0.547 Million PKR

Table 20
Details of Load Shedding Scenario of Proposed Case.

Proposed Case (Actual Scenario):	
With 10 H Load Shedding:	
Total load shedding hours in one year	10 hrs.
Total generators capacity in NUST	8.262 MW (1 Generator at Substation)
Average fuel consumption per hour for each generator	45 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 10 × 45 × 1 = 4.05 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 05 / 24 × 24 = 0.0216 million PKR
With 150 H Load shedding:	
Total load shedding hours in one year	150 hrs.
Total generators capacity in NUST	8.262 MW (1 Generator at Substation)
Average fuel consumption per hour for each generator	1450 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 150 × 1450 × 1 = 60.68 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 75 / 24 × 24 = 0.324 Million PKR
With 250 H Load shedding:	
Total load shedding hours in one year	250 hrs.
Total generators capacity in NUST	8.262 MW (1 Generator at Substation)
Average fuel consumption per hour for each generator	1450 Liters / hr.
Rate of the Fuel (Diesel)	279 Rs / Liter
Total cost of fuel	279 × 250 × 1450 × 1 = 101.13 Million PKR
NUST PV shutdown cost (1.08 MW+2MW)	4320 (kWh) × 125 / 24 × 24 = 0.547 Million PKR

A.6. Power loss analysis

Table 21
Details of Active Losses.

Column1	2MW (PV)	5MW (Load)	10MW (Load)	15MW (Load)
Total generation	4294.65847	5137.000634	10,314.2767	15,461.442
Total PQ load	4169.0145	5015.592774	10,051.07963	15,121.33843
Total Z shunt	58.7768138	58.76883087	58.59327805	58.427342
Total losses	66.8671573	62.63902886	204.6037909	281.6762339

Table 22
Details of Reactive Losses.

	2MW (PV)	5MW (Load)	10MW (Load)	15MW (Load)
Total generation	5418.23436	5406.554146	5602.27659	5780.992607
Total PQ load	5264.03518	5263.995436	5261.941151	5259.78246
Total Z shunt	21.0232299	21.01526359	20.84341584	20.68121574
Total losses	133.175951	121.5434466	319.4920228	500.5289307

A.7. Sensitivity analysis

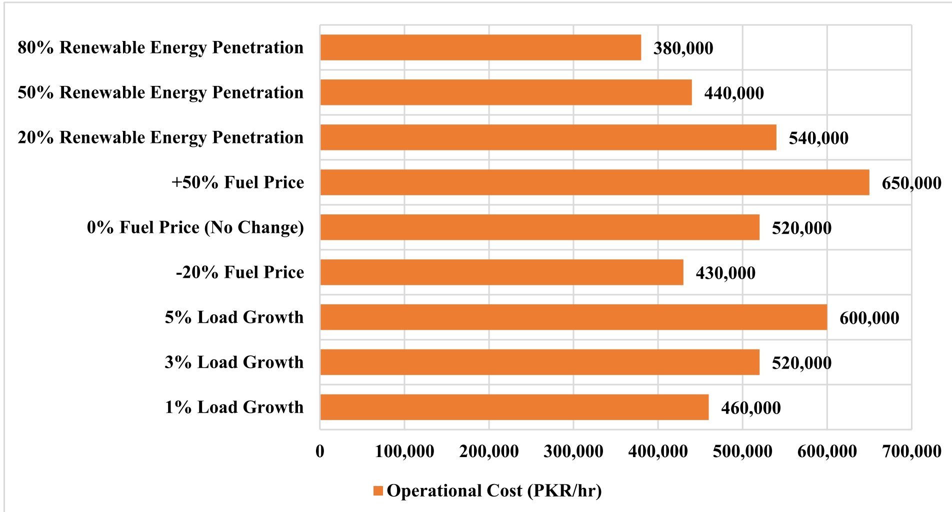

Fig. 23. Comparison of Operational cost for all the scenarios.

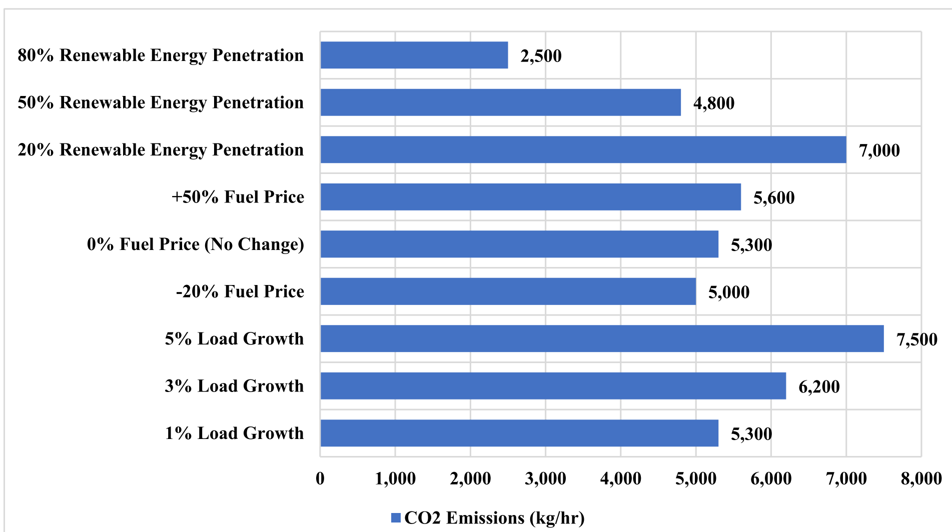

Fig. 24. Comparison of GHG emission for all the scenarios.

Fig. 25. Comparison of Grid Reliability for all the scenarios.

Data availability

The authors do not have permission to share data.

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