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RESEARCH ARTICLE **RENEWABLE ENERGY**

Design and Analysis of an off-Grid PV/Wind/Battery/Diesel Generator Hybrid Renewable Power System for a Healthcare Facility in Gharyan, Libya

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ABSTRACT

This paper studies the efficiency of the proposed grid-tied hybrid renewable energy generation system at a large hospital in Gharyan, Libya. As mentioned earlier, the combination of the Eocycle EO20 wind turbine system with the proposed system involves a solar PV system of 50 kWp. Here, the batteries serve as the energy storage element, while the diesel engine serves as the backup energy source in the event of breakdowns. The energy generated from the sunlight is 94,091 kWh/yr, while that obtained from turbines equals 131,203 kWh/yr. Speaking of economic aspects, it can be stated that the proposed system is highly efficient, which is proved by its low LCOE 0.47$/kWh) and NPC (5,061$/year). Concerning the ecological aspects, the reduction in CO_2 emissions amounts to 83,393 kg/yr = 83.4 tons/year and Avoided Carbon Cost 478 $/year. More precisely, all these emissions come from buying electricity, since no diesel engines were used in the entire process.

تصميم وتحليل منظومة هجينة للطاقة المتجددة (خلايا شمسية- طاقة رياح- بطاريات – مولد كهربائي) لمرفق صحي بمدينة غريان، ليبيا

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الكلمات المفتاحية
الطاقة الشمسية
طاقة الرياح
بطاريات تخزين الطاقة
الطاقات المتجددة الهجينة
ليبيا

الملخص

تهدف هذه الأطروحة العلمية إلى دراسة كفاءة نظام الطاقة المتجددة الهجينة والمرتبطة بشبكة الكهرباء المقترح في مستشفى كبير في مدينة غريان، ليبيا. كما تم الإشارة سابقاً، فإن الجمع بين مولدات الرياح من نوع (Eocycle EO20) والنظام المقترح يشمل نظام طاقة شمسية ضوئية بنظام ذروة قدرة يصل إلى 50 كيلوواط. وعلى الجانب الآخر، تعمل البطاريات كخزان للطاقة، في حين أن المحركات الديزل تعتبر مصدر الطاقة الاحتياطي في حالات الطوارئ والأعطال. حيث أن الطاقة المنتجة من الإشعاع الشمسي وصلت إلى 94,091 كيلوواط ساعة سنوياً، في حين أن الطاقة المأخوذة من التوربينات وصلت إلى 131,203 كيلوواط ساعة سنوياً. من الناحية الاقتصادية، يمكن القول بأن النظام المقترح يعتبر كفاءة عالية، الأمر الذي يبرره بتكلفة التجزئة للكهرباء (LCOE) بقيمة 0.47 دولار / كيلوواط ساعة، وصافي تكلفة الكهرباء الحالية (NPC) بمقدار 5,061 دولار سنوياً. من الجانب البيئي، تم تخفيض في انبعاثات ثاني أكسيد الكربون قدره 83,393 كجم/سنة (أي ما يعادل 83.4 طناً سنوياً)، مع بلوغ تكلفة الكربون المتجنبة 478 دولاراً سنوياً.

Introduction

In light of the current rise in global demands for electricity due to increased industrialization and population growth, The global electricity generation in 2024 reached approximately 30,850 TWh (30.85 PWh) [1-3]. With fossil fuels (coal, gas, oil) providing about 58%, renewables (hydro, wind, solar, bio, geo) around 32%, and nuclear around 10%. These energy sources currently are under threat because they contribute significantly to GHG emissions, including carbon dioxide (CO_2). [4-9], this is because GHGs exacerbate climate change and environmental pollution [10]. Moreover, fluctuations in the costs of fuel around the globe have forced companies to consider renewable energy sources to make sure that all options available remain economically stable [11,12]. Renewable energy technologies would be best suited for this purpose [13-27]. In the end of 2025, the global installed capacities of renewables such as solar energy (PV, thermal and concentrated solar power) [28-50], wind [51-60], bioenergy [61-77], etc., reached about 4,448.1 GW, from them 2,200 GW for PV solar energy systems, 1,320 GW for wind energy, and the total cumulative biopower capacity reached 151 GW. Integrating multi-sources of energy are excellent since they occur in abundance and are affordable to turn into useful forms of energy [78-89]. Lastly, utilizing different energy sources together with energy storage technologies, such as batteries, pumped hydropower energy storage, fuel cells, compressed air storage will eliminate their intermittency issues [90-115]. For this reason, there is an urgent need for the utilization of techno-economic modeling for example, the HOMER software, in optimizing micro-power systems [116-128]. The main purpose of utilizing the technique is to enhance the efficiency micropower systems.

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Moreover, it helps to compare different technologies involved in the production of electrical energy and their applications. The physical processes of the power system and the overall cost of its life cycle are considered by HOMER. Hence, different design options can be analyzed using economic and technological criteria. Consequently, quantification of effects caused by changes in inputs becomes simpler. HOMER assesses many alternatives during the optimization process ranking them according to feasibility with regard to TNPC. The best alternative representing the optimum design for the power system will have the lowest TNPCm. The present paper gives a brief overview of the cogeneration system. The input data of the HOMER simulation are described in [129]. Economic aspects of the feasibility analysis are considered in this study. The cogeneration concept, as well as the data on its costs, are introduced here

Nassar et al., designed a hybrid renewable energy system (HRES) contains solar photovoltaic energy, wind energy integrating with pumped hydropower storage (PV/Wind/PHS). The sizes of the components are optimized based on the minimum levelized cost of electricity (LCOE). The results for the actual case study in Libya show that, the optimum sizes of the combination are (6000 MW-PV and 385 MW-wind and 762,161 MWh-PHS), total annual energy produced by the proposed HRES is 12,029,670 MWh, which is enough to cover 100% of the electrical shortage (9,744,033 MWh). About 41.74% of the generated energy by the power supply system is directly consumed by the load, while 39.26% is pumped to the upper reservoir and stored to used when needed. The rest of energy (about 19.0%) is lost in pumping and generating processes with about 90% efficicy for pump/turbine equiepment. The sizing is based on the minimum values of LCOE ($132.1/MWh), NPV ($19.923 Billion) LPSP (0), PBP (7.54 years), and the E_{CO2} savings is (11,624 kton), which saved ($ 816.246 M) as a social cost and in additional to ($ 2,189 M) as fuel savings [130].

Latiwash, et al., designed and analyzed an off grid PV solar energy integrated with a hydrogen system as an energy storage source to supply electricity to a city located in the southern region of Libya. The proposed system consists of a 625.5 MW PV field, 177 MW fuel cell, 337 MW electrolyser, and 24,285 m^3 hydrogen storage tank. A desalination plant with a production capacity of 186,000 cubic meters per hour and a capacity of 400 kW, as well as a hydrogen compression station with a capacity of 4.1 megawatts, were also attached to the hydrogen system. The results showed that the proposed system is capable of covering the entire load at an investment cost of $1,742 million, with a levelized cost of energy estimated at approximately $338/MWh. with a capital payback period of 16.64 years. The system contributes to reducing carbon emissions by approximately 611,849 tons of CO_2 per year [100].

Fathi, et al., provided a design procedure of reliable standalone utility-scale pumped hydroelectric storage powered by pv/wind hybrid renewable system. System Advisory Model software (SAM) was used to estimate the energy production for various sizes of solar PV fields and wind turbine farms under specific climatic and electrical load conditions. The optimal combination of the offered HRES system, which will cover 100% of an annual electrical load of 513 GWh in addition to a 20% safety factor, consists of a 290 MW wind turbine farm, 154 MW PV solar field, and 508 MW PHS. This is based on the minimum levelized cost of energy (LCOE), which was found to be $211.646/MWh. It will take 11 years to recover the approximately $929.016 million required for the first investment, and then it will only take 9 years. The proposed HRES will prevent 532.167 kton of CO2 emissions annually [131].

El-Khozondar, et al., proposed a hybrid off-grid energy system for electrolyzing the quarantine COVID-19 center in Gaza-Strip. HOMER-Pro program is used to simulate and optimize the system design. It is found that the PV-wind-diesel generators can cover the connected load with the lowest cost ($ 0.348/kWh) in comparison to other possible HES structures. For the considered case study, it is found that a combination of 150 kW PV, 200 kW wind, and two diesel generators with capacities of 500 and 250 kW can meet 100% of the electrical load of the quarantine COVID-19 center. The initial capital cost of the HES is $510,576. The total operation and maintainance cost (O&M) is $268,737, that is, 25.6% for wind turbines, 1.2% for inverters, and 70.7% for diesel electric generators. The HES generates 1,659,038 kWh of electricity. The total energy requirement of 1,442,553 kWh, which means a surplus of 212,553 kWh of energy/year. The cost of yearly consumed fuel is $437,828.769. The payback period for the winning system is 1.8 years. Finally, it is proved that the developed approach gives a reasonable solution to the decision-makers to find a fast, economic and reliable solution to energize the quarantine centers [116].

Numerous studies in this field have been summarized and listed in Table 1.

Table 1: Literature review on design the hybrid systems

Generation system	Storage System	Grid mode	Country	Key findings	Ref.
PV/WT	B	On	Iran	The optimal design of a grid-connected PV/WT/Battery hybrid system has been developed to supply an annual load. The results indicate that, compared to a stand-alone system, the grid-connected system reduces the total system lifespan cost by 0.7–1% and the cost of energy by 0.87–1.2%, while improving reliability by 7–10%.	[132]
PV/WT/BG	-	On/Off	China	Off-grid and on-grid operation modes are evaluated using simulations, optimizations, and sensitivity analysis. In off-grid mode, the optimal system configuration includes 29 kW of PV panels, five 10 kW wind turbines, a 30 kW BDG, 89 Generic 1 kWh Lead Acid batteries, and a 26 kW converter. The initial capital cost is $142,220, with an LCOE of $0.131/kWh. In on-grid mode, the optimal system consists of 64 kW of PV panels, six 10 kW wind turbines, a 30 kW BDG, and a 42 kW converter, with an initial capital cost of $311,634 and an LCOE of $0.084/kWh.	[133]
PV/WT/ BG/DG	B	On/Off	Turkey	A biomass-based hybrid power system integrated with solar energy reduces the net present cost by approximately 12% and increases the	[134]

				renewable energy fraction by 7%. Grid-connected configurations achieve an 88.9% renewable fraction, while energy storage integration further enhances the renewable fraction by 10% and reduces excess energy by 16%.	
PV/BG	B	Off	Bengal	The system avoids approximately 140 tons of CO_2 emissions, with an LCOE ranging from \$0.101/kWh to \$0.105/kWh.	[135]
HCPV	B	Off	Kuwait	The yearly average efficiency of an integrated HCPV-battery system is 39.1%, compared to 40.2% for a standard HCPV system. Over a one-year operation period, the energy loss due to temperature rise in the integrated HCPV-battery system is approximately 2.7% compared to a conventional HCPV-battery installation.	[136]
PV/WT	PHS	Off	Libya	A hybrid renewable energy system (HRES) consisting of a 1000 kWp solar PV array, 5000 kW wind farm, and a PHS system with a 27,954 kWh capacity (equivalent to 166,532 m^3 volume capacity) has been deemed suitable for a sustainable power supply. This system meets an electric load demand of 1.2 MW peak power and an annual energy consumption of 6.14 GWh. About 85% of the load demand is directly supplied by the HRES, while the remaining 15% is covered by PHS. The system avoids approximately 4,385 tons of CO_2 emissions annually, with an LCOE of \$0.132/kWh.	[137]
PV/BG	-	On	India	The hybrid system achieves an LCOE of approximately \$0.099/kWh, saving 27.8 Mt CO_2 per year compared to a diesel-only system.	[138]
PV/WT	-	On	Djibouti	The study highlights that renewable energy can contribute up to 77% of the total energy supply, with 47% from solar and 30% from wind power. The LCOE is estimated at \$0.02/kWh, significantly lower than the average grid cost of \$0.32/kWh.	[139]
PV/WT	B	Off	Algeria	Cost analysis reveals that batteries account for 52% of the total investment cost, wind turbines for 42%, PV panels for 3%, and inverters for 4%. The LCOE is calculated at 0.2388 €/kWh.	[140]
PV	B/FC	On	Japan	A state machine-based energy management strategy, combined with a hysteresis band control approach, has been proposed to ensure system power balance while maintaining battery state of charge and stored hydrogen levels.	[141]
PV/BG/GE	-	Off	Thailand	The LCOE and levelized cost of hydrogen (LCOH) are determined to be \$0.098/kWh and \$5.67/kg, respectively.	[142]
PV/WT/ PHS	B	Off	Ghana	A comprehensive review of hybrid pumped hydro energy storage (PHES) configurations is presented, including existing and future case studies of hybrid systems, while some cases of typical hybrid systems are discussed.	[143]
CSP	PHS	Off	Egypt	A specific hybrid system (CSP/PHS) is evaluated with an LCOE of 4.45 ₡/kWh, a net capital cost of \$150 million, an annual energy output of 131 million kWh, and a capacity of 50 MW.	[144]
PV/DG	B	Off	Sudan	The hybrid system achieves an LCOE of \$0.328/kWh.	[145]
PV/WT	B	Off	Botswana	A fully renewable hybrid system employing 100% clean energy results in zero carbon emissions. Solar energy contributes 53.7% of the total production, while wind energy accounts for 46.3%. The system has a 25-year lifespan, with a return on investment (ROI) of 7.6% and an internal rate of return (IRR) of 11.4%.	[146]
CSP/WT	B/FC	Off	Morocco	Economic analysis estimates a net present cost (NPC) of 3.391 million €, an LCOE of 0.126 €/kWh, and an LCOH of 21.4 €/kg.	[147]
PV/HT/DG	B	Off	Iraq	The study evaluates the techno-economic and environmental performance of various hybrid systems, with sensitivity analysis conducted to assess parameter variations.	[148]
PV	B	Off	Brazil	A novel approach for power battery management and improved maximum power point tracking (MPPT) performance has been proposed to extend battery lifespan.	[149]
PV/WT	B/FC	Off	Canada	The results demonstrate that integrating wind resources with solar and storage technologies can play a crucial role in satisfying electricity demand while significantly reducing costs and greenhouse gas (GHG) emissions. Additionally, the study provides insights into sustainable and cost-effective policy recommendations for renewable energy microgrids (RC MGs).	[150]
PV/WT/DG	B	On	Nigeria	Simulations indicate that integrating solar PV and battery storage into an existing system reduces NPC by 32.3% and decreases annual diesel fuel consumption by 48.9%.	[151]
PV/WT	B/FC	Off	Saudi Arabia	The optimal hybrid system configuration includes 270 kW of PV, a 300 kW wind turbine, a 500 kW electrolyzer, a 100 kg/L hydrogen tank, 70 lithium-ion batteries (each 1 kWh), and a 472 kW converter. This system achieves the lowest LCOE, LCOH, and NPC at \$0.6208/kWh, \$9.34/kg, and \$484,360, respectively.	[152]
PV	B/FC	On/Off	Oman	The analysis has shown that a 3 MWp grid-connected PV system	[153]

				represents a promising green hydrogen production at an LHC of 5.5 €/kg. The system produces 58 615 kg of green hydrogen per year reducing carbon dioxide emission by 8209 kg per year. The LHC in the stand-alone PV system with batteries, and stand-alone PV system with fuel cells are 5.74 €/kg and 7.38 €/kg, respectively.	
PV/WT/BG	B/PHS	On	Cyprus	The HRS is designed for a university camps, it consists of 1.79 MW PV, 2 MW wind and 0.92 MW biomass systems with 24.39 MWh pumped hydro storage system and 148.64 kWh batteries. The LCOE equals to 0.1626 $/kWh.	[154]
CSP/TPP	-	Off	Vietnam	According to the calculations performed for the basic case with no solar radiation, the efficiency of the 4.6MW power station was η = 0.345, the fuel consumption mF = 0.056 kg/s, and for the 11.86 MW station η = 0.317 and mF =0.72 kg/s. The highest intensity of solar radiation is achieved in February and April. At that time the efficiency is increased by 13.3% compared to the basic case, while fuel consumption is reduced by11.7% (for a 4.6 MW station). For a more powerful station, efficiency is increased by 12.3% and fuel is reduced by 11.1%. Thus, due to the use of solar energy, substantial fuel savings are achieved .	[155]
PV	B	On	Poland	For a properly designed photovoltaic system, the energy self-consumption can be up to 90.19%, while self-sufficiency can be up to 82.55% for analysed cases.	[156]
PVT/CSP/HE	FC	Off	Russia	In the present study, a hybrid renewable system to supply the electricity, heating and fresh water demands of a near zero energy building (NZEB) is proposed.	[157]
PV/WT	-	On	The USA	comprehensive assessment of temporal complementarity for co-located wind-PV hybrid systems at greater than 1.7 million locations across the contiguous United States. We model hourly variation in potential wind and solar generation for a period spanning 2007–2013 and evaluate robust evidence for complementarity using multiple metrics to assess correlations and stabilization benefits achieved via hybridization.	[158]
PV/WT/CSP	TS/B/PHS	Off	Chile	The main results indicate that by 2050, and considering a baseline scenario defined for 2016, for most of the scenarios studied the renewable electricity generation would be at least a 90 % and CO2 emissions would be 75 % lower.	[159]
PV/WT	B	Off	Botswana	The results show that the PV/wind/battery system generates the most economic and technical benefits, as measured by the Net Present Cost (NPC). Due to the high initial expenditures on renewable energy systems, the Levelized Cost of Energy (LCOE) of the system is 65 percent higher than the present energy cost in Botswana for households and 57 percent higher for companies.	[160]
PV/WT	B	Off	Italy	The study demonstrated a correlation between the increase in revenue and the capacity installed in the battery and concluded that the use of hybrid VRE storage systems would be feasible in the Iberian Peninsula and Italy for battery installation costs ranging from €14,804/MW to €38,267/MW.	[161]
PV/TS	B/FC	Off	Spain	This study shows that the use of microgrids for a single-family home is a technically viable solution, not only in terms of energy demand, but also in terms of power demand which is not study in any other literature to the best of our knowledge. For this scale, the use of hydrogen technologies is technically possible, but economically unfeasible, because of the high investment costs of the necessary equipment.	[162]
PV/WT/HT/BG	-	-	South Korea	The results show that a convolutional neural network can efficiently predict sequential demand electricity (R2 = 98.79%), with respective Bio, solar, hydro, and wind energies optimally supplied 45.7, 34.52, 14, and 5.78%. under optimal conditions in S. Korea.	[163]
PV/HT	-	Off	Indonesia	This combined power plant can service the electrical load of 962 households. The production of electricity to supply the domestic housing load is 3273 kWh per day. In addition to meeting the needs of the local area, excess electrical power from micro-hydro and solar photovoltaic plants can also be sold to available grid systems. Based on the analysis, the excess electricity that can be sold every year is 4,263,951 kWh.	[164]
PV/WT/DG	B	Off	Malaysia	Results show that scenario B, with the net present cost (NPC) of 188,814$ and the cost of energy (COE) of 0.198$/kWh, is reliable in delivering the electricity required while having a reasonable cost relatively low emission. Sensitivity analysis is also carried out with different parameters to examine its effects on the system's sustainability throughout its lifetime.	[165]
PV/BG	-	On	Argentina	The optimum hybrid system size was the installation of biomass plant with 2.4 kW capacity, and 16 solar panels with a capacity of 5.2 kW. The initial investment required is 17,042 USD, with a payback of 3.4 years and a GHG reduction of 275.9 tons of CO2 eq per year.	[166]

PV/DG	B	Off	Ethiopia	The proposed microgrid configuration is capable to meet an average daily load of 3,596 kWh/day with 405 kW peak power demand. The NPC of $4.13M and at LCOE of $0.149.	[167]
PV/WT/CSP	PHS	Off	Qatar	The results show that increasing the share of RES in electricity production is possible by as much as 80%. The optimum cases for the deployment of wind, PV, and CSP with storage technologies presented a 28.3%, 23.4%, and 38.2% share to electricity produced, respectively. The market economic simulation shows that the total annual cost for some of the scenarios that integrated renewable energy was lower than that of the reference case currently deployed in the country.	[168]
PV/DG	B/FC	Off	UAE	The LCOE was found 0.34 $/kWh after including the capital, recourses, operation and maintenance, and replacement cost for the lifetime of the project which is 25 years. The unmet electrical load and shortage capacity were 0.0102 % and 0.0912 %, respectively. Furthermore, the environmental impact of the system was compared with the diesel energy system based on the carbon footprint and emission as in carbon dioxide, carbon monoxide, unburn hydrocarbon, sulfur dioxide, and nitrogen oxide. The carbon footprint was 90.1 which equivalent to 1000 saving diesel gallons.	[169]
CSP/BG	-	Off	Jordan	Hybrid system of waste incineration — parabolic trough plant was investigated to generate power and desalinate water. Around 34 MWe power can be generated and 13,824 m3/day of water desalinated. Superheated steam temperature can be fixed at 550 °C due to continuous waste loading. Minimum treatment cost of each Ton of MSW is found to be 11.5 US$ in the 15th year of operation. Around 2,450 tons/month of CO2 emissions were reduced due to solar field performance.	[170]
PV/WT	B	On	Chile	The evaluation of the potential of on-site 1MWh steady electricity generation from a hybrid renewable energy system consisting of photovoltaic micro-generation, wind turbines and battery systems shows mixed results for Chile. Only specific regions possess weather conditions where complementarity between solar and wind resources would be an advantage. In regions with very high solar radiation and low cloudiness, such as in the Atacama Desert, there is no apparent advantage of combining PV and wind power. Under those climatic conditions, systems consisting only of PV and Battery would be able to constantly provide 1 MWh of energy at the lowest cost.	[171]
PV/WT	B	Off	Kenya	The techno-economic modelling shows that PV/wind hybrids have both technical and economic potential at average wind speeds above 4.5 m/s but little relevance below. The capacities of the components are PV, WT and bakeries are 72.5 kW, 5.4 kW and 242 kWh, the NPC is $ 440,000 and he LCOE of $0.676 for kWh	[172]
PV/DG	-	Off	Burkina Faso	The results revealed that the hybrid configuration PV/Diesel leads to about 54% decrease of the LCOE when compared to conventional diesel generator stand alone configuration. Furthermore, it has been shown that the discount rate and fuel prices have a sharp impact on the LCOE. A decline of the interest rate from 9% to 0% results in 83% decrease of electricity cost while an increase of fuel cost from $1.2/L to $3/L results in a staggering 110% increase of the LCOE.	[173]
PV/W/BG	B	On	Bulgaria	One tonne MSW can potentially produce up to 1000 kWh of electricity. Biogas generator is found to make the most substantial share of electricity generation (up to 60–65% of total)	[174]
PV/WT	FC	OF	Chad	The results showed that in the electricity generation scenario, the average total NPC for the studied stations was $ 48164 and the average LCOE was $0.573. The lowest LCOE was related to Aouzou station with 0.507 $/kWh and the highest LCOE was obtained for Bol station with 0.604 $/kWh. In the simultaneous electricity and hydrogen generation scenario, the cheapest hydrogen ($4.695/kg) was produced in the “Grid” scenario, which was the same for all of the stations, with a total NPC of $2413770. The most expensive hydrogen ($4.707/kg) was generated in the “Grid-Wind” scenario and Bol stations with a total NPC of $2420186. The paper develops cost effective	[175]
PV/WT	B	On	Denmark	The stability of power injected in the grid is discussed with Battery Storage for a Hybrid Residential PV-Wind System	[176]
PV/WT	B/FC	Off	UK	The cost of electricity (COE) of the new system was £0.776 per kilowatt hour.	[177]
PV/DG	B	On	Lebanon	The optimization approach offers an efficient methodology to evaluate alternative designs in order to select the best source sizes that minimize the LCOE of the system.	[178]
PV/WT/DG	B	Off	Syria	The system consists of photovoltaic (PV) panels and a wind turbine as renewable power sources, a diesel generator for back-up power and	[179]

				batteries to store excess energy and to improve the system reliability. The optimization results show that using a power supply system consisting only of batteries, PV and wind generators may be applicable as well to satisfy the power demand.	
PV/WT/DG	FC	Off	Tunisia	It is shown that the system guarantees a dumped energy of only 4.7%, less than 0.05% of unmet power and reduced power losses resulting from converting procedure of 1.02% from the total production. From a financial perspective, the proposed model presents a competitive LCOE of \$0.0492/kWh and a renewable fraction of 35.52% with further diminished carbon dioxide emission.	[180]
PV/WT	B/FC	On	Bahrain	The annual renewable energy production of the HRES was 3,518 kWh, where 3,285 kWh was produced by the 4.0-kWp PV system with an annual yield of 821 kWh/kWp and 348 kWh was produced by the 1.7-kW WT system with an annual yield of 205 kWh/kW. the HRES reduced the annual CO2 emission from an expected value of 3,800 kg of CO2 – in case of powering the station using the public grid only – to 1,990 kg, a 48%-reduction.	[181]
WT/DG	B	On	Mauritania	Analysis shows that the optimum compination of the hybrid system is (wind /diesel / batteries): 4 wind turbines of 100 kW each, two generators of 100 kW each, 400 batteries of 4 V / 1900 Ah / 7.6 kWh each and a converter of 150 kW. This configuration records a total NPC of 3, 151,076 \$, a cost per kWh of 0.199 \$ with a renewable energy fraction of 0.77 (77%) and finally, the diesel generator runs 2,937 h.	[182]
PV/WT	FC	Off	South Africa	The capital cost of the hybrid system was found to be \$177,600 with a NPC of \$206,323. The LCOE of the system was determined to be 2.34 \$/kWh.	[183]
PV/WT/DG	-	Off	Scotland	The research focused on seeking the optimal size of the batteries and the diesel generator usage in small sizes systems.	[184]
PV/WT		Off	Bangladesh	The work presented a feasibility and sensitivity analysis of on/off grid mode hybrid renewable energy by estimating the potentials of solar and wind energies at different areas in Bangladesh - a country that experiences a tropical climate.	[185]
PV	B	On	Cameroon	The system is designed and optimized for household energy supply in three different locations in Cameroon. The monthly PV/Battery energy represents 58.371% to 74.160% of the load consumed.	[186]
PV/WT/DG	-	Off	Comoros	A study of PV-Wind-Diesel system for energy supply in remote areas applied for telecommunications towers in Comoros was conducted using HOMER software tool. The LCOE of the energy generated by the offered system (0.198 \$/kWh) is cheaper of the Comoros energy (0.31 \$/kWh).	[187]
PV/WT/DG	B	Off	Peru	Technical aspects of implementation, operation, and social impact of a hybrid microgrid installed in Peru has been studied, a rural fishing community composed of about 35 families who have no access to electricity. the wind speed average of 8 m/s and annual average irradiation of 6 kWh/m^2/day. The designed hybrid system is composed of a 6 kWp PV system and two wind turbines of 3 kW each, 4 kW inverters, and a battery bank of 800 Ah, 48 V , which is designed to work at 50% Depth of discharge.	[188]

Abbreviations: B- Battery, PV- Photovoltaic solar panel, WT- Wind turbine, BG- Biogas electrical generator, DG- Diesel electrical generator, FC- Fuel cell, HT- Hydro-turbine, GE-geothermal energy, PHS- pumped hydro storage system, TPP- thermal power plant, HE- Hydrogen engine, CSP- concentrated solar power, TS- thermal storage,

Based on this literature evaluation, the current work could claim to have the following contributions:

- Emphasizing the economic and technological viability of locally available renewable energy resources.
- Identifying the optimal size of grid-connected PV/Wind/Diesel generator hybrid renewable energy system integrated with Lithium battery that meets the load requirements.
- Introducing a comprehensive economic and environmental analysis including the social cost of CO$_2$.
- Broader implications: While this research focused on the Libya situation, the prescribed approach and findings have broader applicability to other developing countries with similar energy contexts.

The article is further organized as follows: Section 2 presents the optimization process including the objective functions and the constraints, states the hypotheses, limitations and uncertainties of the study. The obtained results are presented and discussed in Section 3. Finally, the main conclusions are given in Section 4.

Methodology

Healthcare Facility Load Profile

Two approaches have been suggested in order to establish the electricity consumption of the Garyan Medical Centre [189]. One of the methods is based on the statistics provided by national power suppliers. Yet, this approach has been found unreliable due to its lack of accuracy. Therefore, the approach that is based on direct measurements will be employed as the most precise one. This method includes calculations of electricity consumption per day for each device, taking into account light, equipment, and air conditioners [189]. Using equation (1) to establish the total load for one day, we can conclude from Table 2 what amount of energy is required by health care organizations in Garyan City every day.

$$\text{Daily load} = \sum(\text{appliance power working hours} \times \text{no.appliances})$$

$$\text{Daily load} = (18 \times 10 \times 802) = 144360 \text{ Wh/day}$$

$$\text{Average hourly cons.} = \frac{\text{Total Daily Cons.}}{24} \quad (1)$$

$$\text{Average hourly cons.} = \frac{851450}{24} = 35.477\text{KW}$$

Table 2: Daily Electrical Consumption of Appliances in the Healthcare Facility (Gharyan, Libya) [190-192].

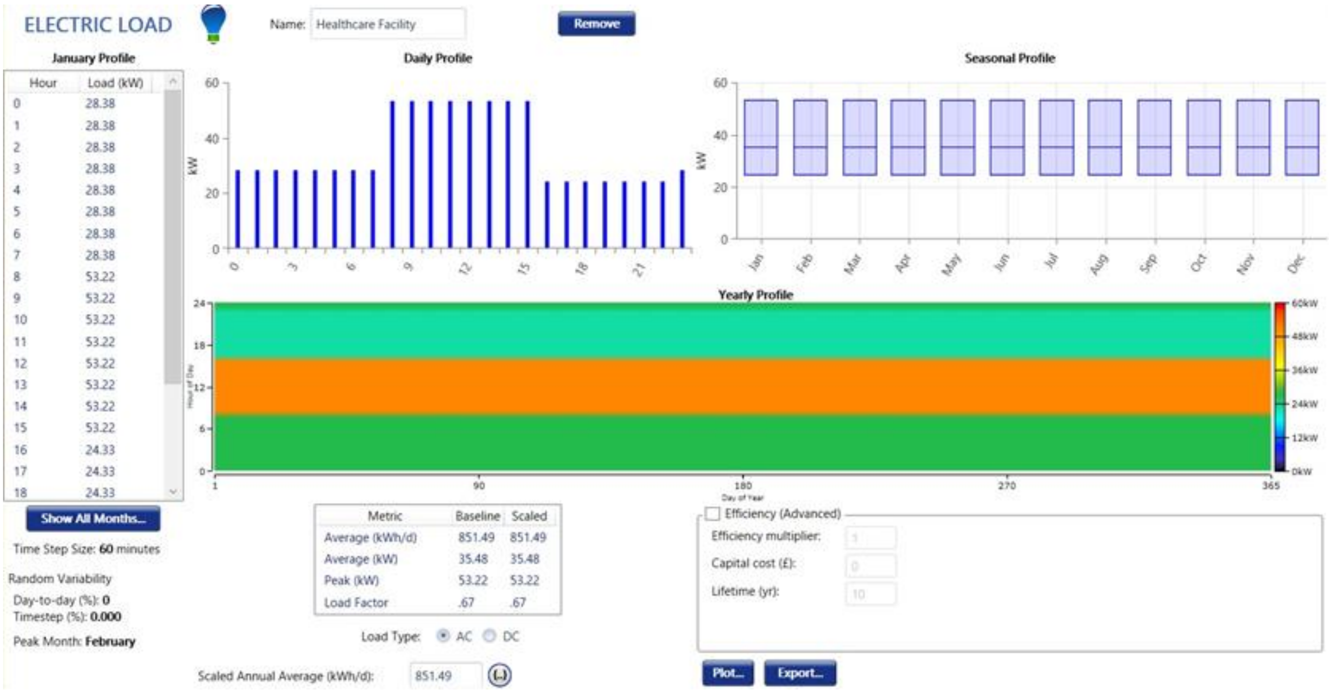
`Appliances	Power (W)	Working hours (h)	Number	Consumption per day (Wh/day)
Lamps	18	10	802	144360
Computers	350	10	20	70000
Air conditioners	1800	8	31	446400
Boiler	1000	4	20	80000
TV	120	8	16	15360
Fridge	150	16	10	24000
C.T scanner	2000	5	1	10000
Incubators	350	8	1	2800
X-ray	3000	8	1	24000
Ultrasound	1350	9	1	12150
Elevator	7460	15	2	22380
Total Daily Consumption = 851.450 kWh/**day**				

The daily energy consumption for a typical day is 851.45kWh, as detailed in Table 3 Energy consumption is allocated according to actual operating schedules: 50% is used during daytime hours (08:00–16:00), 20% in the evening (16:00–23:00), and 30% at night (23:00–08:00). This corresponds to average hourly demands of 53.22 kWh during the day, 24.33 kWh in the evening, and 28.38 kWh at night. This daily distribution is consistently applied year-round, resulting in an 8,760-hour annual load profile for use in HOMER Pro simulations.

Table 3: Distribution of Daily Electrical Load by Time Period (Healthcare Facility in Gharyan, Libya).

Hour (UTC+2)	Number of Hours	Percentage (%)	Hourly Load (kWh)
Night (23:00–08:00)	9	30	28.38
Day (08:00–16:00)	8	50	53.22
Evening (16:00–23:00)	7	20	24.33

Daily electrical loading was distributed proportionately to the similar periods of observation in a real-life healthcare facility usage. Therefore, 50% of the load went to the daytime period, which is from 8:00 to 16:00, 20% of the loading – evening period 16:00 – 23:00; and 30% of the loading – nighttime period, from 23:00 to 08:00. Hence, the average hourly load of the day is 53.22 kWh, evening – 24.33 kWh, night – 28.38 kWh/hour. The total daily loading is 851.45 kWh. Figure 1 illustrates the changes in time of the facility's load with respect to daily, seasonal, and yearly changes in load. As seen in Figure 1, the daily variation demonstrates variations in time of the facility's load in one-hour increments, where there is maximum loading between morning and late afternoon hours when the majority of medical equipment operates, and air conditioners are working. Seasonal variation demonstrates monthly changes in energy demands, but it can be assumed that there is a small variation in demand, which depends only on seasonal weather variations. Annual variation of load shows that there is no change in load demands throughout the year.



Name: Healthcare Facility

January Profile

Hour	Load (kW)
0	28.38
1	28.38
2	28.38
3	28.38
4	28.38
5	28.38
6	28.38
7	28.38
8	53.22
9	53.22
10	53.22
11	53.22
12	53.22
13	53.22
14	53.22
15	53.22
16	24.33
17	24.33
18	24.33

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): **0**
Timestep (%): **0.000**

Peak Month: **February**

Metric	Baseline	Scaled
Average (kWh/d)	851.49	851.49
Average (kW)	35.48	35.48
Peak (kW)	53.22	53.22
Load Factor	.67	.67

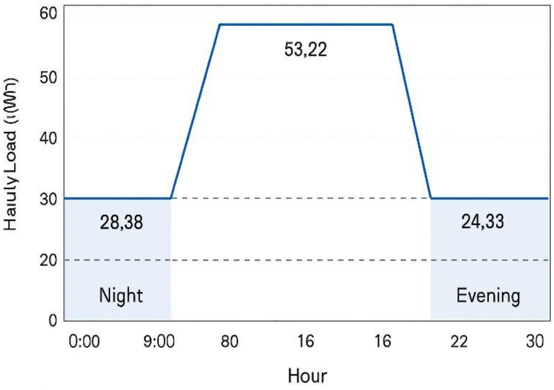
Load Type: ● AC ○ DC

Scaled Annual Average (kWh/d): 851.49

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost (£): 0
Lifetime (yr): 10

Figure 1: The temporal variation of the facility's electrical demand across three scales: daily, seasonal, and year

Daytime (08:00-16:00) hours were equally split into eight hours, hence an equal hourly load demand of 53.22 kWh/hour. The value represents the peak load in the daily load profile because it denotes the hourly load demand when there is high activity in the health institutions. However, compared to the peak load in the ideal case, where it is calculated as the summation of the power rating of appliances used within the whole day, the peak load considered in HOMER Pro simulation will be the highest hourly load demand in the daily load profile. Equally dividing energy demand for each hour of the day is necessary to ensure accuracy and consistency in calculating daily load profiles using the methodology applied. The hourly load curve for the normal day comprises a daily load curve pattern having a daily load demand of 851.45kWh. The pattern is composed of three periods as follows: Night (23:00-08:00) hours with an hourly load of 28.38 kWh; Daytime (08:00-16:00) with an hourly load of 53.22 kWh, and Evening (16:00-23:00) hours with 24.33 kWh as shown in Figure 2 below. The daily load curve is determined by the nature of operations in the health care facilities, where there is high use of energy during the day as compared to the evenings and nights. The data on daily use of the load was duplicated 365 times to get 8760 hours that would be used to run the HOMER pro simulation mode.



Figur 2: Hourly Load Distribution by Time Segments (Healthcare Facility, Gharyan, Libya)

Renewable Resource Assessment

Solar radiation data for the Gharyan region

Gharyan is one of the areas in Libya which benefits from great solar potential. The average amount of solar radiation in Gharyan is estimated to be 5 to 6 kWh/m^2/day [18,19]. In combination with the semi-arid climate, Gharyan becomes an ideal location for photovoltaic as well as solar thermal applications. The high amount of solar radiation gives Gharyan an edge for renewable energy development. Monthly average solar radiation of Gharyan is tabulated in Table 3 [193].

In this context, it is essential noting here that the HOMER program utilizes the HDKR (1990) model [194], while—according to local studies [195-198] the Liu & Jordan model is the appropriate for the region. Also, it is worth mentioning that the solar irradiance incident on solar field is different from that incident on a single panel or that recorded in the metrological stations [199-204]

Wind speed and direction measurements at the hospital site

Wind speed and directions for the Gharyan healthcare center location in Libya are presented in Figure 4. Wind speeds vary from 3 mph to 15 mph (1.5 m/s to 7 m/s), with occasional gusts of 20 mph (9 m/s). Southerly winds (S, SSE, and SSW) are predominant, but north-easterly (NE) and south-west winds (SW) also exist. [205-208].

Climatic Conditions

Climatic parameters for the Gharyan hospital location, Libya, based on wind, solar radiation, and temperature measurements. This chart provides wind velocity and direction, daily average solar radiation, and seasonal temperature variations. These climatic parameters determine the functioning of the renewable energy system in this area [21]—Table 3 Monthly Assessment of Renewable Energy Potential and Climatic Parameters in Gharyan, Libya. Temperature, humidity, and dust content influence the performance of PV and wind [22].

Tale 3: Monthly Evaluation of Renewable Energy Potential and Climatic Conditions in Gharyan, Libya [22].

Months	Solar Irradiance (W/m^2)	Wind Speed (m/s)	Temperature (°C)
January	2.670	5.370	13.840
February	3.660	5.700	14.120
March	4.790	5.690	15.670
April	6.150	5.640	18.130
May	6.980	5.760	21.630
June	7.670	5.670	24.680
July	7.790	4.760	26.510
August	7.050	4.890	27.390
September	5.520	4.920	25.870
October	3.960	5.060	23.200
November	2.750	5.070	19.280
December	2.350	5.210	15.520

Design of system

In this part, the hybrid microgrid design and optimization for a hospital complex in the ESOGU campus are discussed [23]. In this design, the bus for healthcare loads and the utility grid is AC, while the bus that connects the PV array and battery is DC. Energy interchange between the two buses is possible through the use of bidirectional. converters that can operate either as an inverter or a rectifier [24]. Although there are no DC loads at present, the inclusion of healthcare loads in the future cannot be precluded [24]. Parameters such as component specification, rating of capacity, capital cost, replacement cost, and O&M cost for each of the following components: PV array, diesel generator, battery bank, and converter were identified for the design [24,25]. These data have been used in simulations and optimizations [25]. The main constituents of this hybrid power system include six elements, namely: grid access, PV, battery bank, diesel generator, converter, and hospital loads

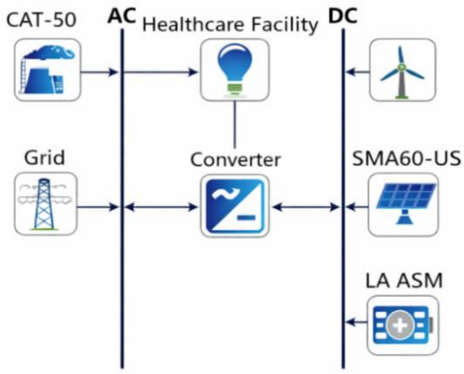


Figure 3: Schematic diagram of the hybrid renewable energy system

Design of wind turbine

Power from the wind energy conversion system (EW) has been modelled using a piecewise function based on the physical operating constraints of the system, it is calculated as shown in equation (2). A wind energy system that is rated at 20 kW begins its operation when the wind speed equals 2.8 m/s. The power continues increasing steadily until the wind speed reaches 7.5 m/s, which marks the point of rated wind speed where the power from the system will be rated Prat until wind speeds reach the cut-out speed of 20 m/s. Should the wind speed exceed 20 m/s, the wind turbine is stopped via feathering or braking and produces no power until it drops below 20 m/s. [75, 209].

$$E_W = \begin{cases} P_{rat} & V_{rat} \le V_{Z,t} \le V_{cut-off} \\ P_{rat}\left(\frac{V_{Z,t}-V_{cut-in}}{V_{rat}-V_{cut-in}}\right) & V_{cut-in} < V_{Z,t} < V_{rat} \\ 0 & V_{Z,t} \le V_{cut-in}\ OR\ V_{Z,t} > V_{cut-off} \end{cases} \quad (2)$$

Where$P_{rat}$is the rated power of the wind turbineat rated wind speed V_{rat}, V_{cut-in} and $V_{cut-off}$ are the cut-in and cut-of wind peeds, and $V_{Z,t}$ is th wind speed at the wind turbine hub height (h_Z) and it is calculated from: $V_{Z,t} = V_{0,t}\left(\frac{h_Z}{h_0}\right)^{\propto}$ where, $V_{0,t}$ is the wind speed at a certain elevation (h_0) and is the wind shear coefficient [210]. However, from the operational conditions of the chosen 20 kW wind turbine, the energy output falls under three major functional regions. First, the wind velocities that are lower than the cut-in wind speed of 2.8 m/s mean that the energy production rate equals zero, or (E_W). Within the second region (cut-in wind velocity to the rated wind velocity), the power output increases proportionally to the wind velocity. For example, with the wind speed equalling 5 m/s, the energy output is estimated to be around 9.36 kW. Finally, starting from the rated wind speed (in this case, 7.5 m/s), the energy output of 20 kW can only drop once the cut-out speed of 20 m/s is reached. Table 4 shows Wind Turbine Technical Specifications and Economic Data.

Table 4: Wind Turbine Technical Specifications and Economic Data

Parameter	Symbol	Value	Unit
Rated Output Power	P_{rat}	20	kW
Investment Cost		35,800	USD
Rated Output Voltage		240V / 60Hz	-
Startup (Cut-in) Wind Speed	V_{cut-in}	2.8	m/s
Rated wind speed	V_{rat}	7.5	m/s
Cut-out Wind Speed	$V_{cut-off}$	20	m/s
Rotor Diameter		15.8	M
Operational Lifetime		20	Years
The energy production	(E_W)	9.36	kW

The capacity factor is one of the important indices that shows the effectiveness of wind turbines. It can be defined as the ratio of the actual energy produced to the maximum theoretical energy that could be produced at its rated capacity. The formula for the calculation of the capacity factor is presented in Equation (3). This index allows us to evaluate the performance of the wind turbine in a way that helps in the sustainable planning of energy

$$CF = \frac{E_{actual}}{p_{rat} \times 24 \times 365} \quad (3)$$

In order to assess the effectiveness of the operation of the wind turbine generator with a power rating of 20 kW, the Capacity Factor (CF) is determined through the comparison between the actual daily energy production and the theoretically maximum possible energy generation. Based on the turbine's characteristics, including its cut-in speed (2.8 m/s) and rated speed (7.5 m/s), the energy generation potential of the system is compared to the maximal theoretical value of 480 kWh per day. For the selected test case, with the wind velocity being 5 m/s, the expected energy production amounts to 225 kWh per day. Consequently, the resulting Capacity Factor equals 46.8%.

Design of PV solar field

Photovoltaic (PV) technology uses PV modules to convert light energy into direct current (DC) electricity. There are certain factors that contribute to the amount of power produced by the PV system. Some of the important factors considered include the nature of panels, rated capacity, derating factor, solar irradiance, cell temperature, and environmental conditions. In addition, flat plate PV panels are represented using Generic PVs while the AC conversion is done through SMA Sunny Tripower 60-US inverter [38-45]. SMA Sunny Tripower 60-US is a specific inverter designed to connect the PV system with the already existing grid; thus, it fits perfectly for industrial/commercial purposes. The main purpose of the inverter is to convert direct current produced by the PV panels into usable AC electricity that can be added to the existing grid network. In addition, Generic PV is basically a standard PV module that mimics the performance of ordinary PV cells (e.g., power output and efficiency) [211]. Capital and replacement cost for PV subsystem will be around \$5,000-\$5,500/kW, operation & maintenance (O&M) cost between \$200-\$400 each year, and a lifetime of 20 years. Effective energy distribution has been achieved in the microgrid structure via the use of the DC bus integration method.

However, the real power generated by a photovoltaic cell depends on environmental factors, which can be estimated using the equation below (4) [212].

$$E_{PV} = P_{STC}\left[1 + \beta_p(T_{cell} - T_{STC})\right]\frac{H_t}{H_{\text{STC}}} \quad (4)$$

In this equation, T_{STC} represents the temperature of the cell under STC, and T_{cell} refers to the cell temperature under real environmental conditions (°C). β_p refers to the temperature coefficient of power (%/°C), while H_{STC} and H_t refer to the solar irradiance of STC and real environmental conditions, respectively (W/m²). One challenge that faces scientists is developing an empirical equation to compute the real cell temperature, T_{cell} (Equation 5) [213].

$$T_{cell} = T_{\infty} + 7.8 \times 10^{-2} H_t \quad (5)$$

Real power generated from the PV panel (E_{PV}) is calculated by modifying the rated capacity (P_{STC}) to consider the variations in solar radiation and temperature. This calculation takes into consideration two important factors: one being linear power scaling, which means that output will change according to the ratio between the actual value of tilt radiation (H_t) and the standard radiation value (H_{STC}), while the other factor is thermal degradation. In this case, an equation with a coefficient (β_p) is used to determine the efficiency drop when the temperature at which the cells operate (T_{cell}) is higher than the reference value of temperature at 25 degrees Celsius (T_{STC}) Table 5 shows demonstrates that the environmental conditions prevailing in the vicinity of the photovoltaic installation have a significant impact on its operation compared to the installed power. For instance, reducing the level of radiation from the typical 1000 W/m² to 800 W/m²leads to a reduction in power production by about 20%. Similarly, raising the cell's temperature from the usual 25°C to 55°C reduces efficiency by about 10.5% due to the power-temperature coefficient. If the two factors are taken into consideration, a 550 W system produces about 393.8 W.

Table 5: Electrical characteristics of the PV solar panel

Parameter	Symbol	Value	Unit
Rated Power	P_{STC}	550	W
Actual solar irradiance	(H_t)	800	W/m²
Reference Solar Irradiance	H_{STC}	1000	W/m²
Operating Cell Temperature	β_p	25	°C
Reference Temperature	T_{cell}	55	°C
Temperature Coefficient	T_{STC}	-0.0035	/°C
efficiency	η	13.1	%
Actual Power Output	E_{PV}	393.8	W

The ability to substitute them with a PV system depends upon the available solar energy resource at that place, as well as the demand for energy per day. Peak Sun Hours (PSH) were found with the help of dividing the average daily irradiation by peak solar irradiation using equation (6). For the case study, the peak Sun Hours were 6 hours. The capacity of the PV system is estimated by considering the daily load demand and with an additional safety margin of 1.3 for the PV system. Besides, the capacity of PV panels was estimated with the help of equation (7). With daily energy consumption being 851.450 kWh/day, the estimated capacity of the PV system is 184.481 kW.

Design of Battery Energy Storage Unit

Energy storage systems have proved very critical in ensuring a continuous energy supply in microgrids where renewable energy is harnessed as the energy source. Any excess energy produced is stored and later released when there are deficits in energy supply or an increase in energy demand. In this study, a kinetic battery energy storage system was used to analyze the dynamic behaviour of the system. Some operational characteristics, such as the maximum charge rate and charge currents, were identified using HOMER software. Through this, the charge.

The state of charge $SoC(t)$ estimation uses a well-defined energy balance technique. which can be estimated using the equation below (6). To begin with, the net energy is calculated by deducting the load demand from the total generation. The net energy is multiplied by the round-trip efficiency of the battery system (ηb) to take into account internal energy losses. Lastly, the net energy is added to the previous SoC, considering the battery's self-discharge rate (σ). The recursive modelling process allows for an accurate monitoring of energy storage capacity, which is essential in ensuring the durability of the battery bank in a hybrid system [215-216].

$$\mathrm{SoC(t)} = \mathrm{SoC(t-1)(1-\sigma)} + \left(\mathrm{P_{sys}(t)} - \frac{\mathrm{P_L(t)}}{\eta_{\mathrm{inv}}}\right) \times \eta_{\mathrm{b}} \qquad (6)$$

The simulation findings, as shown in Table 6 above, illustrate the charging process of the battery storage sub-system in the hybrid grid. Through the consideration of the inverter loss and the efficiency of the batteries (η_b= 0.90), the analysis reveals an excess capacity of 44.74 kW relative to the total energy requirements at that moment. Once the correction is made for the efficiency due to the chemical and thermal losses, a net gain of 40.26 kWh is gained and the $SoC(t)$is increased from 500 kWh to 539.76 kWh. This indicates the capability of the hybrid power system to store surplus energy to meet future demands. Also, the use of this method is crucial in maintaining enough energy storage in the batteries to cover the deficit energy production during periods of less renewable energy production.

Table 5: Battery Modeling Parameters and SoC Calculation Results

Parameter	Symbol	Value	Unit
Initial State of Charge	$SoC(0)$	500	kWh
Total System Power Generation	$\mathrm{P}_{sys}(\mathrm{t})$	150	kW
User Load Demand	$P_L(t)$	100	kW
Inverter Efficiency	η_{inv}	0.95	-
Battery Round-trip Efficiency	η_b	0.90	-
Monthly Self-discharge Rate	σ	0.001	

Capacity of Battery

The calculation of the necessary power of the battery (P_B) depends on the maximum necessary power in a year (max [$SoC(t)$]. Therefore, taking into consideration the maximum power needed in a year, the calculation assumes that the capacity will cover the most difficult hours of the year. To protect the devices and increase their durability, the following equation is multiplied by the DOD or the energy discharged from the battery power. The second factor of this model is called the Temperature Correction Factor (CF_T).

The calculation of the Capacity of the battery is presented in Equation (7). Table 6 demonstrates the Parameters of Battery Capacity [50-52].

$$\mathrm{P_B} = \frac{\mathrm{max[SoC(t)]_{t=1,8760}}}{\mathrm{DOD}} \times \mathrm{CF_T} \qquad (7)$$

Where: $\mathrm{CF}_T = 0.0004T^2 - 0.0246T + 1.3961$

Table 6: Parameters of Battery Capacity

Parameter	Symbol	Value	Unit
Depth of Discharge	DOD	80	%
Temperature Correction	CF_T	1.031	-

Design of Converter

Power conversion is carried out using a bi-directional converter that switches between the roles of being an inverter and a rectifier according to the needs for power generation, consumption, and storage. To maintain energy management reliability, an ABB converter was used. The cost analysis was carried out assuming a 1 kW capacity for the power output with a capital and replacement cost of 10,000.00 SAR/kW, O&M cost of LYD/year, and a useful life period of 15 years. The converter, which was coupled with two busbars, was expected to have an efficiency level of 95% [217-2019].

$$p_{inv}(t) = \frac{P_l^m\,(t)}{\eta_{inv}} \qquad (8)$$

Design of Diesel Generator

Diesel power generators are incorporated in the hybrid renewable energy system in this study to ensure any continuity of supply in case of any shortage in the amount of energy produced from renewable energy sources. The process was conducted by using the HOMER program to calculate the amount of fuel consumed accurately by each load. To compare the systems' efficiency, the CAT 50kVA 50Hz PP diesel generator was chosen, producing an output of 40 kW. The characteristics of the fuel consumption were determined by modelling a linear fuel curve where the intercept equals 0.300 L/hr and the slope is 0.390 L/hr/kW. [105].

$$FC_{(t)} = A_G * P_{DG} + B_G * P_r^{DG} \tag{9}$$

$$FUELC = \left(S_f \sum FC_{(t)}\right) * CPV \tag{10}$$

$$CPV = \frac{r_i(1+r_i)^n}{(1+r_i)^n - 1} \tag{11}$$

Where the in eqn. (9) refers to the fuel consumption that measured in (Liter/kW), is the coefficient of FC that equals 0.24, is the generated power from the DG, is the constant valve or coco efficient of FC equals 0.084, and refers to the rated power, respectively. Additionally, the cost of fuel ($FUELC$) is mathematically formulated in eqn. (10), the denoted as the current price of diesel fuel per liter represents the modeled of fuel consumption, denoted as the cumulative present value which mathematically can be expressed in eqn. (11).

System Input Data

The analysis of the hybrid energy generation system sizing comprised the following key components: PV, diesel, and battery systems, as well as wind power generators and converters. Inputs related to the above system components refer to the costs (capital, replacement, and operating and maintenance (O&M)) connected with the capacity of a particular unit. In relation to the HOMER software, the capacity of a particular unit (1 kW) is used to calculate the cost of that particular unit (capital, replacement, and O&M). Meanwhile, the capacity of a particular system (in kW) refers to the total capacity of a particular device. This means that the cost of a particular energy generation system depends on the capacity selected. Table 7 demonstrates the key characteristics of system component designs.

Table 7: System Input Parameters and Simulated Performance Results.

Component	Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
PV System	393.8	5,000-5,500	5,000 – 5,500	200-400
Wind turbine	9.36	50,000-120,000	10,000-30,000	1000-3000
Generator	40	6,000-10,000	4,000 – 7,000	500–1,500
Batteries	128.9 kWh	50-120	50-120	3-5
Converter	200	10,000 –20,000	7,000 –15,000	200–500

System block diagram

The diagram below illustrates the energy flow between the AC system and the DC system, both ways, in the hybrid system that has been installed at the healthcare facility. The components used in the AC system include the CAT-50 diesel generator, utility power lines, and the converter. Conversely, the components used in the DC system include the EO20 wind turbine, SMA60-US solar PV panels, and LA ASM battery systems, which can produce a sufficient amount of energy, amounting to 851.49 kWh, using 53.22 kW as the peak load

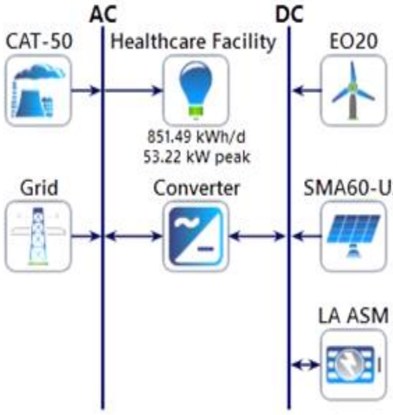


Figure 4: Schematic diagram of energy flow between alternating current (AC) and direct current (DC) sources in a hybrid system

Economic and Environmental Analysis

Accounting for environmental damage costs within an economic framework can improve the relative competitiveness of clean and renewable energy systems, including in contexts where energy prices are supported by subsidies [49]. Among the available metrics, the levelized cost of energy (LCOE) is considered a key indicator for economic–environmental comparison across energy alternatives [50]. In this study, LCOE is calculated as follows [220]:

$$LCOE = \frac{\frac{r(1+r)^n}{(1+r)^n - 1} C_{HRE} + OM_{HRE} - C_{CO_2,E}}{E_{Load}} \tag{12}$$

Where C_{HRE} denotes the capital costs of the hybrid renewable energy system equipment, (USD). OM_{HRE} represents the annual operation and maintenance (O&M) costs of the HRE system (USD/year). $C_{CO_2,E}$ refers to the environmental cost of carbon emissions (USD/year), E_{Load} refers to the annual electricity supplied (kWh/year), and n is the service lifetime of the PV and hydrogen system components.

The real discount rate r is assumed to be 3.4%, and it is determined from the nominal discount rate i (6%) and the inflation rate f (2.5%) as follows [220]:

$$r = \frac{i - f}{1 + f} \tag{13}$$

The net present value (NPV) is evaluated following, and the payback period is estimated according to, as expressed in the following equations [220]:

$$NPV = \frac{\frac{r(1+r)^n}{(1+r)^n - 1} C_{HRE} + OM_{HRE} - C_{CO_2,E}}{\frac{r(1+r)^n}{(1+r)^n - 1}} \tag{14}$$

$$PBTM = \frac{CC_{pv} + CC_{H2}}{Income} \tag{15}$$

The carbon cost associated with CO_2 emissions from electricity generation is determined as follows [220]:

$$C_{CO_2.E} = SC_{CO_2} \times EF_{CO_2,E} \times E_{Load} \tag{16}$$

Where $S_{CO_2,E}$ denotes the social cost of carbon, taken as 70 USD/ton as specified by the International Monetary Fund (IMF) Q_E represents the annual electricity amount, and $EF_{CO_2,E}$ is the carbon emission factor (1.037 kg CO2/kWh) [221].

Results and Discussions

During the simulation phase, the software package HOMER Pro was used to model and optimize the proposed hybrid system. The data set for the input included the geographic. Location of the proposed system, system limitations, control parameters of the generators, dispatching policies, life spans of the different components, interest rates, and the hourly load demand. In addition, the technical specifications, such as tilt angle, efficiency, capacity options, O&M costs, and cost of components, were considered

Figure 5 demonstrates the simulation outcomes achieved for the hybrid energy system based on the HOMER Pro software tool. Table 8 presents a comparative analysis of different alternatives in which solar photovoltaic panels and power converters would constitute the primary sources of electricity production to augment the conventional power grid system. In each line of the table, there is a distinctive configuration of the system along with its techno-economic characteristics. The system configured in the sky-blue colour provides the lowest cost of electricity generation, rendering it economically sound while reducing the net present cost and lifecycle cost. Moreover, this system finds the optimum compromise between initial investment and annual operating expenses, representing economic feasibility

Architecture														Cost				System		CAT-50		
						SMA60-US (kW)	SMA60-US-MPPT (kW)	EO20	CAT-50 (kW)	LA ASM	Grid (kW)	Converter (kW)	Dispatch	COE (د.ل)	NPC (د.ل)	Operating cost (د.ل/yr)	Initial capital (د.ل)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)
				●							999,999		CC	$0.100	$359,908	$31,079	$0.00	0	0			
		●		●					40.0		999,999		CC	$0.102	$367,721	$30,891	$10,000	0	0	0	0	0
			●	●	●					100	999,999	50.0	CC	$0.315	$1.13M	$53,611	$512,000	0	0			
		●	●	●	●				40.0	100	999,999	50.0	CC	$0.317	$1.14M	$53,422	$522,000	0	0	0	0	0
	●			●	●			2			999,999	50.0	CC	$0.320	$1.19M	$42,574	$700,000	38.7	0			
	●	●		●	●			2	40.0		999,999	50.0	CC	$0.322	$1.20M	$42,385	$710,000	38.7	0	0	0	0
	●		●	●	●			2		100	999,999	50.0	CC	$0.327	$1.22M	$43,706	$712,000	38.7	0			
	●	●	●	●	●			2	40.0	100	999,999	50.0	CC	$0.329	$1.23M	$43,517	$722,000	38.7	0	0	0	0
●				●	●	50.0	100				999,999	50.0	CC	$0.387	$1.40M	$53,544	$775,143	28.8	0			
●		●		●	●	50.0	100		40.0		999,999	50.0	CC	$0.389	$1.40M	$53,356	$785,143	28.8	0	0	0	0
●			●	●	●	50.0	100			100	999,999	50.0	CC	$0.394	$1.42M	$54,677	$787,143	28.8	0			
●		●	●	●	●	50.0	100		40.0	100	999,999	50.0	CC	$0.396	$1.43M	$54,488	$797,143	28.8	0	0	0	0
●	●			●	●	50.0	50.0	2			999,999	50.0	CC	$0.396	$1.50M	$45,720	$975,071	59.8	0			
●	●	●		●	●	50.0	50.0	2	40.0		999,999	50.0	CC	$0.398	$1.51M	$45,531	$985,071	59.8	0	0	0	0
●	●		●	●	●	50.0	50.0	2		100	999,999	50.0	CC	$0.402	$1.53M	$46,852	$987,071	59.8	0			
●	●	●	●	●	●	50.0	50.0	2	40.0	100	999,999	50.0	CC	$0.404	$1.54M	$46,663	$997,071	59.8	0	0	0	0

Figure 5: Optimization results of the hybrid energy system using HOMER

Cost Summary and Economic Feasibility

As indicated in Table 8, the economies associated with the hybrid RE system under analysis entail a total lifecycle cost of approximately $ 54 million. These costs include capital ($ 997,071), replacement ($ 153,106), and operations and maintenance ($ 466,922), minus the salvage value of $ 79,655. The highest-cost component is the converter/inverter ($ 747,812), followed by the PV subsystem ($ 390,803). Wind turbine and battery storage constitute moderate costs of $ 161 and $ 111, $25 respectively. On the other hand, the diesel generator and power grid connections constitute very minor cost components. These figures indicate that the hybrid RE system under discussion has an economic structure mainly consisting of capital-intensive components. Efficient operations and maintenance are essential for the long-term viability of hybrid RE systems in critical facilities, such as hospitals. Figure 6 provides an overview of cash flows in a long-term project. In year 0, the capital cost would be approximately JOD 000,000. No operating gains are observed until Year 15, at which point the replacement cost would be approximately 200,000 JOD. In Year 20, the investment yields a positive gain of approximately +300,000 JOD from the residual value and operating profits. Such a cash flow pattern is characterized by large investments at the beginning, an expense at midlife, and an end-of-life gain, usually analyzed via NPV and IRR.

Electrical and System Simulation Results

Power generation from the system for the year totals 357,246 kWh, with photovoltaic modules producing 26.3% (94,091 kWh) and the wind turbines contributing 36.7% (131,203 kWh). It should be noted that the generator was not used throughout the year, which means that using renewable sources for generating electricity is a wise decision. Purchased electricity accounted for 36.9% or 131,951 kWh of total electricity production. In this case, electricity supply could be ensured continuously, and seasonal changes would have been evened out. These proportions show that the renewable energy sources play an important role in generating electricity; however, the integration into the electricity grid plays a key role. Therefore, it is possible to state that a hybrid system can provide stable power and export energy and gain some extra income from it. This system proves to be reliable from the point of view of financial efficiency, since it was able to produce 18,610 kWh/year, which is 5.21% of total electricity generation. Meanwhile, there were no unmet electrical loads and excess capacity. Thus, the results presented in Table 10 show that a combined PV-wind-battery system is effective in ensuring stable generation of electricity. On the other hand, there are no shortages, and even the surplus of electricity generated serves as a good indication of how efficient the operation of such systems can be, and whether such systems may be applied to vital places such as hospitals. The stacked bar graph shows the average monthly electricity produced by the hybrid renewable energy system throughout the year. To put it simply, the graph shows the amount of electricity produced using different sources. Each month on the graph is represented by a single bar, split into the CAT-50 generator, EO20 source, grid power, and SMA60-US photovoltaic modules. It is apparent that electricity generation in the hybrid system is fairly steady throughout the year; electricity generation is roughly equal from all sources**.**

Wind System Results

In the third case, the wind system exhibited the same production pattern as in the first case. Figure 8 shows the wind system's annual production curve, demonstrating its effectiveness over 12 months, while Table 12 shows consistent performance, with a capacity factor of 37.4% and an annual energy output of 131,203 kWh. Its economic viability is reflected in a levelized cost of 147LD/kWh and a wind penetration of 42%.

Grid Results

Because the grid operates only to cover any unmet load, the amount of energy purchased from the grid depends directly on PV and wind system output. When the combined output of PV and wind energy exceeds the load demand, the surplus electricity is exported to the grid. Table 14 summarizes the annual energy purchased from and sold to

Table 8: Cost Summary and Economic Feasibility

System component	Capital ($)	Replacement ($)	Operating &maintenance ($)	Fuel ($)	Salvage ($)	Total ($)
PV	275,000.000	0.00	115,802.750	0.00	0.00	390,802.750
Wind	200,000.000	0.00	23,160.550	0.00	0.00	223,160.550
Generator	10,000.000	0.00	0.00	0.00	-2,187.018	7,812.982
Battery	12,000.000	4,610.294	11,580.275	0.00	-3,079.626	25,110.944
Converter	500,000.000	148,495.840	173,704.126	0.00	-74,388.382	747,811.584
Grid	0.00	0.00	142,666.058	0.00	0.00	142,666.058
Overall system	997,071.429	153,106.134	466,922.031	0.00	-79,655.026	1,537,444.568

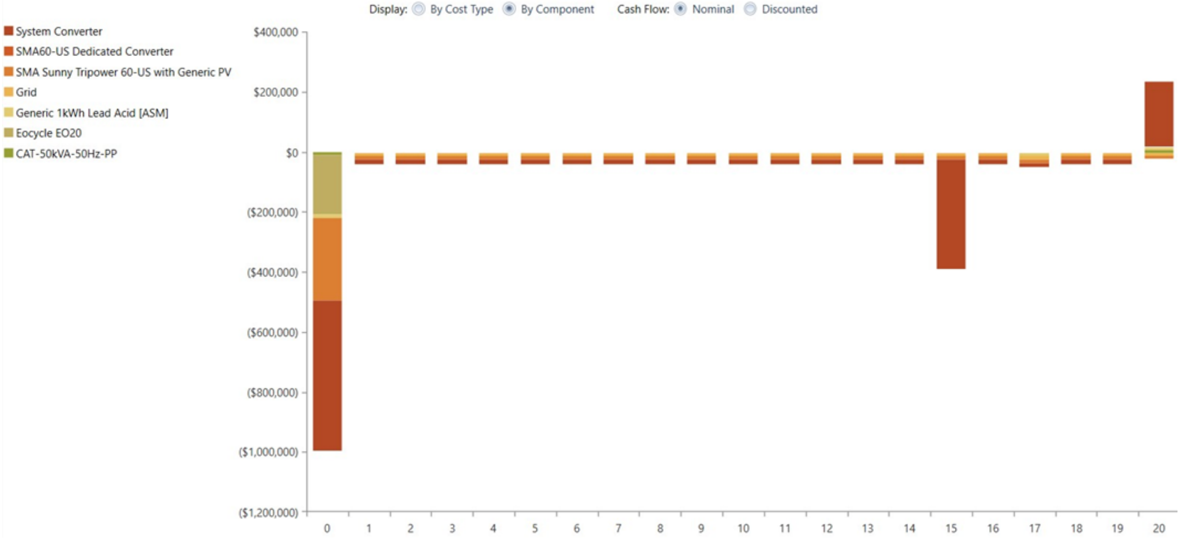


Figure 6: The cash flow profile of a long-term project

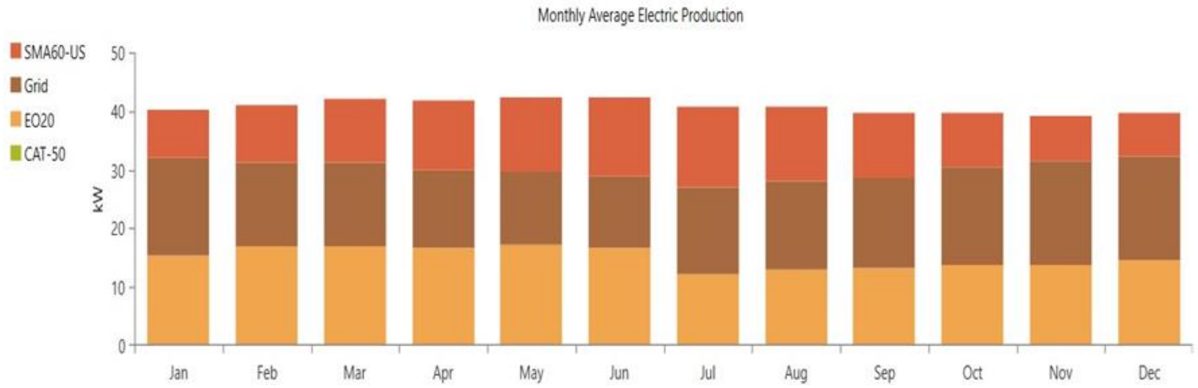


Figure 7: Monthly average electric production

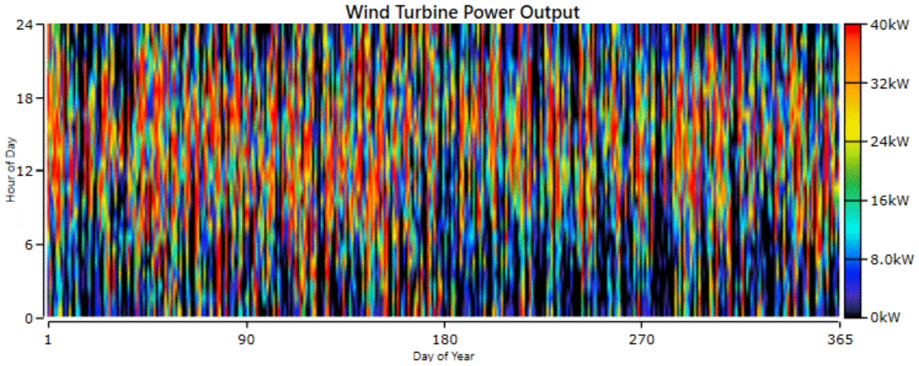


Figure 8: The annual power output profile of the wind energy

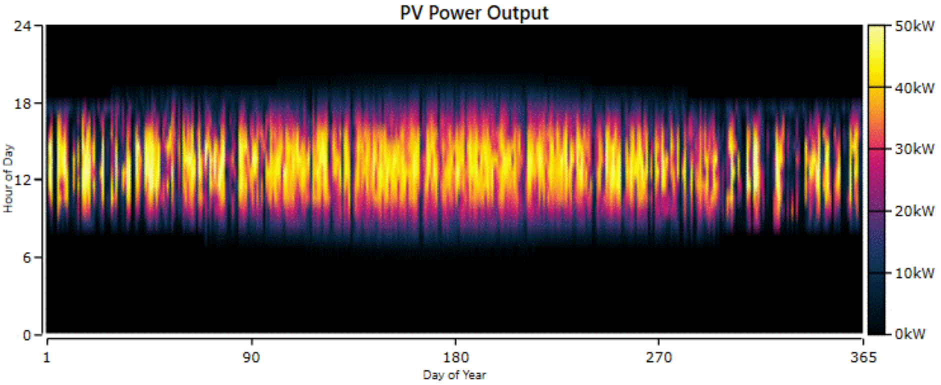


Figure 9: PV power output

Table 9: Technical, Operational, and Economic Performance

Quantity	Value	Units
Rated capacity	40	kW
Mean output	15	kW
Capacity factor	37.4	%
Total production	131,203	kWh/yr
Operational and Economic Characteristics		
Quantity	Value	Units
Minimum output	0	kW
Maximum output	40	kW
wind penetration	42.2	%
Hours of operation	6,964	hr/yr
Levelized cost	0.147	د.ل./kWh

the grid, highlighting the balance between renewable generation and grid interaction (Figures 10 and 11). Heatmap of the energy purchased from the grid over one year. The operating principle of the hybrid system depends on the net energy balance ($E_{ba}(t)$), using the equation below (17) [53-60], which dictates the direction of energy transfer depending on three vital conditions. The excess energy condition E_{su}occurs when generation exceeds demand, allowing battery charging or energy export to the grid. The neutral energy condition (E_{Ne}) holds when there is no excess generation, and the generation level exactly meets the demand level. The shortage of energy condition (Esh) exists when the demand level is higher than the generation level.

Table 10 : Expected electrical output results

Production	(kWh/yr)	%
PV array	94,091	26.3
Wind turbines	131,203	36.7
Generator1	0	0
Grid Purchases	131,951	36.9
Total	357,246	100
Quantity	(kWh/yr)	%
Excess electricity	18,610	5.21
Unmet electric load	0	0
Capacity shortage	0	0

PV System Results

The hybrid system's performance evidences this. With a 50 kW capacity, the hybrid system generates a mean power of 10.7 kW (258 kWh per day) and an annual energy production of 94,091 kWh, with a capacity factor of 21.5%. The system generates between 0 and 50 kW, indicating that photovoltaic panels play an important role in electricity generation in the hybrid system, with a solar contribution of 30%. (See Table 11 and Figure 9.) Therefore, the hybrid system has been designed to produce efficient, reliable, economical, and sustainable electricity suitable for use in a hospital.

Tale 11: Technical, Operational, and Economic Performance of the PV System

Quantity	**Value**	**Units**
Rated capacity	50	kW
Mean output	10.7	kW
Mean output	258	kWh/d
Capacity factor	21.5	%
Total production	94,091	kWh/yr
Operational and Economic Characteristics		
Quantity	Value	Units
Minimum output	0	kW
Maximum output	50	kW
PV penetration	30.3	%
Hours of operation	4,385	hr/yr
Levelized cost	0.359	د.ل./kWh

The analysis of the performance of the hybrid system reveals that there is a great difference between the locally generated energy and that needed by the health centre. Based on the findings in Table 13, the wind and solar systems generate a mean daily output of 26.72 kWh, which represents just 3.1% of the total energy needed of 851.49 kWh per day. This has led to an urgent energy deficiency of 824.77 kWh. It shows a high level of dependence on the external sources of energy, such as the power grid. For reliable medical services, more energy must be generated.

$$E_{ba}(t) = E_{grid}\,(t) - E_{load}(t) \qquad (17)$$

$$\begin{cases} > 0;\;\; Enrgy\ surplus\ \mathrm{E_{load}(t)} \\ \;= 0;\;\; \mathrm{Enrgy\ balance\ E_{Ne}(t)} \\ < 0; Enrgy\ shortae\ \ Esh\ (t) \end{cases}$$

Table 12: The wind and solar systems generate a mean daily output

Parameter	**Symbol**	**Value**	**Unit**
Total Annual Generation	E_{ann}	9,753.8	kWh/year
Average Daily Generation	$p_{l,d}$	851.49	kWh/year
Self-Sufficiency Ratio	SSR	3.1%	**%**
Daily Energy Deficit	Esh	824.77	kWh

The analysis of the performance of the hybrid system reveals that there is a great difference between the locally generated energy and that needed by the health centre. The wind and solar systems generate a mean daily output of 26.72 kWh, which represents just 3.1% of the total energy needed of 851.49 kWh per day. This has led to an urgent energy deficiency of 824.77 kWh. It shows a high level of dependence on the external sources of energy, such as the power grid. For reliable medical services, more energy must be generated.

Converter System Results

The simulation outcome has proven the effectiveness of the bidirectional converter as regards the handling of energy from the AC bus to the DC bus. Depending on the generation, usage, and storage of energy, the converter performs as both the inverter and the rectifier. This enables the microgrid system to perform well all the time. This kind of system improves reliability and saves costs, which are very important in health facilities that should not have power interruptions at all times. The inverter performance is evident from Table 13, recording a capacity factor of 44.8% and yearly energy generation of 196,350 kWh with no effective contribution from the rectifier, whose loss amounts to 10,334 kWh. Figure 12 illustrates the inverter and rectifier output.

Economic Performance and LCOE Analysis of the Hybrid System

Table 13: Technical and Operational Performance of Inverter and Rectifier.

Quantity	Inverter	Rectifier	Units
Capacity	50.0	50.0	kW
Mean output	24.2	0	kW
Minimum output	0	0	kW
Maximum output	50.0	0	kW
Capacity Factor	44.8	0	%
Hours of Operation	7,524	0	hrs/yr
Energy Out	196,350	0	kWh/yr
Energy In	206,685	0	kWh/yr
Losses	10,334	0	kWh/yr

A detailed assessment of the economic feasibility of the hybrid power plant suggests stability and sustainability with a net present cost of $10,537,445, reflecting an appropriate approach in investment terms for this venture. In addition, this system attains a very competitive LCOE of

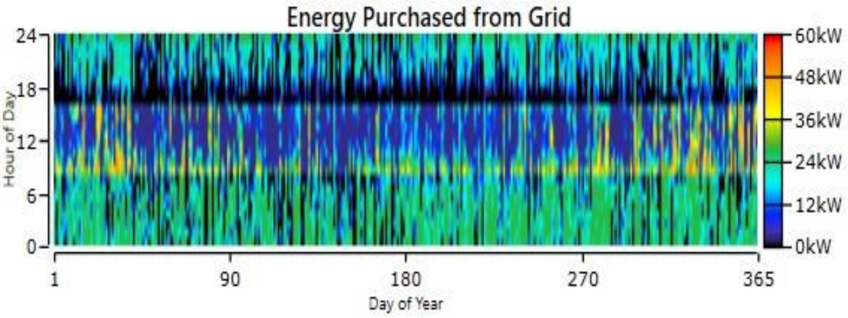


Figure 10: Heatmap of energy sold to the grid throughout the year

Table 14: Annual energy purchased and sold to the grid

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kW)	Peak Demand (kW)	Energy Charge
Jan	12,328	1,282	11,046	53	1,168.690
Feb	9,694	1,519	8,175	52	893.453
Mar	10,778	1,718	9,060	50	991.910
Apr	9,540	1,622	7,917	51	872.849
May	9,267	1,868	7,399	47	833.330
Jun	8,680	2,003	6,677	43	767.872
Jul	11,027	1,592	9,435	41	1,023.086
Aug	11,267	1,249	10,019	41	1,064.284
Sep	11,218	1,149	10,069	49	1,064.328
Oct	12,413	1,161	11,252	52	1,183.247
Nov	12,638	1,272	11,366	52	1,200.235
Dec	13,101	1,074	12,028	53	1,256.463
Annual	131,951	17,508	114,444	53	12,319.747

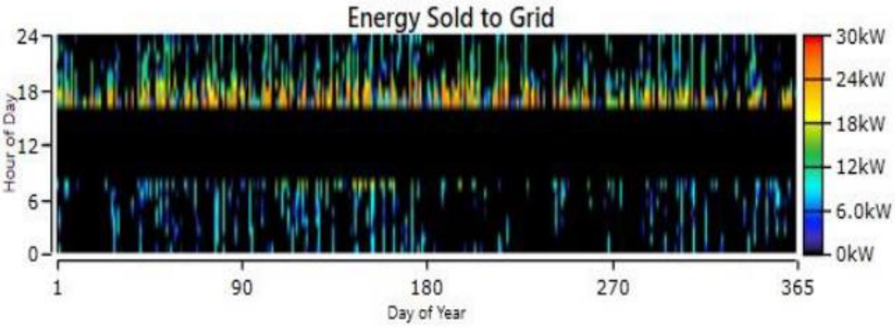


Figure 11: Heatmap of energy sold to the grid throughout the year

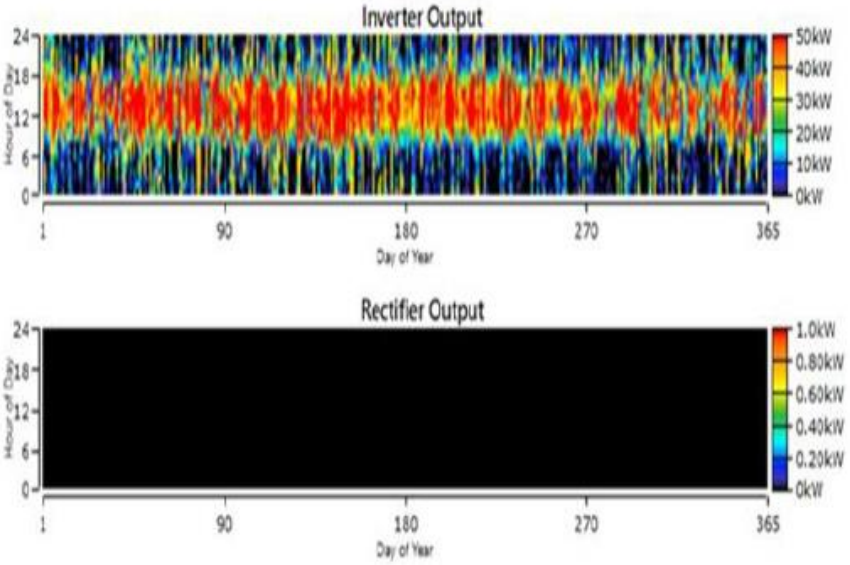


Figure 12: Inverter and rectifier output

$0.4044/kWh, which is lower than the cost of energy generation from conventional means in the region, and the annual carbon dioxide (CO_2) emission of the system is 83,393 kg/year (=83.4 tons/year) as obtained from HOMER Pro simulation results. The economic advantages of the system have been exemplified by its ability to maintain low operational costs at just $4,624,663 per year due to minimized fuel consumption and efficient resource use.

Environmental Benefit (C_{CO2})

One particularity of this approach is the addition of the "Environmental Damage Cost." Since the process produces no carbon dioxide, there are savings associated with this non-emission of carbon dioxide, estimated at $70/ton can be calculated by equation (16) [63]. The operational feasibility of the suggested hybrid system is based on a close coupling of technical and socio-economic factors. Specifically, in calculating LCOE, the economic evaluation model considers the initial capital investment cost ($45,000) and annual operation and maintenance (O&M) costs of $1,200 over 25 years of the system's lifespan. An innovative element of the analysis of economic feasibility in our case is related to the use of the environmental damage cost C_{CO2}. In particular, by assigning a value of $70 per ton to avoided carbon dioxide emissions, the system can create an environmental credit worth approximately $480 per year. In such a way, a part of the annual O&M costs is offset, and an effective energy cost of $0.47 per kWh is provided. As a result, it becomes clear that our hybrid wind and solar energy system is not only an effective but also economically justified means of meeting the load requirements of the healthcare centre. The calculated findings are shown in Table 15.

Table 15: Economic Indicators and LCOE Calculation Results

Parameter	Symbol	Value	Unit
Discount Rate	r	6 - 8	%
System Lifetime	n	20 - 25	
Capital Cost	C	45,000	
O&M Costs	$C_{O\&M}$	1,200	$/ kWh
C_{CO2} Emission Factor	EF_{CO2}	0.5-0.7	$/yere
Carbon Social Cost	$\emptyset_{CO2}$	70	
Carbon Savings Cost	C_{CO2}	480	$/year
Levelized Cost of Energy	$LCOE$	0.47	$/kWh

The calculated findings, as shown in Table 16. Therefore, the hybrid power system's performance is summarized by its storage needs, economic feasibility, and environmental impact. For the uninterrupted work of medical equipment, the necessary capacity of the battery(pB) equals 1,097.3 kWh, calculated based on daily consumption ld of 851.49 kWh, taking into account the 0.8 depth of discharge and temperature compensation coefficient CFT 1.031. From the perspective of economic feasibility, the levelized cost of energy production for the system is $5,061 annually, defined as NPV annuity. calculated by the following equation (14). It is calculated considering the cost C of $45,000 allocated to purchase equipment, amortized via capital recovery factor over 25 years, along with additional annual operating costs (O&M). However, the environmental cost_C_{CO2} of $480 per year can be considered a benefit in terms of avoiding carbon emissions that otherwise would have cost society $70 per ton.

Table 16: Integrated Technical-Economic and Environmental Sustainability and Calculation Results

Parameter	Symbol	Value	Unit
Required Battery Capacity	P_B	1,097.3	kWh
Annualized System Cost	NPV	5,061	$/year
Avoided Carbon Cost	C_{CO2}	478	$/year
Levelized Cost of Energy	$LCOE$	0.47	$/kWh
Temperature Correction Factor	CF_T	1.031	-

Conclusions

Through the study, it is evident that there is the possibility for a hybrid renewable energy system that combines solar PV and wind energy systems to meet the energy demands for a health care facility in Gharyan, Libya. Through the optimization model, it is clear that the hybrid energy system has been effective in meeting the demands without having to rely on fossil fuel energy sources. The total energy production for the year has been determined, with an impressive energy output from both the solar PV and wind subsystems. The output energy will be controlled by the grid, which considers variations in energy demands. It is important to note that the absence of diesel generators in the energy production process shows that there is the possibility of meeting the demands through renewable energy sources.

Author Contributions: Aisa: conceptualization and

methodology, simulation, writing original manuscript. Alharari and Elarb: software, data analysis. Nassar and El-Khozondar: visualization and critical review of the work. all authors have read and approved the final version of the manuscript for publication.

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