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Techno-Economic Operation of a Hybrid PV-WT-Battery System Installed in Aljouf Region

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Abstract:- Electrification of remote places is typically accomplished by expensive and environmentally unfriendly diesel generator (DG) systems, with extra financial challenges resulting from the delivery of diesel fuel. For isolated locations, hybrid renewable energy systems (HRESs) provide an innovative method of electrification. To determine whether RES is viable in these areas, a techno-economic analysis is necessary. This work examines a microgrid (MG) installed in Aljouf region of Saudi Arabia, which is known to have great renewable potential due to its high solar irradiance and moderate wind resources. A techno-economic analysis of a hybrid photovoltaic (PV), wind turbine (WT), and battery setup, customized to the local climate and energy requirements, has been studied in this research. The performance of six HRES configurations using HOMER Pro software simulations is analyzed to reveal the net present cost (NPC), levelized cost of energy (LCOE), reliability, and environmental impact. The findings show that, the performance in grid-connected mode is far superior to stand-alone mode in terms of cost, reliability, and environmental sustainability. The optimal grid-connected system acheived LCOE of $0.0148/kWh and negative stack carbon footprint due to the surplus of renewable energy fed-in the grid. On the other hand, stand-alone systems can manage renewable energy variability only through large batteries. These results further emphasize the importance of plugging into the grid to balance the energy supply and demand. The findings of this study offer a systematic framework for designing cost-effective and sustainable hybrid renewable systems in regions with similar resource profiles.

Keywords: *Hybrid renewable energy systems; Photovoltaic; Wind turbine; Battery storage; HOMER Pro; Techno-economic; Aljouf region.*

1. Introduction

The shift towards renewable energy systems (RESs) worldwide has emerged as a key goal in combating climate change, ensuring energy security, and achieving sustainable development targets. Hybrid renewable energy systems (HRES), hybridizing more than two RESs, including solar photovoltaic (PV) panels, wind turbines (WTs), and battery storage, create the potential for supplying clean, reliable, and affordable energy [1]. This applies to regions like Aljouf, Saudi Arabia with a high solar irradiance and moderate wind potential. Innovative hybrid configurations that leverage these assets can lower reliance on fossil-based fuels, decrease carbon emissions, and increase energy resiliency [2]. Aljouf region, located in a desert climate, faces particular energy challenges and opportunities. The region's robust renewable energy

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potential and relatively high cooling demands in the summer make it suitable testbed for HRES. However, in designing and implementing optimal hybrid systems, many important aspects related to local energy demand patterns, renewable resource availability, and economic factors need to be considered [3]. This study uses advanced simulation tools of HOMER Pro to assess the techno-economic viability of multiple hybrid configurations designed for Aljouf's conditions. The growing demand for energy in Aljouf, driven by urbanization and population growth, creates enormous pressure on this region's conventional energy systems. Dependence on fossil fuel-based energy sources drives high greenhouse gas (GHG) emissions and exposes the area to fuel price volatility [4]. Though renewable energy resources provide a sustainable alternative, the intermittent nature of these resources and their mismatch with load demand make reliability an issue. Furthermore, without coherent framework for coupling solar, wind, and battery systems, the region cannot fully capitalize on its renewable resource potential. The main challenge is designing hybrid energy system with trade-off between cost, reliability, and environmental sustainability [5]. Fighting these problems involves analyzing a range of system renditions, spotting the best combinations of sustainable and traditional sources of vitality, and searching for methods for achieving operational and financial bottlenecks. Numerous studies that examined the techno-economics of microgrids using various renewable energy sources were evaluated in the following section.

The document's remaining sections are organized as follows: Section 2 reviewed numerous published works, section 3 formulated the problem mathematically, section 4 addressed the HOMER Pro-based solution methodology, section 5 presented the findings and discussions, and section 6 provided conclusions.

2. Literature review

In [6], the authors evaluated a hybrid energy system for rural health clinics, focusing on setup combining PV panels, diesel generators, and battery banks to provide consistent power. The analysis has been done using HOMER software in different configurations to face the problems of fuel scarcity, excess electricity, and fluctuations of demand. The outcome of this study is related to only one geographical context, and it could be different under varying conditions. A techno-economic feasibility study on hybrid renewable energy systems for university campuses in Saudi Arabia has been examined using HOMER software to achieve economic and emission aspects [7]. A hybrid solar panels, wind turbines, diesel generators, and battery storage designed to a rural health clinic in Rijal Almaa, Saudi Arabia has been constructed and optimized through HOMER software to achieve economic operation, energy reliability, excess electricity management, and CO2 reduction [8]. The presented model is limited by its geographic focus and reliance on specific climate conditions. In [9], the authors explored the feasibility of rooftop PV systems combined with battery storage via HOMER Pro simulation to meet residential energy needs in Neom, Saudi Arabia, in alignment with Saudi Vision 2030.

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An overview of techno-economic viability of grid-connected PV systems under Saudi Arabia's regulatory framework has been reviewed [10], the authors examined Saudi Arabia's policies and economic incentives supporting PV adoption in residential and commercial buildings, identifying benefits and potential challenges. The study in [11] analyzed a hybrid energy system combining wind, PV, and battery storage for an industrial plant in Shiraz, Iran via HOMER Pro. The authors evaluated four types of batteries, lead-acid, lithium-ion, vanadium redox, and zinc-bromine, to determine the most cost-effective and sustainable option. Numerous hybrid energy systems for residential communities of Jubail industrial city, Saudi Arabia designed via HOMER Pro have been reviewed in [12]. The authors of [13] evaluated the techno-economic feasibility of hybrid energy systems for shipboard applications, specifically for passenger vessels, different configurations have been examined through HOMER Pro to achieve economic and emission issues. In [14], the authors focused on hybrid energy solutions for agricultural irrigation in Shaqra, Saudi Arabia. By integrating solar and wind resources, they investigated the systems capable of meeting the water demands for crops like wheat and barley using FAO's CROPWAT and HOMER Pro. Rural electrification has been discussed in [15], the performance of hybrid renewable energy systems integrated with demand-side management techniques has been evaluated for Qena and red sea governorates, Egypt. Configurations using PV, WT, diesel generator, and battery storage were modeled using HOMER Pro. The viability of hybrid energy systems with hydrogen storage has been examined across various regions, including Saudi Arabia, Toronto, and Sydney [16], six configurations were analyzed using HOMER Pro for optimizing the costs of energy production and hydrogen storage. In [17], a model combining solar PV, wind turbines, diesel generators, and battery storage installed in Iran has been presented using HOMER Pro. A comparison between isolated and grid-connected systems for an educational institution in Pakistan, focusing on hydrogen storage has been conducted with the aid of HOMER Pro [18]. In [19], a hybrid system including solar, wind, diesel, and battery storage to supply power to a desalination plant in Egypt has been evaluated using HOMER Pro to reduce the costs and CO2 emissions. PV-diesel-battery, PV-wind-battery, and PV-biogas-battery configurations installed in rural areas have been analyzed [20]. A hybrid energy system for remote households integrating PV, diesel generators, battery storage, and biomass fireplaces for heating operated at Geece weather conditions has been constructed and optimized through HOMER Pro and RETScreen [21]. A hybrid renewable power systems for electric vehicle (EV) charging station applications has been studied in five cities in China [22]. The optimized configuration of Nanjing's/wind/battery for Nanjing city has been obtained through through HOMER Pro simulation. The authors in [23] investigated a hybrid energy system for an industrial facility with integrated solar PV, diesel generators and storage batteries for acheiving least cost and emission via HOMER Pro. The study in [24] was related to the feasibility of hybrid solar and wind systems to power an RO desalination plant along coastal regions of Saudi Arabia. The study in [25] examined the

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hybrid energy system including solar PV, wind, and hydrogen storage, which would yield a reliable power supply to an extensive research facility located in Pakistan. While in [26], the authors have investigated, for remote agricultural applications, the performance of a hybrid energy system that uses solar PV, wind, and biogas to supply irrigation systems with electricity in rural Pakistan. In [27], the authors assessed the techno-economic feasibility of electrification in remote villages of India using hybrid renewable energy systems, such as PV, wind, and biomass. In [28], the feasibility of meeting the electrical energy demand of off-grid vacation homes in Turkey's coastal regions has been examined, which experience high solar radiation, using PV, wind, and FC hybrid energy systems. Using HOMER software, 24 simulations were conducted under the climatic conditions of Çeşme, İzmir, a location with significant solar and wind energy potential. The authors of [29] used HOMER Pro to design a hybrid energy solution for addressing off-grid health care needs by combining solar PV and wind turbines with diesel generators and batteries for electricity supply in the rural health facilities of Uganda. In a comprehensive analysis of rural electrification challenges in Nepal, the authors of [30] investigated hybrid renewable energy systems that combined solar PV, diesel generators, and battery storage.

Finally, several critical gaps and challenges emerge in current hybrid renewable energy systems research. While each study offers valuable insights into specific applications and configurations, there is a need for further development in certain areas to make hybrid systems more adaptable, resilient, and accessible across a range of environments and uses. Many studies are geographically limited, often focusing on specific climates or regions, which restricts the applicability of their findings to diverse environments. Furthermore, while research usually examined either the technical or economic aspects of hybrid systems, few studies adopted a comprehensive techno-economic perspective that balanced performance with cost-effectiveness. Additionally, storage solutions, vital for ensuring consistent power supply were underexplored especially in configurations tailored for regions with high renewable potential but variable resource availability. Finally, although some studies investigated hybrid systems for rural or remote areas, fewer considered unique environmental and economic dynamics of specific regions like Aljouf region, Abu Ajram city, which combines high solar irradiance with intermittent wind resources. In order to help the reader in understanding the reported works employed, Table 1 summarizes the reported works considering the limitation of each one.

This study addresses these gaps by evaluating the techno-economic feasibility of a hybrid system including PV, wind, battery, diesel generator, and grid system tailored to Aljouf's climatic conditions. By optimizing system configurations and assessing the impact of battery storage on overall performance, this research provides a scalable and replicable model for HRES deployment in similar arid regions. The findings contribute to the growing knowledge

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of sustainable energy solutions and support global efforts toward achieving energy security and environmental sustainability.

The following is a list of this work's contributions:

- The renewable energy potential through analyzing solar and wind resource availability in Aljouf is assessed to identify viable energy generation options.
- Various HRES configurations incorporating PV, WT, battery storage, diesel generator (DG), and grid connectivity are simulated via HOMER Pro to evaluate their performances under local conditions.
- Economic and environmental metrics have been optimized via minimizing total net present cost (NPC) and levelized cost of energy (LCOE) while maximizing renewable energy penetration.

Table 1 Summary of the major rationale for the reviewed methods

Ref.	Study objective	System components	Location/Climate	Fitness function	Limitations
[6]	Cost reduction in rural healthcare	PV, diesel, and battery	Rural health clinics	Reducing fuel dependency and lowering CO2 emission	Region-specific findings
[7]	CO2 reduction in university campuses	PV, grid, and battery	Saudi Arabia (4 provinces)	Reducing CO2 emission	Sensitive to solar and tariff variances
[8]	Reliability improvement in rural clinics	PV, wind, diesel, and battery	Rijal Almaa, Saudi Arabia	Reducing CO2 emission	Limited geographic focus
[9]	Renewable energy for residential needs	PV and battery	Neom, Saudi Arabia	62.4-68.2% renewable fraction	Dependent on tariff adjustments
[10]	Regulatory impact on PV grid-integration	Grid and PV	Saudi Arabia (general)	Enhancing PV peneteration	Lacking experimental data
[11]	Industrial energy reduction	PV, wind, and battery	Shiraz, Iran	Reducing CO2 emission	Load variation challenges
[12]	Techno-economic analysis of off-grid hybrid systems	PV, wind, and fuel cell	Jubail industrial city, Saudi Arabia	Minimizing NPC and LCOE	Alternative storage
[13]	Enhancing energy efficiency	PV, wind, battery, and fuel cell	Gwadar port (Pakistan) to Salalah port (Oman) maritime route	Minimizing LCOE and NPC	Extended maritime applications

[14]	Agricultural irrigation	PV, wind, and battery	Shaqra, Saudi Arabia	Minimizing NPC and COE	Seasonal demand consideration
[15]	Demand side management (DSM) integration in rural electrification	PV, wind, diesel, and battery	Rural Egypt	Minimizing NPC and COE	Expanded demand side management strategies
[16]	Hydrogen storage viability	PV, wind, and hydrogen storage	Saudi Arabia, Toronto, Sydney	Minimizing LCOE and NPC	Cost-effective hydrogen storage
[17]	Hybrid system for disaster relief	PV, wind, diesel, and battery	Disaster-prone regions, in Iran	Minimizing NPC and COE	Alternative to fuel dependency
[18]	Stand-alone and grid-connected renewable systems	PV, wind, fuel cell, and hydrogen	Educational institutions in Pakistan	Minimizing NPC and COE	Enhanced fuel cell tech
[19]	Renewable-powered desalination	PV, wind, and RO desalination	Coastal regions in Egypt	Minimizing NPC and COE	Continuous desalination optimization
[20]	Rural electrification with biogas	PV, wind, biogas, and battery	Rural Afghanistan	Minimizing NPC and COE	Expanding biogas scope
[21]	Heating and electricity for remote areas	PV, diesel, battery, and biomass	Mountainous Greece	Minimizing NPC and COE	Advanced heating solutions
[22]	EV charging infrastructure	PV, wind, and battery	China (urban)	Minimizing NPC and COE	Urban EV charging expansion
[23]	Energy and hydrogen production	PV, biogas, fuel cell, and electrolyzer	Maroua, Cameroon	Minimizing NPC, LCOE, and levelized cost of heat (LCOH)	Integration of hydro and wind
[24]	Battery vs. flywheel in tropical climates	PV, wind, flywheel, and battery	Aghajari, Iran	Minimizing NPC and LCOE	Exploring biogenerators and advanced battery cooling
[25]	Off-grid power supply and hydrogen production	PV, wind, and hydrogen storage	Canada, USA, Australia	Minimizing NPC, LCOE, and LCOH	Integrating geothermal or hydro
[26]	On-grid and off-grid hybrid systems for	PV, diesel, battery, and grid	Tamil Nadu, India	Minimizing NPC and COE	Exploring additional control strategies

	educational institutions				
[27]	Multi-objective optimization of hybrid energy systems	PV, wind, fuel cell, and hydrogen	Shiraz University, Iran	Minimizing NPC and LCOE	Expanding to other renewable sources
[28]	Energy demand of off-grid vacation homes	PV, wind, and fuel cell	Turkey	Enhancing solar and wind energy potential	Supply and fuel issues
[29]	Hybrid micro-grid optimization with demand response	PV, Wind, Battery	Northwest Iran	Minimizing NPC	Increasing demand response percentage and exploring load forecasting
[30]	Hydrogen production from renewable hybrid systems	PV, wind, and fuel cell	Shagaya renewable power plant, Kuwait	Minimizing NPC, LCOE, and LCOH	Exploring other renewable sources

3. Mathematical formulation of problem

HOMER Pro's primary objective is to minimize the net present cost (NPC), often referred to as the life-cycle cost, which characterizes the present value of all system costs over its operational lifetime. It includes capital expenditures, replacement, operation and maintenance (O&M), fuel, and electricity purchases. The latter is not relevant in this study due to the absence of grid connectivity. Income sources include salvage value as well as the place of installation and grid sales. HOMER Pro evaluates these inputs incorporating salvage value and other factors to calculate the annualized cost based on Eq. (1). This annualized cost reflects a consistent yearly expense that aligns with the total NPC, balancing all system costs and revenues across its lifespan [31].

$$C_{ann,i} = \sum_i C_{capital,i} + C_{O\&M,i} + C_{replacement,i} + C_{fuel,i} - SV \tag{1}$$

In this context, $C_{ann,i}$ represents the annualized cost, $C_{capital,i}$ denotes the capital expenditure, $C_{O\&M,i}$ refers to the fixed operation and maintenance costs, $C_{replacement,i}$ indicates the replacement expenses, $C_{fuel,i}$ is the fuel costs for component i, SV signifies each component's salvage value. HOMER Pro aggregates these annualized costs for all components incorporating any additional costs like penalties for emissions to determine the system's total annualized cost, denoted as $C_{ann,tot}$. This parameter holds significant importance as it serves as the foundation for HOMER Pro to compute two key economic metrics of the system: NPC and the levelized cost of energy (LCOE). The total NPC is derived using Eq. (1). Additionally, the software employs a linear approach to estimate the salvage value of each component, which represents

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the residual value of the element at the end of the system's operational lifespan, commonly referred to as depreciation. The salvage value is determined using the following formula [32]:

$$SV = \frac{C_{replacement} \times RCLT}{CLT} \tag{2}$$

where $RCLT$ refers to the remaining component lifetime at the conclusion of HRES operational period (measured in years), while CLT represents the total lifespan of the component (in years). It is important to note that, the salvage value is deducted from the overall costs during the calculation of the NPC, as it is treated as a cash inflow. Subsequently, the total annualized cost of the proposed HRES, $C_{ann,tot}$, is determined by summing up the NPC of each individual component. The primary components considered in the system include diesel generators, PV modules, WTs, inverters, and battery storage system. The total cost of the system can be expressed as follows [33]:

$$C_{ann,tot} = C_{ann,diesel} + C_{ann,PV} + C_{ann,wind} + C_{ann,Converter} + C_{ann,battery} - (SV_{diesel} + SV_{PV} + SV_{wind} + SV_{converter} + SV_{battery}) \tag{3}$$

where $C_{ann,diesel}$ represents the net present cost of the diesel generator, $C_{ann,PV}$ denotes the net present cost of the PV, $C_{ann,wind}$ signifies the net present cost associated with the wind turbine, $C_{ann,Converter}$ refers to the net present cost of the converter, and $C_{ann,battery}$ accounts for the net present cost of the battery storage system. Similarly, SV_{diesel} represents the salvage value of the diesel generator, SV_{PV} corresponds to the salvage value of the PV panels, SV_{wind} indicates the salvage value of the wind turbines, $SV_{converter}$ refers to the salvage value of the converter, and $SV_{battery}$ signifies the salvage value of the battery storage system.

The power output of the PV array is calculated as follows:

$$P_{PV} = Y_{PV} \times x_{PV} \times \frac{G_T}{G_{T,STC}} \times \left(1 + \alpha_p * \left(T_c - T_{c,STC}\right)\right) \tag{4}$$

where Y_{PV} is the the rated capacity of the PV array (kW), x_{PV} is the PV derating factor (%), G_T is the solar radiation incident on the PV array in the current time step (kW/m2), $G_{T,STC}$is the incident radiation at standard test conditions (1 kW/m2), α_p is the temperature coefficient of power (%/°C), T_c is the PV cell temperature in the current time step (°C), $T_{c,STC}$ is the PV cell temperature under standard test conditions (25 °C).

Wind turbines convert kinetic energy from wind into electrical energy. The power output depends on wind speed and the turbine's specific characteristics, it can be computed as,

$$P_{WT} = \begin{cases} 0 & if\ v < v_{cut-in}\ or\ v > v_{cut-out} \\ P_{rated} & if\ v_{rated} < v \leq V_{cut-off} \\ k \cdot v^3 & if\ v_{cut-in} \leq v < v_{rated} \end{cases} \tag{5}$$

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where v represents the wind speed measured in meters per second (m/s) at the turbine's hub height, which is a critical determinant of power generation. The turbine begins to produce power only when the wind speed reaches the cut-in speed, v_{cut-in}, which is the minimum operational threshold. Beyond the cut-out speed, $v_{cut-out}$, the turbine shuts down to avoid damage from excessive wind speeds. The turbine operates optimally within the range between these thresholds, reaching its maximum output, known as the rated power P_{rated}, under ideal conditions. Additionally, k is a proportional constant that reflects the turbine's design and efficiency, influencing the relationship between wind speed and power output [34].

A battery bank comprises one or more individual batteries, HOMER Pro represents a singular battery as a mechanism for storing a specified quantity of DC electricity. It characterized by a constant round-trip energy efficiency (RTE), alongside constraints regarding the rate of charging and discharging, the permissible depth of discharge to prevent damage, and the total energy throughput before necessitating replacement [35]. The state of charge (SOC) evolves over time as a function of charging and discharging processes:

$$E_{battery}(t+1) = E_{battery}(t) + \eta_{charge} \, . P_{charge}(t) - \frac{P_{discharge}(t)}{\eta_{discharge}} \tag{6}$$

where $E_{battery}$ (t) is the energy stored in the battery at time t, η_{charge} denotes the charging efficiency, accounting for energy losses during storage, $P_{charge}(t)$ is the charging power input (kW), $\eta_{discharge}$ represents the discharging efficiency, representing losses when releasing stored energy, $P_{discharge}(t)$ refers to discharging power output (kW). Converter plays a pivotal role in hybrid systems by facilitating the conversion between AC and DC powers, it can be modeled as,

$$P_{AC} = \eta_{conv} \, . P_{DC} \tag{7}$$

where P_{AC} is the AC power output (kW), η_{conv} refers to the conversion efficiency, indicating the fraction of input power successfully converted, and P_{DC} represents the DC power input (kW).

The generator utilizes fuel to generate electricity and simultaneously produces heat that may be employed in combined heat and power (CHP) applications. The generator's primary physical attributes are its maximum and minimum electrical power output, anticipated operational lifespan in hours, fuel type, and fuel curve, which correlates fuel consumption with electrical power generation [36]. HOMER Pro presumes the fuel curve is linear with y-intercept to get the generator's fuel consumption rate as follows:

$$F = F_0 \times Y_{gen} + F_1 \times P_{gen} \tag{8}$$

where F_0 is the fuel curve intercept coefficient, Y_{gen} is the rated capacity of the generator (kW), F_1 is the fuel curve slope, and P_{gen} is the electrical output of the generator (kW).

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HOMER Pro combines the annualized costs of each component with any additional expenses, such as penalties for environmental pollution, to compute the total annualized cost of the system, denoted as $C_{ann,tot}$. This value is critical because HOMER Pro utilizes it to derive two key economic indicators for the system: the total NPC and LCOE. Equation (9) is employed by HOMER Pro to calculate the total net present cost [31]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(x,R_{proj})}, \tag{9}$$

where $C_{ann,tot}$ is the total annualized cost, x is the annual real discount rate, R_{proj} is the project lifetime, and CRF is the capital recovery factor given by the Eq. (10).

$$CRF(x,R) = \frac{x(1+x)^R}{(1+x)^R-1} \tag{10}$$

where R is the project lifetime (in years). The NPC aggregates all expenditures and profits across a system's lifespan into a single present value, discounting future cash flows to the present using a discount rate defined by the designer. HOMER Pro presumes that, all prices increase at a uniform pace over the project's duration. Inflation may be excluded from the study by employing a real discount rate (adjusted for inflation) rather than a nominal discount rate. [31]. The designer can specify both the nominal discount rate and the inflation rate. Subsequently, it employs Eq. (11) to ascertain the actual discount rate.

$$x = \frac{x'-f}{1+f} \tag{11}$$

where x represent the actual discount rate, x' denote the nominal discount rate, and f signify the inflation rate. HOMER Pro uses Eq. (10) to compute the levelized cost of energy E_{prim} represents the principal load, E_{def} denotes the deferrable load served by the system annually, and $E_{grid,sales}$ indicates the quantity of electrical energy sold to the grid each year. The flowchart that represents the methodology framework of the study shown in Fig. 1. The framework consists of two main stages:

1. Pre-HOMER Evaluation

In this stage, the local resource data including solar and wind are collected and the energy demand profiles are analyzed. Also, the geographic and environmental attributes are evaluated and the feasibility of renewable energy sources is determined.

2. HOMER Optimization

In this phase, the collected data are fed to the HOMER software, then the configuration of the microgrid is constructed, and the electrical and economic profiles are developed. The software is implemented and Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) are analyzed. Finally, the optimal configuration of microgrid is selected.

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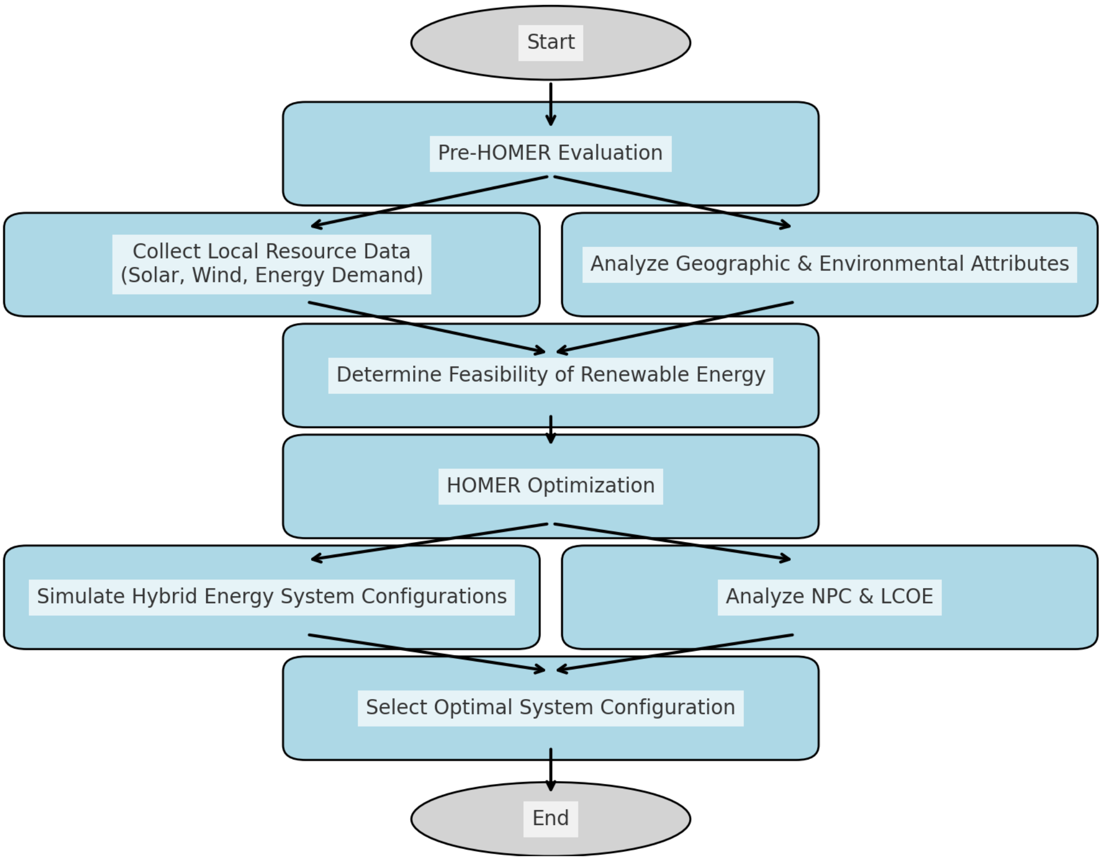

Fig. 1 Flow-diagram of the methodology

4. The proposed solution methodology based on HOMER Pro

HOMER Pro is a widely recognized optimization tool for simulating and identifying the most efficient configurations of energy systems. Its applications span from designing off-grid systems for remote areas to modeling grid-connected systems. The software integrates engineering and economic considerations by analyzing key parameters, including NPC, representing the total system cost over its lifetime. It also evaluates the LCOE to indicate the cost per unit of energy produced and quantifies carbon emissions to measure the system's environmental impact. Fig. 2 displays a vibrant and detailed screenshot of the HOMER Pro homepage, featuring Aljouf region, Abu Ajram city, which is prominently displayed on the map.

4.1 Load Profile

The peak load is central to understand the seasonal and daily dynamics of the power demand in Aljouf region, Abu Ajram city which highlights the requirements for an energy system to address variations across seasons and hours as shown in Figs. (3)-(5). The data shows a notable

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seasonality, with the highest monthly demand peaking at 23,700 kW in August. This amplitude displays the amplified cooling demands during the summer when outside temperatures reach their maximum. In July and June, the high peak loads are 22,700 kW and 20,300 kW, respectively. The average peak summer demand of 366,395 kWh/day indicates a significant energy requirement in the summertime. When using the load profile, a random variability factor is prescribed in HOMER software to cater for normal daily variations within a specific month. To ensure optimal power consumption estimates, HOMER has accounted for a 10 % error margin in day-to-day variations [37] and 10 % error margin in time-step fluctuations [33].

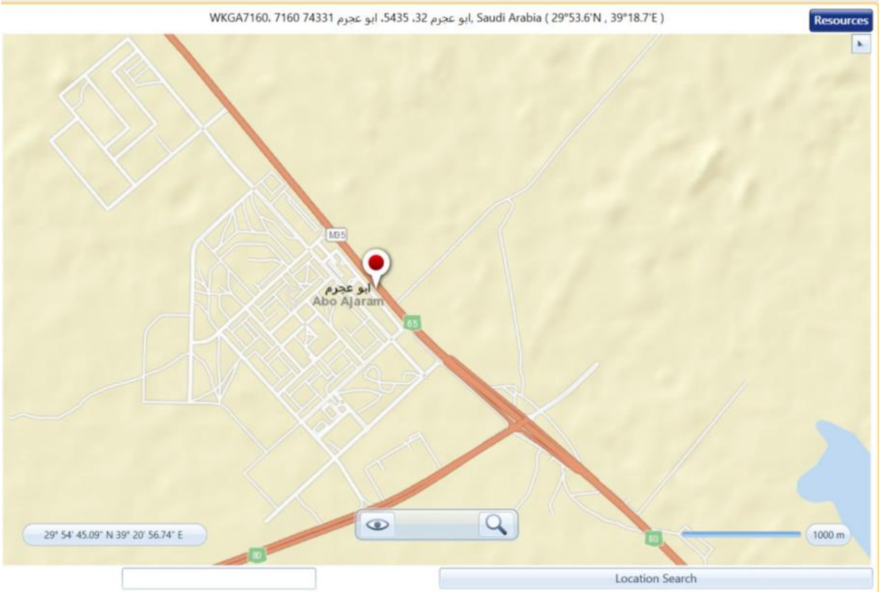

Fig. 2 HOMER Pro homepage highlighting Aljouf region, Abu Ajram city on the map

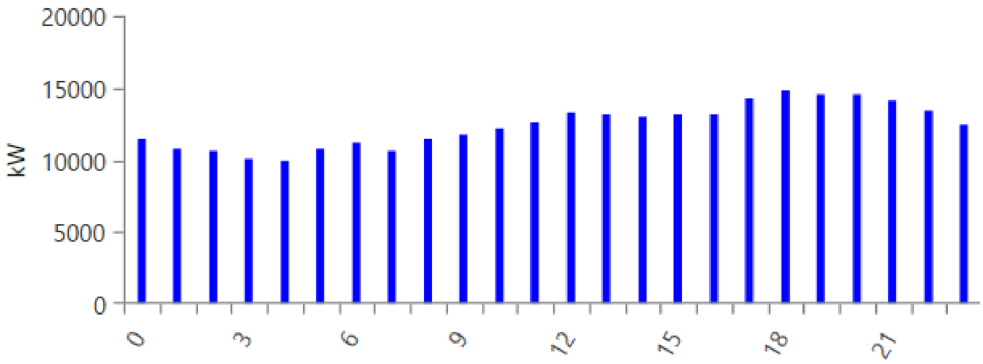

Fig. 3 Daily load distribution of Aljouf region, Abu Ajram city

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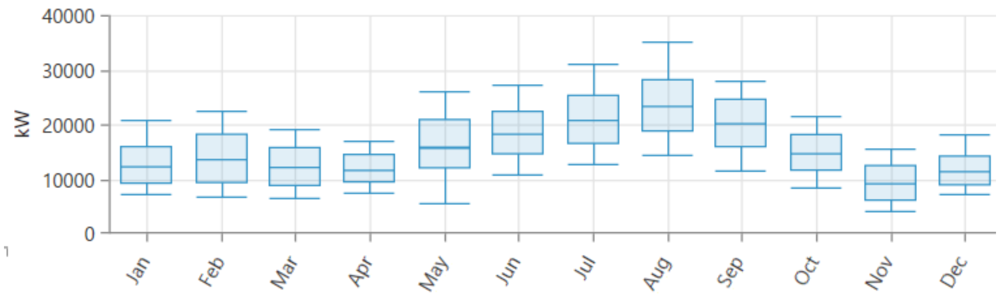

Fig. 4 Monthly load profile in Aljouf region, Abu Ajram city

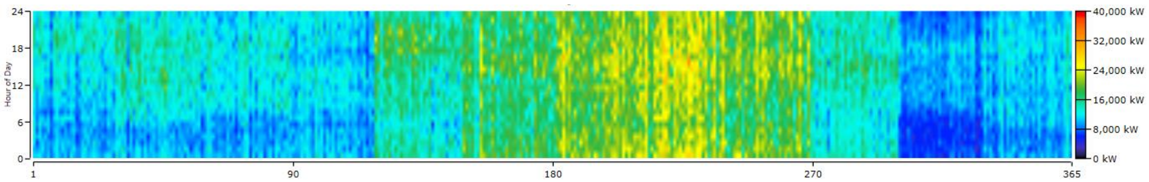

Fig. 5 Yearly load profile in Aljouf region, Abu Ajram city

4.2 Solar global horizontal irradiance resource

Aljouf region, Abu Ajram city is characterized by global horizontal irradiance (GHI) profile with high variation throughout the seasons, indicating the region's strong solar energy potential. Fig.6 shows the GHI in kWh/m²/day is high during months May-August, as June month contributes the highest radiation at almost 8,000 kWh/m²/day. This peak aligns with the summer months when the region enjoys longer daylight hours and greater solar insolation, making this season optimal for solar energy production. Conversely, during winter, specifically December and January, the GHI values reach the lowest levels with averages below 3,000 kWh/m²/day [38].

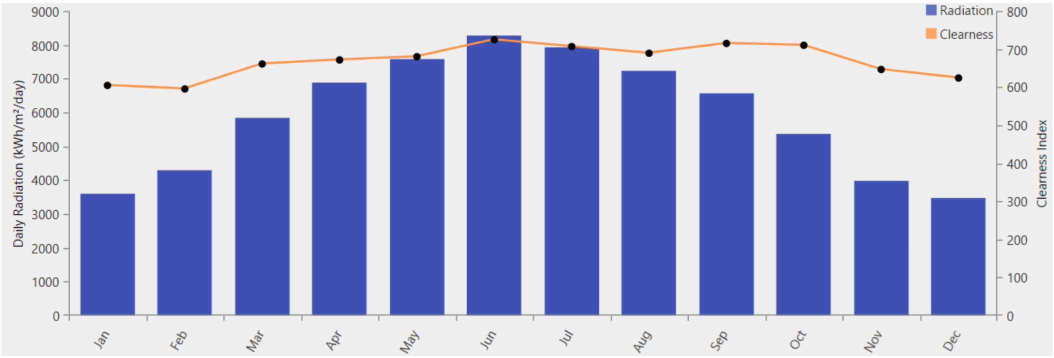

Fig. 6 Average monthly GHI for Aljouf region, Abu Ajram city

4.3 Wind resource

Fig. 7 shows the average monthly wind speed data for the Aljouf region, Abu Ajram city; it is a high potential area for wind energy generation. The mean monthly wind speed varies between

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about 4.0 m/s in the calmer months, like September and October, to close to 5.0 m/s in the peak months of May, July, and August. A key metric in assessing the potential of wind energy projects is the consistency of wind speeds above 4.0 m/s throughout the year and wind current speeds of 6.6 m/s or more when the average velocity of wind currents exceeds 5.4 m/s. Modern wind turbines can now successfully and effectively handle the development of wind turbines at such wind speeds and can be used in the later stages of wind power generation in Aljouf region, Abu Ajram city [38].

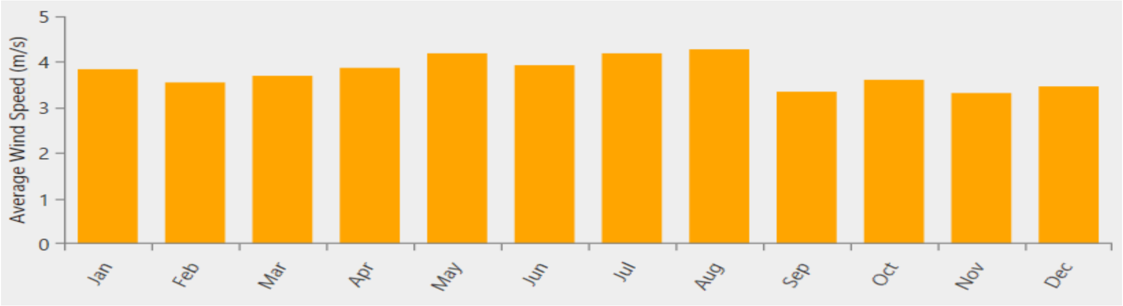

Fig. 7 Average monthly wind speed data for Aljouf region, Abu Ajram city

4.4 Input data

This subsection outlines the input parameters for each system component as configured in HOMER Pro. These parameters were utilized to optimize the sizing of solar PV, battery storage, and converters. For the generators and wind turbines, multiple discrete size options were tested through iterative analysis to determine the optimal configuration that minimizes the system's NPC. A generic flat plate PV system was considered, the input specifications of the PV system are described in Table 2.

Table 2 Specifications of PV System

Parameter	Value
Capital cost ($/kW)	1000
O&M cost ($/kW/year)	10
Replacement cost ($/kW)	1000
Lifetime (years)	25
Efficiency (%)	20
Temperature coefficient	-0.35
Operating temperature	40

A generic 1650 kW model has been selected for the wind turbines utilized in the considered HRES. These turbines produce an alternating current output. The cost parameters including capital, replacement, and operational costs are summarized in Table 3. Additionally, the input specifications of the diesel generators are described in Table 4.

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Table 3 Wind turbine parameters

Parameter	Value
Capital cost ($)	1500000
O&M cost ($/year)	10000
Replacement cost ($)	750000
Lifetime (years)	25
Highet	78
Rated speed	11m/s

Table 4 Specifications of diesel generator

Parameter	**Value**
Capital Cost ($) installed	140,000 each
O&M Cost ($/op. hr)	1
Replacement Cost ($)	126,000
Minimum load ratio	25
Lifetime (h)	15,000

The nominal discount rate for the project, spanning a 25-year lifetime, is established at 6.86%, with an inflation rate of 2.5%. A simulation time step of one hour is utilized for all system configurations in operation. The system design precision, representing the maximum allowable relative precision of decision variables for simulation convergence, is set to 0.01. Similarly, the NPC precision, indicating the maximum allowable relative error in NPC for simulation convergence, is also maintained at 0.01 [39].

5. Discussion Results and discussion

This section evaluates the techno-economic and environmental performance of six microgrid configurations designed for Aljouf region, Abu Ajram city. Each configuration integrates renewable energy sources, solar PV and WTs, as well as battery storage, diesel generators, and grid connectivity. The analysis focuses on key performance metrics including NPC, LCOE, system reliability, and environmental impact. The findings provide insights into the optimal design of HRES for remote and arid regions. The six microgrid configurations are simulated using HOMER Pro to assess their performances under varying conditions. The first considered case is shown in Fig. 8, it's a stand-alone system combining 117.8 MW of solar PV, 8,250 kW of wind turbines, 87 strings of 4-hour Li-ion batteries, and 3,500 kW diesel generator. This configuration achieved NPC of $227.4 million and LCOE of $0.112/kWh. In this configuration, the solar PV contributed 91.1% of the total energy production, while wind accounted for 8.8%. Despite high renewable energy penetration, the system generated 107.9 GWh/year of excess electricity, highlighting inefficiencies in demand-supply alignment. The

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system's CO2 emission is 311,965 kg/year, primarily due to minimal diesel usage. Recommendation for improving stand-alone systems include optimizing system sizing, integrating advanced storage technologies, and exploring energy export applications to reduce curtailment is essential.

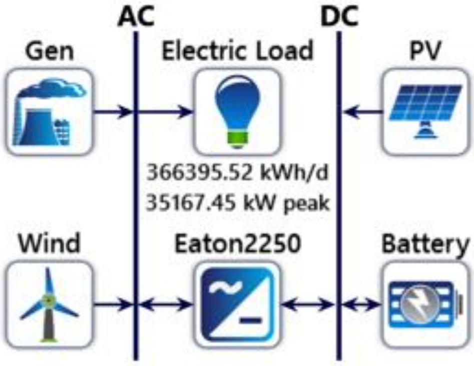

Fig. 8 Schematic of case 1

The second considered scheme is shown in Fig. 9, it's a grid-connected system with 122.1 MW wind turbines, 154 kW of solar PV, and 3,500 kW diesel generator. The system demonstrated superior performance with NPC of 88.6 million and LCOE of 0.0148/kWh. In this configuration, the wind energy contributed 86.0% of the total production, while grid purchases accounted for 14.0%. The system achieved negative CO2 emission with a value of -130,131,900 kg/year as the renewable energy exports offsetting grid emissions. However, its reliance on grid connectivity limits energy autonomy. Increasing PV capacity and implementing demand-side management can enhance system resilience and reduce grid dependency.

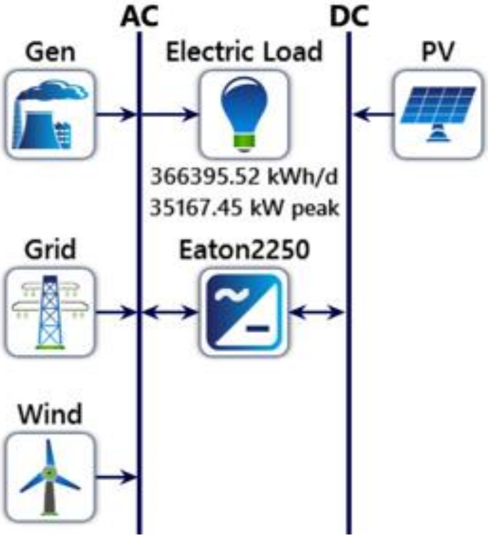

Fig. 9 Schematic of case 2

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Fig. 10 shows the third considered system which comprises 313.5 MW of wind turbines, 278 strings of 4-hour Li-ion batteries, and 3,500 kW diesel generator. The system faced significant challenges as it achieved NPC of 555 million and an LCOE of 0.273/kWh, this is the most expensive configuration. In this configuration, the wind energy contributed 100% of the total production, but the system generated 724 GWh/year of excess electricity, reflecting inefficiencies in aligning renewable generation with demand. Despite low CO2 emission, this configuration's high costs and inefficiencies highlight the need for optimizing wind capacity and exploring energy export applications.

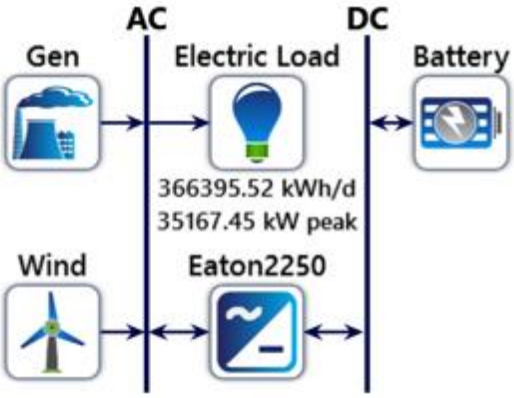

Fig. 10 Schematic of case 3

The fourth case is shown in Fig. 11, it's a grid-connected system integrating 46.2 MW of wind turbines, grid connectivity, and 3,500 kW diesel generator. The configuration acheived NPC of \$82.1 million and LCOE of \$0.0263/kWh. Wind energy contributed 62.5% of the total production, while grid purchases accounted for 37.5%. The system's CO2 emission is 3,367,524 kg/year due to grid energy sourced from fossil fuels. Battery storage can improve energy autonomy and reduce grid reliance, enhancing the system's sustainability.

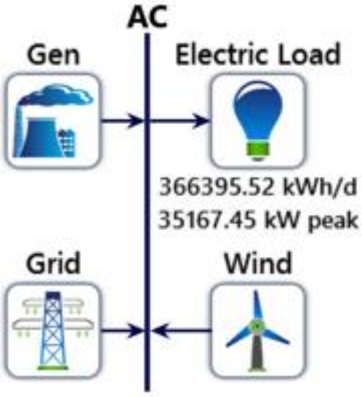

Fig. 11 Schematic of case 4

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Fig. 12 shows the fifth considered configuration, it's a stand-alone system combining 124,320 kW of solar PV, 96 strings of 4-hour Li-ion batteries, and 3,500 kW diesel generator. The fetched NPC is $235 million and LCOE is $0.116/kWh. In this scheme, the solar PV contributed 99.9% of the total production, with minimal diesel usage of 0.0645%. However, the system generated 94.4 GWh/year of excess electricity, reflecting inefficiencies in demand-supply alignment. The system's CO2 emission is 131,745 kg/year. Optimizing PV capacity and integrating advanced storage technologies can improve system efficiency and reduce costs.

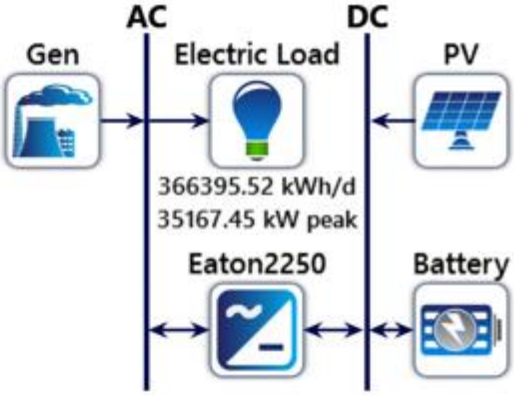

Fig. 12 Schematic of case 5

The last considered case is shown in Fig. 13, it's a grid-connected system with 31,814 kW of solar PV, grid connectivity, and 3,500 kW diesel generator, the fetched values of NPC and LCOE are $107 million and $0.0491/kWh, respectively. The solar PV contributed 43.0% of the total production, while grid purchases accounted for 57.0%. The system's CO2 emission of this configuration is 48.4 million kg/year due to grid energy sourced from fossil fuels. Expanding PV capacity and reducing grid reliance can enhance sustainability and energy autonomy.

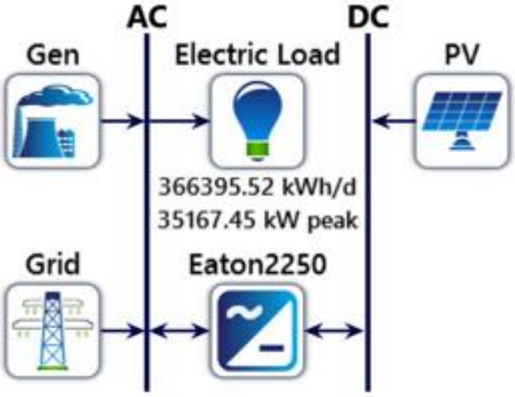

Fig. 13 Schematic of case 6

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A comparison between the considered stand-alone systems, Cases 1, 3, and 5, is tabulated in Table 5, the configurations achieved energy independence but faced significant challenges, including high NPC and LCOE due to battery storage costs and excess electricity generation. Case 1, which combines solar PV, wind turbines, and battery storage, is the most viable stand-alone option, balancing cost, reliability, and environmental impact. However, optimizing renewable energy capacity and integrating advanced storage technologies are essential to improve efficiency and reduce costs.

Table 5 Comparison of the considered stand-alone systems

Case	NPC ($M)	LCOE ($/kWh)	CO2 emissions (kg/yr)	Excess energy (GWh/yr)	Unmet load (kWh/yr)	Key challenges
Case 1: Wind, PV, generator, and battery	227.4	0.112	311,965	107.9	1,187	High excess energy and costly battery storage
Case 3: Wind, generator, and battery	555.0	0.273	0	724.0	78,455	Very high excess energy and expensive batteries
Case 5: PV, generator, and battery	235.0	0.116	131,745	94.4	21,478	High excess PV generation and costly batteries

Also, the comparison between the considered grid-connected systems, Cases 2, 4, and 6, is given in Table 6, these schemes offer superior cost-effectiveness and reliability. Case 2, which integrates wind turbines, solar PV, and grid connectivity, is the optimal configuration, with NPC of $88.6 million and LCOE of $0.0148/kWh, and negative CO2 emissions. However, grid dependency limits energy autonomy and increasing renewable energy capacity are necessary to reduce reliance on grid imports.

Table 6 Comparison of the studied grid-connected Systems

Case	NPC ($M)	LCOE ($/kWh)	CO2 emissions (kg/yr)	Excess energy (GWh/yr)	Unmet load (kWh/yr)	Key challenges
Case 2: Wind, PV, generator, and grid	88.6	0.0148	-130,131,900	0	0	Grid dependency and minimal PV utilization
Case 4: Wind, generator, and grid	82.1	0.0263	3,367,524	0	0	Grid reliance and no storage for excess wind

Case 6: PV, generator, and grid	107.0	0.0491	48,382,340	0.828	0	Grid dependency and moderate CO2 emission

The fetched results confirmed the reliability and competence of the HOMER Pro in getting the best economic HRES configuration installed in Aljouf Region, Saudi Arabia. It can be recommended as a reliable tool for designing a MG including RESs in many locations inside Saudi Arabia.

6. Conclusion

In this study, a microgrid (MG) situated in the Aljouf region of Saudi Arabia, renowned for its high solar irradiation and moderate wind resources, is examined. This region is believed to have significant renewable potential. In this study, a hybrid photovoltaic (PV)-wind turbine (WT)-battery system tailored to the local environment and energy needs has been examined from a techno-economic perspective. The reliability, environmental effect, levelized cost of energy (LCOE), and net present cost (NPC) of six HRES configurations are determined through simulations using HOMER Pro software. The findings demonstrate that, the grid-connected systems, particularly Case 2, offer the most cost-effective and sustainable solution achieving LCOE of \$0.0148/kWh and negative carbon emissions due to renewable energy exports. Additionally, stand-alone systems faced significant challenges including high costs and excess electricity generation, primarily due to their reliance on battery storage for managing renewable energy variability. The analysis underscored the importance of grid connectivity in enhancing system reliability and reducing costs. However, stand-alone systems remain viable for remote areas without grid access, providing advanced storage technologies and demand-side management strategies are implemented to optimize performance. The future work will focus on exploring innovative storage solutions such as hydrogen, and tailoring system designs to regional climatic conditions. Also, long-term performance evaluations as well as region-specific optimization to further enhance the feasibility and scalability of HRES will be considered in the next works.

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Competing interests

The authors declare no competing interests.

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