

Techno-economic-environmental evaluation of a hybrid energy system in a residential building integrated renewable energies and comparison of different climate conditions

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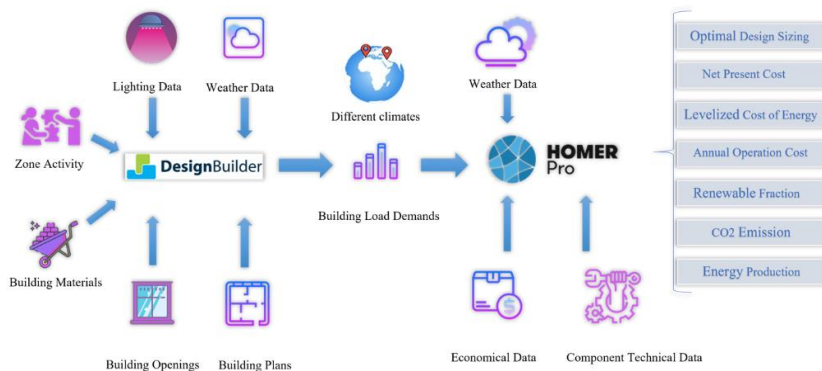
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Abstract

The purpose of this research is to investigate the technical, economic, and environmental aspects of the use of distributed and renewable production resources which causes reducing the reliance on fossil resources and greenhouse gas emissions. Also, examining the participation rate of renewable energies in supplying electricity, heating and cooling required by consumers, as well as technical and economic examination of the establishment of hybrid systems. Design Builder software has been employed to simulate and obtain the building's electrical, heating and cooling loads. In the next step, after simulating the exist in conditions, the potential of renewable energies such as solar and wind energy and their combination with the simultaneous production system to supply the building's load was investigated. HOMER Pro software has been employed to simulate renewable energies. The results indicate that the energy system in Tarifa with 0.318 \$/kWh has a more expensive Levelized Cost of Energy (LCOE) rather than Basrah with 0.205 \$/kWh. Additionally, the Net Present Cost (NPC) for Basrah and Tarifa is \$ 5,557,327 and \$ 6,542,097, respectively. Optimized system configurations reveal that this system in Basrah generates 728,341 kg of CO₂ annually while in Tarifa produces 280,702 kg of CO₂ annually. The optimal size of the wind turbine, photovoltaic, diesel generator, battery, and converter, are 102 Units, 495 kW, 1200 kW, 994 Strings, 416 kW for Basrah and 87 Units, 393 kW, 910 kW, 785 Strings, and 471 kW for Tarifa.

Graphical Abstract



1. Introduction

Sustainable development is a general concept in all aspects of human life, including social, economic, environmental, etc. The United Nations solves the pressing challenges for humanity by providing a guideline, named sustainable development goals (SDGs). This program includes SDG7, which is pursued by having access to clean and affordable energy due to stringent environmental quality standards and increasing energy supply requirements. Therefore, achieving this goal requires renewable development [1]. In whole developing countries energy sustainability on a global scale must be considered seriously as a policy, so renewable energy is an important issue [2]. Renewable energy possesses nonpolluting characteristics, also is abundant and free. To achieve the seventh SDGs, efforts should be made using renewable energy sources such as wind, hydro, solar and thermal energy, particularly, in all developing countries to encourage power generation growth and help the environment [3]. Since one of the axes of achieving sustainable development is optimizing energy consumption, it is very important to provide solutions that can reduce energy consumption in the building sector by using renewable energies. One of the solutions to this problem is the use of hybrid systems. Hybrid systems consist of renewable and non-renewable resources, and is necessary to be present in the hybrid system. Hybrid systems which propose the new technological options attended considerable interest because of their suppleness of operation, flexibility and economical attractiveness [4].

1.1 Literature Review

Olatomiwa *et al.* through assessing environmental impact of a hybrid energy system design, techno-economic analysis and demand side management (DSM) methods, minimize the cost and increasing the renewable energy shares of a health institution [5]. By combining the renewable energy to the existing system, Arunachalam *et al.* minimize the emissions and select a reliable hybrid microgrid system and optimize the size to meet the load [6]. Trinh *et al.* discuss about the renewable energy converting into electrical power in purpose of green energy globalization, industrial application, sustainable electrical production and integration, while increasing development of sustainable electricity has been applied by smart-grids, micro-grids, hybrid systems and optimal algorithm methods [7]. Towards supporting SDGs target and resiliency, Bertheau *et al.* hybridize 132 diesel-based grids with solar PV with renewable energy sharing of 25 %, which saves 230 million liters annually [8].

For an off-grid residential sector, Al-Falahi *et al.* analysis the performance, optimize the size and model the standalone hybrid energy system which includes photovoltaic/wind turbine/battery (PWB), used in Anson Bay, Tasmania, Australia [9]. Ameur *et al.* designing, sizing a hybrid power system that combines a PV system with battery storages and network grid in which meeting the energy demands of a house located in the Ifrane region, Morocco [10]. Also, Mehdizadeh Marzebali and Mohamadian designed an off-grid hybrid energy system combining solar, wind, and battery-hydrogen storage for a faculty building at Amirkabir University. Using Design Builder and HOMER, they optimized solar to supply 89% and wind 10% of energy. The system costs \$6.77M, with \$0.377/*kWh* production cost, reducing CO₂ emissions to 102,586 *kg/year* [11].

Due to sustainability in transportation, Boddapati *et al.* analysis the performance of a hybrid energy-based electric vehicle charging station (EVCS) by HOMER Software, which includes WTs, PV panels, DG and battery storage in its configuration at four different locations in Denmark [12]. Also, Nassar *et al.* proposed a hybrid renewable energy system integrating 6000 *MW* solar PV, 385 *MW* wind, and 762,161 *MWh* pumped hydro storage (PHS) to address Libya's 9,744,033 *MWh* electricity shortfall. Using multi-criteria optimization, they minimized LCOE (\$132.1/*MWh*), payback period (7.54 years), and CO₂

emissions (11,624 *kton*), achieving full grid stability. The study highlights PHS as a viable solution, saving \$816.246M in social costs and \$2.189B in fuel costs.

Tariq *et al.* Provide a sustainable water solution by utilizing PV panels, WTs, diesel generators, Absorbent Glass Mat (AGM), Li-ion (Lithium-ion) and Pb-acid (Lead-acid) as a hybrid energy system component to support the energy requirements of a portable water filtration plants in Mayan region of Yucatan, Mexico [13]. To achieve sustainable, affordable and reliable way to access energy through modern energy systems towards SDGs, the grid-independent hybrid renewable energy microgrid (HREM) with a proposed configuration of wind turbine/photovoltaic /battery energy storage system/diesel generator (WT/ PV /BESS/DG) has been modeled. Also has been optimized TEE to meet the remote community residential in South India load demands [14]. Karunanithi *et al.* consider a hybrid renewable energy microgrid HREM that employs WT, PV arrays, diesel generator set and a battery energy storage system (BESS) in its configuration to satisfy the load demands of a remote, rural community residential area in the south Indian state of Tamil Nadu. Then they optimize this off-grid (HREM) that focuses on the efficient, sustainable, reliable and affordable growth of energy systems due to the principal aim of SDGs [15].

Al-Ghussain *et al.* maximize the renewable energy share while minimizing the levelized cost of electricity less than or equal to the local electricity tariff in Middle East Technical University Northern Cyprus Campus by optimizing the size of hybrid energy system which include PV and WT with battery-bank and pumped hydro storage [16]. A simulation of a hybrid energy system includes wind turbines, solar PV, DG, and lithium-ion batteries has been done in different configuration for an off-grid area in Philippine which is a 147 diesel-based plant with 0.227 USD/*kWh* levelized electricity, 58.58 % renewable energy share and saves 108 million USD annually [17].

As observed before, most of these researches, proposed a backup system that can increase the reliability of the system. Where the supply is more than demands it will save in the storage system and if there is supply shortage, storage system or DG support the system. If the storage capacity becomes larger the initial cost will increase and when it becomes smaller, cost of conventional fuels increases and causes instabilities. Hence, the proper capacity size of the energy storage system is important for the microgrid to have efficient, reliable and economical operation. Hence, ElBidairi *et al.* find the optimal size of the energy storage system and does a hybrid energy management for standalone microgrid in Flinders Island, Australia [18]. Storage capacity requirements can be reduced if a regulated micro-hydropower system integrate with a small pond. Therefore, Poudel *et al.* using Hybrid2 framework to analysis micro-hydropower system in a non-dimensional form by empirical modeling [19]. Zheng *et al.* Employ the PV and WT by hybrid energy management approach to supply the requirements of the electric charger by boosting renewable energy, notably with flexible reverse supply in storing the excessive energy to the storage modules or selling it back to power grid [20]. Ogarek *et al.* investigate the works which does the feasibility, ecological and economic analysis about hybrid renewable energy system (HRES) and hybrid energy storage system (HESS) which includes hydrogen and their operation in aspect of lifespan and work efficiency are optimized [21]. Mentioned in all sources, optimization is an inseparable part of the designing which is done through different methods. Hassan *et al.* do multi-objective sizing optimization using non-dominated sorting genetic algorithm-II, while assessing six scenarios to meet the demand and reliability and technical constraints are satisfied and considering job creation as a social indicator. A hybrid renewable energy system comprising WT, solar PV, biogas generator (BG), micro-hydro turbine (MHT) with vanadium redox flow (VRF) battery is proposed to meet

the load demand which is in the range of 951-1526 kWh/day in a remote rural part of Bangladesh [22]. Wang *et al.* provides a promising off-grid hybrid energy system by combining WTs and hydrogen storage system while optimizing by biological-inspired algorithm also due to sustainable development, introduces wind energy resources stand on hydrogen storage, as clean alternative sources [23]. Through HOMER Pro software, techno-economic evaluation and the potential of available resources assessment is done to define the feasibility of a standalone HRES to supply the load demands of a remote area in Bangladesh [24, 25].

Tan and Luo proposed a distributed energy system combining solar, geothermal, aerothermal, natural gas, and grid resources, optimized through a novel heuristic operation strategy. Simulations demonstrated its feasibility, achieving a 16.7% reduction in operation costs, 4.2% lower CO_2 emissions, and a 117% rise in the non-renewable energy ratio compared to conventional methods, showcasing its practicality in engineering applications [26]. Baghel *et al.* investigate the techno-economic analysis of a HRES that encompasses PV modules and biomass gasifiers for the mechanical engineering department at Delhi University of Technology, India. The building's peak load and daily energy consumption are 65 kW and 588 kWh , respectively. Optimization results through HOMER Pro demonstrate that Net Present Cost (NPC) is \$ 507,737, Cost of Energy (COE) is \$ 0.207 with 3,76,780 kWh annually power generation that PV generates 76.6 % and 23.4 % is generated by biomass gasifier [27].

Araoye *et al.* study techno-economic analysis of four HRES configurations including PV, WT, DG, Hydropower and Biogas generator for 88 Nsukka villages as remote Community villages. The metaheuristic novel Grasshopper Optimization algorithm (GOA) method and HOMER Pro software employed to minimize NPC, COE and unmet load [28]. The optimized configuration which comprises (biogas/DG) has \$0.01783 per kWh as COE. To supply the average 15545 kWh daily load demand, El-Maaroufi *et al.* through HOMER Pro, analysis different configurations of HRESs comprise biomass, wind, and solar in residential areas in Zoumi [29]. The most cost-effective economic results show NPC, and COE are \$ 0.125/ kWh , and \$ 8.29 million, respectively. Technically the system produces 11.14 GWh power annually with 100 % renewable fraction and reduces CO_2 by 5900 tons annually. Different configurations of HRESs which consist of biogas, PV, battery, and converter are studied by Ennemiri *et al.* through HOMER Pro for a commercial building in Berkane-Morocco. The winner configuration (biogas/PV) generates 594,436 kWh of electricity annually, and 263 kg of CO_2 annually, while the PV and biogas generator capacities are 231 kW and 170 kW . Optimal economic results show NPC of \$ 1.41 M and LCOE of \$ 0.280 / kWh [30]. Nadeem *et al.* designed an off-grid HRES encompassing Biomass and PV as renewable energies, and Li-ion batteries for storage systems. The optimization results have been done through HOMER Pro software showing the capacity of PV panels, biogas generator, and Li-ion batteries, 11.5 kW , 15 kW , and 16 kW , respectively, generating 71,280 $kWh/year$. NPC and LCOE are \$ 95,858 and \$ 0.104/ kWh , respectively while the period payback is 7.7 years [31].

Toward achieving SDG 6 & 7 Kumar *et al.* design a poly-generation energy system consisting of a biogas-based micro gas turbine, biodigester, PV, and biogas storage for un-electrified regions of Mago, Thingbu. Using solid waste as a biogas source increases social hygiene and energy efficiency. The Output results from HOMER software show the system generates 59330 kWh of electricity, 17842 kWh of heating, and 5469 kg of CO_2 annually, while NPC and COE are Rs. 38.87 lakh, Rs. 5.49/ kWh [32]. Amer *et al.* optimized a 30-kW photovoltaic (PV) system for Wadi AlShatti University, Libya, achieving an LCOE of

\$0.156/*kWh* and an 11-year payback period. The system reduces CO₂ emissions by 611,850 tons annually, supporting Libya's renewable energy goals. Their study highlights PV solar as a cost-effective, sustainable solution for institutional energy needs [33]. Campos *et al.* analyzed HRES economic and ecological for isolated rural communities in Joao Pinheiro to find an efficient configuration that encompasses solar and biomass as renewable energy sources. The optimized configuration results in LCOE, \$ 0.034/*kWh*, and 17.43% as overall energy efficiency with 9.28e-05 kgCO₂/\$ for ecological efficiency indicator and environmental impacts [34].

Kumar and Rao used HOMER Pro to model hybrid renewable energy systems (HRES) in Vaddeswaram, Andhra Pradesh, proposing two configurations: HRES-1 (solar panels and wind turbines) and HRES-2 (solar panels, wind turbines, and bio-generator). The study emphasized minimal net present cost and environmental impact, validating year-round efficiency [35].

1.2 Novel Aspects of This Research

This research introduces a novel approach to evaluating the integration of scattered and renewable energy resources for reducing fossil fuel consumption and greenhouse gas emissions. The study is distinguished by its detailed dynamic energy simulation, conducted hourly throughout the year using Design Builder software, rather than relying on typical days or monthly averages. This allows for a more accurate assessment of the building's electrical, heating, and cooling loads. The research considers two distinct locations with varying weather, climate, geographical, and economic data, such as interest and inflation rates and fuel prices. These variations present unique challenges and opportunities in simulating building energy demand, system sizing, optimization, and energy system design. The innovative aspect lies in the comparative analysis of these locations, highlighting the differences in LCOE and NPC, as well as the environmental impact in terms of CO₂ emissions [36].

The study employs a hybrid energy system combining wind turbines and solar panels, which utilize less conventional, green energy sources. The integration of lead-acid battery energy storage enhances the system's performance and stability, while the inclusion of a diesel generator ensures reliability by providing backup power. Optimization is achieved through HOMER Pro software, which dynamically simulates and optimizes the TEE aspects from an economic perspective, aiming to reduce CO₂ emissions and improve overall efficiency.

The results demonstrate significant differences between the two locations. The optimal sizes of the WT, PVs system, DG, battery, and converter are also compared, providing valuable insights into the most efficient configurations for each location.

The study is structured as follows:

- 1 the first part introduces the literature of previous works;
- 2 the second part describes the locations and their characteristics, such as weather data;
- 3 the third part details the building geometry and sample plan;
- 4 the fourth part models the system components through equations and presents their technical and economic data;
- 5 the fifth part shows the outputs and compares the locations;
- 6 and the final part abstracts and discusses the results, offering proposals for future work.

This comprehensive approach not only advances the understanding of hybrid renewable energy systems, but also provides a robust framework for future research and practical applications in diverse geographical and economic contexts.

2. Methodology

Steps of this article is shown in the **Fig. 1**. Building data such as zone activity, plans, location, weather and materials data are essential to simulate the building energy and determine electrical, heating and cooling load requirements. The next step after finding the load demand, is designing the system energy via HOMER Pro software. HOMER Pro requires components technical, economics and weather data of the location along with constraints of resources and controller strategy of the system.



Fig. 1. Research methodology.

2.1 Location and Weather Data

Two cities with different economic, weather and location characteristics have been chosen to do the analysis. Tarifa is a Spanish municipality in the province of Cádiz, Andalusia with $36^{\circ} 0.9'$ Latitude (North), $5^{\circ} 36.3'$ Longitude (East), also 17.7°C , 6.13 (m/s) and 4.87 (kWh/m²/day) as annual average of temperature, wind speed and solar radiation, respectively.



Fig. 2. Case Study Locations Across Various Climates.

Basrah is a city in southern Iraq located on the Shatt al-Arab with $30^{\circ}31.6'$ Latitude (North), $47^{\circ} 46.4'$ Longitude (East), also 26.07°C , 5.94 (m/s) and 5.09 (kWh/m²/day) as annual average of temperature, wind speed and solar radiation, respectively.

Fig. 2 illustrates the locations in different climates. Fig. 3 shows the comparison monthly average of wind speed (m/s), temperature (°C) and radiation ($kWh/m^2/day$) which is gathered from NASA.

2.2 Design Builder Software

Design Builder software is used for building modeling from various aspects such as building physics (building materials), building architecture, cooling and heating systems, lighting system, etc. It can model all aspects of the building.

In addition to modeling the building's heating and cooling load, it dynamically models various building energy consumption such as heating, cooling, lighting, household appliances, hot water consumption, etc. The modeling engine of this software is Energy Plus, developed by the U.S. Department of Energy and is one of the most accurate software available.

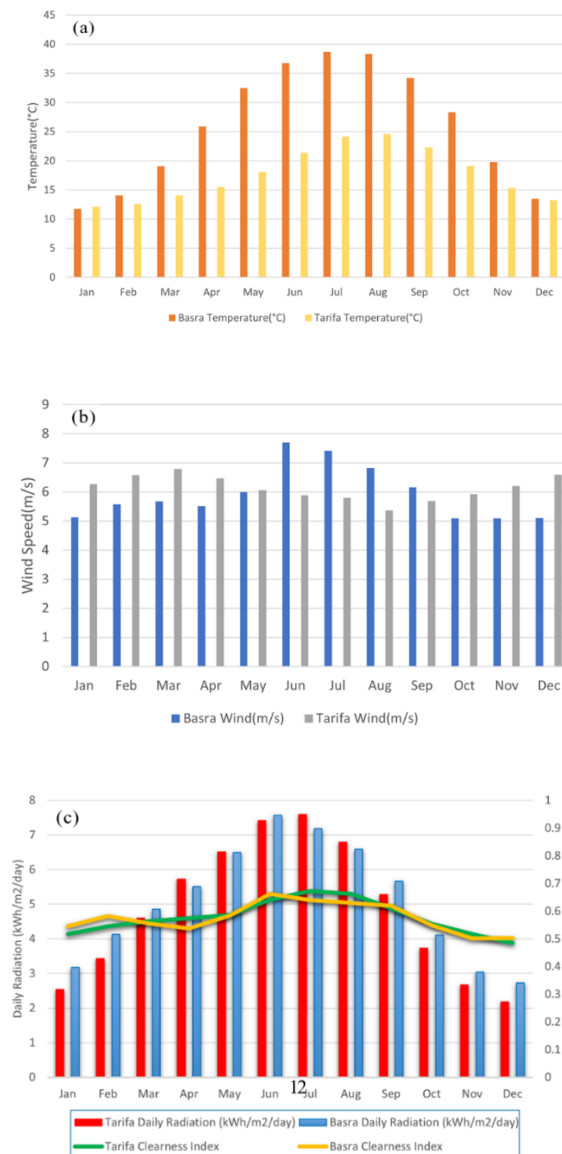


Fig. 3. (a) Temperature (°C). (b) Wind Speed (m/s). c) Radiation ($kWh/m^2/day$) of Basrah and Tarifa.

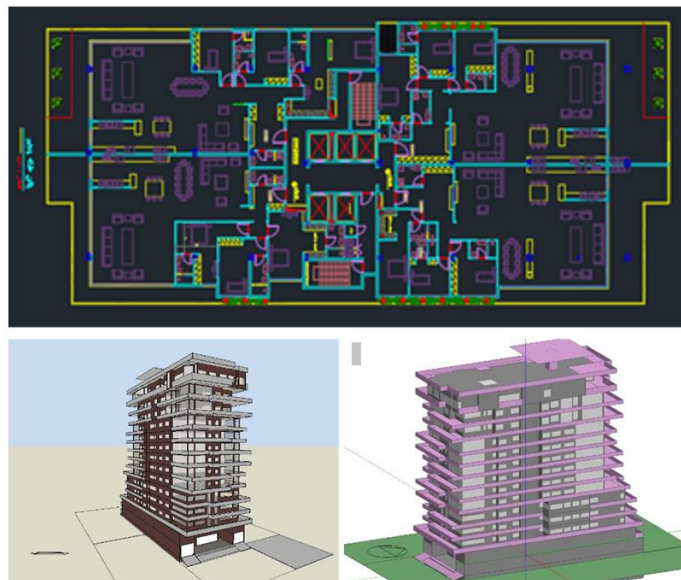


Fig. 4. Fifth floor plan and rendered view of the building structure.

2.3 Case Study

In this study, the residential building was considered to be simulated in the design builder software. **Fig. 4** shows the sample plan of the fifth floor of the building and the structure of the building during the simulation process. This building presents a new design of a high-rise residential building, featuring a penthouse, residential units, public pool and sauna, Turki bath, book cafe, and fourteen floors on the ground floor and three basement levels dedicated to parking. In particular, this project incorporates a novel approach that takes into account the temperature of the soil at depth in the calculations. The simulation load demands as output are shown in the results. Furthermore, the differences between these two regions are not solely related to climate; there are also distinctions in terms of the economy and the regulations established in the area, which significantly impact and determine energy cost calculations.

2.4 Systems Description

Having enough information about the structure of each component is essential to design the optimal system and observe the system's performance under different conditions. The desired hybrid system consists of photovoltaic panels, wind turbines, diesel generator, battery energy storage, boiler, and electrical chiller.

Fig. 5 shows the schematic description of the proposed hybrid system to supply the load demands of the building.

The operation strategy of the system is in this way that photovoltaic array and wind turbine as renewable energy sources supply the demand of the building simultaneously. Surplus produced power will charge the battery bank until it getting fully charged. When electricity is produced below the load demand, battery bank storage and diesel generator will operate as backup and supply the load. Diesel generator also has heat recovery system and also can produce heat power which is useful in the cold months of the year. At the same time, boiler uses natural gas to produce the main heat load of the building and electrical chiller uses electrical power.



Fig. 5. Schematic diagram of the hybrid system.

2.5 Components modeling

2.5.1 Wind Turbine

The wind turbine converts the kinetic energy of the wind into mechanical energy and produces electricity by transferring mechanical energy to the generator axis. The output power of the wind turbine is a function of the wind speed. This power is different depending on different manufacturers in different wind speed values. The power output of the wind turbine can be calculated using the following formula [37]:

$$P_{WT} = \begin{cases} 0 & V \leq V_I \text{ or } V \geq V_O \\ P_{Nom} \left(\frac{V - V_I}{V_R - V_I} \right)^3 & V_I < V < V_R \\ P_{Nom} & V_R \leq V < V_O \end{cases} \quad (1)$$

Where P_{WT} is wind turbine generated power, P_{Nom} is wind turbine rated power, V_R is wind turbine nominal speed, V is wind speed, V_I is cut in speed, V_O is cut out speed. And also, $V_{Z,t}$ is the wind speed at the wind turbine hub height (h_z) and it is calculated from:

$$V_{Z,t} = V_{0,t} \left(\frac{h_z}{h_0} \right)^\alpha \quad (2)$$

where, $V_{0,t}$ is the wind speed at a certain elevation (h_0) and α is the wind shear coefficient and often it is considered as 1/7.

2.5.2 Photovoltaic Panel

In Photovoltaic system, the radiant energy of the sun is directly converted into electricity. The power produced in the photovoltaic panel is DC, therefore, a direct current to alternating current converter is used in this system. The production power of the photovoltaic panel is obtained from the first part of equation 3 [35].

In the first part of this equation photovoltaic temperature is not considered in the output power. If the cell temperature goes up the power output goes down, so the second parts of Eq. 3 is considered [38]:

$$P_{pv} = W_{pv} f_{pv} \frac{G_T}{G_S} \left[1 + \kappa_p (T_C - T_{STC}) \right] \quad (3)$$

$$T_{cell} = T_\infty + 7.8 \times 10^{-2} H t \quad (4)$$

Where W_{pv} is the module's maximum output power (kW), G_S is the received radiation under standard test conditions ($1 kW/m^2$), G_T is the solar radiation received on the PV module in the current hour (kW/m^2) and f_{pv} is the PV derating factor (%), T_{STC} and T_C are the module temperature under test conditions ($25^\circ C$) and in the current hour ($^\circ C$), α_p is the power temperature coefficient ($\%/C$). And also, the cell surface temperature T_{cell} mentioned in **Eq. 4** where T_∞ is ambient temperature and H_t is solar radiation flux on the cell [39].

2.5.3 Battery

A hybrid power plant needs an energy storage system to store the production power in the times of reduced load consumption and when the consumption increases or a reduction in power plant production due to reduced wind speed or solar radiation will return it to the grid. Therefore, in this system, a lead acid battery bank is used as a storage device. B is the battery capacity and excessive power output of the energy system which is calculated by below equation [40]:

$$B = \frac{E_L \times A_d}{D \times V} \quad (5)$$

Where, V is the nominal voltage of the battery [V], D is the depth of discharge [%], A_d is the days of autonomy and E_L is the load demand. Additionally, the battery sizing is often modeled using **Eq. 6**.

$$SoC(t) = SoC(t - 1) \cdot (1 - \sigma) + (P_{HRES}(t) - \frac{P_L(t)}{\eta_{inv}}) \times \eta_b \quad (6)$$

The capacity of the Battery will be:

$$PBT = Max[SoC(t)]_{t=1,8760} \quad (7)$$

where $SoC(t)$ is the energy level in the battery at certain time t , η_b and η_{inv} represent the batter and inverter efficiencies, 95% and 90%, respectively. σ is the daily self-energy consumption 1%/day. $P_{HRES}(t)$ the input power from HRES, and $P_L(t)$ the electrical load [41].

2.5.4. Diesel Generator

Diesel generators have always been one of the most widely used technologies in supplying electricity to areas independent of the grid. Also, the use of these generators along with renewable sources can improve the reliability of supplying consumer loads. The production power of the diesel generator is obtained from the following equation [42]:

$$F_g = A_g \times P_{ng} + B_g \times P_g \quad (8)$$

F_g is fuel consumption in every hour, A_g with 0.246 L/kWh is fuel curve slope, P_{ng} is power generated by diesel generator, B_g with 0.0845 L/kWh is intercept coefficients and P_g is nominal power.

2.5.5. Inverter

The inverter is actually a power converter from DC to AC or vice versa. Considering that the electricity produced by solar panels and battery electricity is direct current type, therefore, a converter will be needed to use them in the alternating current power system. P_{inv} is the inverter capacity which is given [43]:

$$P_{inv} = \frac{E_L(max)}{\eta_{dc/ac}} \quad (9)$$

Where, $\eta_{(dc/ac)}$ is the efficiency of the inverter, $E_{L(max)}$ is the maximum of energy demand by load system (Wh). **Table 1** and **Table 2** show economical and technical specification of the energy system components.

Table 1. Economic data of different components.

Component	Capital Cost	Replacement Cost	Operation and Maintenance Cost	Reference
Wind Turbine	2000 (\$/kW)	1600 (\$/kW)	50 (\$/# year)	[44]
Photovoltaic Panel	2000 (\$/kW)	2000 (\$/kW)	10 (\$/kW year)	[44]
Diesel Generator	300 (\$/kW)	300 (\$/kW)	0.02 (\$/kWh)	[42]
Battery	1100 (\$/Unit)	1000 (\$/Unit)	10 (\$/year)	[45]
Inverter	200 (\$/kW)	200 (\$/kW)	10 (\$/kW)	[46]

Table 2. Technical specifications of the system components.

Component	Model	Technical Specifications	Reference
Wind Turbine	Bergvx Excel 6 (XL6)	Lifetime: 20yr Rated capacity: 6 kW Hub height: 30 m Rotor diameter: 6.2 m Electrical bus: AC Cut-in wind speed: 2.5 m/s Cut-out wind speed: none	[44]
		Lifetime: 25yr Rated capacity: 4.4 kW Derating factor: 96% Operating temperature: 45 °C Temperature coefficient: -0.41%/°C Efficiency at standard test conditions: 17.3% Ground reflectance: 20% Electrical bus: AC Tracking system: no tracking Panel type: flat plate Minimum load ratio: 25%	[44]
Diesel Generator	-	fuel curve slope: 0.246 L/(h kWh) intercept coefficients: 0.0845 L/(g kWh) Heat Recovery Ratio: 25%	[42]
Battery	Surette 6CS25P	Lifetime throughout: 9645 kWh Nominal capacity: 1156 Ah (6.94 kWh) Nominal voltage: 6 V - Lead Acid	[45]
Inverter	-	Lifetime: 10 years Efficiency: 90%	[46]
Boiler	-	Fuel: Natural Gas LHV: 45 (MJ/kg) Efficiency: 85%	-

2.6. Assumptions, Limitations, and Uncertainties

outline the underlying assumptions made during the modeling and simulation process. Furthermore, recognizing the inherent complexities of such comprehensive analyses, this study also acknowledges specific limitations and addresses potential uncertainties that might influence the reported results. These considerations are detailed in the following subsections.

2.6.1. Assumptions

- **Building Model Consistency:** The architectural design, structural components, and material properties of the residential building are assumed to be identical across both studied locations (Basra, Iraq, and Tarifa, Spain). This standardization facilitates a direct comparison of renewable energy potentials and system performance under varying climatic conditions, despite inherent differences in local building codes or traditional materials.
- **Negligible Shading and Neighboring Building Effects:** The impact of adjacent buildings and external shading on the building's thermal performance and solar/wind resource availability has been disregarded. This simplification was adopted to streamline the simulation process, considering the specific objective of evaluating the standalone building's energy system.
- **Simplified Thermal Zoning:** To mitigate computational burden, software errors, and potential crashes during Design Builder simulations of the large-scale building, thermal zones with identical functionalities were merged by removing internal partitions. While this streamlined the simulation process, it introduces a potential discrepancy in the precise calculation of heating and cooling loads, and consequently, the overall building energy consumption.
- **Off-Grid System Operation:** The hybrid energy system is designed as a completely off-grid (standalone) system for both locations. This assumption is primarily driven by the paper's emphasis on maximizing renewable energy utilization and reducing fossil fuel dependency, thereby promoting energy, economic, and environmental sustainability. This design choice, while increasing the required capacities of renewable energy components, batteries, and diesel generators (and thus the overall system cost), allows for the simplification of the Loss of Power Supply Probability (LPSP) to near zero, as the system's independence from unreliable national grids eliminates grid-related outages.
- **Zero Loss of Power Supply Probability (LPSP):** For both standalone system configurations, the maximum annual capacity shortage is assumed to be zero, effectively setting the LPSP to zero [47]. This ensures that the system is sized to reliably meet 100% of the building's energy demand at all times.
- **Ideal Control System Operation:** All control devices within the hybrid energy system are assumed to operate without energy losses [47].
- **Consistent Occupancy and Activity Profiles:** Occupancy density and activity profiles within the building are assumed to be uniform across both study locations. This simplification is made despite potential cultural, customary, and climatic variations that might influence human behavior and energy consumption patterns.
- **Uniform Equipment Costs:** International equipment prices for all components (PV panels, wind turbines, batteries, diesel generators) are assumed to be consistent across both countries. Local factors such as tariffs, customs duties, and varying tax policies, which could lead to different final consumer prices, are not considered.
- **Standard HVAC System Configuration:** For comparative consistency, a uniform HVAC system design is applied to both climates. Specifically, a 4-pipe fan coil unit with a Coefficient of Performance (COP) of 1.8 is used for cooling, and a gas boiler with an efficiency of 73% is used for heating. This standardization is adopted despite the potential for climate-specific optimal HVAC designs.

- Unlimited Fuel Availability: The availability of fuels for the diesel generator and gas boiler is assumed to be unrestricted, and fuels consumption limitations that might exist in certain countries are not considered.

- Fixed Diesel Generator Capacity (Basra & Tarifa): The diesel generator capacity for Basra is fixed at 1200 *kW*, and for Tarifa at 900 *kW*. These capacities are determined by the sum of the building's peak loads in each location to ensure 100% load coverage in case of primary system component failures, and are not part of the optimization process for the other system components.

2.6.2. Limitations

- Fixed Building Design: The study utilizes a specific building design (from Azimieh, Karaj, Iran) that does not physically exist in the selected study cities (Basra and Tarifa). This limits the direct real-world applicability of the results to these specific locations.

- Absence of Grid-Tied Comparison: The exclusive focus on off-grid system design limits the direct comparison of system performance and economics with grid-connected scenarios, which typically benefit from lower overall system costs due to grid reliability and potentially subsidized electricity prices. The impact of varying national electricity subsidies and grid technologies on overall economic outcomes is not captured.

- Simplified Thermal Zoning Impact: The simplification of thermal zones in Design Builder, while necessary for computational efficiency, introduces a degree of inaccuracy in the calculated heating and cooling loads, which may lead to discrepancies in the final calculated building energy consumption.

- Lack of Sensitivity Analysis (for some parameters): The current scope of the study does not include a sensitivity analysis for all parameters, which could provide further insights into the robustness of the results against variations in input data.

2.6.3. Uncertainties

- Discrepancy in Weather Data Sources: Weather data for Design Builder simulations are sourced from climate.onebuilding.org (or Energy Plus websites), while HOMER Pro utilizes global NASA weather data. This discrepancy in data sources may introduce computational inaccuracies.

- Historical Nature of Weather Data: The reliance on historical average weather data for simulations may not accurately reflect current or future climatic conditions, potentially affecting the precision of energy consumption and renewable energy generation forecasts.

2.7. Objective Function

To evaluate the system in TEE aspect, defining energy system performance indicators are necessary. Indicators including Net Present Cost (\$), annual operating cost (\$/year), Levelized cost of energy (\$/*kWh*), renewable energy fraction (%) and annual CO₂ emission.

The Net Present Cost is the present value of all the costs of installation and operation of the components during the project's life, including the present value of all the incomes obtained during the project's life. The NPC is calculated within HOMER through below equation [48]:

$$NPC(\$) = \frac{TAC}{CRF} \quad (10)$$

TAC is the total annualized cost, calculated by summing all system component costs annually. It includes both Annual Operating Costs (AOC) and Annual Capital Costs (ACC). Annual Operating Cost is a subtraction between total annual cost and total capital cost.

The relation between them is shown in the below equation.

$$AOC = ATC - ACC \quad (11)$$

CRF is the capital recovery factor which is shown as **Eq. (12)** [48]:

$$CRF(\$) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (12)$$

Where i is the annual interest rate (%) and N is the number of years. The real annual interest rate depends on the inflation rate and nominal interest rate which have below function [49]:

$$i = \frac{(i' - f)}{(1 + f)} \quad (13)$$

Where f is the annual inflation rate i is the nominal interest rate.

LCOE is the average cost per kilowatt-hour of useful electrical energy produced by the system, expressed by the **Eq. (14)** [50]:

$$LCOE = \frac{TAC}{E_{served}} \quad (14)$$

Where, E_{served} is the total electrical load served ($kWh/yr.$). However, LCOE included the cost of environmental damage produced by carbon dioxide (C_{CO_2}) expressed the following **Eq. (15)** and also the payback time money (PBTM) by **Eq. (16)**:

$$LCOE = \frac{\left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \times C + C_{O\&M} - C_{CO_2}}{E_t} \quad (15)$$

$$PBTM = \frac{C}{I} \quad (16)$$

Where, I is the annual income \$/year, C is the capital cost \$, $C_{O\&M}$ is the annual operation and maintenance expenditures \$/year and E_t is the annual energy load covered by the proposed system $kWh/year$. The cost of environmental damage (C_{CO_2}) caused by CO_2 gas can be calculated by the following equation.

$$C_{CO_2} = EF_{CO_2} \times E_t \times \Phi_{CO_2} \quad (17)$$

Where EF_{CO_2} represents the CO_2 emission factor of the electric power generation system ($kg\ CO_2/kWh$), Φ_{CO_2} represents the carbon social cost (\$/ton CO_2), which may be considered as \$ 70/ton CO_2 .

The core optimization algorithm within HOMER Pro aims to minimize the Total Net Present Cost of the hybrid energy system over its 25-year project lifetime. The NPC serves as the primary objective function, encompassing all project-related expenditures, such as initial capital investments, replacement costs, operation and maintenance (O&M) expenses, fuel costs, and any salvage value over the system's economic lifespan. Through the minimization of NPC, the optimization process inherently identifies configurations that yield the lowest LCOE, reflecting the overall economic viability of the proposed system. This optimization methodology, which balances economic efficiency with system reliability, aligns with approaches found in similar studies on hybrid renewable energy system design.

2.7.1. System Reliability Constraints

To ensure the continuous and reliable supply of energy to the residential building, the optimization was subjected to critical technical constraints. A paramount constraint in the system design was the Loss of Power Supply Probability (LPSP), which was rigorously set to zero (LPSP = 0%). This stringent condition guarantees that the hybrid system is consistently capable of meeting 100% of the building's calculated electrical, heating, and cooling demands at all times, thereby eliminating any power outages. The LPSP represents the ratio of the total unsupplied energy to the total load demand over a given period, and its calculation is detailed as follows [51]:

$$LPSP = \frac{\sum_{t=1}^T \max(0, P_{load}(t) - (P_{PV}(t) + P_{wind}(t) + P_{DG}(t) + P_{disch}(t)))}{\sum_{t=1}^T P_{load}(t)} \times 100\% \quad (18)$$

Where T represents the total period of analysis in hours (e.g., 8760 hours for a year). $P_{load}(t)$ is the total electrical, heating, and cooling load power demand of the building at time t (in kW). $P_{PV}(t)$ is the power generated by the photovoltaic array at time t (in kW). $P_{wind}(t)$ is the power generated by the wind turbines at time t (in kW). $P_{DG}(t)$ is the power generated by the diesel generator at time t (in kW). $P_{disch}(t)$ is the power discharged from the battery storage system at time t (in kW).

This critical reliability criterion, ensuring an uninterrupted power supply, is consistent with methodologies found in similar studies focusing on reliable standalone hybrid energy systems [51]. Other important operational constraints considered in the HOMER Pro simulation included the available renewable resource profiles (solar irradiance and wind speed), and the permissible range for sizing each component (e.g., PV array size, wind turbine quantity, battery bank capacity).

Renewable penetration is a fraction of the production energy delivered to the load, which is generated from renewable energy sources. After simulating is done, HOMER gives renewable fractions for each different simulated design by following equation [52]:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \quad (19)$$

Where, E_{nonren} is nonrenewable electrical production [$kWh/yr.$] H_{nonren} is nonrenewable thermal production [$kWh/yr.$] E_{served} is the total electrical load served. H_{served} is the total thermal load served.

This off-grid energy system has diesel generator and gas boiler, produce greenhouse gas by burning fuel. Each of them has emission factor of consumption, by multiplying to fuel consumption in every year, calculate the annually CO_2 emission (CE) like the below equation:

$$CE = CE_{DG} \cdot F_{DG} + CE_B \cdot F_B \quad (20)$$

CE_{DG} and CE_B are emission coefficients of diesel generator and boiler, F_{DG} and F_B are diesel/gas and boiler fuel consumed respectively.

2.8. HOMER Pro Software

The National Renewable Energy Laboratory (NREL) of the United States of America produces and develops HOMER Pro Software. This software is responsible for designing and simplifying the technical and economic evaluation of the small power generation system in two modes, independent and connected to the network. HOMER software implements the three basic things of simulation, optimization and sensitivity analysis in the modeling process. HOMER models the performance of a specific energy system configuration for each hour of the year by determining the possible methods of supplying the required energy and its life cycle cost. In the optimization process of this software, all the different configurations of power supply that satisfy the technical constraints are searched in order to achieve the most economical mode for the life cycle cost. **Table 3** shows the project economic data input.

3. Results

In this part, output results of Design Builder and HOMER for these two locations are compared in aspect of load demands, optimal component sizing, economic, energy production, renewable penetration and CO_2 emission. Basrah has a warmer summer rather than Tarifa, as **Fig. 6** shows, Basrah has more cooling demand in the hot months with 830 kW peak load and 3642 kWh/d average, while Tarifa has 624 kW peak load and 973 kWh/d average.

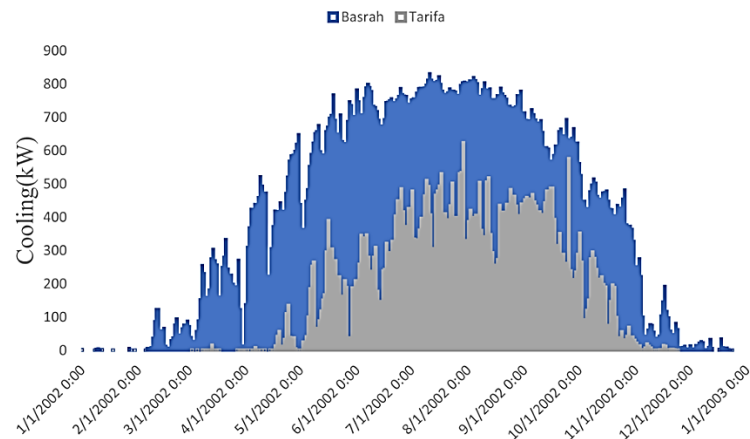


Fig. 6. Cooling load of Basrah and Tarifa.

Table 3. Project characteristics.

Project info	Location		Reference
Description	Basrah (Iraq)	Tarifa (Spain)	
Interest rate (%)	6%	9%	[42, 53]
Inflation rate (%)	0.4%	3%	[42, 54]
Diesel Price (\$/L)	0.3	1.8	[53, 55]
Natural Gas Price (\$/L)	0.35	1.75	[55, 56]
Project Life Time	20 years		

Heating load involves heating air conditioning system as a variable energy consumer active in cold season and domestic hot water as constant energy consumer which is almost equal for both locations and because of sauna and pool, has higher load than usual as seen in Fig. 7.

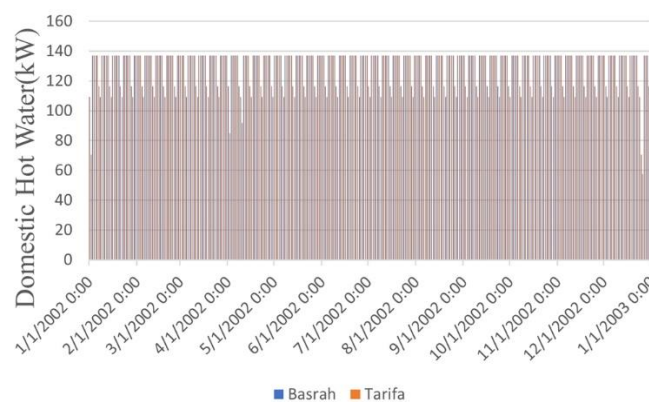


Fig. 7. Domestic hot water energy consumption of the building.

Tarifa has a colder winter, so as shown in Fig. 8 needs more average heating load to keep the interior building space warm and comfortable. Average heating load of Tarifa and Basrah are 1907 kWh/d and 1775 kWh/d, respectively.

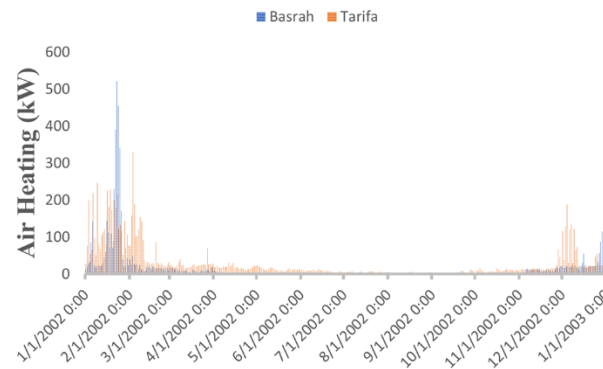


Figure 8. Heating load of warming interior space.

Electrical load of the building includes equipment, computers, lighting, room electricity and miscellaneous. Weather and locations usually don't affect electrical load as **Fig. 9** shows the comparison of the electrical loads. Tarifa and Basrah have 197 kW and 193 kW peak load and 2171 kWh/d and 2122 kWh/d average daily load, respectively.

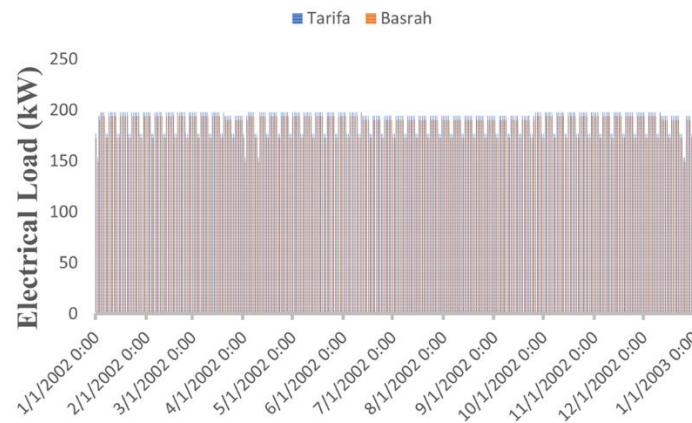


Fig. 9. Electrical load demand of the building for two locations.

Different characteristics of locations, creates this challenge that how much of each renewable and conventional source should be used. After the building simulation, load demands which are the input of HOMER to calculate the sizing of the system, obtain as shown in the **Table 4**. Diesel generator is backup, increasing the system's reliability when there is a shortage of energy supply. Hence, it should support the total electrical peak demands alone, which has heat recovery system, that helps the boiler to supply the thermal loads. Time schedule is defined to force the diesel generator off from 11 AM to 7 PM, where the solar energy is available to reduce CO₂ emission, increase the renewable fraction in simulation and avoid additional electrical battery charging in solar peak radiation time.

Table 4. Optimal size to meet the electrical and thermal loads.

Components	Basrah (Iraq)	Tarifa (Spain)
W T – Bergey Excel 6 (XL6) (6 kW)	102 Unit	87 Unit
P V – Fronius Symo 4.5-3-S (Fron4.5) (4.4 kW)	495 kW	393 kW
Diesel generator– Generic large size (kW)	1200 kW	910 kW
Battery– Surrette 6CS25P (6.91 kW)	994 Strings	785 Strings
Converter– System Converter (kW)	416 kW	471 kW

Table 5. Optimal project cost in different locations.

Parameters	Basrah (Iraq)	Tarifa (Spain)
Net Present Cost (\$)	5,557,327	6,542,097
Levelized Cost of Energy (\$ / kWh)	0.205	0.318
Total Annualized Cost (\$)	468,035	562,305

Sizing of components for Basrah is more than Tarifa because of higher peak load in Basrah. Hence, more component size increases the cost of the energy system. So, it seems Basrah will have more cost, but **Table 5** shows Tarifa has more cost despite of lower size, because of expensive conventional fuels with 1.75 \$/L and 1.8 \$/L for natural gas and diesel, respectively. **Fig. 10** shows the NPC share of each component in detail, which includes Capital, Operating, Replacement, resources and salvage.

Comparison shows how diesel generator and specially boiler, assign significant portion of total costs by consuming expensive resources in Tarifa. **Fig. 11** also shows this significant portion in annual operating cost in the chart.

Diesel generators in both locations have most portion of both capacity and cost between electricity generators while wind turbines in both locations have most electricity production with 1952 MWh/year and 1783 MWh/year for Basrah and Tarifa, respectively as seen in **Table 6**. It seems both Basrah and Tarifa are the suitable locations for wind source renewable energy, even much better than solar renewable energy for investment.

Diesel generator has a low portion of electricity production in both cities as **Fig. 12** shows. In warmer months, when an electrical chiller is activated, renewable energies are not enough, So diesel generator and battery bank, holdup the unmet demands.



Fig. 10. NPC (\$) components portion summary.

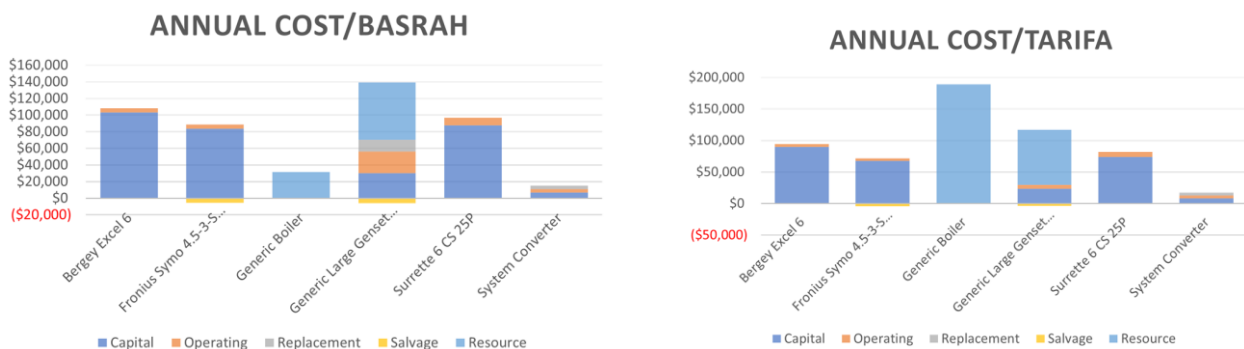


Fig. 11. Annual cost of components for different locations.

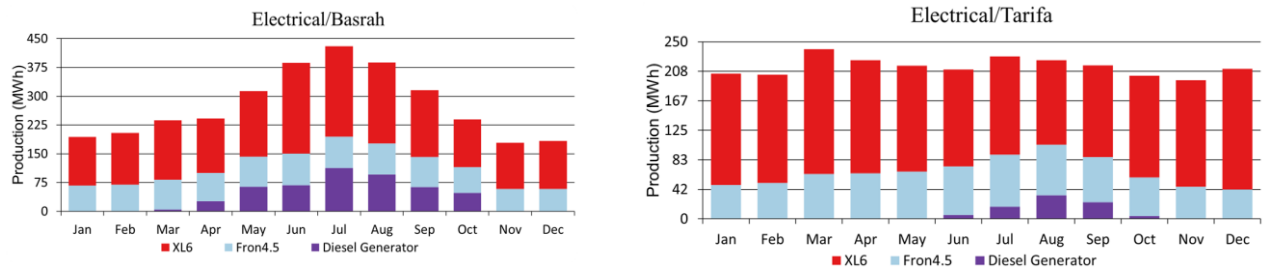


Fig. 12. Electrical production of the system.

Table 6. Generated electricity of the system yearly.

Components	Basrah	Tarifa
W T – Bergey Excel 6 (XL6) (kWh/year)	1,952,219	1,782,832
P V – Fronius Symo 4.5-3-S (Fron4.5) (kWh/year)	875,974	711,557
Diesel generator– Generic large size (kWh/year)	483,800	84,073

Despite the low portion of diesel generator, it is more effective in generating thermal load in Basrah than Tarifa, as Fig. 13 shows the rate between boiler and diesel generator in two cities. Since both locations have good potential for renewable energies, the renewable fraction of the energy system in Basrah is 46.1%, and 54% in Tarifa. Conventional fuel is cheaper in Basrah, therefore more fuel is consumed and as a result, Basrah with 728,341 kg/year has more CO₂ emissions rather than Tarifa with 280,702 kg/year.

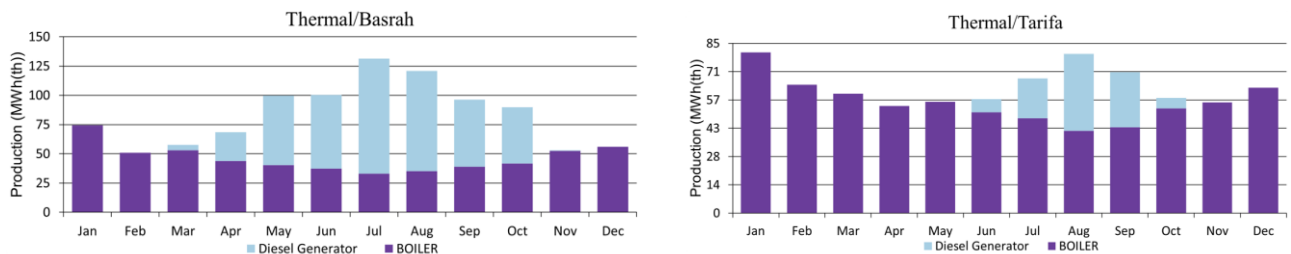


Figure 13. Thermal production of the system, yearly.

4. Conclusion

In this research, two distinct locations from Europe and Asia with differing climates have been selected, each representing different conditions. Equal geometry is simulated in different locations by the Design Builder. Then, the energy system is designed for each location separately in HOMER Pro software. Basrah has a higher average temperature, so it is harder to cool in the summer. Hence, 830 kW peak load and 3642 kWh/d average have more cooling load than Tarifa, while colder winter in Tarifa needs more thermal load than Basrah. Tarifa has higher prices of conventional fuels to make the building warm, so has a higher operating cost and LCOE because of the boiler and diesel generator. Due to the boiler's higher thermal load production and higher cost of conventional fuel in Spain rather than Iraq, it has more NPC, LCOE, and annual cost. NPC, COE and Annual Operating costs are 5,557,327 \$, 0.205 \$/kWh and 468,035 \$, respectively for Basrah and 6,542,097 \$, 0.318 \$/kWh and 562,305 \$ for Tarifa. Because of the higher cooling load in results, the electrical peak load in the Basrah relative to Tarifa is higher, Hence, a diesel generator is defined as 1200 kW which is more than Tarifa with a 910kW diesel generator. Both cities have perfect wind renewable energy source rather than solar renewable energy source. Renewable fraction of 46.1% and 54% in

Basrah and Tarifa shows that both locations have good potential of renewable energy sources to get sustainable and SDG targets. Total electricity production is higher in Basrah, because of hot summer. Due to amount of power production, Basrah has more CO₂ emission with 728,341kg/year.

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.

Data availability

No data is used in this article.

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