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Hybrid solar, wind, and energy storage system for a sustainable campus: A simulation study

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Abstract. The reliance on grid electricity generated from fossil fuels in many countries continues to contribute to annual CO_2 emissions. Implementing renewable energy systems helps reduce the carbon footprint and enhances local grid stability, particularly in areas with high demand where power outages are frequent. This study used the Hybrid Optimization of Multiple Energy Resources (HOMER) software to determine the most cost-effective composition of a Hybrid Renewable Energy System (HRES). Simulation results indicate that a system comprising a 3007 PV array, two 1.5 MW wind turbines, and a 1927 kW converter is most suitable. Combining solar panels and wind turbines remains the most economically feasible option for on-site electricity production. The study demonstrates that installing a hybrid renewable energy system is viable on an academic campus, with an initial investment cost of US $6.58 million and yearly operational costs of US $1.38 million, which is 40.8% lower than the current system. The project payback time is estimated to be 10.11 years. These findings may be used to recommend similar systems in other regions with comparable climatic conditions. The positive monetary effects may incentivize policymakers to implement comparable systems, contributing to a carbon-neutral goal.

Keywords: Green campus, HOMER software, Technical analysis, Economic analysis, Hybrid energy.

1 Introduction

With climate change representing the biggest threat to the global economy and, consequently, our livelihoods, a reduction of the atmosphere's greenhouse-effect potential is needed more than ever before. Worldwide electricity generation accounts for 25% [1] of all global greenhouse gas emissions, representing the most significant emitting sector. A decrease in emissions in this area would therefore have a considerable impact. Hence, countries with a high share of fossil fuel-based electricity generation should be incentivized to implement more carbon-neutral sources. With India still heavily relying on electricity by thermal generation (63.4%) [2], the latter condition is sufficiently satisfied.

In developing countries, renewable energy sources can be crucial in supplying energy demand, even in remote areas. By definition, a typical HRES includes multiple sources of renewable energy generation that are compatible with increasing overall system efficiency [3]. Hybrid Optimization of Multiple Energy Resources (HOMER) software has been proven to be an adequate and reliable solution to identify approaches for specific applications, including different geographical regions and varying load profiles. It has already been widely used for various previous assessments [4].

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HOMER is widely used for simulation as it is a powerful tool for simulating hybrid systems hourly. This software hands in suitable results by approximating the feasibility and performance of the systems. When simulating solar energy systems and PV, this software is stable, while some extent of uncertainty enters when simulating wind energy. The other point about this software is that it works based on the previous data obtained for that area and does not account for current data and situations. Another drawback of this tool is that the software does not separate essential and non-essential loads [5].

Renewable energy has gained significant attention in recent years due to its potential to reduce greenhouse gas emissions and mitigate the effects of climate change. The transition to renewable energy has become increasingly important in tackling climate change and promoting sustainable development. Integrating renewable energy into the power grid requires a comprehensive analysis of various factors, such as the availability of resources, geographic location, and technological advancements.

Solar power is an excellent source of Energy due to the smooth scaling of the power input source. Due to its various advantages like abundance, emission-free, and renewability, solar power becomes an optimal choice as a renewable energy source. Other technical benefits include:

- High power handling capabilities.
- Ability to function without being attended.
- Rapid response in output to input radiation changes.

Recent solar panel technology enhancements have increased overall electrical efficiency and drastically reduced costs per unit [6]. Furthermore, universities are well suited for local renewable energy production, comprising vast open areas [7]. Various factors influence the total output power. To maximize power output, voltage, and current should be varied. Other than electromechanical methods such as fixed, single, or double access trackers, the user of Maximum Power Point Trackers (MPPT) can also be used to achieve this aim. Wind energy already has a share of 8.4% of the Indian energy generation capacity. Wind energy over the Indian Subcontinent is regarded as a source of Energy with immense potential. However, no wind turbines have been installed in this region (*e.g.* compared to Tamil Nadu State), raising doubts about feasibility. Various studies to improve power output have provided solutions to increase energy efficiency.

The integration of solar energy systems into a hybrid energy system has led to a reduction in the consumption of non-renewable fuels. A similar hybrid system of solar energy sources has also proved to be an economical option for powering a residential community. However, integrating renewable energy into the power grid can be challenging in some regions due to their intermittency and variability.

2 Literature review

Several studies have been conducted on the optimal configuration of hybrid renewable energy systems for various locations and applications.

Shiroudi *et al.* [8] conducted a study in Iran and found that a PV–wind–diesel–battery system was the best solution for independent applications. Similarly, a survey conducted in Odisha, India found that a combined PV–battery system could achieve a 100% renewable energy fraction [9]. Several studies have used simulation software such as HOMER and RET Screen to optimize the performance of hybrid renewable energy systems. These models offer various capabilities, including modelling standalone wind systems, PV standalone systems, and PV–wind hybrid systems. However, some challenges regarding openness and representation of spatiotemporal variability still need to be addressed [10–12]. Studies have also been conducted on the cost of sustainable renewable energy for domestic utilization [13]. Simulation and modelling have been used to find the most suitable configuration of the renewable energy–efficient system for various numbers of houses. In addition, the design of standalone PV–biogas systems and integrated renewable energy systems using wind turbines and solar photovoltaic systems have been evaluated using HOMER [14].

Several studies have focused on the techno-economical aspects of hybrid renewable energy systems.

For example, a study in Indonesia found that a PV–diesel system could generate about 309.6 kWh of electricity annually at the cost of 0.318 \$/kWh [15]. A study conducted in Thailand proposed a configuration of PV panels, converters, and batteries that achieved a 100% renewable fraction at the cost of 0.728 \$/kWh [16]. Finally, a feasibility study of an integrated renewable energy system for a rural health clinic in Nigeria found that the optimal configuration included a PV array, a wind turbine, and a battery system [17]. One study focused on a resort in the Maldives and determined the optimum technical combination of a hybrid energy system using HOMER software [18]. The study evaluated the feasibility of the systems using parameters such as net present cost and Levelized Cost Of Energy (LCOE). Another study explored the economic and technical implications of a hybrid system for electricity production in rural areas of Nigeria, where the NPC and COE values were attributed to the availability of renewable energy resources [19]. In Jordan, a techno-economic study of microgrid deployment was conducted, and the economic effect of a hybrid renewable energy system was analyzed for a household [20]. Various scenarios were built using minimum, maximum, and average wind speed and solar radiation data, and three hybrid renewable energy systems were studied for the microgrid. The study found that the best possible configuration for the hybrid renewable energy system consisted of a 1.3 kW photovoltaic generator, a 1.6 kW diesel generator, a 9 kW wind turbine, and a bank of six batteries. Similarly, a study conducted in a remote village in Saudi Arabia showed the possibility of supplying electricity demands using a Hybrid Power System (HPS) [21], while a study in Barwani, India found that the best configuration from the view of emission and cost was the PV–Wind–Battery–DG hybrid system [22]. Another study conducted in Bandar Dayyer surveyed the techno-economic analysis for two hybrid renewable energy systems and found the region to be a viable place to investigate hybrid renewable energy due to its suitable capacity for solar radiation and wind speed [23]. One study conducted a simulation and feasibility study of a battery HPS/solar PhotoVoltaic (PV) system and reported a 59.6% reduction in NPC and an 80.7% reduction in operating cost for LCOE compared to conventional methods [24]. The HOMER software conducted the reliability and stability of an energy–efficient system and self-sufficient buildings in terms of energy generation [25]. Another study examined the potential of a standalone hybrid system that includes a wind turbine and PV to meet the energy demands of a hotel in Jordan and found that a 10 kW wind turbine and a 20 kW PV system could adequately meet the needs with a payback time of 11 years [26]. Furthermore, a study from Sudan [27] compared different hybrid systems and found that a solar–wind–diesel–battery–converter system had the best performance with a LCOE of 0.387 $/kWh, a total NPC of 24.16 M$, a 40% return on investment, and a 95% reduction in fuel consumption and carbon emissions. Another study presented the optimum mapping of hybrid energy systems based on PV and wind for household electricity demand in six different cities in Nigeria, with payback times ranging from 3.7 to 5.4 years and a Cost Of Energy (COE) for the hybrid systems varying from 0.459 to 0.562 US $/kWh [28]. Another study by Kartie *et al.* provides a review of various structures and operating conditions used in HRES and the software utilized to investigate these systems [29]. One study conducted in Colorado, USA, aimed to simulate the optimal size of components and achieve an economical configuration for PV, WT, battery banks, a hydrogen tank, and an electro-laser. The study found that hydrogen was more economically advantageous than batteries for long-term energy saving, but if the battery bank was not used in the same location, the minimum COE increased to 0.78 $/kWh due to the high cost of hydrogen technology [30]. In another study, the feasibility of HRES in Benin was examined, and the HOMER software was used for simulation and optimization. The study found that a hybrid PV/DG/battery system was the most suitable option for the future in Benin, as solar radiation is a commonly available resource in the country. This system reduced the required batteries by 70% and reached a 97% reduction in CO_2 emission compared to a DG [31]. Similarly, a study conducted in Nigeria examined the feasibility of a hybrid system using wind and solar energies [32]. The HOMER software was used for environmental and techno-economic surveys, and the optimal NPC, COE, GHG, and RF were selected. The study found that the system was environmentally friendly with a GHG emission of 2889.4 kg/year and a renewable fraction of 98.3% [33]. Another study aimed to meet the energy needs of a group of people using a smart–grid hybrid energy system. The HOMER software was used for simulation, and the study found that this system was environmentally and economically friendly, with a reduction of CO_2 emission and NPC by around 29.7% per year compared to conventional power plants. Finally, a study conducted in Pakistan's Punjab province examined the techno-economic feasibility of a grid–tied hybrid microgrid system [34] The HOMER software was used for modelling and simulation, and the study found that a HPS may generate more than 50 MW. The system's estimated cost with a peak load of 73.6 MW was around 180 million dollars, with a LCOE of around 0.0574 kWh. A clear demonstration of energy generation from RE sources is given by the suggested HREI system [35]. Another study discusses the optimal conditions for energy management of smart homes with hybrid energy resources in India, which includes an economic analysis to motivate families to integrate HECS into their houses [36]. Similarly, a study aims to suggest the best possible hybrid technology configuration for electricity production using a mix of renewable energy sources in Palari, India, for institutional, commercial, agricultural, and small-scale industries [37]. The third study compares two configurations of a wind/PV on-grid system in an educational facility to determine the most cost-effective and renewable solution [38]. Finally, a study at the *University of Victoria* evaluates the life-cycle cost of gasification and hybrid plants for trash conversion to renewable power and heat energy using independent and hybrid waste-to-energy scenarios [39]. It is important to note that the load profiles of educational institutions are unique compared to residential, commercial, and industrial loads, as they vary based on semester lengths, vacations, weekdays, and weekends [40].

2.1 Research gap and problem statement

The reviewed literature highlights several studies investigating the techno-economic feasibility of Hybrid Renewable Energy Systems (HRES) in different locations worldwide. These studies have explored the potential of HRES to provide sustainable and cost-effective electricity, and their findings emphasize the economic, technical, and environmental conditions for optimum renewable energy systems. However, the availability of specific literature regarding the most effective combinations of renewable power opportunities for a relevant geographical area is still limited, hindering the initiation of a paradigm shift towards a more sustainable and renewable energy future. To address this research gap, this study aims to identify the combinations of renewable power opportunities most effective for a relevant geographical area. It utilises existing literature to determine the most effective renewable energy technologies and their potential for integration into the power grid.

Additionally, the study aims to validate other research results presented in the literature. The findings of this study could inform policymakers, energy planners, and other stakeholders to accelerate the adoption of renewable energy and achieve a sustainable future. Ultimately, the study highlights the importance of identifying specific renewable power opportunities to facilitate the integration of renewable energy into the power grid, thereby contributing to mitigating the effects of climate change while promoting renewable energy sources.

2.2 Objective and contribution of this study

This work aims to present and verify the model of hybrid renewable systems in large-scale commercial applications (academic campus as an example) using the HOMER software for optimum sizing. It helps find the most

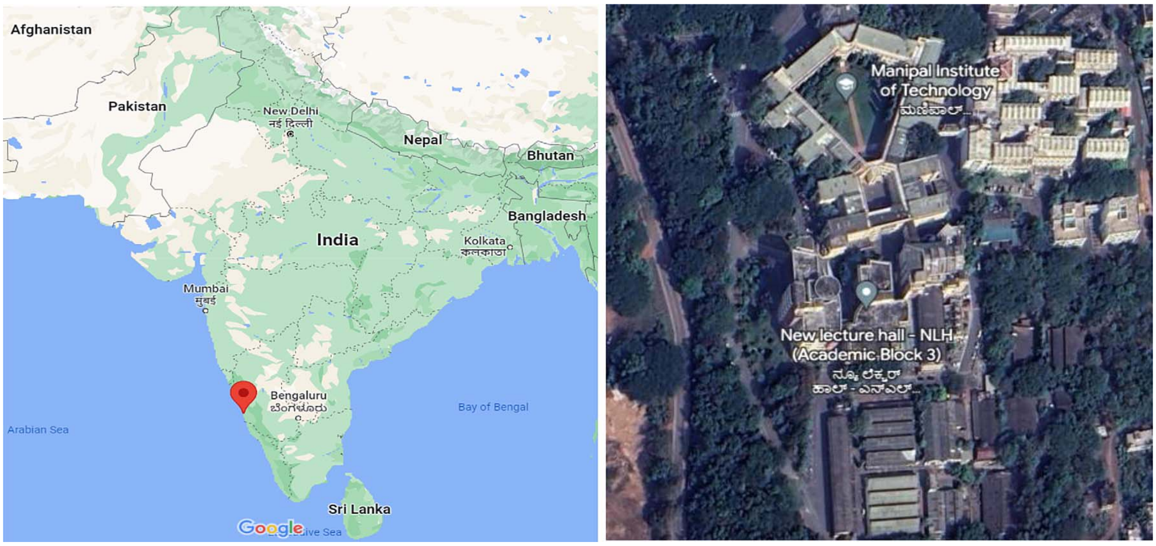

Fig. 1. Localization of Manipal's position in the Karnataka state, India and the vacant/rooftop area of the university site.

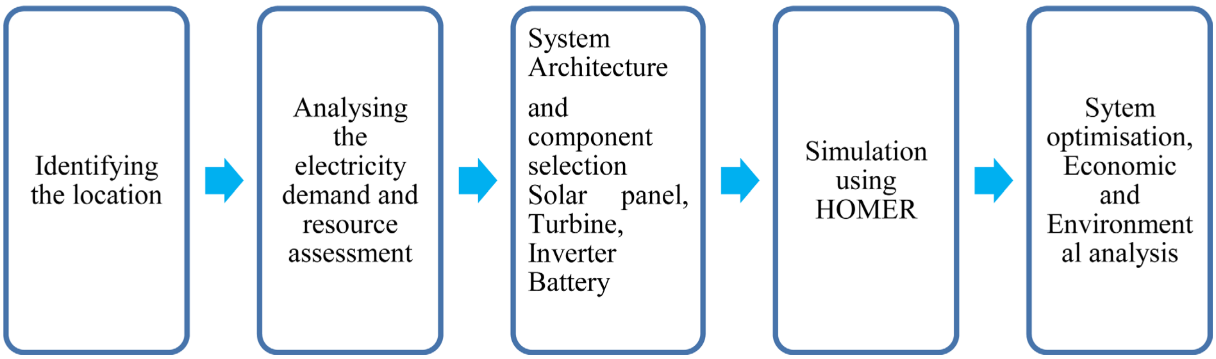

Fig. 2. Methodology of the simulation study

cost-effective way of integrating renewable sources into the mix used by our institute and the adjacent campus area. At the same time, CO_2 emissions, the main driver of global warming, are sought to be minimized. By calculating current emissions from Indian electricity production, the potential for reduction by introducing a hybrid electricity system is presented.

3 Methodology

3.1 Site description and load assessment

The chosen site is considered one of India's reputed academic institutes. *Manipal Institute of Technology (MIT)* is well-known for being India's innovation and education centre. Situated in Karnataka State in South-western India, the region boasts an electrified household rate of 90.6% [41]. However, power outages during peak-demand hours are still quite common. Of all on-site electricity, 0.68% is still generated by auxiliary diesel generators. Figure 1 shows the geographical location and the rooftop area of the campus.

To make it easier to comprehend, a flowchart illustrating the simulation study conducted with HOMER software is presented in Figure 2. Before assessing any opportunities for electricity generation, the electrical load's scale should be determined. However, a more accurate load determination is indispensable to designing generator and storage facilities. Data for electricity consumption of large entities such as university campuses are usually available utilizing a monthly electricity bill, stating the maximal demand for tariff fixing and the total Energy used. An average load can be determined using the latter for the day in the middle of each corresponding month. Days in between have been linearly interpolated. The most recent available data points from two consecutive years have been used to account for the campus area's ongoing growth and the increasing power demand. Figure 3 shows how the latter sharply decreases during semester breaks, only to return to the same value once the students return to campus. This results in a peak load of 4400 kW in October, averaging 2160 kW. A synthetical model has been introduced to increase accuracy on how demand varies daily. This step is crucial to allow for a precise reckoning of storage units and appropriate installation sizing

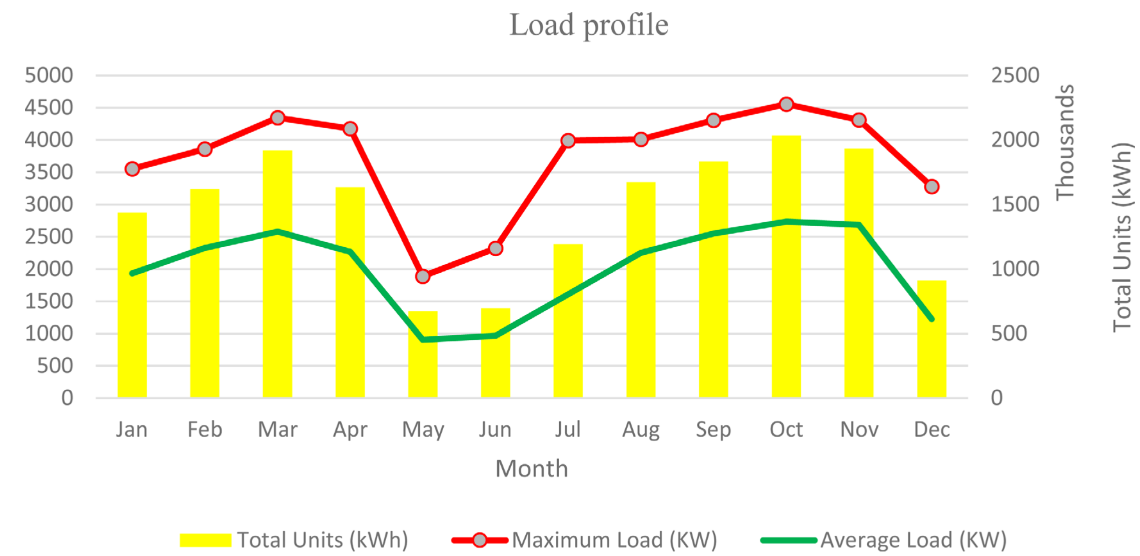

Fig. 3. Load profile and energy demand of the campus during the study year.

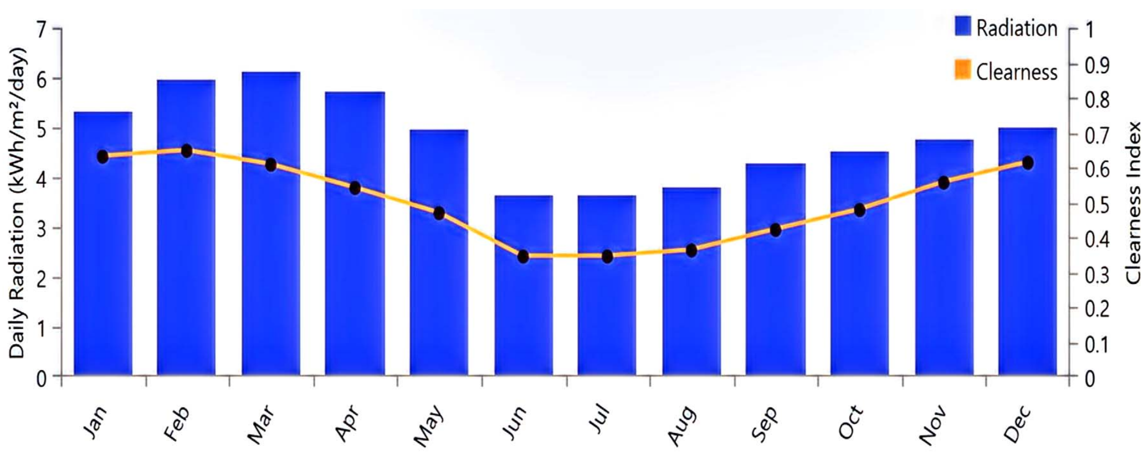

Fig. 4. Total daily insolation (as daily radiation) and corresponding clearness factors.

Losses in the distribution grid and appliances (power factor) have been estimated, as no official values were available. Data have been calculated as empirical values of around 0.96. This fact raised the total needed generation whenever substitution was deemed possible.

3.2 Solar and wind resource assessment

Although there cannot be a single source of renewable energy production as the climate in the area demands different sources of Energy during other months of the year. This is due to the ever-changing and robust nature of the environment in the coastal regions of the Indian Subcontinent. The warm summers, followed by the windy monsoons, increase the scope of multiple solar and wind energy sources to be installed to generate power. On a longitude of 13.34°, plenty of insolation potential can be expected throughout the entire year, ensuring the efficient operation of a solar power plant. The exact distribution is visualized in Figure 4.

Active monsoon phases over Central India are characterized by robust convection and heavy rainfall. Wind power could complement solar energy, as monsoon months (from June to August) specifically yield high wind speeds while cloud coverage reduces solar potential (Fig. 5). Wind could also result in a solution for an alternate source that leads to the reduces.

The active and break phases can be predicted using a predefined monsoon index that captures the dynamics of intraseasonal variance. NASA's wind energy data, however, is somewhat optimistic. Average wind speeds are much higher when compared to other sources [42].

3.3 Biomass (food waste) and Municipal Waste Incinerator

Students on campus are expected to be responsible for 64.3 kg of food waste per year, whereas non-residents would account for 17.1 kg [43]. In the case of the whole academic campus area with its 30 000 students, 25 000 of them living

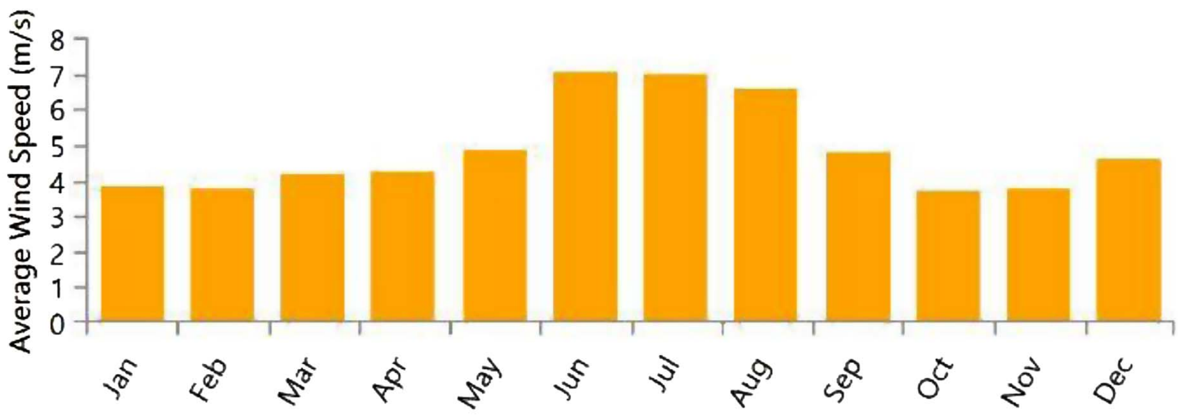

Fig. 5. Average wind speed in Udupi in a year.

on-site, there is a total potential to convert 1693 tons of food waste into electricity. This corresponds to a calorific value of 50.8 kW of electricity [44]. The need for processed heat in this area is limited, so the actual output is relatively low compared to high investment costs. Directly converting biomass into biogas for further usage in household or mobility appliances would be more adequately allocated [45]. Karnataka state, with its 61 130 704 people, is estimated to produce 22 618.4 tons of municipal trash daily [46]. Thereof, 12% are likely suitable for thermal treatment, accounting for 2714 tons per day [47]. Assuming a conservative calorific value of 6.8 MJ/kg [48], a daily energy potential of 18 455.2 GJ can be determined, corresponding to a constant 24 h power output of 42 720 MW when assuming a typical energy-to-power efficiency of 20% [49]. Hence, to supply the entire campus without any need for storage devices, a trash catchment area encompassing 6600 people would theoretically already suffice to accommodate peak load electricity supply. Introducing a municipal waste incinerator would not only enable providing a constant and adjustable baseload but also reduce the volume taken up by landfills to accommodate for non-degradable trash by up to 90% [50].

3.4 HOMER system design and simulation

Introducing a Hybrid Renewable Energy System (HRES) would decrease indirect greenhouse gas emissions and improve grid stability after adding storage capacity. By definition, a typical HRES includes multiple sources of renewable energy generation that are compatible with increasing overall system efficiency [3]. HOMER software has been proven to be an adequate and reliable solution to identify approaches for specific applications, including different geographical regions and varying load profiles. It has already been widely used for various previous assessments [4]. HOMER software provides generic load profiles for residential, industrial, and other complexes. To enable the usage of this methodology for other similar projects, every significant currently available possibility of renewable electricity production is listed and evaluated. One should remember that some options might not be financially profitable but environmentally beneficial. The latter factors

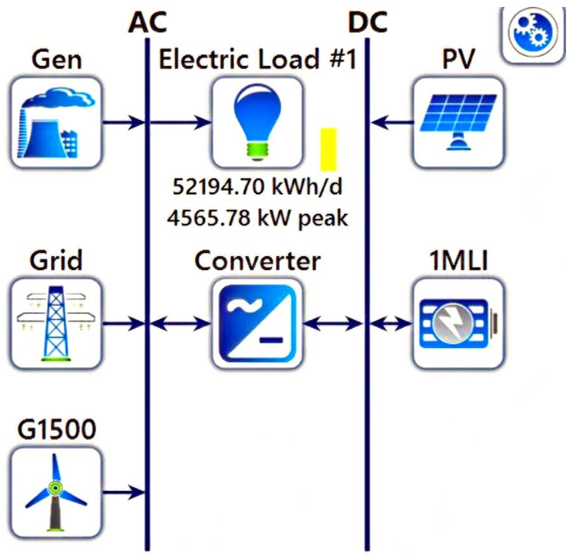

Fig. 6. System architecture before optimization.

should also be considered because future emission taxes for fossil-fuel combustion might be introduced or raised, depending on the pollutant. PV and a wind turbine have been assessed as the most realistic options of all the previously proposed system components and thus have been implemented into the system (Fig. 6).

It needs to be mentioned here that upon calculating and evaluating the Lowest Cost System (LCS), HOMER is capable of resizing all components to their most effective size (chosen base case: 1 MWh). The chosen base case has been taken as 1 MWh per the software's best recommendations. As the PV array's size is expected to be rather significant, a comparably low cost of US $900 per power unit installed (kW) can be assumed for Operational and Maintenance expenses (O&M); the literature provides values of US $10/kW [51]. Lastly, converters in the lower MW range were estimated to have an efficiency of 98%. It can be categorised into various concepts based on the types of generators, power electronics, speed control, or limitations on aerodynamic power. The differences between Standard Test Conditions (STCs) and actual values are generally

Table 1. List of non-renewable energy carriers and their respective share in India [2, 52].

Energy carrier	Share	Emissions (g CO_2/kWh)	Weighted average (g CO_2/kWh)
Coal	0.545	860	511.51
Lignite	0.018	1020	
Gas	0.07	330	
Oil	0.002	675	
Rest*	0.365	0	

* Rest includes Hydropower and Renewable Energy Sources.

Operational emissions were assumed to be 0 for simplicity.

described as "Derating Factors", which usually range between 0 and 0.77 [51]. A higher value can be used for large modules due to a more efficient design. For this particular study, a base value of 0.7 has been used. However, a sensitivity analysis for lower and higher values has also been conducted, ensuring financial safety margins. Deferrable loads like water pumps have not been considered, as appliances like computers and lighting are known to be the biggest electricity consumers in a campus environment. A lithium-ion battery with a round-trip efficiency of 80% has been selected as a storage unit. They currently offer the highest energy density and are considered the most viable option for clean energy storage [53]. In the context of this study, HOMER introduced a dynamic efficiency range for wind turbines, varying with changing wind speeds. Most countries have a detailed outline of how the source should behave for integrating wind power into grids. This makes it a regulated power source and an active generation unit that produces electricity according to consumer demand by fluctuating the voltage and frequency for grid support. Removing wind turbines from the whole setup in favour of more solar panels could be one solution, which would prompt a need for more storage capacity, as a power supply would occur intermittently.

3.5 Economic parameters

Before evaluating a project's economics, some economic parameters need to be defined. As of July 2021, a discount rate of 6.25% can be assumed for India [54]. The inflation rate was determined to be 3% [55]. Other specifications to be resolved include the lifespans of individual components. Different sensitivity values can be selected to allow for a simulation of uncertainties. For the PV array, a life expectancy of 25 years has been used, representing the manufacturers' standard product warranty [56]. To account for unforeseeable occurrences, a lifetime of 15 years has been simulated too. This has facilitated a complete financial assessment of this project.

3.6 CO_2 emissions

CO_2 emissions are the leading contributor to historical warming. Prior studies suggest that there will be an 11% increase in carbon emissions by 2025, making it a significant health hazard for humankind all over the planet due to substantial environmental and health risks. Reducing CO_2 has become a goal that has gained worldwide consensus as part of the framework to mitigate global warming processes. India, producing 699 metric tons of carbon emissions a year, is now part of the modelled framework for international CO_2 trade, which as an import, is used as a product for intermediate or final consumption. To estimate direct emission savings and similar financial benefits, the current carbon dioxide production rates of the Indian power sector need to be quantified (Tab. 1).

Hence, the entire institute's average daily electricity consumption of 46 559 kWh currently accounts for 23.82 tons of CO_2 daily.

4 Results and discussion

4.1 System design optimization

The selection and system dimension creation has been done through the HOMER software. An input of 1 year of electrical load data has been given to perform the simulation. The monthly average global radiation, monthly clearness index, and monthly average wind speeds for the given geographical location have been downloaded and fed in by HOMER. The system has been simulated and optimized to appraise its characteristics, electricity production, annual electricity load curve, renewable energy fraction, carbon emissions, etc. Load control following strategies has been used during the simulation; the addition of the central grid has been considered to ensure the product that matches the required demand. The various simulations were ranked based on the different customization of the components based on the total LCC and Net Present Cost.

In Figure 7, the LCS layout can be viewed. HOMER has determined the optimal system to comprise a new photovoltaic array of 3007 kW, a system converter of 1927 kW capacity, and two wind turbines of 1500 kW each. This is assumed to be a realistic project due to the vast availability of free space in the campus' vicinity.

The HOMER software identifies this as the best combination of equipment to perform efficiently in the given geographical location. The simulations have shown that 3830.081 MWh/year, or 19% of the Energy, has been produced by solar sources and 4532.579 MWh/year or 22.5% of energy from wind sources. This gives 41.5% of electricity produced by renewable sources of the system. The actual monthly energy production of each added source can be viewed in Figure 8. In the peak production month of March, the solar source produces a higher amount of energy; however, in the monsoon months of June, July, and August, the wind source is seen to pay a higher percentage of Energy. The introduction of a chemical storage unit has been established to be unprofitable, presumably due to a PV–based system's congruent production and load curves and a high purchase price. It is noteworthy to mention that the actual outcome of the present simulation highly depends on input parameters like investment costs for new generating facilities and their operation and maintenance costs [57].

To find further potential for improvement, Figure 8 helps to pick out periods of high grid electricity demand.

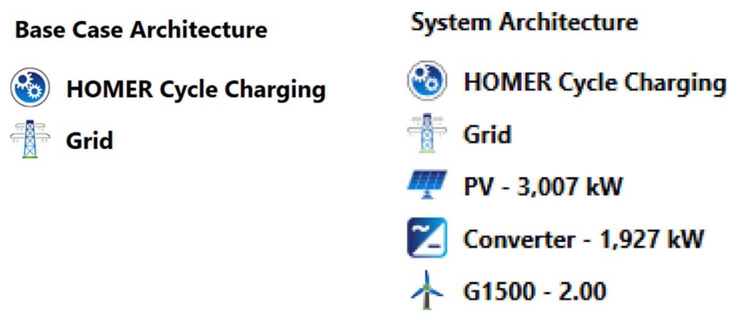

Fig. 7. Different illustrations of system architecture.

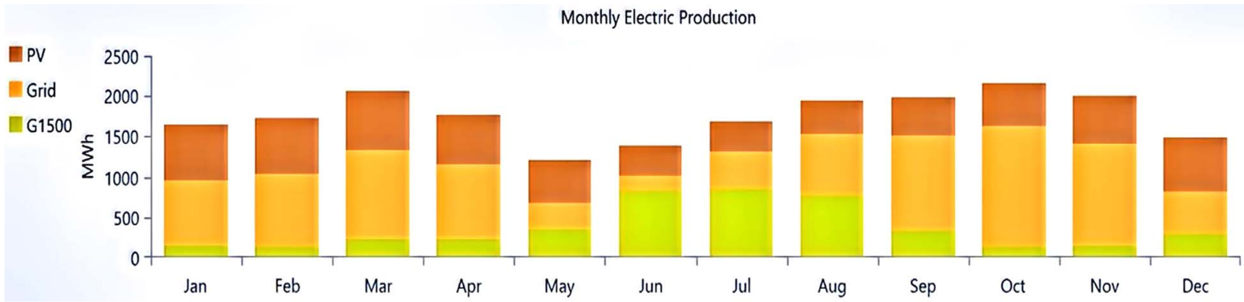

Fig. 8. Illustration of each source's share in the new electricity mix provided by the Lowest Cost System (LCS).

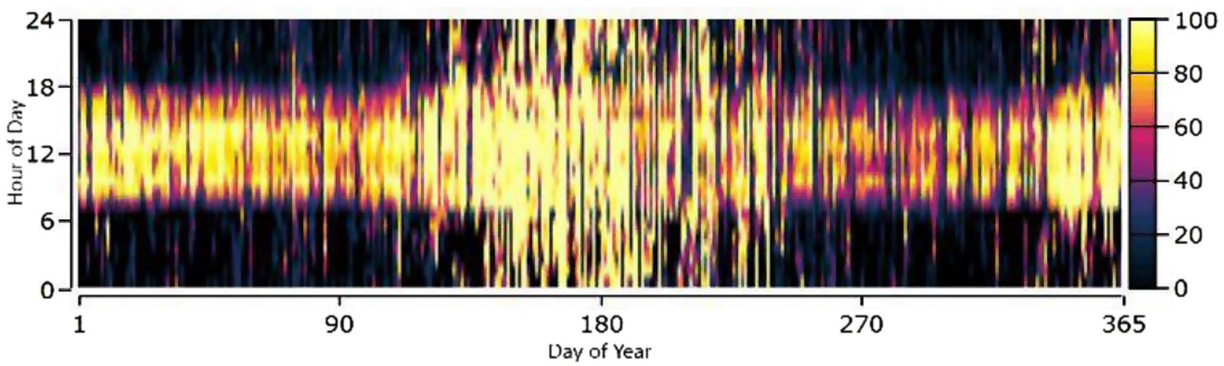

Fig. 9. Projected instantaneous share (in %) of renewable electricity usage compared to the total consumption.

If a PV array cost of US $500 according to a different source [58], the LCS will not make use of additional wind turbines [58]. It's evident that the electricity mix of months of high campus activities like March and October still heavily relies on grid provision. It is worthy of remark that throughout the whole year, power from newly introduced sources follows two patterns. Firstly, non-conventional energy production peaks during daylight time, boosted by the PV array's output. During monsoon months (from days 150 to 220, *i.e.*, from June until mid of August), increased average wind speeds lead to enhanced wind turbine production, represented by a 24-hourly elevated share of over 100%. This results in a condition where power can be connected directly to the commercial grid. Introducing a non-intermittent facility with a baseload similar to output could significantly reduce the previously mentioned demand without causing a need for storage units. As an example, a waste incinerator system would be a suitable solution since the extent of its renewable fuel accumulation (non-recyclable waste) coincides with electricity demand. This would reduce the need for waste storage infrastructure and, consequently, lower construction costs. Moreover, instantaneous shares of renewable electricity generation were assessed, presented in Figure 9.

Technical potentials of renewable electricity on the campus are enormous, and socio-acceptability attributes provide vital support from the local users of the campus. The above results could be beneficial for energy planning, renewable grid infrastructure development and implementation of Hybrid energy systems.

4.2 Economic analysis

The system's lifetime has been projected to be 25 years, with an annual interest rate of 4%. To account for future savings by reducing the need for direct grid electricity

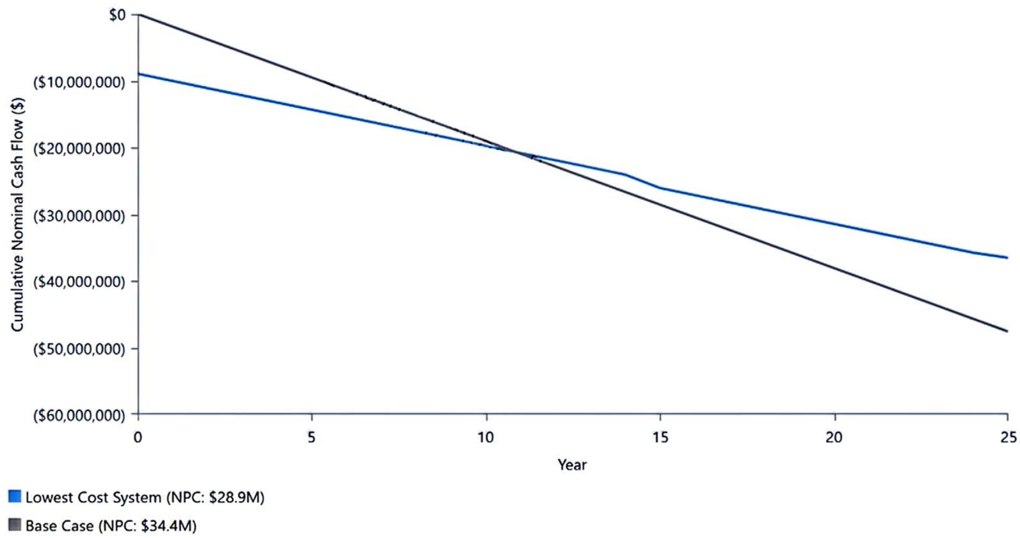

Fig. 10. The forecasted cash flow of the scenario and the lowest-cost system.

Table 2. Economic metrics.

Parameter	Value
IRR (%)	7.5
ROI (%)	4.9
Simple payback (yr)	10.9

purchases, cumulative savings of around US $6.5 million could be achieved. The simulations have also revealed that the initial investment needed for the installation would be US $6.58 M, operating at a yearly cost of US $1.38 M. A detailed analysis of how the costs of the Base Case (BC) and the LCS develop over time can be perceived in Figure 10. The payback time is predicted to be reached after 10.9 years, as shown in Table 2. After 15 years, the converter unit is set to end its lifecycle by default, prompting another investment to purchase a replacement. However, the running costs of the LCS still prove to be smaller. Subsequently, the savings increase during the following years due to lower operating costs per year (as shown in Tab. 3). Any increase in electricity generation and revenues would positively contribute to an ever-higher Internal Rate of Return (IRR).

These findings are backed by an IRR of 7.5%, which exceeds the cost of capital, financially justifying the investment.

4.3 Emission analysis

Using the Hybrid System, a reduction of 42.4% in overall operational CO_2 emissions can be achieved [59]. The World Bank has developed a plan to trade "virtual carbon" with India due to a high production rate within the country. Once in place, the university could finance a viable project by selling carbon credits on the market. Furthermore, realizing this project would contribute to an increased share of solar power in India, which the government has laid out to reach 175 GW in 2022 [60]. As of December 2022, India has only achieved 122 GW, with solar power accounting for only 62 GW. The emission analysis of the optimized energy system is presented in Table 4.

Table 3. Cost summary.

	Base Case	Lowest Cost System
Initial capital	$0.00	$8.98 M
Operating cost per annum	$1.91 M	$1.10 M
Levelized Cost of Energy (LCOE) (kWh)	$0.100	$0.0780

Table 4. CO_2 emission reduction.

	Base Case	Optimised hybrid system
Annual CO_2	0	4306.76 tonnes
Emission factor (gCO_2/kWh)	511.57	212.301
% Reduction	N/A	42%

4.4 Comparison with other literature

A comparison table of Hybrid Energy (Solar, wind and battery) system LCOE and CO_2 emission results for an educational campus building using the simulation tool HOMER is provided. The specific information about the campus building's energy demand and the location's solar and wind resource data are used for comparison. The determined LCOE of the LCS of 0.078 $/kWh is relatively low, falling

Table 5. Comparison of study results with other literature.

Reference	LCOE ($/kWh)
[26]	0.459–0.562
[30]	0.11
[36]	0.0272
[38]	0.127
This study	0.078

short of all the LCOEs reported, which is highlighted in Table 5.

The actual LCOE and CO_2 emissions will depend on the campus building's energy demand, location, solar and wind resource data, and other system design and configuration parameters. Another explanation could be reduced investment and Operating and Maintenance costs for the following reasons:

(i) Economies of scale: The campus power demand is higher than most scenarios reported in the literature. This decreases costs for higher plants since expenses do not scale linearly with capacity.
(ii) Decreasing manufacturing costs: Especially in the battery and PV manufacturing context, prices decrease annually, leading to fewer investment costs for even more produced power. Moreover, comparatively cheap labour in India implies low Operating and Maintenance costs, which is also reflected in a lower LCOE.

4.5 Limitations of the study

Sensitivity analysis is critical to HOMER simulation, especially for solar PV, wind, and hybrid battery systems. Some essential parameters affecting the system performance are PV array size, Wind turbine capacity, Battery capacity, Load profile and climate profile. Overall, a sensitivity analysis of a solar PV, wind, and battery hybrid system is critical in determining the most vital parameters that affect the system's performance. Varying these parameters in the sensitivity analysis will help determine the optimal design and configuration of the system for maximum performance and efficiency. Limitations to this approach include the lack of sensitivity parameters. For instance, the lifetime could be estimated to vary, yielding differing results. The same goes for climate variations, which were not considered in the context of this study.

Furthermore, the capital cost of all generation technologies is subject to substantial variations. It is expected to decrease further in the upcoming years due to the effect of the economy of scale and improved manufacturing efficiency. However, the applied numerical parameters and the corresponding results help to identify trends and general concepts applicable to other contexts, such as industrial complexes or residential areas.

5 Conclusion

The analysis of wind energy and solar energy configuration, along with their output, has also been done to evaluate feasibility and cost analysis. Moreover, the average monthly generation of Energy by each component of the grid has been manifested:

- The result analysis portrays a combination of solar PV, WG, and battery, which is the optimal choice for the grid system in Manipal, India. This is promoted by the daylight-congruent load curve, which tends to peak around noon until late afternoon and when high insolation levels can be observed. This circumstance reduces the need for a storage facility. Wind energy utilisation has been done to its maximum capacity, which helps reduce the load on the PV cells.
- The COE from this system is $0.087 kWh. The returns of investment in the project are predicted by 4.1%, with an operating cost of $1.38 M per year. The utilization of solar panels and two wind turbines were determined to result in minimal costs over a project lifetime of 25 years due to the efficient performance and relatively low operational expenses.
- Furthermore, a total cutback of over 42% in CO_2 emissions could be determined, translating to an annual reduction of 3686.4 tonnes. These savings could also be monetized by considering the carbon trade system method, contributing to a higher return on investment.
- Thus, combining solar panels and wind turbines is still the most viable and economical option for on-site electricity production. The study has shown that in the given geographical location, the installation of an HRES is possible.
- After successfully operating the new system, this techno-economic study could convince decision-makers of other educational institutions, large industrial complexes, companies, or communities to introduce a similar strategy.

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