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Techno-Economic Modeling of Hybrid PV Systems in Riyadh, Saudi Arabia: A HOMER-Based Case Study on Integrating Efficiency, Sustainability, and Economic Viability

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ABSTRACT Solar power has the potential to provide a significant portion of the electricity required by cities in a sustainable manner. This paper assesses the potential of renewable energy sources, specifically solar power, to achieve sustainable electricity supply to Saudi Arabian cities. Photovoltaic systems are compared with thermal storage systems in supplying base-load electricity since the Kingdom does have ample solar resources with average wind speeds ranging from moderate. It is a methodology that uses HOMER software to identify the most efficient and technically feasible renewable-based energy conservation system across diverse Saudi Arabian households. One of the most critical concerns in the strategic planning of fossil fuel substitutes to meet the local energy demand is the utilization of renewable and new energy sources that are currently accessible in Saudi Arabia. In terms of renewable energy, the Kingdom of Saudi Arabia serves as an important case study. It has a lengthy history of relying on renewable energy sources to satisfy its energy requirements, and it will remain unfeasible to install grid-connected electric systems for its residents in the future. The nation's hybrid options include wind resources. The study optimizes the hybrid-solar wind resources systems that provide the most cost-effective and practical solution for energy production. It studies the cost of energy per unit (1.7 kWh) for 25 household appliances, depicting the economic viability of renewable energy systems in the Saudi Arabian context. This study will research the exclusiveness of the Kingdom's energy landscape and its transition phase from conventional energy to non-conventional energy sources for insightful viewpoints on how best to strategically plan the development of fossil fuel alternatives to meet the local energy demand.
Keywords: homer, integrated photovoltaic, Sustainability, Riyadh, Saudi Arabia

INTRODUCTION

HOMER (Hybrid Optimization Model for Electric Renewables), a micro-power optimization program developed by the National Renewable Energy Laboratory (NREL) in the United States, was applied to identify the most effective energy-efficient renewable-based hybrid system options for the area. [1] Analyses have been conducted to ascertain the best technically and economically viable options for individual home users, as well as for groups of 10 and 50 home users.[2].

By 2024, the National Renewable Energy Program projects are anticipated to generate 15,108,701 MWh of electricity yearly, facilitating power for 692,557 families. By the conclusion of 2024, the initiatives of the National Renewable Energy Program are anticipated to provide 7,870 additional employment opportunities. The decrease in fossil fuel consumption is anticipated to yield a reduction of 9,828,156 tons of carbon dioxide (CO_2) emissions per year by 2024.[3]

1.1 Climates in Riyadh

One of the cities with the highest levels of sun radiation is the capital of Saudi Arabia, Riyadh. 24 ° 55' N and 46 ° 14' E are its coordinates. Data on incident diffuse solar radiation (Hd), clearance index (Kt), radiation on a horizontal surface (H), and interplanetary solar radiation on both horizontal and normal surfaces are all included in the current study, which attempts to provide average daily and monthly solar measurements for Riyadh City, Saudi Arabia [4]

1.2 Overview of Solar Potential

Saudi Arabia's capital, Riyadh, is ideally situated for the utilization of solar energy due to its high levels of solar radiation. In addition to a pleasant average temperature of 26.3 °C, Riyadh experiences an average annual sun radiation of about 2.63 MWh/m². This combination of factors increases the efficiency of the region's photovoltaic (PV) installations.

1.3 Geospatial Analysis

A recent study combined GIS (Geographic Information Systems) and the Analytic Hierarchy Process (AHP) to estimate how effectively solar energy might function in various locations in Riyadh. With a fit score above 80%, the results showed that Afif is the best place for solar projects because it is flat and gets a lot of sunlight. Other places, like Dawadmi and Al Majma'ah, also had promise, but they weren't as good because of where they were located.[5].

1. THE POSSIBILITIES FOR INTEGRATED PHOTOVOLTAIC SYSTEMS IN BUILDINGS

Large utility-scale solar power projects that cover huge areas of desert have often been thought of by people who plan energy use. There are many good things about this idea, but economics needs to be looked at more closely. Getting land and getting it ready for the installation of ground-mounted solar systems is necessary. Either the cost of building or getting the land ready could be high. Large-scale stand-alone PV growth has been stopped in Saudi Arabia and many other developed countries because there isn't enough empty land. Increasing numbers of individuals are getting interested in solar energy, and most believe that distributed photovoltaic systems that generate power at or near the point of consumption will be the first to become widely available. It makes sense to employ a dispersed solar system[6] Follow up with the grid, especially in places where demand is highest in the summer. -Get rid of the costs and losses of transmission and marketing. -usually don't have the right permissions (NASA surface weather and solar energy [7] The notable advantages that render photovoltaic (PV) power systems for individual buildings the most appealing distributed applications include: - The substantial electricity consumption by the buildings and processes they accommodate; - The PV system and the land supporting it are exempt from real estate fees.

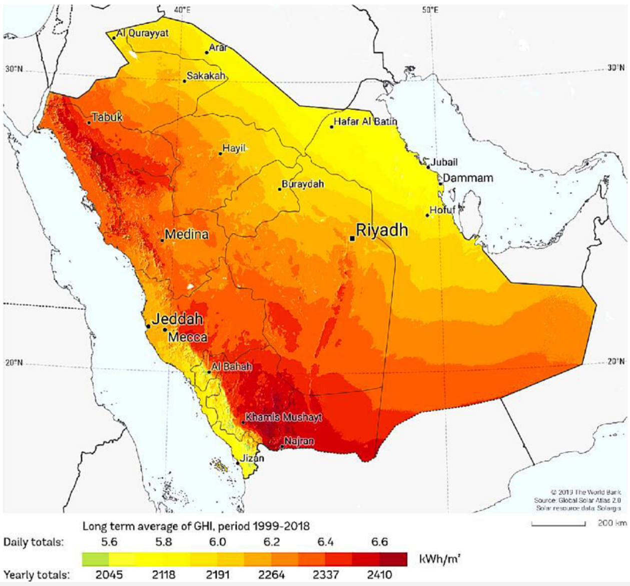


Figure 1: Map of Global Horizontal Solar Irradiation of Saudi Arabia (kWh/m2 /year)
Source: Solar GIS. Solar GIS data validation for the Kingdom of Saudi Arabia, http://geomodel solar.eu/_docs/various/Solar GIS_ validation_ SaudiArabia_2013-02.pdf.

2.1 Performance of Photovoltaic Systems

Research has demonstrated that PV systems in Riyadh can achieve significant energy outputs, particularly in dry conditions with low humidity. Multiple PV installations in Riyadh were compared, and the results showed that the systems there reliably generate a lot of power, even during peak demand times. Possibilities & Public Service Initiatives Renewable energy, and solar power, in particular, is highlighted in Saudi Arabia's Vision 2030.

The government has initiated several projects, including the Sakaka Solar Power Plant, which showcases advanced photovoltaic technology and aims to diversify the energy mix while reducing carbon emissions2. The plant is expected to generate over 930 GWh annually, powering approximately 55,000 homes2. Riyadh's solar resources present a significant opportunity for renewable energy development. The combination of high solar irradiance, supportive government policies, and ongoing research into optimizing PV system performance positions Riyadh as a leader in solar energy within the region.[8] Riyadh's solar resources present a significant opportunity for renewable energy development. The combination of high solar irradiance, supportive government policies, and ongoing research into optimizing PV system performance positions Riyadh as a leader in solar energy within the region.[9]

2. ASSESSMENT OF HYBRID ALTERNATIVES FOR A COST-EFFECTIVE RENEWABLE ENERGY SYSTEM

A main source of energy and backup secondary power storage units are commonly combined in hybrid energy systems. Martin's most energy-efficient system has been improved [10] taking into consideration various loads and combinations of wind and photovoltaics utilizing HOMER [11]. Figure 2 shows the fundamental concept of a hybrid energy system for producing electricity. Figure 2(b) shows the proposed design in operation with the HOMER simulation program. HOMER examines the energy balance to determine how a system might function with 9,690 hours in a year. By comparing the system's energy production capability with the electric and thermal demand, HOMER calculates the amount of energy entering and leaving each system component for each hour. Hourly choices are also made by HOMER on the operation of fuel-powered generators and the charging or discharging of batteries in systems that use these components. [12] For every arrangement that anyone wants to think of, HOMER does these energy management calculations. It then estimates the system's installation and operating costs throughout the project's lifespan and determines if a design is viable, defined as its capacity to supply power under the given circumstances. Initial investment, replacement, operational and maintenance, fuel, and interest expenses are all factors in determining the total cost of the system.[13]

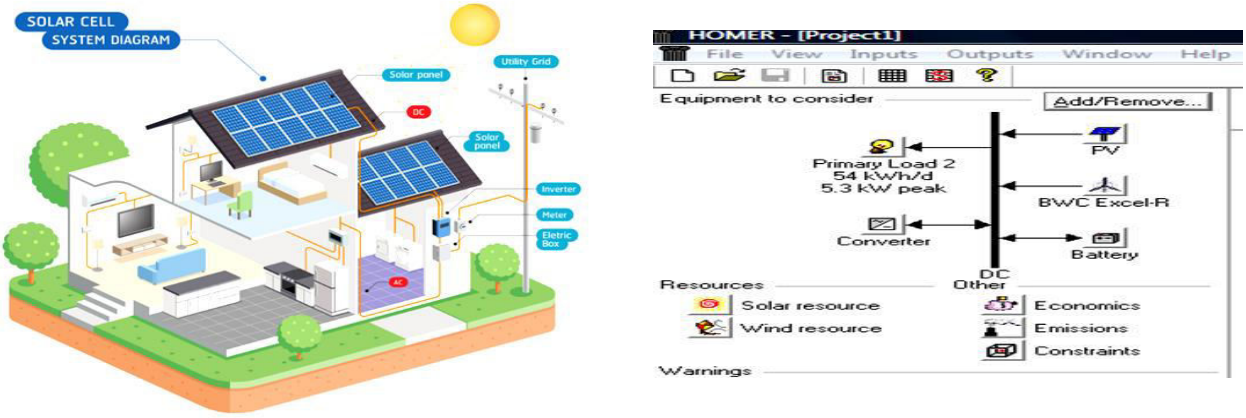


Figure 2: (a) The Diagram representation of a hybrid energy system, (b) HOMER proposed a hybrid system: The sections following address the load, resources, financial constraints, controls, and additional characteristics used by HOMER

Table 1: Minimum Equipment for a single in middle income householder

Equipment	Numbers	LOAD (W)	Used Per Day
LED Lamps	18	33	8
TV	2	45	12
Other appliances	8	27	12

Source: Authors (2024).

HOMER software simulates the performance of photovoltaic (PV) systems in Riyadh through a comprehensive analysis that incorporates various inputs and methodologies. Here's a detailed overview of how HOMER operates in this context:

Data Input and Resource Assessment

• HOMER utilizes regional solar radiation measurements.
which for Riyadh norms around 6.95 kWh/m²/day. This data is crucial for estimating the energy generation potential of PV systems throughout the year

• Load Profiles: The software requires hourly electricity demand data over a full year (8,760 hours) to accurately model the energy consumption patterns typical for residential buildings in Riyadh[14]

A common load system for a single house in remote locations was taken into account throughout the evaluation (see Table 1). A daily and 2.3-monthly load profile for a year is produced by HOMER using monthly average hourly load demand (as seen from a Sudanese perspective) as input (Figure 2). With this approach, it has been found that each household user uses about 338 Wh per day, with a peak demand of over 115 W. Grid-connected PV systems' system configuration modeling accounts for initial funding, ongoing expenses, and maintenance fees.[14, 15]

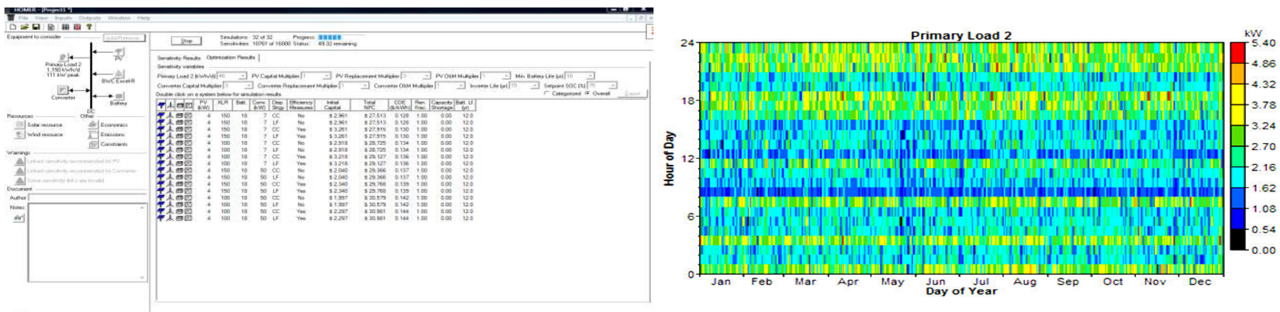


Figure 3: (a) Shown Hybrid System in HOMER.

Subsequent sections include information regarding the load, resources, controls, economic constraints, and additional characteristics of HOMER. (b) A Schematic Illustration of a Hybrid Energy System.
Source: Authors (2024); based on data exported from HOMER software

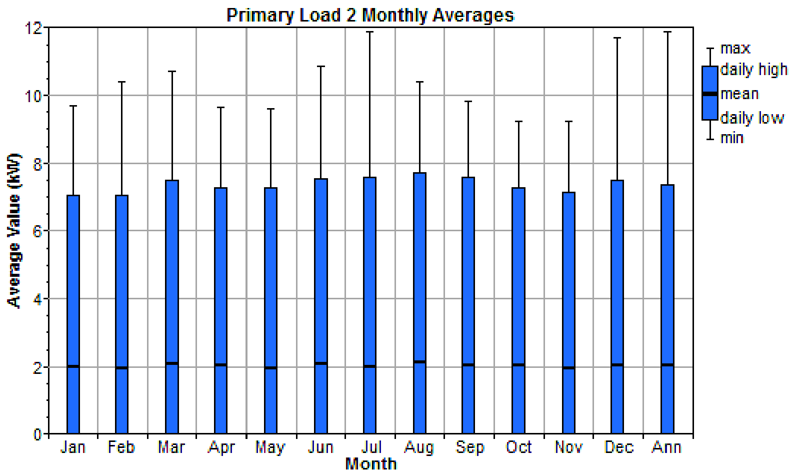


Figure 4: The additional principal load ((a) hourly-(b) annually)

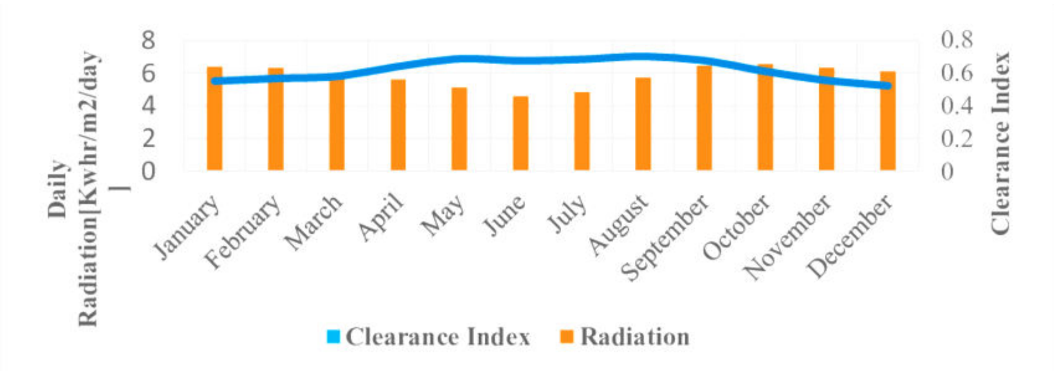
3. SIMULATION AND OPTIMIZATION:

• HOMER conducts simulations to evaluate the performance of various setups under diverse scenarios. It evaluates energy generation from solar panels utilizing solar irradiance data.
• Cycles of battery charging and draining.
• Equilibrium of power to guarantee that energy provision satisfies demand.
• The application uses optimization methodologies to find the most cost-effective system designs by reducing the Remaining Current Charge) [16].

4. RESULTS AND DISCUSIONS

As hourly data was not accessible, NASA provided monthly average global radiation numbers. Using the latitude data from the specified location, Homer provides the clearness index (figure 3). Homer uses the Graham technique to provide simulated hourly data for a year.[17], Approaches for absorbing the sun's rays and generating artificial hourly radiation for use in power generation [16]. It produces a data series that includes authentic autocorrelation as well as daily and hourly changes. Figure 4 displays (a) the probability distribution curve for wind speed and (b) the average hourly wind speed over a one-year period. Wind was approximated using monthly averaged observed data from SEI, using characteristics such as height of 30m, elevation of 3m above sea level, and 0.1 m of surface roughness. Homer combined these monthly average data to create hourly data for a year using additional variables such as a Weibull factor "k" of 2.6, an autocorrelation factor (which indicates wind speed randomness) of 0.85, a diurnal pattern strength (which represents the variation in wind speed throughout a day) of 0.35, and the hour of peak wind speed at 22.[18]

Figure 5 :Monthly Average Solar Global Horizontal Irradiation (GHI) data



4.1. Elements of Hybrid Systems

The Module Utilized by The Rooftop Solar Panels:

The average price of a solar energy module, includes installation, has been assessed to be 220 SP/W in Saudi Arabia. The modules have a life of 25 years and are inclined at 21° with no monitoring capability. (1 USD = 3.77SR 2024)

Winds producers:
Due to the limited demand of a single house system, low-capacity wind turbines are much more expensive per KW than high-capacity ones. Furthermore, few low-capacity wind turbines are available on the market. Research and development are currently underway to allow low-capacity turbines with cut-in speeds of approximately 3.0 m/s. These calculations are based on a Synergy S 4000 turbine with a capacity of 0.8 KW. The anticipated cost of one turbine, including the tower and installation, is 90.000SR. Southwest Wind Power's W180 turbine, which has a 3 KW capacity and costs 400000 SR per unit, is being tested for loads larger than 1 KW. It requires tower installation. Alternative research focused entirely on wind and photovoltaics. [19] .

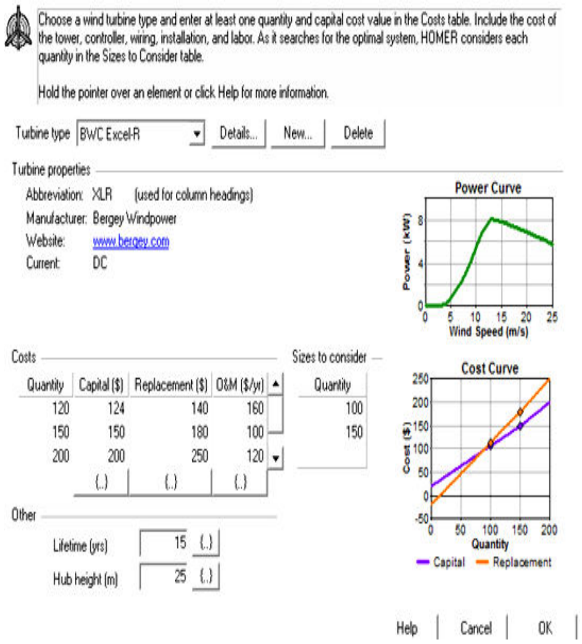


Figure 6 Wind Turbine Input
Source: Authors' own elaboration (2024); based on data exported from HOMER software

Batteries and Controller of Operations:
The battery and controller become crucial components of the system as it focuses on the DC load. Each Trojan Company battery with charge controller cost 11.000.00 SR. The batteries used were Trojan T-109 models with nominal voltages of 8V and capacities of 334 Ah.[19, 20].

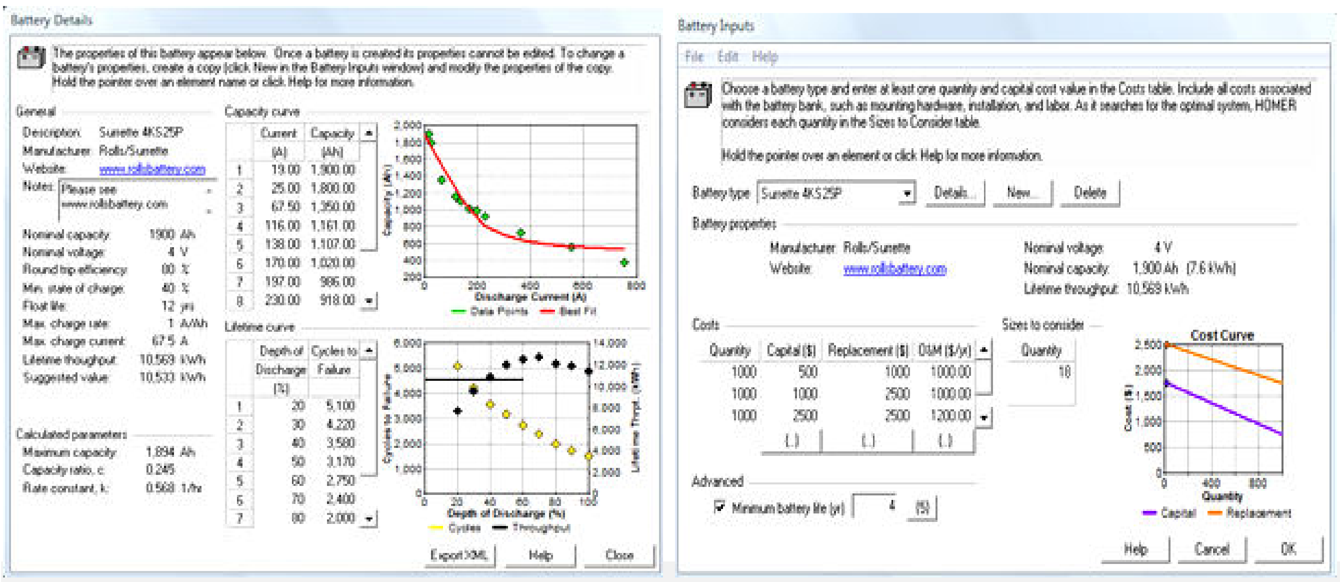


Figure 7: Battery analysis, (a) Battery Details, (b)Battery Inputs
Source: Authors (2024); based on data exported from HOMER software

Table 2: HOMER analysis and results

Household	***Load***	***Solar Panel (KW)***	***Winds Producer (the amount)***	***Battery (quantity)***	***Minimum Prices SR***	***NPC Total***	***COE (SR/ KWh)***
Single	*667 Wh/day 230 KW Mount*	*0.30*	*0*	*4*	*102,891*	*99,455*	*49.7*
20	*12.5 KWh/day 4.6 KW Mount*	*2.0*	*1*	*32*	*680,600*	*896,890*	*22.6*
30	*20.2 KWh/day 7.6 KW*	*4.0*	*1*	*48*	*978,910*	*2,234,600*	*23.6*
40	*26.9 KWh/day 9.7 KW*	*5.5*	*2*	*48*	*2,188,440*	*2,456,660*	*21.5*
50	*33.6 KWh/day 12.6 KW*	*7.5*	*2*	*16*	*2,567,333*	*2,987,987*	*20.2*

Source: Authors (2024).

According to an assessment, with 25 families, the system has a low energy cost (KWh). Table 2 displays each house combination's load demand together with the system design and financial breakdown.[21]. For the 25 -home system, a thorough analysis and system architecture have been provided. Figure 5: This research assists stakeholders in making well-informed choices on investments in Riyadh's renewable energy technology.[14]

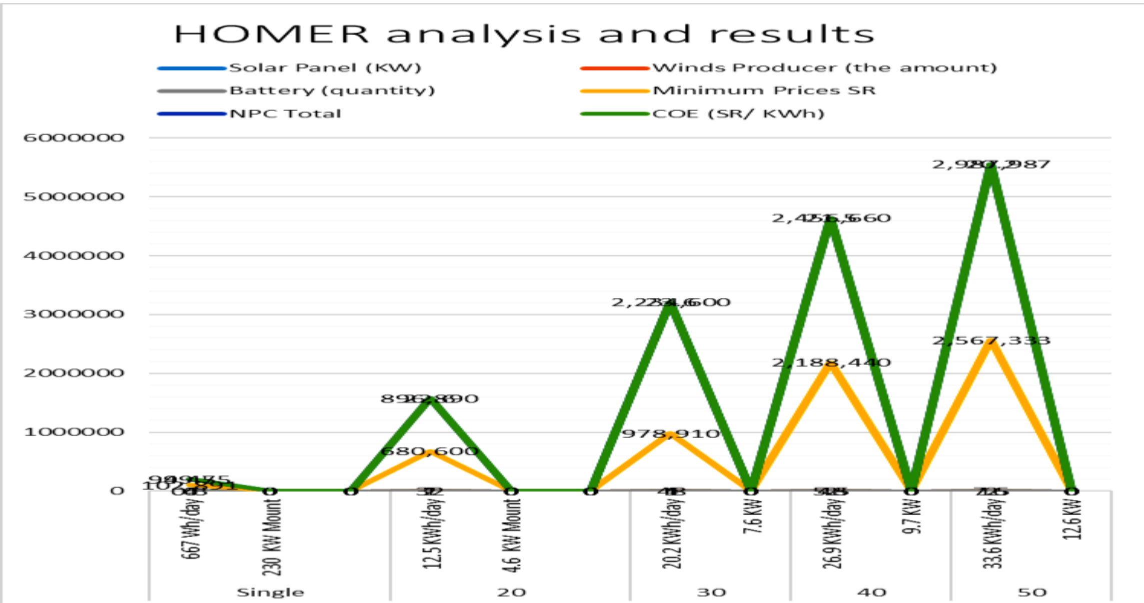


Figure 8 homer analysis and results
Source: Authors' own elaboration (2024); based on data exported from HOMER software

4.2. Constraints and Economics

HOMER provides detailed economic analyses, including:

• Calculation of NPC, which reflects the total lifecycle costs of the energy system.

• Sensitivity analysis to understand how changes in input variables (like fuel prices or solar panel costs) affect system performance and economics.

Considering an estimated economic benefit rate of 4% per year, the project is expected to last for 25 years[22]. Depending on the user's load, the system can support anywhere from one user to a large number of users (10 to 25), which has resulted in an annual operating and maintenance cost of 5000 SR. Ten percent of the system's hourly demand is its functional reserve, indicating that it has sufficient capacity. 50 families make up the system, and an investigation shows that its cost per kilowatt-hour is affordable [23] in addition to the outcome of the hybrid system design's modeling and optimization using the Homer program. A 20-year payback period, a 76% return on investment, and a 65% reduction in greenhouse gas emissions are the outcomes of simulations showing that the grid/renewable energy source (RES) hybrid configuration has the same net present cost (NPC) as grid-only supply at 2020 pricing. Three Vest WECS units (1.9 MW each), 4,000 batteries, and a 900-kW converter are projected to have a minimal net present cost (NPC) of $29.3 million after 20 years. This is still true even though a RES-only system might generate all the electricity needed [24] The duration of the compensation term and the benefits-to-costs ratio were set at about two years, eight years, and sixteen percent, respectively. The investigation of energy consumption, environmental impact, and remote accessibility indicates that most coastal states are appropriate for residential systems.[24]

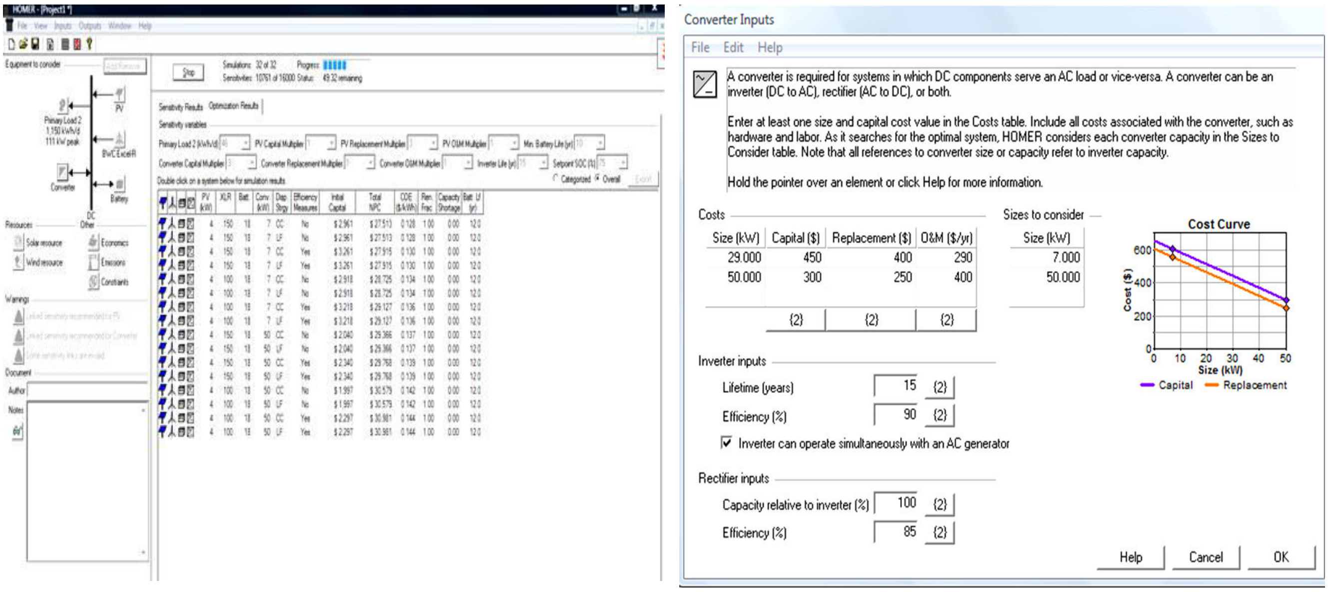


Figure 9 Results of the 25-home simulation system

Source: Authors' own elaboration (2024); based on data exported from HOMER software

It was determined that integrating a 15 kWh PV system with a 200-kWh battery storage capacity is the best way to make use of the two diesel generators that are currently available, given a daily requirement of 308 kWh. A minor adjustment to the diesel-powered generator's operating strategy can effectively handle future demand increases. Because of the improved operational efficiency of the PV generators, the configurations of this system have lower overall net current costs even if they require more starting resources. It is evident from the photovoltaic system that when sun radiation decreases, so do system emissions. The incentive program also considers if there is enough electricity available for household use, which is necessary for the residents of this particular location [25].

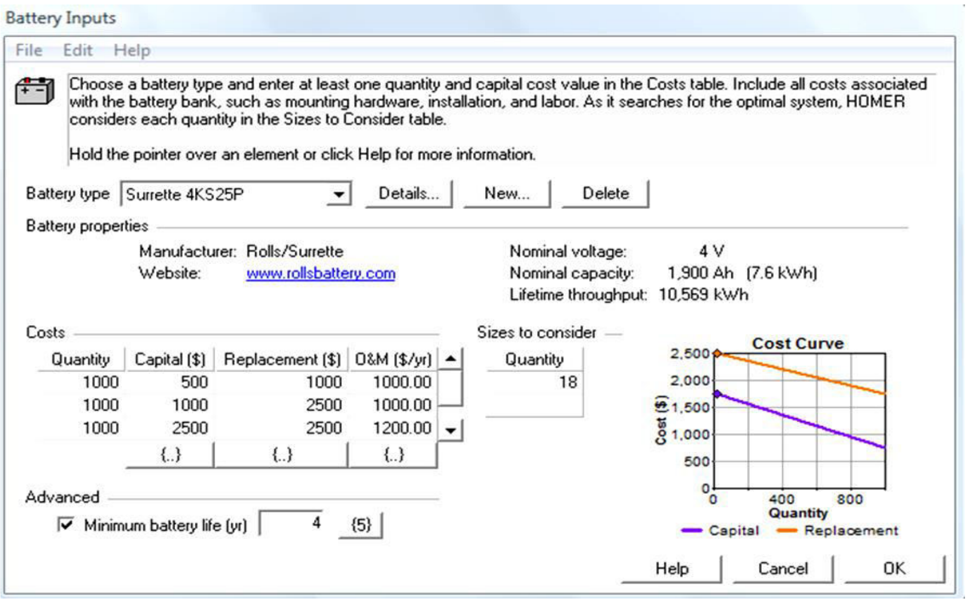


Figure 10 homer analysis and results

Source: Authors (2024); based on data exported from HOMER software

5. CONCLUSION

The estimates given above suggest that it is more efficient to have a wind-PV-combination system than a single-home system for 25 homes. The overall cost of electricity would go rather low if the price of the turbines dropped. A project life of 30 years is assumed with an annual real interest rate of 6%. Yet it can outfit individual users and 10 to 25 home users, the cuts associated with operation and maintenance are not very high as the demand for the systems by these types of users is low. The study summarizes the increased efficiency and economic viability of hybrid wind-photovoltaic systems for powering several dwellings in Saudi Arabia. This is reinforced over the noteworthy progress made by the Saudi Kingdom in increasing its renewable energy sector, endorsed by the 300% growth in renewable power capacity from 2022 to early 2024, at 2.8 GW. The committed target for Saudi Arabia is to install 58.7 GW of renewable energy capacity by 2030, out of which 40 GW shall be from solar PV systems. The present study, though limited to simulated hourly data, has quite useful information for policymakers as well as investors. Further research will relate to the actual data analysis, the use of energy storage, and the resultant economic and environmental implications of hybrid systems in large quantities.
These findings underpin Saudi Arabia's "Vision 2030" in further diversifying its energy mix and reducing its reliance on fossil fuels, toward the path of a more sustainable future in the Kingdom.

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