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RESEARCH ARTICLE

A Novel Doubly-Green Stand-Alone Electric Vehicle Charging Station in Saudi Arabia: An Overview and a Comprehensive Feasibility Study

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ABSTRACT In Saudi Arabia, the energy sector is presently the most significant contributor to carbon emissions, followed by the transportation sector, which contributes about 26% of the gross greenhouse gas emissions. The adoption of electric vehicles (EVs) in the transportation sector worldwide is one way to bring about a global green solution that can support the decarbonization of the environment, which now constitutes a new electric power demand for the utility grid network. To preserve the environment, and reduce the pressure on the existing grid network, we propose the utilization of EV charging stations (EVCSs) in off-grid locations. It is essential to have an alternative stand-alone renewables-based electrification framework to secure the charging demand needed for the electric vehicles. The present study performs a techno-economic investigation of a novel off-grid scheme that combines renewable energy resources to provide clean electricity for EV charging stations. The optimized system for the EVCS is compared with the alternative option of grid extension using economic criteria evaluation metrics and distance limitations. The optimization and comparative analysis results reveal that the option of an optimum stand-alone hybrid charging station is an economical, sustainable, and eco-friendly alternative to the option of grid expansion.

INDEX TERMS Saudi Arabia, transportation sector, electric vehicle charging station, stand-alone renewables-based electrification framework, grid extension.

NOMENCLATURE

Abbreviations

SA	Saudi Arabia.
EV	Electric Vehicle.
GE	Grid Extension.
RES	Renewable Energy Sources.
ITA	International Trade Administration.
GCC	Gulf Cooperation Council.
MENA	Middle East/North Africa.
CS	Charging Station.
RE	Renewable Energy.
GH	Green Hydrogen.
PV	Photovoltaic.
EVCS	Electric Vehicle Charging Station.
DG	Diesel Generator.
WT	Wind Turbine.
NASA	National Aeronautics and Space Administration.
NREL	National Renewable Energy Laboratory.

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COE	Cost Of Energy.
NPC	Net Present Cost.
POWER	Prediction Of Worldwide Energy Resources.
V2G	Vehicle-to-Grid.
FIT	Feed-in Tariff.
HCS	Hybrid Charging Station.
CRF	Capital Recovery Factor.
SOC	State Of Charge.
MTC	Makkah Transport Company.
GEC	Grid Expansion Cost.
O&M	Operations and Maintenance.
EVSE	Electric Vehicle Supply Equipment.
GHG	Greenhouse Gas.
PAC	Publicly Accessible Chargers.
PHV	Plug-in Hybrid Vehicles.
SWF	Sovereign Wealth Fund.
PWF	Public Wealth Fund.
SASO	Saudi Standards, Metrology, and Quality Organization.
SCoA	Saudi Model Certificate of Accreditation.
GDP	Gross Domestic Product.
SASCO	Saudi Automotive Services Company.
RET	Renewable Energy Technology.
HOMER	Hybrid Optimization Model for Electric Renewables.
HES	Hybrid Energy System.
NIR	Nominal Interest Rate.
GPP	Grid Power Price.
RF	Renewable Fraction.
PI	Profitability Index.
ROI	Return On Investment.
GV	Gasoline vehicle.
GET	Grid Electricity Tariff.
CNS	Central Network Substation.
WS	Wind Speed.
AF	Autocorrelation Factor.
GHSI	Global Horizontal Solar Irradiation.
AT	Air Temperature.
WCES	Wind Conversion Energy System.
WD	Weibull Distribution.
DPS	Diurnal Pattern Strength.
STC	Standard Test Condition.
DF	Derating Factors.
SRI	Solar Radiation Incident.
SEC	Saudi Electricity Company.
DC	Direct Current.
AC	Alternating Current.
CRF	Capital Recovery Factor.
RDR	Real Discount Rate.
MPND	Maximum Permissible Network Distance.
EPBP	Expected Payback Period.
SC	System Scenario.
IRR	Internal Rate of Return.
PO	Perturb and Observe.

I. INTRODUCTION

In Saudi Arabia (SA), the power sector is presently the highest contributor to gross greenhouse gas (GHG) emissions (also known as carbon emissions) [1], followed by the transportation sector, which contributes about 26% of these inadvertent emissions [2]. In fact, one of the major sources of GHG emissions is due to traditional gasoline vehicles (GVs) [3]. Adopting electric vehicles (EVs) in the transportation sector is a promising way to bring about a green solution to the emissions problem. If these vehicles are charged through a scheme that is also emission-free, the aforementioned solution might be labeled as doubly-green, because it does not harm the environment in either the charging phase or the operation phase. We consider our present solution offered by an electric vehicle charging station doubly-green one, since this station is a stand-alone one whose energy sources are solely renewable ones.

Global heating, environmental issues, varying fuel prices of conventionally-produced electricity, and climate emergencies constitute plausible reasons why the adoption of renewable energy sources (RESs) is now essential for fulfilling the energy demand of transportation and other sectors [4]. Furthermore, in recent times, the demand for transportation fuels in SA is increasing as there are now more automobiles on the road than there have ever been. According to the International Trade Administration (ITA), in 2020, vehicles sold in SA constituted nearly 52% of the vehicles sold in the Gulf Cooperation Council (GCC) countries and mounted to 35% of vehicles sold in the Middle East/North Africa (MENA) region. In 2019 and 2020, the overall vehicles sold in SA were 556,000 and 436,000, respectively. However, sales are estimated to reach 543,000 units by 2025, with EVs accounting for about 32,000 units. The sale share of non-electric cars is very high compared to that of electric vehicles. This situation is expected to continue for the next 20 years [5] and is anticipated to cause a continuing increase in the production of harmful gases (and noise pollution) as the intake of oil rises with the further expansion of the transportation sector. In fact, renewable energy has not been primarily utilized in the transportation sector, and the country's population continues to suffer from environmental pollution attributed to vehicles running on fossil. Most cars continue to be powered with petroleum products, emitting harmful emissions and causing noise pollution. The expansion of the transportation sector is not just a local phenomenon confined to Saudi Arabia, but it is a manifestation of a typical global trend that spreads worldwide. Additionally, the need for energy in the transport sector was observed to rise by about 2.2% yearly in the 1990s. It was also estimated to rise by about 2.8% yearly between 1999 and 2020 [6], an estimation that turned out to be true. In SA, transport fuels still constitute a large part of the gross oil demand.

Moreover, the decreasing oil reserves, the urgent need to protect the environment, and reducing the effect of climate change have given a strong incentive to find a sustainable and cleaner way of producing the energy demand in the transport sector of the country. Besides, according to (Electromaps 2022), there are currently 14 locations with only 15 charging station (CS) connectors within Saudi Arabia. Most of the CSs in the country are utility grid-based types. This indicates that it is essential to have an alternative stand-alone renewables-based electrification framework to secure the EVs' needed charging demand. Renewable sources (RESs) such as solar and wind resources are among the sustainable categories of energy that can be used to meet the EV charging demand. In fact, SA has enormous potential for both solar and wind energies. The mean solar radiation in SA is very high indeed, attaining a value of 4.479 kWh/m^2 in the north-western region of Tabuk and a value of 7.004 kWh/m^2 in the south-western province of Bisha [8], whereas the mean wind speed reaches values of 7.5-8 m/s and 7-7.5 m/s in the eastern and western coasts of SA, while the mean wind speed of 5-6.5 m/s is obtainable in the central reign of SA [9].

Furthermore, the share of renewable energy (RE) was a meagre value of about 0.02% of the country's gross final energy consumption in 2018 (according to World Bank data [10]). However, the recent launch of "The SA Green Initiative" [11] aims to promote more RESs for power generation, which is expected to be at 50% of the country's energy by 2030. The utilization of RESs to meet the energy demand in the transport sector could also be achieved under this initiative. Also, King Abdullah City for Atomic and Renewable Energy (KA CARE), which is tasked with the responsibility of RE development in the country, has set up a target of producing a mean power of 54 GW from RESs by 2032. The plentiful land and optimal location for RE development would economically and technically support the adoption of RE-powered EVs and green hydrogen (GH) in SA, which is in line with its diversification plan of Vision 2030 [12]. Moreover, reports have shown that the transport sector recorded a high percentage (24%) of direct global CO$_2$ emissions from fuel-burning, with passenger road vehicles contributing the most significant share at 3.6 Gt in 2020.

Also, RESs such as solar and wind sources often vary because of their intermittent nature. Due to their unpredictable nature, an electricity generation system with some RES components does not have as much reliability, stability, and consistency as one without such components [13]. Moreover, a storage system would have to be introduced to ensure a continuous electricity supply, especially when such a system is designed for off-grid operation [14]. To overcome all these problems/limitations and to effectively and efficiently use the different RESs available, two or more of these resources can be integrated and utilized together as an electricity production system that can be deployed to fulfill the charging demand of an EV. The utilization of RESs minimizes carbon emissions from the combustion of conventional energy resources, thereby reducing the impact of global warming. At present, many photovoltaic (PV)-based energy systems are globally being utilized for powering EV applications as their paradigm of operation is well understood.

Also, wind power is an attractive alternative for electricity production due to its higher transformation efficiency [9]. It can ensure an uninterrupted and reliable supply of electric power in addition to being a cost-effective system when combined with storage devices (like batteries) and PV systems [15].

II. PRESENT STATUS OF EVs AND CHARGING STATIONS GLOBALLY AND IN SAUDI ARABIA

An electric vehicle charging station (EVCS), also known as EV supply equipment (EVSE), is a machine used to connect an EV to an electric power source to recharge plug-in EVs, including buses, cars, neighborhood EVs, etc. [16]. Some EVs have onboard power converters that plug into higher voltage or standard electrical outlets, while others utilize custom EVCSs. Some EVSEs have cellular capability, smart metering, and network connectivity as advanced features. By contrast, others possess only basic features. Generally, EVCSs channel EV integration to the electric grid (or to other power sources). The implemented EVCSs are of two categories: residential EVCSs and non-residential ones [17], and depending on the power rating of their charger, charging stations (CSs) can provide slow, fast, and rapid charging [18]. Because of their considerable contribution to mitigating greenhouse gas (GHG) emissions [19], EVs have seen a significant increase in their worldwide adoption in the last decade [20]. Besides, many expansions and constructions are expected to start in EV facilities and the EV supply equipment infrastructure soon due to their recently attained popularity [21] in the transportation sector.

The fast evolution of EVCS infrastructure continued in 2020 and at the beginning of 2021. Some nations' efforts are ongoing in strategically planning and setting up large-scale interconnected EVCSs along major transportation routes [22]. Also, in 2021, publicly accessible chargers (PAC) increased in their global number to become 1.8 million units, with 33.3% of them being fast chargers, and the rest being slow ones. The setting up of PACs moved slower at an annual increase rate of 37% in 2021, compared to a previous rate of 45% in 2020, probably due to work interruption experienced in significant markets because of the Covid-19 pandemic. Globally, China has the highest number of both slow and fast PACs [23] (Fig. 1). Besides, the number of public EVCSs (from 2016 to 2021) rose by 431% across Europe to above 356,000 [24], while the US has around 140,000 public EVCSs scattered across about 53,000 charging points [25].

Furthermore, the increase in recent times in some parts of the world in the number of CSs for EVs has been due to the expanding market of EVs, with China, Europe, and the USA leading the way. In 2021, electric car registrations nearly doubled according to [23] After a continuous decade of fast growth in the number of electric cars registered, around 6.6 million new registrations were reported in 2021

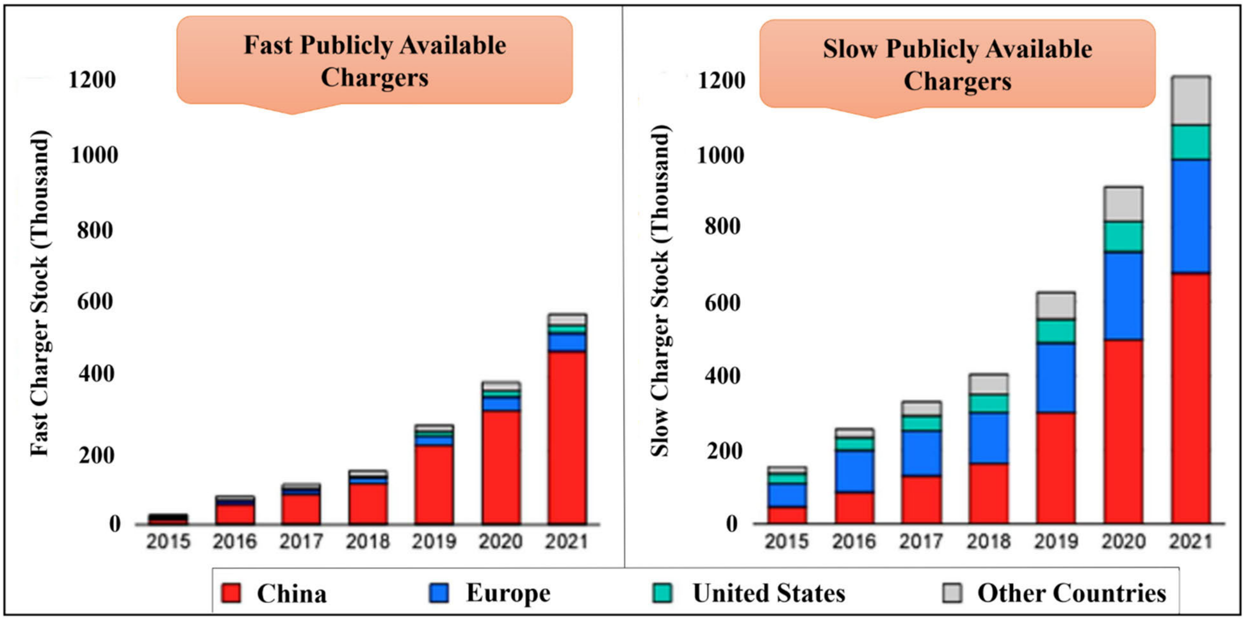


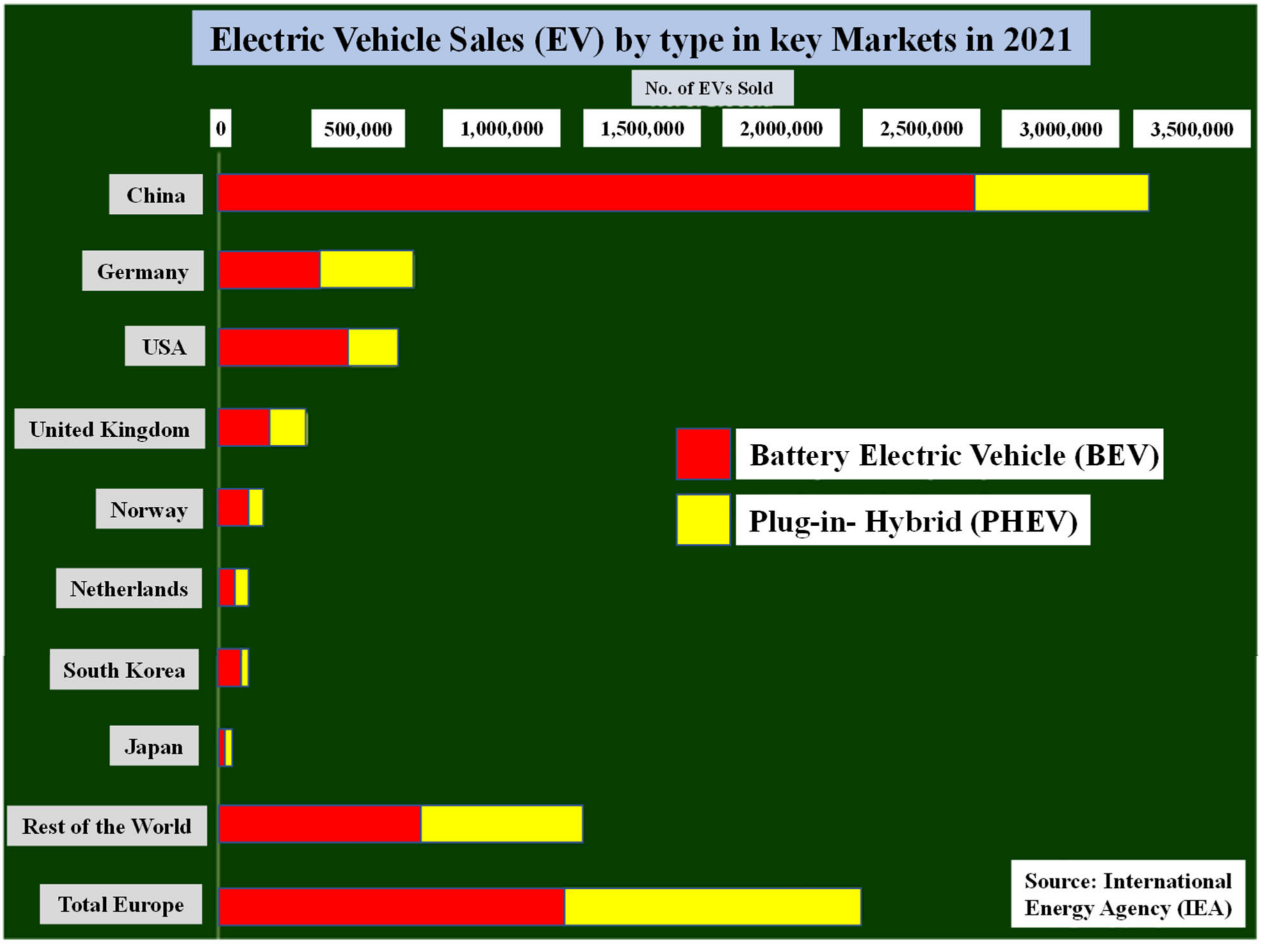
FIGURE 1. The stock of fast and slow PACs for EVs (light-duty).

(putting the gross number of EVs on today's road to more than 16.5 million), out of which China led the way with 3.3 million registrations (a 16% sales share). Europe has closely followed by about 2.3 million registrations, which results in a 17% sales share. In comparison, the United States had a low percentage of around 10% (630,000 registrations) representing a sales share of 5% [26] (Fig. 2). However, in view of other major EV market standards, including share of gross car sales and existing car inventories as well as sales per million people, Europe has attained a remarkable lead [27]. It is worth noting that globally, in 2021, battery EVs accounted for more than two-thirds (around 70%) of the new registrations and stock, while electric car totals comprised battery EVs, and plug-in hybrid vehicles (PHV) [23]. In the sustainable development scenario, the world EV fleet will increase to 230 million vehicles in 2030 (without the two/three-wheelers, 12% stock share) [22].

In 2020, the vehicles sold in SA constituted nearly 52% of the total vehicles sold in the GCC area and 35% of those sold in the MENA region. In 2019 and 2020, the overall vehicles sold in SA were 556,000 and 436,000, respectively. However, vehicle sales are estimated to reach 543,000 units by 2025, with EVs accounting for about 32,000 units [5]. The hybrid and electric cars sold in SA in 2020 added up to below 3% of the overall new vehicle sales [28]. As part of the country's vision 2030 and to reduce harmful emissions in the kingdom, SA has targeted 30% electric cars in the total number of cars in the Saudi capital Riyadh in the next nine years. For many years, there has been investment in EVs by the country's Public Wealth Fund (also called the Sovereign Wealth Fund (SWF)), founded in 1971. In the last part of the third quarter of 2018, the SWF disclosed its first investment of 1 billion dollars in Lucid, a US-based EV producer [28]. The acquisition was targeted at providing the required funding to commercially introduce the 2020 Lucid's first EV, called the Lucid Air. The EV metals group of Australia has recently disclosed an investment project worth $3 billion in SA to process minerals utilized in EV batteries [29]. The organization charged with the kingdom's affairs relating to standardization, metrology, and quality (SASO), had recently provided the Saudi model Certificate of Accreditation (SCoA) to one of the producers of e-cars. This producer has been granted permission to import EVs and their chargers commercially, and therefore the SCoA is provided for the targeted models before the beginning of the importation procedure [30]. Besides, SASO has approved 16 EV models [31].

Furthermore, in 2022, SA launched its first EV brand, "Ceer" [32], and plans to produce and export 150,000 (or more) EVs by 2026 [33]. By 2034, this EV brand is estimated to contribute about US$8 billion to SA's GDP [32]. In an attempt to diversify its transportation sector to be more eco-friendly, SA has agreed to purchase between 50,000 and 100,000 EVs from Lucid Motors over a decade [34].

According to (Electromaps 2022), there are currently 14 locations with 15 CS connectors within Saudi Arabia. Based on the connector distribution, the Schuko (EU Plug) connector has the largest share. Moreover, the country plans to designate 5% of all accessible parking spaces for EVs [35]. The Saudi Automotive Services Company (SASCO) has introduced the electric vehicle charger project for EVs in some stations [36]. In 2019, ABB, the global pioneering company in EV infrastructure, installed the first commercial CS in SASCO's petrol stations [37]. Besides, the company has provided EV chargers for one of the premier residential buildings in SA [38]. The EVCS (eVolve CS) installed



Source: International Energy Agency (IEA)

FIGURE 2. The 2021 electric vehicle sales by type in key markets.

in the Riyadh Marriott hotel is equipped with the fastest possible alternating current electric power speed and is well suited to all car producers. This smart, fast charger is for residential and commercial usage [39]. With its EVLink range of charging solutions located all over Saudi Arabia, SA Schneider Electric, and GREENER, a part of IHCC, collaborate to expand the e-mobility infrastructure in the country's flourishing EV sector [40]. According to the Saudi Electricity Company (SEC), the regulatory framework for charging EVs was approved in 2020 [41]. In several major roads in Al-Madinah, Saudi Arabia, about 12 EV charging points are expected to be established and operated [42].

III. REVIEW, SCOPE, AND MOTIVATION

A. LITERATURE REVIEW

Extensive research has been conducted to design EV charging stations for both off-grid and grid-connected operations. The techno-economic assessment and environmental feasibility for these operations have been studied *via* different techniques and software tools. A feasibility study and the design of a specialized EVCS model considering the current, and subsequently the vehicular topology, and a differential pricing approach utilized to efficiently manage the load were investigated using the HOMER Grid tool. Based on the evaluation of three different scenarios for electric vehicle supply equipment (EVSE), an annual profit of $63,680 was expected, and it was anticipated that the CS's setup costs could possibly be recovered in two and a half years. Besides, the level-2 EVCS is found to be the most effective scheme, minimizing GHG emissions by 104t [4]. The HOMER analysis tool was utilized to optimize and design a hybrid RE-based charging station [20]. The outcomes reveal that the optimized solution for the hybrid energy system (HES) comprises 44.4% wind power and 55.6% solar power at a component sizing of 200 kilowatts of wind turbine (WT) and 250 kW of PV modules. The yearly electricity generation of the hybrid charging station is 843,150 kWh, while the cost of the energy generated is $0.064 per kilowatt-hour. Moreover, a techno-economic investigation for a novel autonomous charging station using renewable energies was carried out to find the optimum system to produce the required charging demand per day [43]. This indicated that under the optimal scenarios, the net present cost (NPC) is between $2.53 M to $2.92 M, while its cost of energy (COE) varies between $0.285 and $0.329 per kWh. Another study [44] examined the techno-financial feasibility assessment of electric and renewable energy integration as a case study considering three possible scenarios. The V2G scheme and the RE integration result revealed the cost benefits and minimal power intake during the peak loading time of the design. The EVs coupled with RE and clean power production constituted a measure that can considerably minimize environmental pollution in addition to supplementing the electric system in fulfilling the new electrical load demand. Ye et al. [45] performed the viability analysis of a solar-based EVSE model for application in Shenzhen City, China. Their outcome shows prospects of the proposed model in terms of pollutant emissions reduction and the satisfaction of the enormous demand required for EVs. Moreover, their investigation recommends that carbon pricing promotes RE only when the cost of carbon is more than \$20/t [45]. Regarding the feed-in tariff strategy variation, Huda et al. [46] carried out a technical and economic performance evaluation of the V2G system model in Indonesia's most extensive power grid system. Their analysis reveals that the utilization of electric vehicles can potentially minimize the peak hour supply by approximately 2.8% and 8.8%, respectively, for coal and gas fuels. From the electricity company's point of view and due to the possibility of fuel replacement, the yearly revenue can be improved by about 3.65% with the implementation of the vehicle-to-grid (V2G) scheme. A single-ended primary-inductor converter (SEPIC) was employed in the design of a PV-battery-DG-based HES utilizing the PO algorithm for peak power extraction from the solar system [47]. In the ensuing analysis, the CS scheme utilizes the grid and DG whenever the storage device is depleted and PV production is unavailable. The simulated output of utilizing the PI control technique is compared with the fuzzy-PI control technique. In Bangladesh, a design and viability analysis of a renewable power-based hybrid configuration EVSE was conducted to minimize the pressure on the utility network due to the rapid increase in EVs in the country [48]. The proposed hybrid charging station comprises a PV panel, three bio-gas generators, lead-acid battery storage, a converter, and a charging assembly. The system estimates a COE of \$0.1302 per kWh, a gross net present cost (NPC) of \$56,202, and minimizes carbon dioxide emissions by approximately 34.7% compared to a conventional grid-dependent CS. The optimum system configuration of PV-powered EVCSs is techno-economically assessed under various solar radiation conditions by Minh et al. [49], who stated that the optimized system and investment efficiency of the CS in each urban location are significantly influenced by the solar radiation value and the feed-in tariff (FIT) cost of rooftop solar energy. In [50], the techno-economic viability of an EVCS is analyzed using renewable energy resources in six different locations across the geo-political zones in Nigeria. The results of this analysis indicate that the PV/WT/battery charging station located in the Nigerian northwestern city of Sokoto provides the best economic metrics with the minimum net present and energy costs. Also, the sensitivity evaluation carried out shows that the techno-economic performance indicators of the optimal charging scheme are sensitive to the variation in the sensitivity parameters. The technical. economic and environmental components of combined solar-wind EVCSs for highways in various sites in India are investigated in [51]. The realization of the EVCS scheme confirms that among the selected sites, the Tamil Nadu District of Virudhunagar has the minimum NPC (\$303,291.26) and COE (\$0.072/kWh) with significant mitigation of the emissions value, while the nearby Madurai District generates 70% additional electricity than other selected sites.

A novel method to investigate the technical and economic viability of retrofitting an existing fuel station with an EVSE infrastructure is proposed in [52], wherein the analysis is given for the potential of incorporating a storage device (battery) with the EVSE, which gives rise to minimizing the grid connectivity costs. Observation of the outcome in [50] shows that a system with 4 EVCSs, 1 storage battery for 8 hr. of working and a system with 4 EVCSs, 1 battery system, and 1 PV panel for 8 hr. of working are economically feasible (with regard to the net present, IRR and the discounted PP values). The establishment of electric CSs considering the financial viability is studied by Danial and Azis [53]. Their results indicate that an electric CS is only viable when the acquisition cost is maintained at the lowest to return 1.47 times the initial investment with regard to the life-cycle cost. The study in [54] assesses different systems of RE-based HES for EV charging in the capital city of the UAE. It is ascertained that the optimal system could generate annual surplus electricity of 22,006 kWh with a COE of about \$0.06743/kWh. The analysis in [54] also reveals the environmental benefit of the proposed model. Muna and Kuo [55] investigate the techno-economic and environmental analysis of EVCSs using hybrid energy systems with various storage device technologies in three different locations in Ethiopia. Their outcome reveals that the viable system configuration, which comprises a solar PV device, a DG, and a battery provides the best economic metrics in terms of the NPC and COE values in the considered locations. Economically, their results prove the ZnBr battery to be the best choice (utilizing the system) among the considered battery types. The design and performance assessment of a solar-PV powered EVCS for a security bike in Pakistan is investigated in [56] with the results compared to grid-based CSs. The outcomes in [56] further emphasize the expected environmental and financial benefits of the RE sources powered EVCS. A summary of the recent research conducted to design and investigate the performance assessment of EVCSs in different parts of the world is given in Table 1.

B. MOTIVATION, SCOPE, AND CONTRIBUTIONS

To minimize the burden on the network grid system and provide an environment-friendly and an economically-feasible solution for efficiently meeting the charging demand of EVs, an alternative and creative way of reliably producing clean electric power at a low cost is needed. As stated above,

TABLE 1. Recently studied EVCS designs with breakeven grid extension distance calculated.

References	System Configuration	Application location	Break-even grid extension distance (km)	Year	Analysis Variables
[57]	PV/Wind/Fuel cell/battery	India	X	2022	NPC/OPEX/COE
[49]	PV/Grid/battery	Vietnam	X	2021	NPC/COE/RF
[58]	PV/WT/Battery	China	X	2022	NPC/COE/OC/Unmet Load
[50]	PV/WT/Battery	Nigeria	X	2023	NPC/COE/ Unmet Load
[43]	CPV/WT/Bio-Gen/FC/Battery	Qatar	✓	2021	NPC/COE/Unmet Load
[4]	PV/Grid/Battery	India	X	2021	RF/COE/Elec. Prod./GHG
[20]	Wind/PV/battery	Turkey	X	2020	NPC/Elec. Prod./COE
[59]	PV/Wind/Fuel cell/battery	Romania	X	2020	COE/NPC/GHG
[44]	PV/WT/Grid/V2G	Brazil	X	2020	LCOE/Elec. Prod./NPV
[46]	V2G technology	Indonesia	X	2020	GHG/Energy-Supply/Cost
[48]	PV/Biogas Gen/Grid/Battery	Bangladesh	X	2018	NPC/COE/GHG
[19]	DG/PV/Grid/Battery	Canada	✓	2017	NPC/COE/GHG
[60]	PV/Grid/Battery	Bulgaria	X	2016	COE/NPC/GHG
[45]	PV-Grid based	Shenzhen City, China	X	2015	COE/GHG/NPC
[51]	PV/Wind-based	Tamil Nadu, India	X	2022	NPC/COE/GHG
[52]	EVSE/Battery/PV	UK	X	2022	NPV/IRR/Connection Cost
[53]	EVCS	Brunei Darussalam	X	2021	Life Cycle Cost/Subsidy
[54]	PV/WT/Battery/Grid	UAE	X	2022	Excess-Elec./GHG/COE/RF
[55]	PV/DG/Battery	Ethiopia	X	2022	NPC/COE/ROI/Elec. Prod./GHG
[56]	Solar-PV-based	Pakistan	X	2022	NPC/Elec. Prod. /Elect. Bill/GHG

all the existing EVCSs are grid-based and supply AC power to fulfill the EV charge demand. According to [61], even though, EV charging provides eco-friendly and financial benefits, it also negatively influences the performance of the existing network. Besides, the increasing trends for EV utilization and development in SA despite the existence of too few charging stations show the country still needs efficient, cost-effective, and eco-friendly alternatives for the power supply of EVCS. A lack of adequate EVCSs can slow down EV utilization in the country. Therefore, a hybrid RE system where one energy source can complement the limitation or unavailability of another (to increase the overall system reliability) is required. Also, a few of the EVCS systems previously studied in the open literature have calculated the break-even grid extension distance using microgrid optimization tools (Table 1). However, it is essential to analyze the EVCS electrification option (grid connectivity) through economic feasibility analysis to ascertain the cost-benefit and the distance limit of the system configuration concerning the grid connection. The design and cost-benefit of RE-based stand-alone systems are often suggested in the literature to minimize the pressure on the grid network due to many EVCS connections, which can negatively influence the power quality and stability of the electric distribution network. To the best of our knowledge, no such hybridized system has been explored in a Saudi Arabian context for providing electricity for EVCS, an observation that serves as a motivation behind our present study. Actually, RESs have continued to replace conventional energy sources in many parts of the world since they deliver reliable electricity supplies, aid natural resource conservation, diversify energy resources and extend their ''lives'' indefinitely on a human time scale. The results of utilizing RESs are manifested in the enhancement of energy security, reduction in the demand for fossil fuels, and mitigation of the menace of fuel spills, which can disastrously affect the environment and habitats. These resources are eco-friendly and can produce a large amount of clean electricity to power EVs and support commercial efficiency in addition to having fewer carbon emissions in an urban center [62] while maintaining a clean atmosphere. For instance, SA was placed seventh worldwide in the ten best locations in clean energy globally. Saudi Arabia has suitable climatic features such as endless clear skies, geographical location, enormous unutilized landscape, and no artificial obstacles. These characteristics reveal the vast potential for exploiting solar and wind energies in the country [7] to meet the EV charging demand.

The major novelties and contributions of the present study are summarized as follows:

- Discussing the present status of EVs and charging stations in the world and Saudi Arabia and the potential of the country's RESs (solar and wind energies) to highlight the country's potential in the area of EV development to decarbonize the environment and the economy and to facilitate RESs utilization to meet the ''SA Green Initiative'' target by 2030.
- Presenting a detailed and robust approach to evaluating the optimum design and techno-economic optimization of a hybrid renewable energy-based system for an eco-friendly EV charging system.
- The possibility of utilizing and integrating solar and wind-based electricity generation system configurations with location-based metrological data and technical and economic specifications of the integrating components to supply reliable and cost-effective power for EVCS is proposed and analyzed in detail. At the same time, the

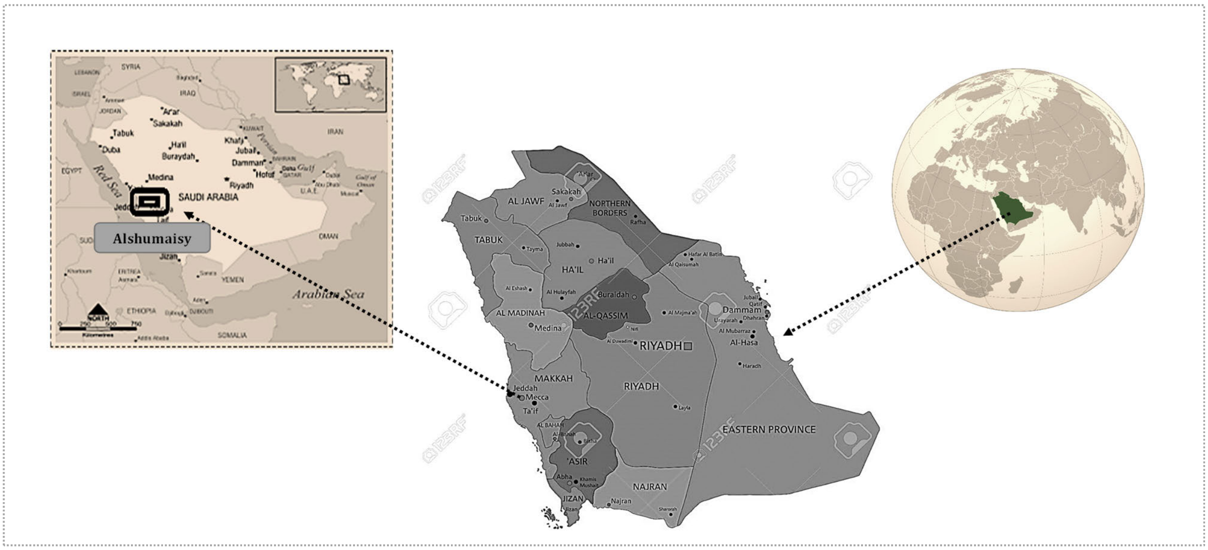


FIGURE 3. The geographical site of the chosen area (Alshumaisy) in SA [64].

environmental feasibility aspect of the proposed scheme is analyzed using pertinent emission parameters.

- Comparing the optimal system configuration investigated with the grid-connection option using extensive economic criteria evaluation metrics, and economic distance limitations.
- Utilizing additional economic evaluation parameters such as payback period (PP), return on investment (ROI), internal rate of return (IRR), and profitability index (PI) as comparative financial analysis metrics for the off-grid and grid-connected alternatives.
- Providing a brief insight as regards electric vehicles utilization (and its charging infrastructures) and future research direction need.

Also, the proposed stand-alone system is expected to reduce the difficulty EV users experience while traveling for far distances and being covered solely by out-of-grid connections. The planned location of the proposed EVCS is close to the highway and is within a densely-populated area, prominent advantages that will allow EV customers to recharge on the go quickly and efficiently.

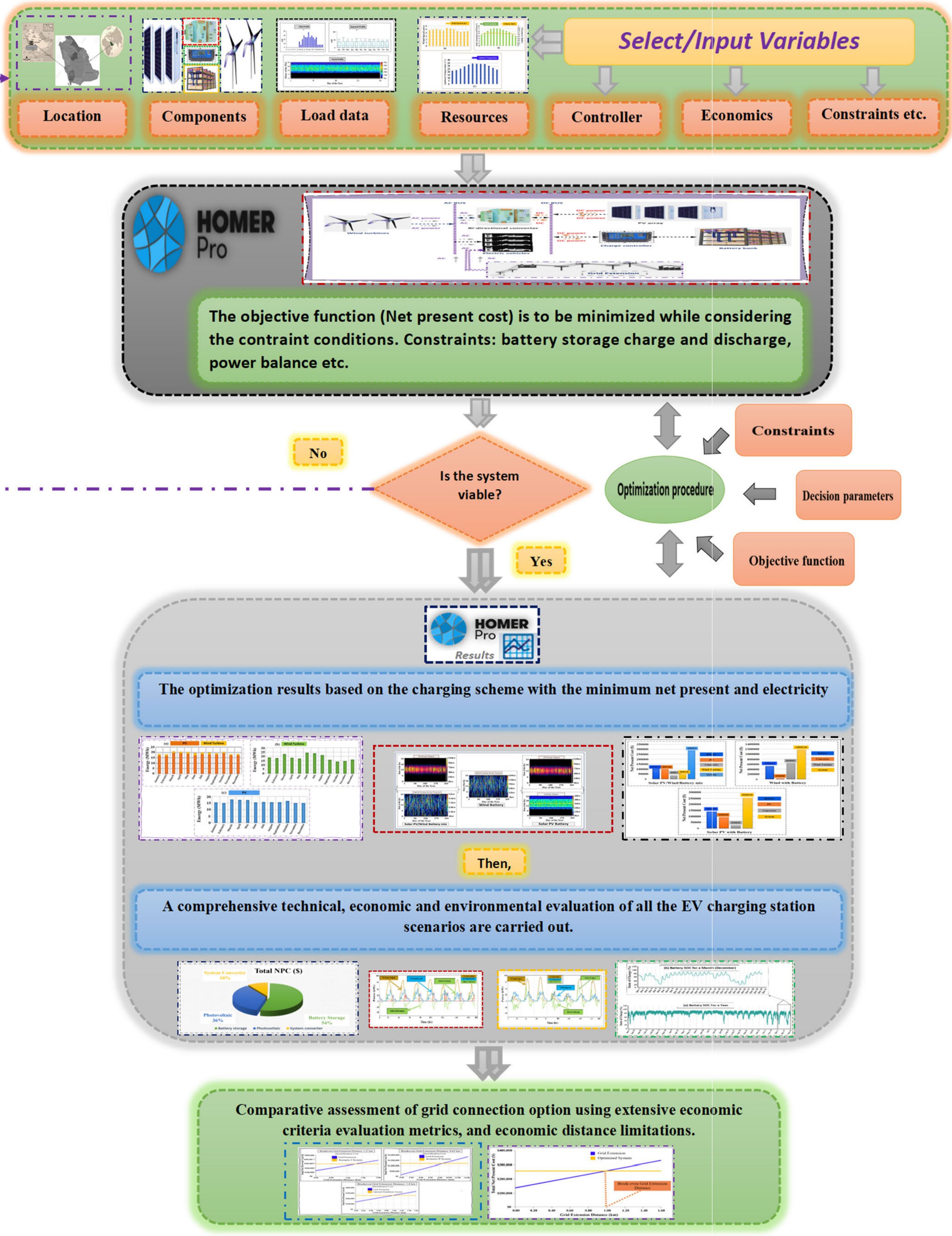
IV. LOCATIONS, ENERGY OPTIMIZATION SOFTWARE, OPERATING STRATEGY, AND LOAD PROFILE

A. CLIMATIC FEATURES OF THE SELECTED LOCATION

Saudi Arabia is situated in the furthermost section of southwestern Asia and bordered in the East by the Arabian Gulf, UAE, Bahrain, and Qatar, and in the West by the Red Sea. It is bordered in the North by Kuwait, Iraq, and Jordan, and in the South by Yemen and Oman [63]. The country is located at a coordinate between latitudes 31°N and 17.5°N. It falls entirely in the area often regarded as the Sunbelt (between latitudes 40°N and 40°S). It has a mean sunshine duration of about 8.89 h/day with solar irradiation that varies between 4.479 and 7.004 kWh/m^2 [8] in addition to enjoying a yearly mean wind speed that goes between 6.0 and 8.0 m/s in most locations [9]. These meteorological data show that the country has the advantage of possessing plenty of both solar and wind energies. This research considers an off-grid site in the Makkah province as a case study for the EVCS installation. The area is situated in the Alshumaisy region. Geographically, this site is located at 16°13′07.87″ North latitude and 52°30′52.37″ East longitude, respectively as shown in Fig. 3.

B. ENERGY OPTIMIZATION SOFTWARE AND OPERATING STRATEGY

The hybrid optimization model for electric renewable (HOMER) Pro simulation tool is an important and widely used simulation software tool. It was developed in 1993 by the National Renewable Energy Laboratory (NREL) in the USA [65]. This software is utilized for analyzing various system design options for both standalone and grid-connected designs in a simplified way for different applications. It performs three main tasks: simulation, optimization, and sensitivity analysis. For the simulation, HOMER models hourly the performance of each of the system subunits to ensure the optimal possible matching between the energy demand and supply. It models various system designs in the optimization section to find the systems that meet the technical constraints as well as fulfill the load requirement at a low life-cycle cost. Lastly, HOMER performs numerous optimization operations with various ranges of input variables, to check the effects of changes in input parameters on the selected system in the sensitivity analysis section [66]. The HOMER Pro® microgrid software with the grid-search and proprietary derivative-free optimization techniques has been used in this study to assess the viability of the proposed renewable energy-based system for an eco-friendly electric vehicle charging system. The analysis flowchart used in



The objective function (Net present cost) is to be minimized while considering the contraint conditions. Constraints: battery storage charge and discharge, power balance etc.

The optimization results based on the charging scheme with the minimum net present and electricity

A comprehensive technical, economic and environmental evaluation of all the EV charging station scenarios are carried out.

Comparative assessment of grid connection option using extensive economic criteria evaluation metrics, and economic distance limitations.

FIGURE 4. Evaluation flowchart and the design scheme for the proposed hybrid charging station model.

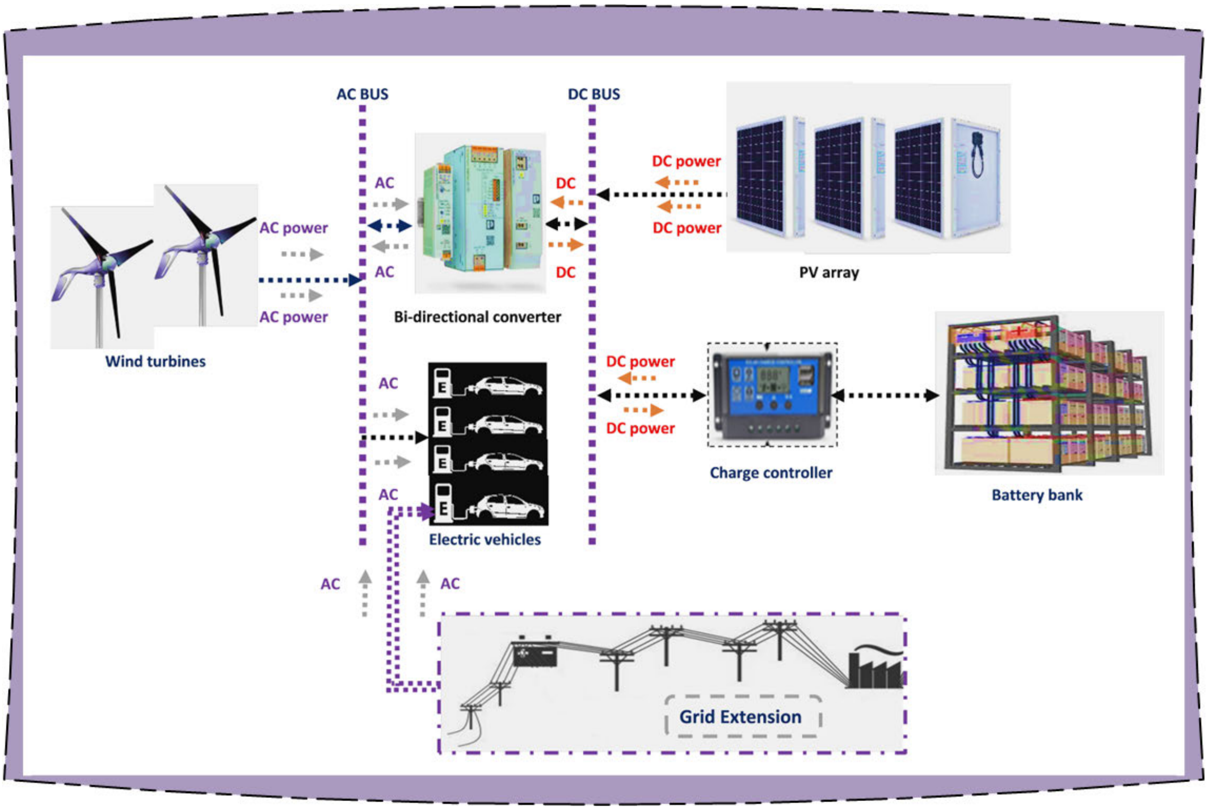


FIGURE 5. Hybrid renewable energy system-EV charging model with a grid extension option.

the HOMER Pro® software tool and the design scheme is shown in Fig. 4. The optimization evaluation and the outcomes are based on the constraints, objective function, and decision parameters. Selecting a suitable charging approach is essential in reducing the RES output variation.

Furthermore, the schematic and energy flow diagram of the proposed hybrid charging station (HCS) model with battery is provided in Fig 5. The real-time input parameters needed for realistic and accurate sizing and a proper technical and economic investigation of the power system have been obtained by carefully studying the selected site's potential renewable resources, EV charge demand estimation, and geographical location. The control of the hybrid system model is quite simple.

1) On the one hand, whenever the energy supplied by the renewable component resources exceeds what is needed to meet the charging demand of the EVs, extra electricity is utilized to charge the storage device. Any surplus of electricity that remains unused (beyond charging the EVs and the storage device) can be injected into the grid electric distribution system.
2) On the other hand, if the energy provided by the renewable systems, is insufficient to meet the charging requirement of the EVs, the storage device releases electricity to serve the EVs. This way, the proposed HCS reliability, and efficiency can be improved, and the excess electricity generated can be adequately managed.

The charging time depends on the storage device's capacity and state of charge (SOC). In the HCS scheme, there will be many charging spots to recharge the EV battery from the alternating current (AC) bus via the charging device.

The techno-economic specifications of different components have been extracted from various sources in the open literature. The optimized stand-alone hybrid charging station is compared, via comparative study, with the grid-connected network option as an alternative power source for the EVCS. The break-even grid expansion distance limit is computed when evaluating the economic feasibility of the off-grid RE-based EVCS against the grid-tied EVCS. It is the distance from the electricity distribution network that makes the NPC of extending the electrical distribution network the same as the NPC of the stand-alone system configuration. The stand-alone design is optimum farther away from the network, but closer to the network, the grid connection is optimum [67].

C. LOAD DEMAND ESTIMATION OF THE EVCS

A significant section in the energy resources optimal design and sizing of the system components concerns the modeling of the energy requirement. The present hybrid system model addresses the electric power for an EVCS. The HCS model designed for the chosen site, which operates in an off-grid mode, is expected to compete with the grid-connected

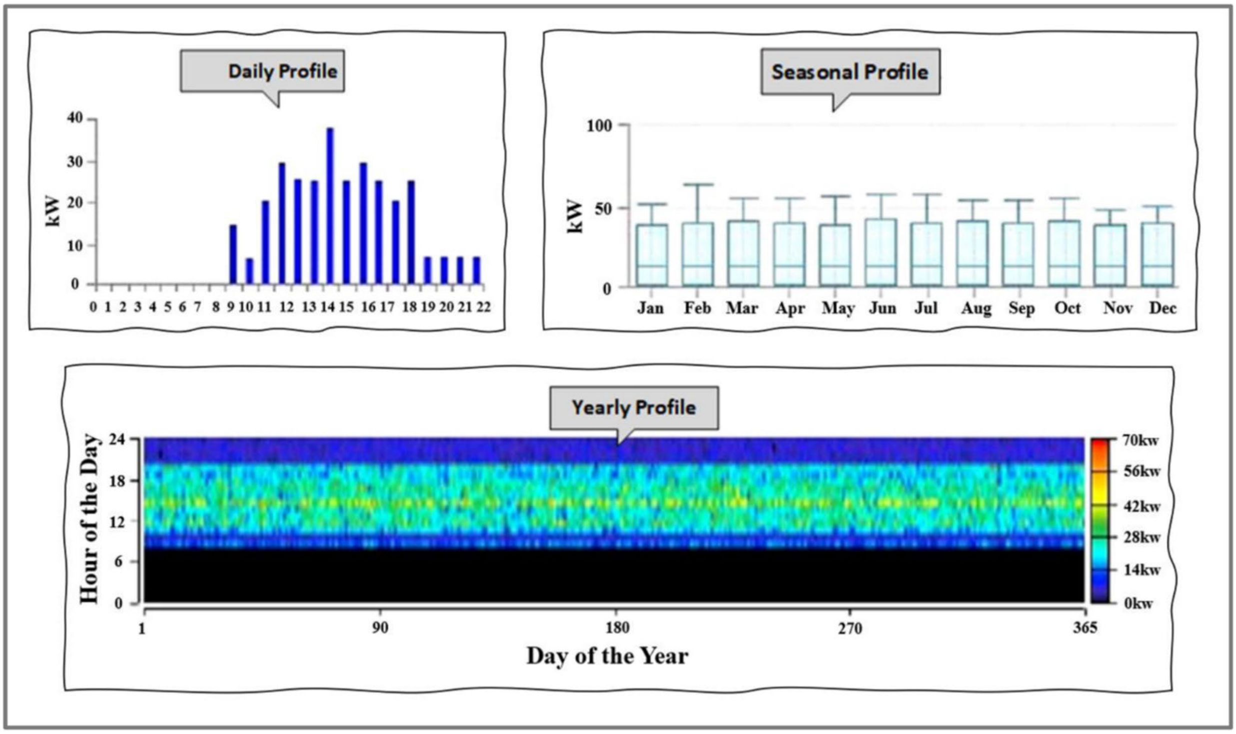


FIGURE 6. The hourly and seasonal EV load profile data from HOMER.

charging station option with a minimized cost, 100% free of pollutant emissions, and enhanced efficiency in the electrification approach. The main premises and headquarters of the Makkah Transport Company (MTC) are situated in the selected off-grid location. Saudi Arabia has a limited number of charging points with a minimum number of electric vehicles on its roads. Therefore, the daily charge demand is easily predictable. A daily charge demand of 30 kWh of electricity per electric vehicle id assumed in the present analysis. Therefore, the energy consumed by an EV can power it for approximately 160 km. Hence, 0.1875 kWh of energy is needed per kilometer run. The distance between the planned installation location of the HCS and the center of Makkah city is about 40 km; therefore, the EV can run two round trips per day. The EV load demand profile, including the seasonal daily energy consumption, is illustrated in Fig. 6, where the estimated charge demand per day for at least 10 EVs is 300 kWh. The working time for the HCS will be from 8:00 AM to 11:00 PM. The hybrid CS system operates for 15 h a day, while the EV is utilized for 26 days per month. Subsequently, the average EV demand is synthesized by inserting some randomness for various days and months to produce for this HCS, in a year, a relatively realistic demand.

V. GRID EXTENSION (GE) COST EVALUATION

The study of grid extension or expansion differs from that of a stand-alone hybrid power configuration. The total capital costs for grid extension regarding the grid expansion length (L) and the number of connections (N) can be computed linearly as a weighted sum of L and N:

$$\text{Cost}_{\text{grid}} = a_1 L + a_2 N \tag{1}$$

Here, $\text{Cost}_{\text{grid}}$ = Grid expansion cost (GEC), which includes the capital cost and the operations and maintenance (O&M) cost ($), a_1 is the grid expansion cost coefficient corresponding to the distance (in $/km), a_2 represents the grid expansion cost coefficient corresponding to the number of connections (in $/connection). L is the distance from the utility network expansion (here taken as 20 km), and N denotes the number of connections in the planned location (here taken as 5 connections, i.e., 5 EVCSs).

The cost of grid extension is used in this analysis to compare the grid expansion option with the proposed optimal stand-alone system to identify the best power supply alternative for the planned EVCS location. This was estimated based on the grid extension parameters reported for SA in [68]. The grid capital cost and the cost of the distribution line for each EVCS stand are assumed as a_1 = $94,000/km and a_2 = 1000 $/Connection, respectively. According to the Saudi Electricity Company, the grid electricity tariff (GET) is $0.08 per kilowatt-hour [41]. The annual O&M costs are taken as 2% of the capital cost. The distance between the chosen EVCS location and the central network substation (CNS) is 20 km, while the number of connections in the planned site is 5 (i.e., five EVCSs). Utilizing the grid extension cost parameters above, we compute the total capital costs for grid

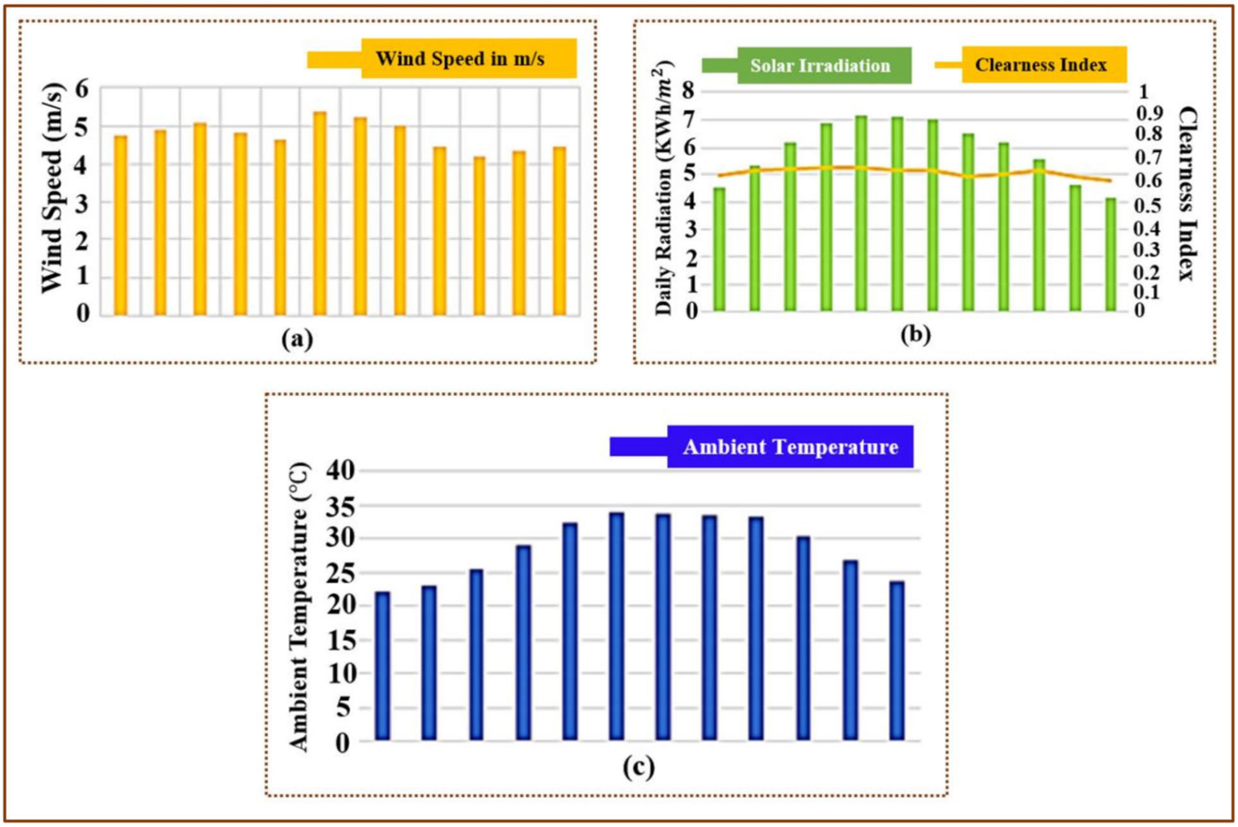


FIGURE 7. The monthly average (a) Wind speed, (b) Solar radiation, and (c) Ambient temperature. These data pertain to the selected location in western SA.

extension from (1) as follows:

$$\begin{aligned}\mathrm{Cost}_{\mathrm{grid}} &= a_1L + a_2N \\ &= (94,000\$/km \times 20km) \\ &\quad + (1000\$/\mathrm{Connection} \times 5\ \mathrm{connections}) \\ &= \$1,885,000.\end{aligned}$$

VI. RENEWABLE RESOURCES POTENTIAL, DATA, AND THEORETICAL ORGANIZATION

A. WIND POWER RESOURCES POTENTIAL

The kinetic energy manifested by air motion can be transformed into electric energy by a wind turbine. It is essential to precisely investigate the wind power potential in the country to exploit the maximum electricity output. Saudi Arabia has a vast land size (an area of 2.15 million km^2), where there is enough prospect to set up wind energy systems to produce a considerable amount of electricity, which could support the 2030 developmental plan. Besides, there is a great potential for abundant wind energy, thanks to the high wind speed (WS) in many country regions, which can accelerate sustainable energy production and establish both small-scale and large-scale wind farms. Conventional energy resources could be partially saved and some significant portion of the electricity generated from fossil fuel combustion could be replaced by RESs. Some previous studies [69], [70], [71] have indicated that the western part of the country, including our selected area for the planned EVCS, has considerable potential for wind sources more than other parts of the country do. The wind information, for the selected location in the western SA region, retrieved from the National Aeronautics and Space Administration (NASA) Prediction Of Worldwide Energy Resources (POWER) database [72] is presented in Fig. 7(a). The mean monthly wind speed information is measured at 50 m above the earth's surface for 30 years (January 1984 to December 2013). The details of the wind reveal that there is variation in the wind speed recorded all year round. Moreover, the wind speed data shows that the lowest and highest wind speeds are registered in October and June at 4.18 m/s and 5.34 m/s, respectively, when the percent of 1 hr. autocorrelation factor (AF) was 85% at a maximum wind speed hour of 15 h. The yearly average wind speed obtained is 4.75 m/s.

B. SOLAR POWER RESOURCES POTENTIAL

The western region of SA is characterized by hot weather for most months, while the mean sunlight energy of 2200 thermal kWh/m^2 is obtainable in the country as a whole [73]. Therefore, this region's solar potential is higher than that of the other parts of the country, especially that of the southern and northern areas. Saudi Arabia could produce clean electricity via direct sunlight and PV cells [74]. The

TABLE 2. Simulation information of the hybrid system components.

Wind turbine	Model/Values	PV module	Model/Values	Battery bank	Model/Values
Model	B-Excel 10-R	Model	Peimar SG370M	Model	Surrette 6 CS 25P
Rated power	10 kW	Manufacturer	Peimar Inc.	Weight	144 kg
Hub heights	30 m	Type	Flat plate	Nominal capacity	6.91 kWh
Rotor diameter	7.0 m	Weight	22.5 kg	Nominal voltage	6 V
Tower options	18-49 m	Efficiency	19.1%	Roundtrip efficiency	80%
Weight	460 kg	Op. cell temp.	47 ºC	Depth of discharge	20%
Cut-in speed	2.2 m/s	Ground reflectance	20%	Maximum capacity	1,150 Ah
Start-up speed	2.2 m/s	Temperature coefficient	−0.4%/°C	Lifetime throughput	9,645 kWh
Rotor speed	0-400 rpm	Capital cost	\$ 640/kW	SOC_{min}	20 %
Lifetime	20 years	Cost of replacement.	\$ 640/kW	Replacement time	20 years
Capital cost	\$ 3,200/kW	O&M cost	\$ 10/kW/year	Capital cost	\$1,100
Cost of rep.	\$ 3,000/kW	Derating factor	80%	Replacement cost	\$1,100
O&M cost	\$ 80/kW/year	Slope (degree)	22.3	O&M cost	\$10/year

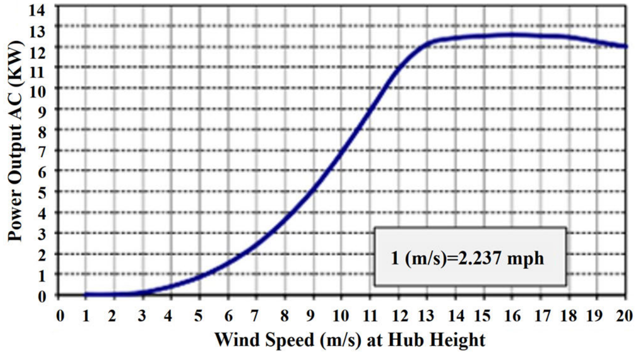


FIGURE 8. The wind turbine power curve.

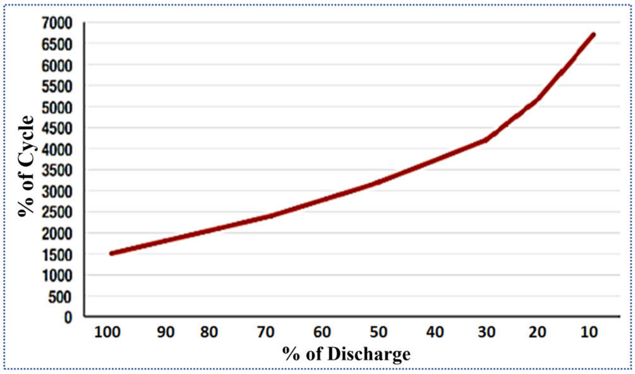


FIGURE 9. The relationship between the battery's cycle life and depth of discharge.

selected site's global horizontal solar irradiation (GHSI) data is retrieved from the NASA POWER database [72] by specifying the coordinates of the EVCS planned location. The information retrieved covers more than two decades (from July 1983 to June 2005). The monthly mean solar global horizontal irradiance variation is presented in Fig. 7(b), from which the annual average value of 5.94 kWh/m^2/day was obtained. Investigation of the graph reveals that during the months from March to September (the country's extended summer months), the solar radiations are on the high side in comparison with their values during the other months. The minimum and maximum radiations of 4.15 kWh/m^2/day at a clearness index of 0.599 and 7.17 kWh/m^2/day at a clearness index of 0.655 are obtained in December and May, respectively. Also, the average annual air temperature (AT) of 28.96°C was reported for about 30 years [72] with monthly minimum and maximum averages of 22.19°C and 33.84°C (Fig 7(c)).

C. MODELLING AND DETAILED SPECIFICATIONS OF MAIN SYSTEM COMPONENTS

1) WIND TURBINE POWER SYSTEM

To design the optimal HCS system, we utilize a wind conversion energy system (WCES) model 'Bergey Excel 10-R' of 10 kW rated capacity, taken from [50]. The WT employed by this system is of the 3-Blade Upwind Horizontal Axis type. The details, including the cost information, for this WCES system, are presented in the left part (first and second columns) of Table 2, reproduced from [75]. The WCES is connected to the AC link in the HCS model. The random variable WS follows a Weibull distribution (WD) whose parameter k is taken as 2, while the diurnal pattern strength (DPS) measures how strong WS depends on the daytime, assumed as 0.25. The HOMER Pro® software's one-hour autocorrelation factor is considered to be 0.85. The hour of maximum wind speed is taken as 15. Figure 8 shows the power curve of the chosen WCES. The WCES height significantly impacts the amount of energy it receives, thus affecting its output. The mechanical power P_m of the WCES is related to the air density ρ (1.22 kg/m^3), the surface area A swept by the rotor (m^2), and the linear velocity V (m/s) by:

$$P_m = \frac{1}{2} \times \rho \times A \times V^3 \tag{2}$$

While the electrical power P_e is expressed in terms of the power coefficient C_p as:

$$P_e = \frac{1}{2} \times \rho \times C_p \times A \times V^3 \times 10^{-3} \tag{3}$$

2) SOLAR PV SYSTEM

The PV panel (model: Peimar SG370M) was utilized in this analysis. The primary information on the chosen PV component is given in the middle part (third and fourth columns) of Table 2, taken from [65]. The efficiency at standard test conditions (STC) and derating factors (DF) of the PV panel is 19.1 % and 80 %, respectively. No tracking system was utilized and the lifetime of the PV system is 25 years. The output power P_{PV} of the PV module is evaluated in terms of the solar irradiation, the derating factor, and the temperature impact as follows [76]:

$$P_{PV} = Y_{PV} f_{PV} (\frac{G_T}{G_{T,STC}})[1 + \alpha_P (T_C - T_{C,STC})] \qquad (4)$$

where Y_{PV} refers to the PV power output under STC in kW, f_{PV} represents the PV de-rating factor (%), G_T is the solar radiation incident (SRI) on the PV panel in the current time step (kW/m^2), $G_{T,STC}$ refers to the incident radiation under [77] standard test conditions (1 kW/m^2), α_P is the temperature coefficient of power (%/degree Celsius), T_C is the temperature of the PV cell (degree Celsius), and $T_{C,STC}$ is the PV cell temperature at STC (25 degree Celsius) [52].

The PV module efficiency reduces as the temperature increases. The temperature derating factor f_{temp} in terms of the PV efficiency and the temperature parameters is given as [78]:

$$f_{temp} = \frac{1 + \propto_p [T_a + I_T \left(\frac{T_{C,NOCT} - T_{a,NOCT}}{I_{T,NOCT}}\right) - T_{C,STC}]}{1 + \propto_P I_T (\left(\frac{T_{C,NOCT} - T_{a,NOCT}}{I_{T,NOCT}}\right) \frac{\eta_{mp,STC}}{0.9}} \qquad (5)$$

3) BATTERY STORAGE SYSTEM

The lead-acid type storage device is used in this analysis. Deep cycle storage is generally utilized in grid-independent renewable power systems. The techno-economic specifications of the chosen storage device are presented in the right part (fifth and sixth columns) of Table 2, taken from [79]. The graph showing the relationship between the cycle life and storage device discharge depth is illustrated in Fig. 9. The string of the storage device comprises 24 batteries per string. The storage device capacity C_{Bat} is calculated by utilizing the autonomy days (AD) and the load energy per day E_L.

$$C_{Bat} = \frac{\mathrm{E_L AD}}{\eta_{inv} DOD \eta_{bat}} \qquad (6)$$

The storage state of charge $SOC_B(\%)$ is given in [80] as a percentage of the ratio of its charge q_b to its maximum charge q_{bm}:

$$\mathrm{SOC_B}(\%) = \frac{q_b}{q_{bm}} \times 100 \qquad (7)$$

4) CONVERTER COMPONENT

As a power electronic device, the converter changes the electricity between direct current (DC) and alternating current (AC). In the inverter mode, it changes the electricity from DC to AC, while in the rectifier mode, it changes the electricity from AC to DC. The converter is utilized as a power conditioning component to aid the flow of electricity between AC and DC links. The efficiency of the selected converter is 90% at a rated capacity of 1 kW. The capital and replacement costs are \$300/kW for a lifetime of 15 years [65].

VII. CRITERIA OF PERFORMANCE ASSESSMENT FOR THE HYBRID ENERGY MODEL

The economic investigation is a vital part of the HOMER Pro® analysis tool due to its principal target, which is cost reduction. HOMER does the financial analysis of the proposed system configurations. In this analysis, the optimization and performance assessment of HCS models is performed using different determinant criteria under three other domains as illustrated below: Technical (Unmet charge demand, Annual power generation), Economic (COE, NPC, operating and initial capital costs), and Environment (Renewable fraction (RF), greenhouse gas (GHG) emissions, renewable resources accessibility). It is essential to investigate whether it is viable to choose a stand-alone EVCS or an EV charging station with a grid connection from technical and economic viewpoints. Therefore, the other part of the criteria assessment compares the optimized system configuration for the EVCS with the alternative option of grid expansion based on economic factors and economic distance limitations.

A. THE NET PRESENT COST (NPC)

The NPC is a primary economic parameter often utilized to evaluate the optimized system design of various combinations of system configurations. It comprises the initial cost, replacement of individual components, operation cost, maintenance cost, etc. Also, as an economic parameter, the NPC demonstrates high reliability because of its mathematical foundation compared to the Levelized energy cost, which is a bit arbitrary. Moreover, HOMER uses this variable to rank different feasible system configurations. The following expression is used to evaluate the NPC (for convenience, denoted as C_{NPC}) [81]:

$$C_{NPC} = \frac{\mathrm{TAC}}{\mathrm{CRF(i, N)}} \qquad (8)$$

where TAC represents the total annualized cost (\$/year), N represents the number of years, and i is the annual real discount rate (%). The capital recovery factor (CRF) is determined using equation (9) below [82]:

$$\mathrm{CRF(i, N)} = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (9)$$

Based on the value of the yearly anticipated inflation rate and yearly nominal interest rate (NIR), equation (10) is utilized in HOMER to determine the yearly real discount rate (RDR):

$$i = \frac{i' - f}{1 + f} \qquad (10)$$

where i refers to the yearly real interest rate, f is the yearly anticipated inflation rate and i' represents the yearly nominal discount rate (also called the yearly simple interest rate). In this study, the yearly simple interest rate i' is 4.66%, the yearly anticipated inflation rate f is 0.5%, and the yearly real interest rate i is obtained as 4.14%. (From equation (10)) [75].

B. THE LEVELIZED COST OF ENERGY (COE)

The Levelized cost of energy (COE) in $/kWh is defined as the mean cost per unit of adequate electric power generated by the HCS model [83] over the system's whole lifespan. The COE is calculated as follows [84]:

$$\mathrm{COE} = \frac{\mathrm{TAC}}{E_{anloadserved}} \tag{11}$$

where *TAC* is the total annualized cost ($/year), while $\mathrm{E}_{\mathrm{anloadserved}}$ refers to the entire annual load (kWh/year) served by the system. The lifespan of the project is taken as 25 years.

C. UNFULFILLED DEMAND

The unfulfilled demand is the electric charging demand that the system cannot meet. The event of unfulfilling demand happens when the load demand is more than the electrical supply. The unmet demand in terms of annual unserved demand and the total yearly demand is illustrated in eq. (12) below as a ratio of these two parameters [80]:

$$Unmet\ load = \frac{\text{Yearly Non} - \text{served Load}}{\text{yearly Entire Load}} \tag{12}$$

D. ECONOMIC DISTANCE LIMITATION

The distance from the electrical distribution network makes the NPC of extending the utility network the same as the NPC of the stand-alone system configuration. The break-even distance is calculated to determine the maximum permissible network distance (MPND), after which a stand-alone electric vehicle charging station would be more viable.

HOMER uses eq. (13) to compute the break-even grid extension distance:

$$D_{grid} = \frac{\left(C_{NPC} \times \mathrm{CRF}\left(i, R_{proj}\right)\right) - \left(C_{power} \times L_{tot}\right)}{C_{cap} \times CRF\left(i, R_{proj}\right) + C_{om}} \tag{13}$$

Here, $\mathrm{C}_{\mathrm{NPC}}$ denotes the total NPC, $\mathrm{R}_{\mathrm{proj}}$ represents the project lifespan (years), $\mathrm{C}_{\mathrm{power}}$ is the grid power price (GPP) ($/kWh), $\mathrm{L}_{\mathrm{tot}}$ refers to the entire primary and deferrable load (kWh/year), $\mathrm{C}_{\mathrm{cap}}$ denotes grid expansion capital cost ($/km), and C_{om} denotes the O&M cost of grid expansion ($/year/km).

E. RENEWABLE FRACTION

The renewable fraction (RF) is the percentage of the gross power (kWh/year) produced by sustainable resources compared to that served by the whole HCS system configuration [85]. Renewable penetration is utilized for finding the RF of power generated by a hybrid system [86]. The RF is calculated under the assumption that the whole power served to the HCS system comprises the power of the sustainable resources plus that from non-renewable ones (diesel sources which originate from crude oil and biomass) [87]:

$$\mathrm{RF}\,(\%) = \left(1 - \frac{\sum P_{diesel}}{\sum Pren}\right) \times 100 \tag{14}$$

F. EXPECTED PAYBACK PERIOD

The expected payback period (EPBP) is used to calculate the needed time for the cash inflows of investment to become the same as cash outflows. The EPBP is computed using equation (15) below [88]. This economic evaluation tool reveals the period after which the project will become profitable.

$$\mathrm{EPBP} = \frac{\sum C_{CAP} + C_{O\&M} + C_{Repl.}}{C_{Cashinflow}} \tag{15}$$

$\mathrm{C}_{\mathrm{cap}}$, $\mathrm{C}_{\mathrm{O\&M}}$, and $\mathrm{C}_{\mathrm{Repl}}$ represent the capital, O&M, and replacement costs, and $\mathrm{C}_{\mathrm{cashinflow}}$ denotes the yearly cash inflow.

G. THE PROFITABILITY INDEX

The profitability index (PI) as an economic assessment parameter plays an integral part in a project to find out whether an investment is worth executing or not. If the PI value is more than 1, the project is worth investing in as it is deemed to be profitable. However, the project must be abandoned if the profitability index value is less than 1. The PI can be computed as follows [80]:

$$\mathrm{PI} = \frac{T \cdot C_{Cashin\,flow}}{\sum C_{cap} + C_{O\&M} + C_{Repl.}} \tag{16}$$

Here, T is the project lifetime (years). Combining (15) and (16), we obtain

$$\mathrm{PI} = \frac{T}{\mathrm{EPBP}} \tag{17}$$

VIII. RESULTS ANALYSIS AND DISCUSSION

The technical and economic viability, and the environmental benefits of a solar-wind-battery hybrid configuration for providing off-grid electrification to an EV charging station, are investigated using the HOMER Pro® optimization tool. The optimized HCS is compared with the grid expansion option in terms of economic criteria factors. For simulation purposes, HOMER modeled the hourly performance of each system subunit to ensure the optimal possible matching between the energy demand and the energy supply. The details of the renewable sources, system components specifications, and EV energy demand were utilized to evaluate the optimized HCS and provide a list of ranked feasible systems according to least NPC and COE. The optimized solution is based on the hybrid configuration with the lowest NPC and COE values in this analysis. Three different hybrid charging system models were designed and investigated to obtain the optimum system in terms of techno-economic feasibility. The viability of the proposed HCSs has been assessed based on the COE, NPC, electricity production, maximum renewable penetration, unmet load, and operating cost. From the simulation results, it was observed that there were only three feasible solutions out of the solutions attempted in the thousands of simulations run by HOMER. The corresponding possible combinations of energy sources were categorized according to the different parameters and were ranked according to the respective NPC

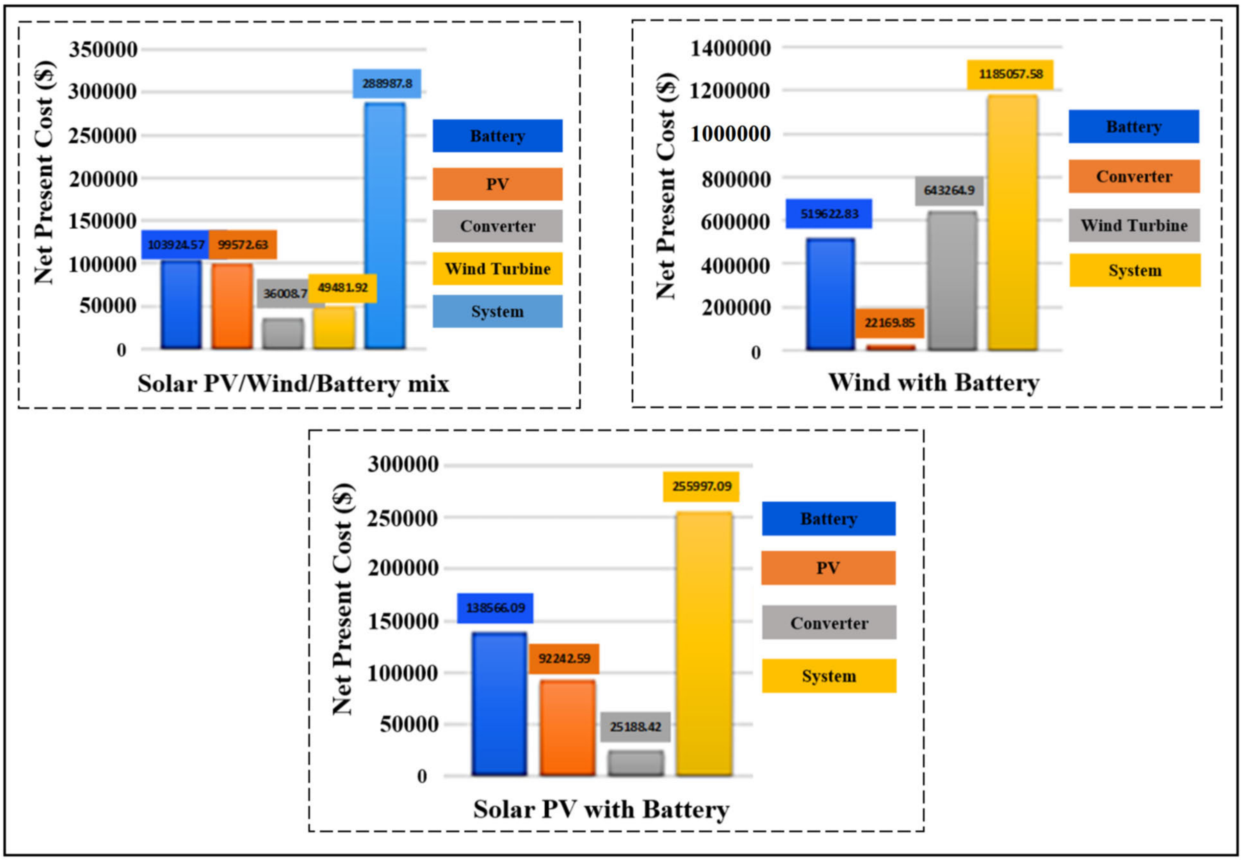


FIGURE 10. Categorized cost distributions for different system model scenarios.

values. The feasible system scenarios are further elucidated in section VIII-A.

A. SYSTEM CONFIGURATIONS OF DIFFERENT FEASIBLE HCS SCENARIOS

1) SCENARIO I (SCI): PV/WIND HYBRID CHARGING STATION WITH A BATTERY BANK

In the first feasible scenario (depicted SCI), the system architecture comprises a PV panel and a wind turbine with battery storage. The techno-economic results of this scenario, which include the total NPC and the COE, are given in the first data column of Table 3. The table indicates that the SCI system has an NPC and a Levelized COE of $288,988 and $0.172 per kWh, respectively. The operational performance of the various components of the SCI scenario is presented in the first data column of Table 4. The Levelized costs of the wind and PV systems are $0.188 and $0.0313 per kWh, respectively. The PV Levelized cost is about 18.2% of the system's COE, while the storage system wear's cost of $0.128/kWh is about 74.4% of the system's electricity cost. The storage wear cost is considered too much and even far above that of the photovoltaic system. Many consumers might prefer to install many PV generators and lower the quantity of the storage device or even get rid of them. But, this could increase the percent of surplus energy.

In this system arrangement, the contribution of the WCES, PV, and storage devices to the NPC are $49,482, $99,573, and $103,925, respectively (Fig. 10).

Furthermore, this system model's annualized capital cost ($14,082), replacement cost ($4,046), and operating cost ($2,774) are second to those of the system scenario with the least cost (Table 5). The PV and WT operated for 4,404 hrs and 7,877 hrs. per year at a penetration of 189% and 15.6 % each. The wind/PV/battery system had the highest annual power produced (223,488 kWh) from the WCES and PV module among the different configuration scenarios that serve the EV charge demand. The PV system has the highest contribution of about 92.36%, while the WT supplies the remaining share of 7.64%. The RF of this system model is a perfect 100% and the system has no operational emissions like CO_2, CO, particulate matter, unburned carbon, etc. The monthly electricity generation shown in Fig. 11 (a) shows that more electricity was produced from the PV between March and September (i.e., during months with the highest solar irradiation). The least energy was produced in November and December, as the lowest solar radiation was reported in these months. Maximum wind electric power was produced in June through August (The months with the highest wind speed), while the minimum production was encountered in October. The hourly electricity generation of the solar PV and wind

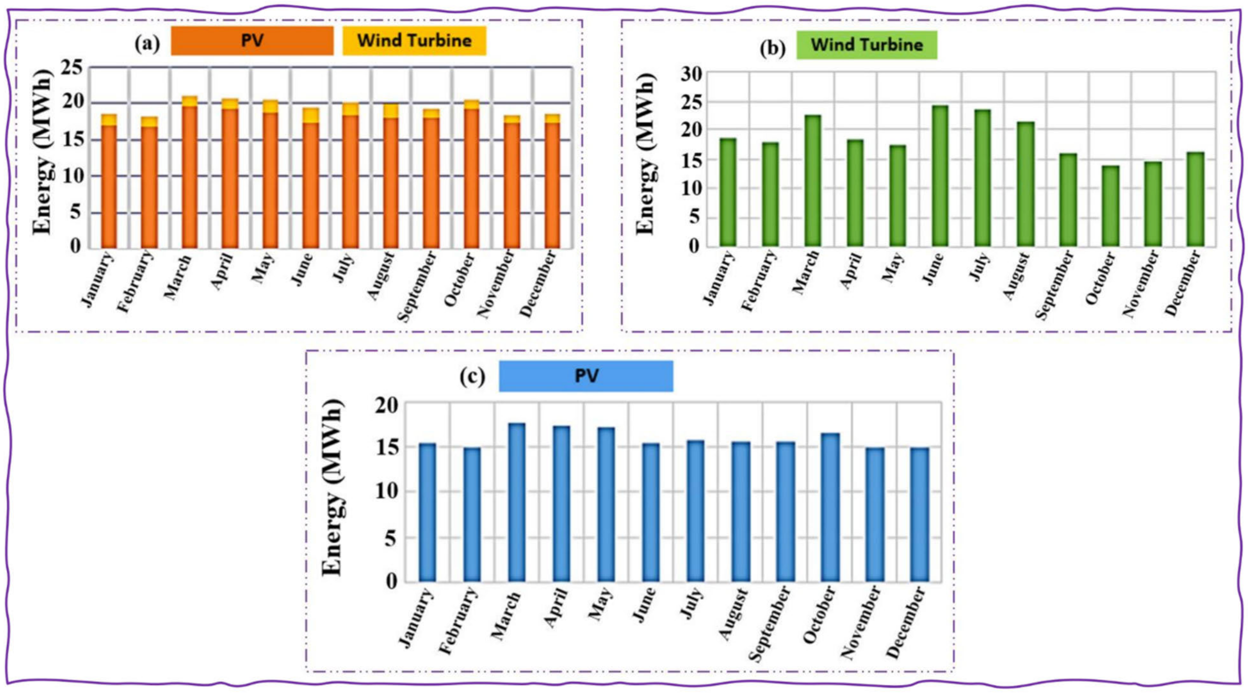


FIGURE 11. Distribution of the electric power produced by the (a) solar-wind-battery, (b) Wind/battery, and (c) PV/battery (optimal design).

turbine (WT) is illustrated in Fig. 12. It is indicated from this figure that the peak output of the PV system was obtained at 108 kW with an average output power of 23.6 kW and a Levelized cost of \$0.031/kWh. The maximum output power reported by the WT is 11 kW at a mean output of 1.95 kW with a Levelized cost of \$0.188 per kWh.

The daily and monthly mean SOC of the storage device for the scenario I system is presented in Fig. 13. The minimum charging cycles were recorded between October and December due to the low solar radiation and low wind speed encountered during these periods. The battery energy losses relating to the energy in, energy out, and storage depletion is 7,679 kWh/year at a lifetime throughput of 688,804 kWh. The energy losses per year of the converter component are 10,701 kWh/year (as an inverter) and 345 kWh/year (as a rectifier) at a capacity factor of 13% and 0.421%, respectively.

Also, the present system scenario has the lowest percentage of capacity shortage of 0.0516%, which implies this scenario had a maximum operating time and can satisfy most of the charge demand of the EVCS location as it has a minimal unmet load of 38.4 kWh/year (about 0.035% of the entire load). This system scenario produces the highest excess energy at 42.7% of all energy production. It, therefore, presents a considerably low-capacity factor for the PV modules and WT, which indicates that this system scenario had a significant waste of electricity. Besides, this system architecture does not provide a competitive cost-benefit advantage when compared to the other scenario cases for EV charging station design and installation in the proposed location.

2) SCENARIO II (SCII): WIND/BATTERY HYBRID CHARGING STATION

The arrangement in the second scenario (SCII) has 130 kW of the wind energy system, 360 units (or 15 strings) of storage devices at a nominal capacity of 2,487 kWh, and 51.9 kW of the inverter and rectifier modes of the converter, as illustrated in the second data column of Table 3. Among the three feasible scenarios considered, this wind/battery configuration presented the highest total NPC of \$1,185,058. The wind turbine (\$643,265) has the largest share of the gross NPC, followed by the battery at \$519,623 (Fig. 10). Besides, the highest cost of energy of \$0.703/kWh (Table 3) was obtained in this system scenario. The COE of this scenario was approximately \$0.531 and \$0.551 per kWh more than the COE values for scenarios I and III, respectively. The comparative performance of the various components of the design for this scenario is given in the second data column of Table 4. According to this table, the Levelized cost of the WT is \$0.188/kWh (26.7 % of the system COE), while the storage wear cost is \$0.128 kWh. The storage device wear cost is about 18.2 % of the system COE and is approximately 32 % less than the WT Levelized cost. The system battery SOC is presented in Fig. 14. It is evident from the mean SOC of the storage device that minimal charging cycles were experienced from the beginning of September (from day 243 of the year) to the end of December (to day 365 of the year) as the lowest wind speed values were reported during these months. The wind/battery arrangement (Scenario II) produces the least annual energy around 132,762 kWh/year from the WT system, which operated annually for about 7,877 hours with a penetration of 203 %.

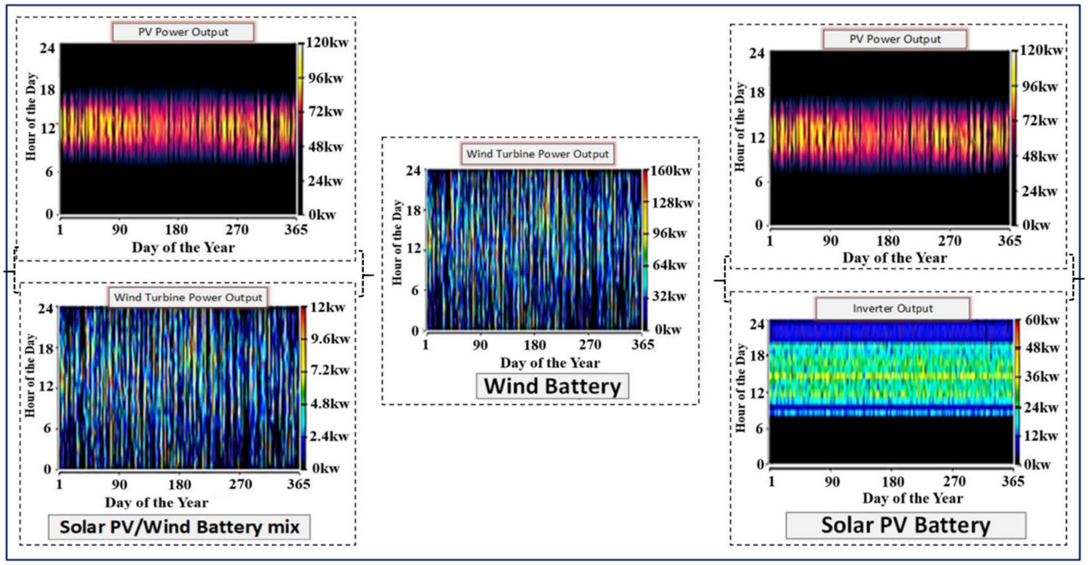


FIGURE 12. The hourly electricity generation of different system model components.

Moreover, Scenario II presented the highest maximum value of renewable penetration of 4,144% compared to the values of other feasible system scenarios. The renewable penetration is 100%, and hence the system has no carbon footprints (no emissions of carbon dioxide and methane). The storage losses, which depend on the annual amount of energy in, energy out, and battery depletion, were 10,870 kWh at a yearly throughput of 48,842 kWh/year. The inverter and rectifier modes of the converter have annual electricity losses related to the energy in and energy out of 4,369 kWh and 6,014 kWh, respectively. Moreover, a considerably low-capacity factor of 19.5% was reported for the WT as there is a high surplus of electricity.

Also, the Scenario II system structure has the highest capital cost ($827,577), the highest cost of replacement ($357,674), and also the highest O&M cost ($215,508) among the system scenarios considered. Additionally, this system model requires many battery devices, which usually need periodic maintenance, and this could further increase the overall maintenance cost and therefore increase the total system cost. According to Table 5, the total annualized capital cost ($53,762) of the wind/battery model is the highest among the three considered scenarios. It is approximately four times that of SCI and slightly above four times that of SCIII. For the wind/battery model, the annualized operating cost is $ 14,000, and the total cost is $76,985. The monthly energy production depicted in Fig. 11(b) shows that maximum energy was produced from June through August (The months with the highest wind speed). The minimum energy was generated from September to December since the lowest wind speed was reported in these months.

The only power-generating component in this system setup is the wind turbine. The hourly power output of the WT system is presented in Fig. 12. The highest power output reaches about 143 kW at an average of 25.3 kW. This system structure's total annual production (from WT only) is 221,936 kWh with a Levelized cost of $0.188 per kWh. This system configuration presents the highest capacity shortage of 109 kWh/year (0.1 %), which indicates that the system configuration has a minimum operable time compared to the other system scenarios. However, this system could satisfy approximately all the EV charging demands of the studied location. It has a minimal unfulfilled load of 29.7 kWh/year (0.027% of the overall load). However, techno-economically, this system arrangement is not feasible for the intended purpose of providing electricity to EVCS located in an off-grid site like the one under study.

3) SCENARIO III (SCIII): PV/BATTERY HYBRID SYSTEM MODEL

Lastly, our study investigated the hybrid system model with a PV module and a battery storage device (depicted in Scenario III or SCIII). This model presented the lowest COE and NPC values as shown in the third data column of Table 3 among the configuration models studied. The total NPC and COE were obtained at $ 255,997 and $ 0.152/kWh. The system's initial capital cost of $ 197,655 at an operating cost of $ 3,790 per year was achieved. The battery storage ($ 138,566) had the highest contribution to the total NPC. In this system arrangement, the solar PV system is the only electricity-producing component, and the annual total energy generated by the PV modules is 191,221 kWh/year. This system could satisfy almost all the EV charge demands of the planned EVCS off-grid location. Also, the PV/battery arrangement had a 100% renewable fraction and emitted no pollutant emissions to the atmosphere with zero carbon footprint.

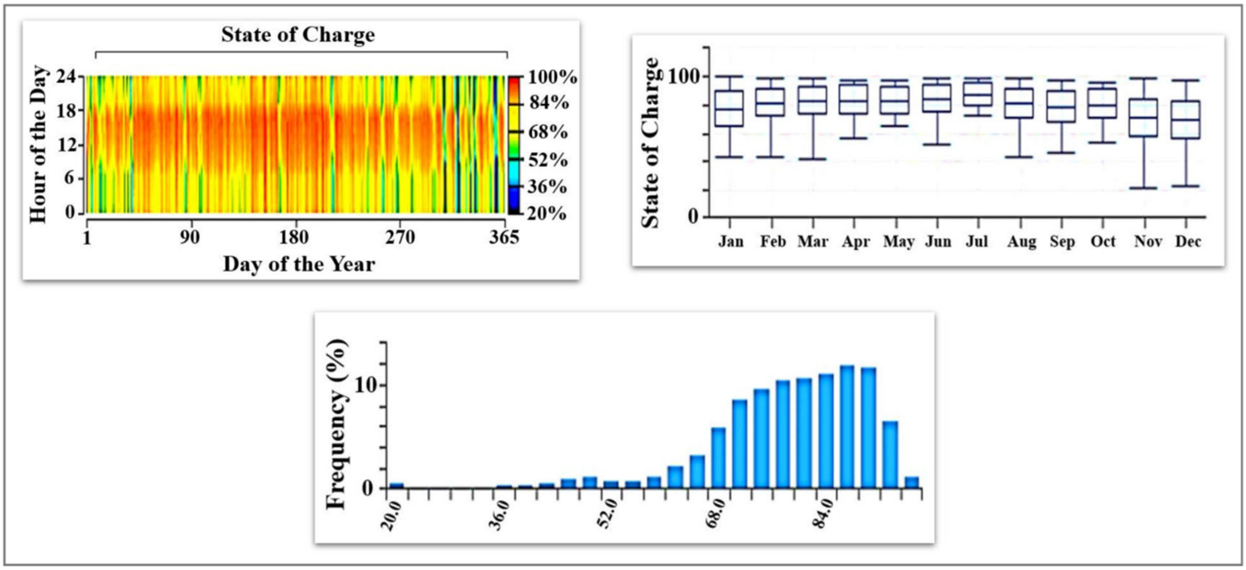


FIGURE 13. The SOC of the battery system for the solar-wind-battery system (Scenario I).

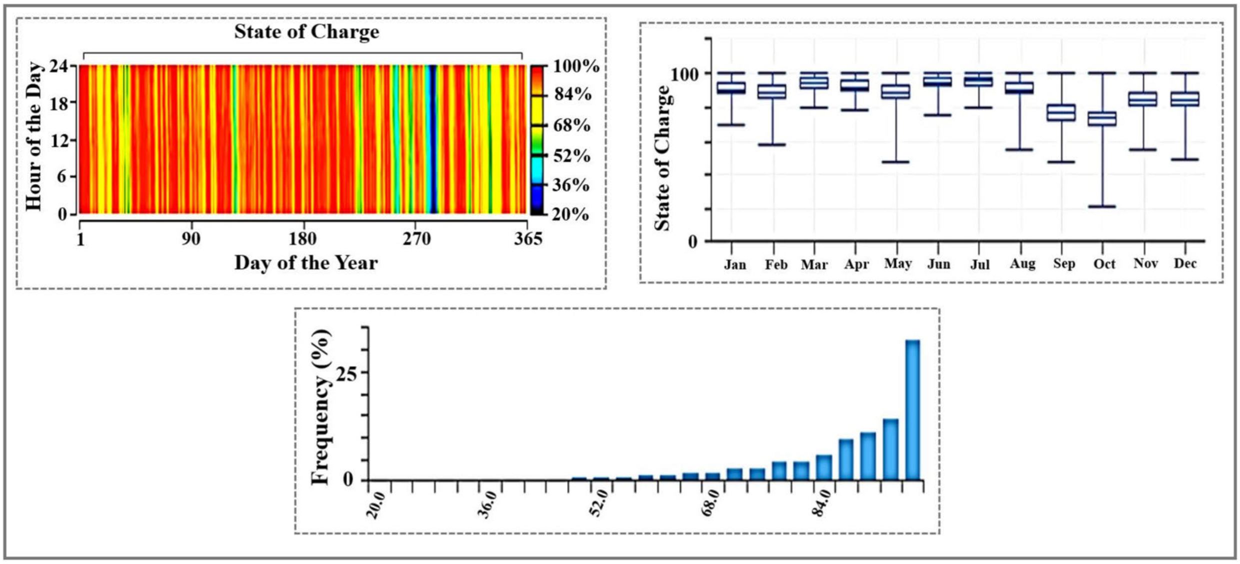


FIGURE 14. The battery device SOC for the Scenario II system model.

B. OPTIMAL CONFIGURATION PERFORMANCE (SCENARIO III: PV/BATTERY HCS SYSTEM)

1) OUTLINE OF THE TECHNICAL PERFORMANCE OF THE OPTIMIZED HCS SOLUTION

The outcomes of the operating performance of the different system components in the technical domain are provided in Table 4. The table shows that the optimal HCS (Scenario III) consisted of a PV of 116 kW rated capacity, a 59 kW inverter, a 59 kW rectifier, and 96 batteries with a nominal capacity of 663 kWh. It can also be seen that the capacity factors of the PV and inverter that form the optimized HCS structure are obtained at 18.8% and 21.2%, respectively, with a battery autonomy of 42.4 h. The PV module's capacity factor was relatively small due to the amount of electricity wasted, and the configuration's orientation is of a fixed tilt. This factor is an essential variable that determines the economic feasibility of this HCS. This system has a comparable maximum renewable penetration of about 2,064% during the simulated year (Table 3) with a renewable fraction of 100%. Therefore, this system has no operational emissions such as CO_2, CO, CH_4, particulate matter, unburned carbon, and the like.

Also, the monthly distribution of the electric power generated by the optimized HCS model (Fig. 11(c)) shows that the PV system produces annual electricity of 191,221 kWh/year (100%). However, about 31.7% (least among all considered system scenarios) of the entire power production was surplus due to a lack of battery capacity or EV charge requirements. The surplus energy could be sold to the national grid

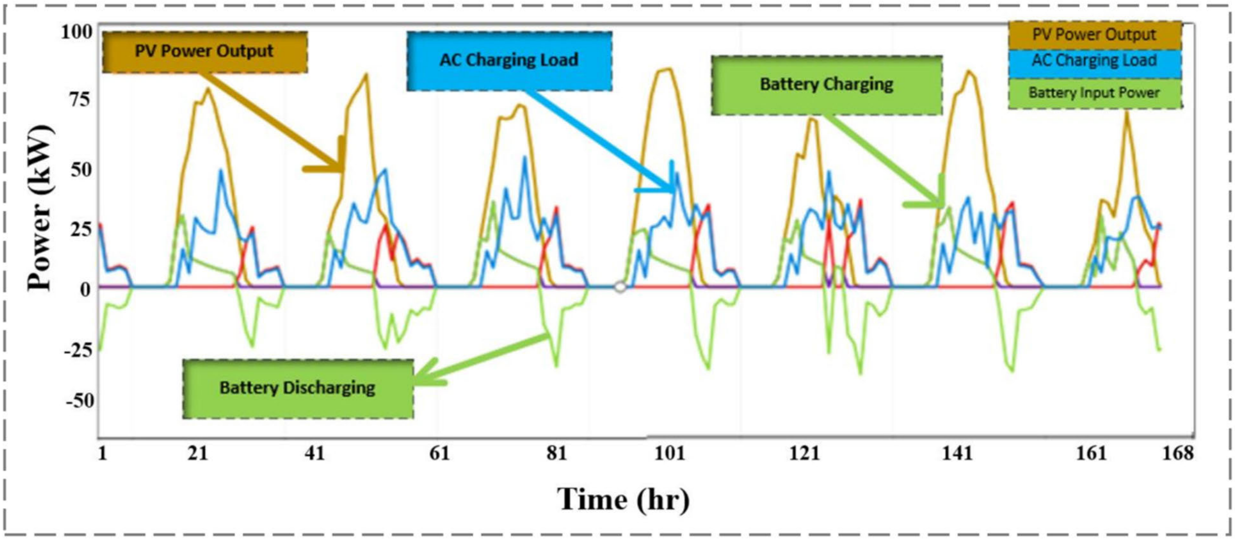


FIGURE 15. Satisfying the EV charging demand using different configurations for a week in August (peak of the summer season).

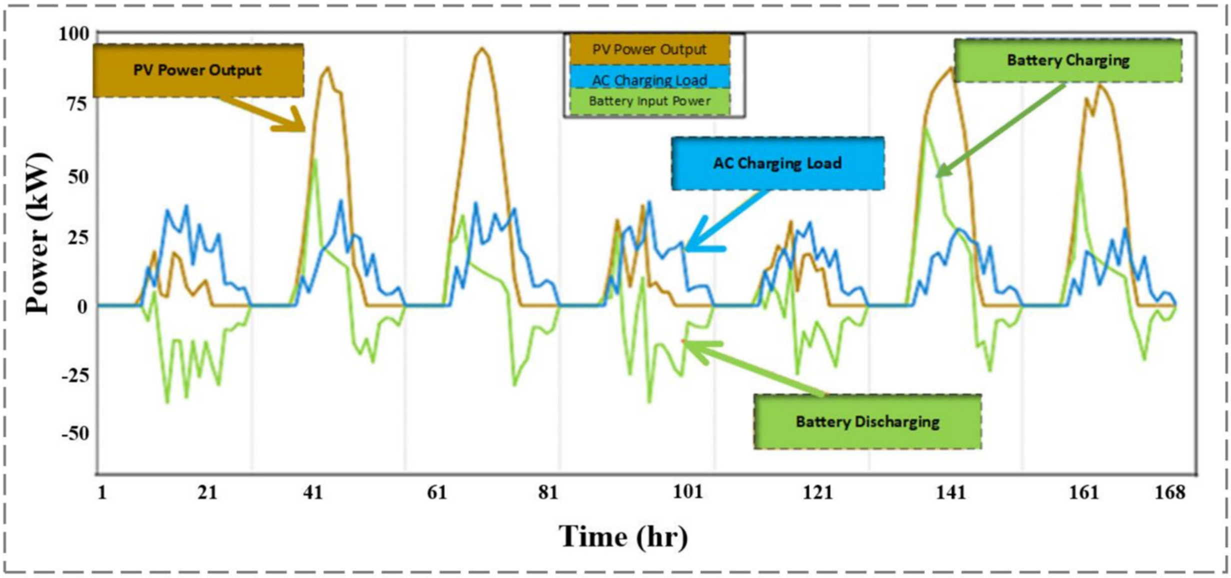


FIGURE 16. Meeting the EV charging demand using different configurations for a week in January (peak of the winter season).

network via vehicle-to-grid technology if no additional electricity is needed at the charging station. The PV solar generates most of its electric power in the period from March through October because of the high solar radiation available during these months. As an advantage, these months fall in the summer season, when EV charging demand is high because of the large number of people visiting the holy site (Makkah) during the summer holiday. By contrast, the least amount of energy is generated in the winter months from November to January. The capacity shortage of the optimized configuration is 0.09% of the gross generation, which is considerably small, indicating that the system had a maximum uptime. Besides, the optimal design can meet most of the EV charge demand as only a significantly small unmet electric load of 79.1 kWh/year (about 0.07% of the entire load) was encountered during the simulated year.

Furthermore, the hourly output of the PV system and that of the inverter are given in Fig. 12. The PV's lowest and highest output powers are 0 kW and 100 kW with an average output of 21.8 kW. Meanwhile, the inverter's maximum output is 59 kW with an average output of 12.5 kW. The PV operated for 4.404 hrs. /year to produce a total annual energy of 191,221 kWh at a penetration of 175 %. The daily average output energy of 524 kWh per day was reported for the PV system. On the other hand, the inverter had an annual energy-in of 121,579 kWh and operated more than the PV at 5,835 hrs./year to give an energy-out of around 109,421 kWh/year, which resulted in a yearly energy loss of 12,158 kWh.

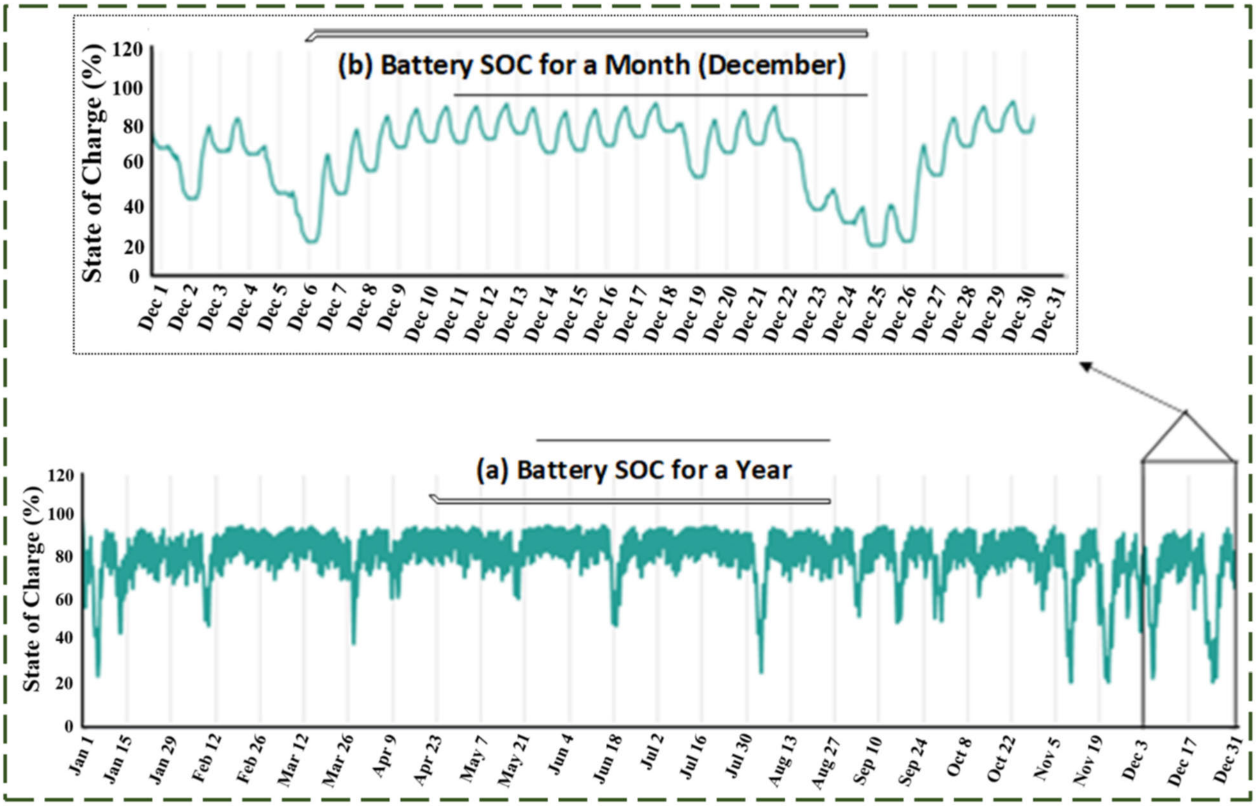


FIGURE 17. The battery SOC (a) for a year, (b) for a month (December).

TABLE 3. Summarized results of different hybrid system charging scenarios.

S/no Characteristics	Scenario I	Scenario II	Scenario III
1. Component ratings			
Photovoltaic (kW)	125	-	116
Wind turbine (kW)	(1 unit, 10 kW)	(13 units, 130 kW)	-
Inverter (kW)	84.3	51.9	59
Rectifier	84.3	51.9	59
Battery:			
Strings; Number (unit)	3 strings (72 units)	15 strings (360 units)	4 strings (96 units)
Nominal capacity (kWh)	497	2,487	663
2. Cost ($)			
Initial capital cost	216,767	827,577	197,655
The total NPC	288,988	1,185,058	255,997
Levelized COE	0.172/kWh	0.703/kWh	0.152
Operating cost	4,692/year	23,223/year	3,790
3. Production (kWh/year)			
Electricity	223,488	221,936	191,221
AC charging load	109,462	109,470	109,421
DC charging load	0	0	0
Deferrable load	0	0	0
Unmet charging load	38.4	0.027	0.072
Capacity shortage	56.5	0.10	0.09
4. RE penetration (%)			
Max. renewable penetration	2,546	4,144	2,064
Renewable fraction.	100	100	100
Dispatch strategy	LF	LF	LF

Figure 15 shows the graph of different system components (PV and battery systems) operating together to meet the load requirement for one week in August (the peak of the summer season). By contrast, Fig. 16 illustrates a week in January (the peak of the winter season). It can be observed from Fig. 15 that the PV fulfills the highest share of the EV charge demand during the summer time with the excess power being used for charging the battery

TABLE 4. The results of the performance parameters for the different system components.

Parameters/Data	Scenario I	Scenario II	Scenario III
1. Wind turbine			
Rated capacity	10 kW	130 kW	-
Average output	1.95 kW	25.3 kW	-
Capacity factor	19.5 %	19.5 %	-
Total generation	17,072 kWh/year	221,936 kWh/year	-
Lowest output	0 kW	0 kW	-
Highest output	11 kW	143 kW	-
Wind penetration	15.6 %	203 %	-
Hours of operation	7,877 hrs./year	7,877 hrs./year	-
Levelized cost	$ 0.188/kWh	$0.188/kWh	-
2. Photovoltaic (PV)			
Rated capacity	125 kW	-	116 kW
Average output	23.6 kW	-	21.8 kW
Daily average output	566 kWh	-	524 kWh
Capacity factor	18.8 %	-	18.8 %
Total generation	206,416 kWh/year	-	191,221 kWh/year
Lowest output	0 kW	-	0 kW
Highest output	108 kW	-	100 kW
PV penetration	189 5	-	175 %
Hours of operation	4,404 hrs./year	-	4,404 hrs./year
Levelized cost	$ 0.0313/kWh	-	$0.0313/kWh
3. Inverter			
Capacity	84.3 kW	51.9 kW	59 kW
Average output	11 kW	4.49 kW	12.5 kW
Lowest output	0 kW	0 kW	0 kW
Highest output	59.4 kW	51.9 kW	59 kW
Capacity factor	13 %	8.64 %	21.2 %
Hours of operation	5,712 hrs./year	2,962 hrs./year	5,835 hrs./year
Energy out	96,306 kWh/year	39,317 kWh/year	109,421 kWh/year
Energy in	107,007 kWh/year	43,686 kWh/year	121,579 kWh/year
Losses	10,701 kWh/year	4,369 kWh/year	12,158 kWh/year
4. Rectifier			
Capacity	84.3 kW	51.9 kW	59 kW
Average output	0.355 kW	6.18 kW	0 kW
Lowest output	0 kW	0 kW	0 kW
Highest output	9.88 kW	51.9 kW	0 kW
Capacity factor	0.421 %	11.9 %	0 %
Hours of operation	2,453 hrs./year	5,281 hrs./year	0 hrs./year
Energy out	3,108 kWh/year	54,122 kWh/year	0 kWh/year
Energy in	3,454 kWh/year	60,136 kWh/year	0 kWh/year
Losses	345 kWh/year	6,014 kWh/year	0 kWh/year
5. Battery storage			
Number of batteries	72 qty.	360 qty.	96 qty.
Autonomy	31.8 hr.	159 hr.	42.4 hr.
Wear cost of battery	$ 0.128/kWh	$0.128/kWh	$0.128/kWh
Nominal capacity (Usable)	398 kWh	1,990 kWh	531 kWh
Lifespan throughput	688,804 kWh	976,847 kWh	838,555 kWh
Expected life	20 years	20 years	20 years
Energy in	38,295 kWh/year	54,122 kWh/year	46,615 kWh/year
Energy out.	30,804 kWh/year	43,686 kWh/year	37,501 kWh/year
Battery depletion	188 kWh/year	434 kWh/year	234 kWh/year
Losses	7,679 kWh/year	10,870 kWh/year	9,348 kWh/year
Yearly throughput	34,440 kWh/year	48,842 kWh/year	41,928 kWh/year

TABLE 5. Annualized cost of various categorized hybrid system models.

System Models	Capital Cost ($)	Replacement Cost ($)	Operating Cost ($)	Salvage ($)	Fuel Cost ($)	Total Cost ($)
Scenario I	14,082	4,046	2,774	-2,129	0.00	18,773
Scenario II	53,762	23,236	14,000	-14,013	0.00	76,985
Scenario III	12,840	3,673	2,122	-2,005	0.00	16,630

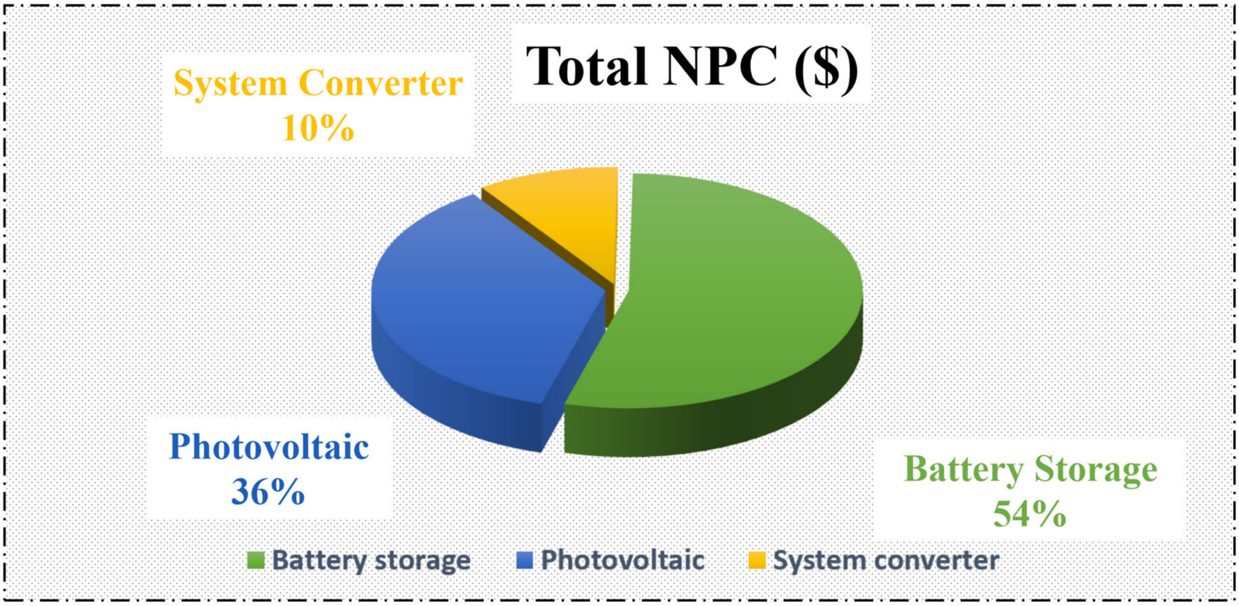


FIGURE 18. Percentage costs share of various components within the total NPC.

TABLE 6. Cost summary of the optimal hybrid EV charging station system model.

Components	Capital ($)	Replacement ($)	Operating ($)	Salvage ($)	Total ($)
Battery	105,600	46,915	14,778	-28,727	138,566
PV	74,358	0.00	17,885	-0.00	92,243
Converter	17,698	9,631	0.00	-2,140	25,188
System	197,655	56,546	32,662	-30,866	255,997

bank, and as a result, with less storage discharge being reported. During the summer season, the battery system is utilized for satisfying the load requirement in the absence of the photovoltaic system. However, according to Fig. 16, more battery discharge is seen during the winter period as the output power of the PV is less during this season compared to the summer period. Therefore, the storage battery discharges to provide the electricity required by the EV when the renewables are unavailable to fulfill the EV charging demand. For example, the storage device met part of the load demand at the beginning and the middle of the week in January demonstrated in Fig. 16, since the output of the PV was insufficient at this time, which resulted in more battery discharge. The battery SOC for the solar-battery hybrid configuration model is given in Fig. 17. The battery SOC reveals the amount of power stored in the storage device for both a year and a month (December). A minimum SOC of 20% was selected in this study. The storage device absorbs electric power when the electricity from the renewables exceeds the charging demand and discharges power whenever the charging demand exceeds the energy provided by the renewables. Moreover, immediately after the SOC of the storage device goes down to its minimum level, the load ceases to be fulfilled.

2) ECONOMIC ASPECTS OF THE OPTIMIZED HCS SYSTEM

Table 3 indicates that the total NPC and COE of the optimal system (Scenario III) were $ 255,997 and $ 0.152/kWh, respectively. Figure 18 illustrates the percentage cost shares of the storage, photovoltaic, and converter components within the total NPC. The storage device has the maximum contribution to the entire NPC, followed by the PV panel. Specifically, the storage device cost and the PV cost are about 54% and 36% of the total NPC. The power converter has the lowest share at 10%. The cost summary of the optimized HCS is presented in Table 6, wherein the table partitions the NPC by cost type for various system components. The combined initial capital cost ($197,655) from the PV, the battery, and the converter has the highest share of the total NPC. The battery has the maximum contribution to each of the capital costs and the replacement cost, whereas the PV has the largest share of the operating cost. Besides, the optimized configuration has the lowest capital and operating costs of $197,655 and $3,790/year compared to the SCI and SCII systems.

The annualized cost of Scenario III shown in Table 5 reveals that it has the lowest capital, replacement, and operating costs among all system scenarios. The nominal and discounted cash flow during the project lifespan (25 years) for the optimal HCS is depicted in Fig. 19. The outcome

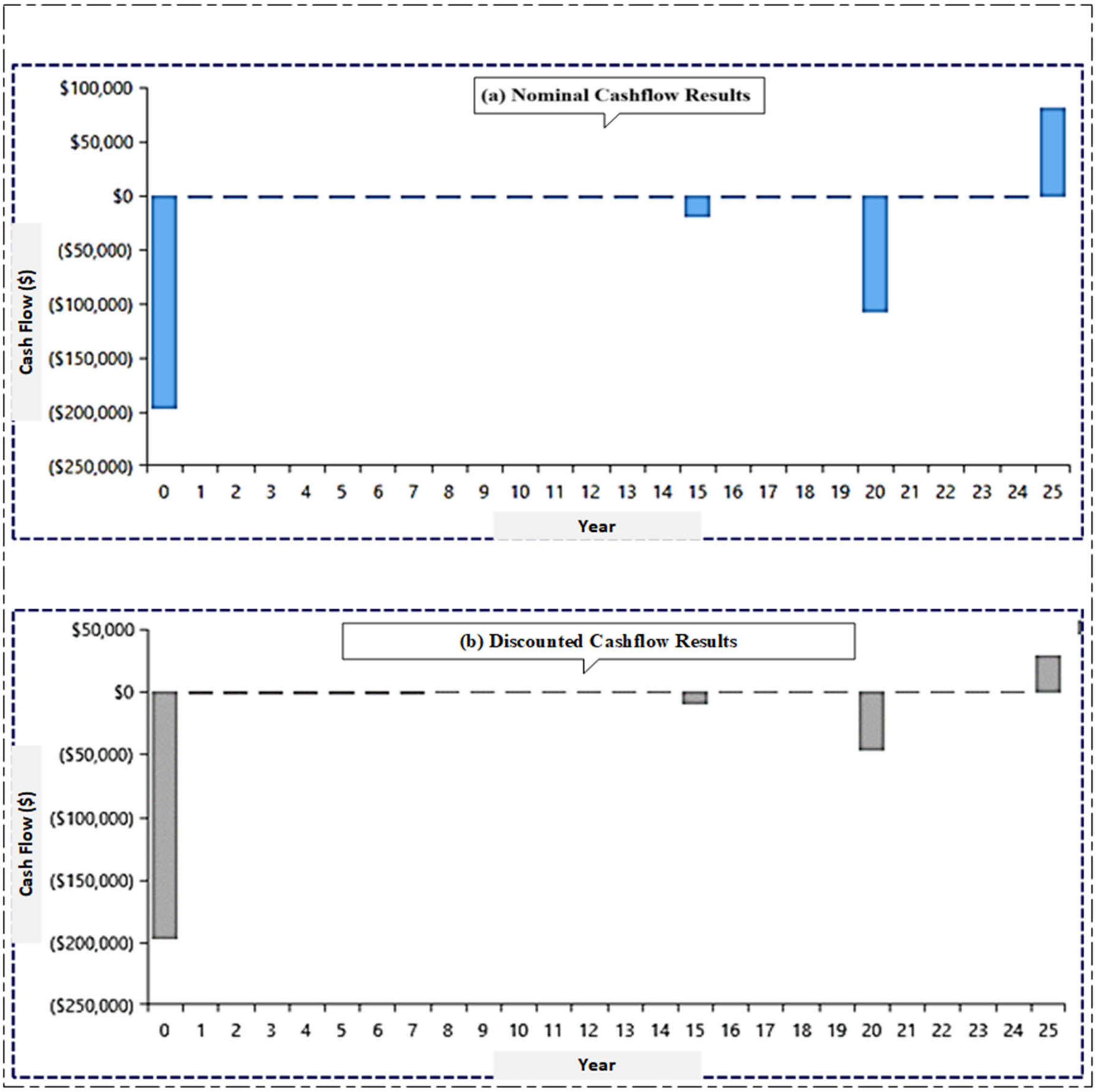


FIGURE 19. The optimal system configuration (a) Nominal and (b) Discounted cash flow results.

TABLE 7. Break-even distance of the various system configurations.

System Design Scenarios	NPC ($)	COE ($/kWh)	Breakeven distance (km)
Scenario I (solar/wind/battery)	288,988	0.172	1.27
Scenario II (wind/battery)	1,185,058	0.703	8.63
Scenario III (Optimal system)	255,997	0.152	1.00

TABLE 8. The standalone and grid-tied EVCS economic metrics.

EVCS System	Payback Period	ROI	IRR	PI
Stand-alone EVCS	10.66 years	4.9%	7.4%	> 1
Grid-connected EVCS	12.51 years	3.9%	6.1%	< 1

indicates that the optimized system's cash flow is steadily maintained for both the nominal and discounted case at the lowest value for the whole of the project lifetime. It can be observed that the discounted cash flow during year 25 is much

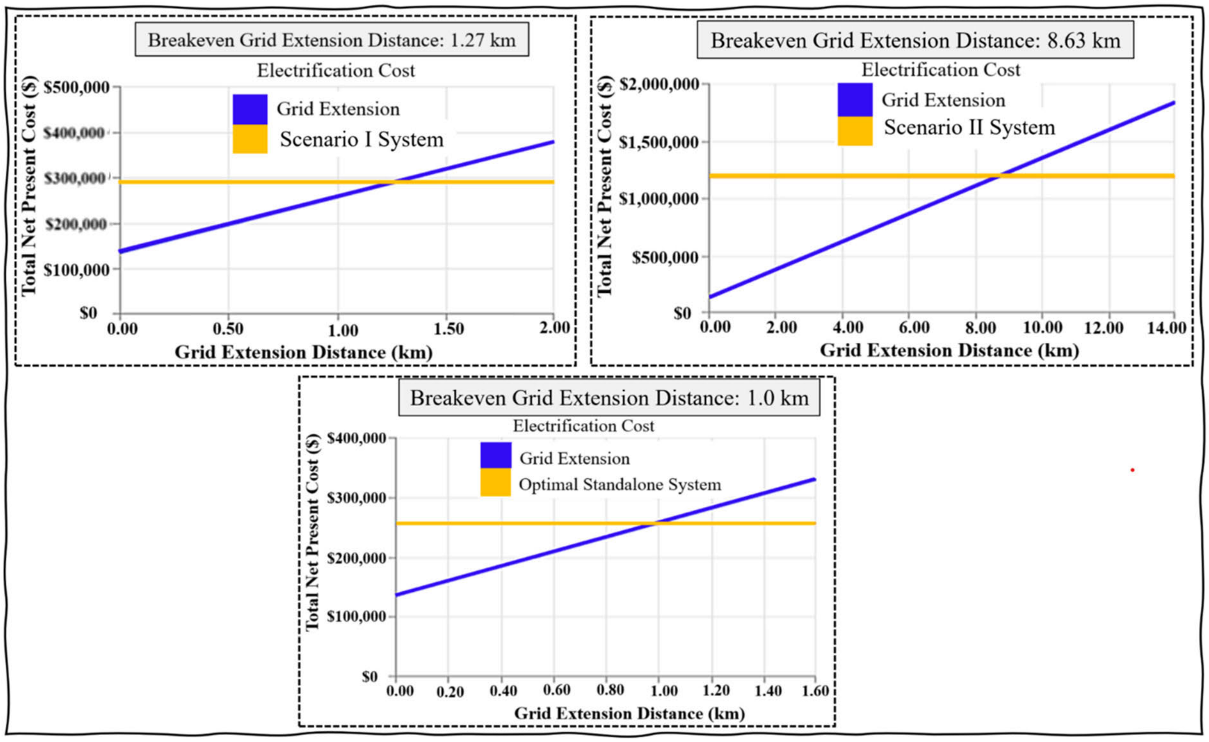


FIGURE 20. Breakeven grid expansion distance and the NPC variation for each system scenario.

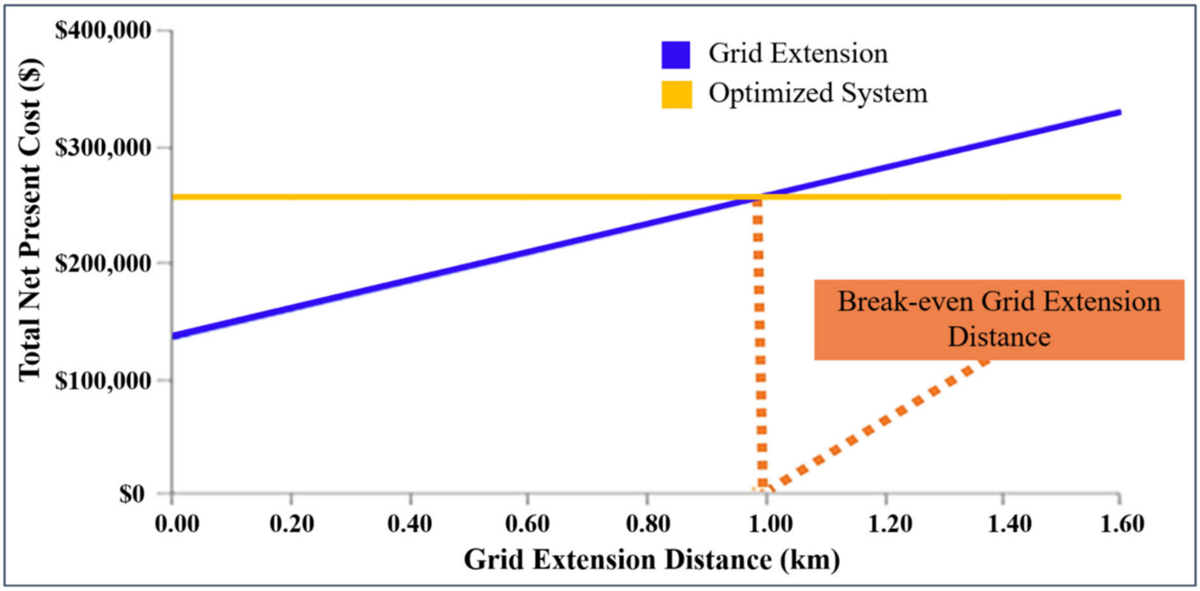


FIGURE 21. Optimal system break-even distance and cost comparison with the grid extension option.

lower (discounted by about $50,000) than that of the nominal cash flow for the same year.

Furthermore, the PV has a Levelized cost of $0.0313/kWh, while the storage wear cost is about $0.128/kWh. The wear cost of the storage device is more than that of the PV panel, which gives an insight into why some users prefer the policy of reducing the number of batteries and introducing more RE generators, although such a policy can give rise to a considerable waste of electricity. Economically, the slightly high NPC and COE values of Scenario I (the PV/wind/battery system) prevented this scenario from being viable over scenario III (the optimal scenario). In fact, the optimal system model offers insight into the economic viability of a stand-alone HCS model for EVCS in SA.

IX. COMPARATIVE ASSESSMENT OF THE PROPOSED SYSTEM

A. COMPARISON WITH A GRID CONNECTION OPTION

It is essential to analyze the EVCS electrification option (grid connectivity) through economic feasibility analysis to ascertain the cost-benefit and the distance limit of the proposed stand-alone system configuration concerning the grid connection. The design and cost-benefit of renewable energy-based stand-alone systems are often suggested in the literature to minimize the pressure on the grid network due to many EVCS connections, which can negatively influence the power quality and stability of the electric distribution network. The break-even grid extension distance is computed in the planned site to determine the maximum permissible network distance, a stand-alone electric vehicle charging station would be more viable. Besides, this distance serves as a deciding factor on whether to go for the off-grid or the grid-connectivity option based on the economic outcomes. The outcomes of the grid extension (GE) analysis conducted using the HOMER Pro® software for the different system configurations assessed in this study are presented in Table 7. The grid expansion break-even distances (points where the NPC of the grid-tied system equals that of the stand-alone power system for each scenario) are indicated for each system design scenario in Fig. 20.

Furthermore, since there are transportation companies around the selected EVCS location within 30 km of a network supply, a break-even distance of 40 km is considered the threshold for utility network expansions. The solar-wind-battery and wind-battery systems are good options for grid network expansion. However, from an economic viewpoint, the optimal system configuration (solar/battery system) is the most reasonable alternative to utility grid extension, having a small break-even grid extension distance (Table 7). The break-even distance of the optimal system configuration and cost comparison with the grid extension is illustrated in Fig. 21. The point of intersection of the grid extension and the stand-alone NPC lines depicts the break-even distance. The EVCS stand-alone electrification option is more economically viable for distances longer than this break-even distance. The proposed optimal stand-alone system option is economically preferable, provided the distance between the planned EV charging station site and the utility network is greater than or equal to the break-even distance. But if the distance is less, then the grid connectivity alternative is more realistic and is preferred. Moreover, as per the vast deposit of gas and oil reserves in SA, most of the total grid electricity supply is produced from burning conventional energy resources. Therefore, the optimal stand-alone RE-based system would be a more environmentally feasible option for grid extension.

Furthermore, additional economic evaluation parameters such as payback period (PBP), return on investment (ROI), internal rate of return (IRR), and profitability index (PI) were analyzed as comparative financial analysis metrics for the off-grid and grid-connected comparison assessment. These economic metrics of the off-grid and grid-tied EVCS are presented in Table 8. The EVs and their charging stations in Saudi Arabia are still in their early stages of development as a comprehensive scheme for the large-scale adoption of EV and EVCS infrastructures is still rolling out. Although, a regulatory framework for the charging of EVs was approved in 2020. The EV charging selling cost has not been announced yet. In this analysis, the electric vehicle charging selling price is assumed and taken as \$0.048/kWh based on the figures presented in [89]. According to Saudi Electricity Company (SEC), the grid electricity tariff is \$0.08 per kilowatt-hour. The payback period is essential for selecting the project. It is used to calculate the needed time for an investment's cash inflows to become the same as cash outflows. The investment return evaluation regarding the yearly cash flow summary and the PBP are computed for both the stand-alone and the grid-connected options. The economic investigation outcome reveals that the payback period of the stand-alone solar-based EV charging station system is 10.66 years. In comparison, that of the grid-connected EVCS was obtained as 12.51 years.

The IRR and the ROI of the stand-alone EV charging station are found to be 7.4% and 4.9%, respectively. The grid-connected system's IRR and ROI are calculated as 6.1% and 3.9%, respectively. For the stand-alone EVCS system, the IRR value is higher, which reveals that the system is preferable financially and is expected to produce more favorable returns. Lastly, the PI is utilized to determine the viability analysis of the proposed EVCS. The results indicate that the profitability index of the off-grid EVCS is greater than 1, showing that the system is a viable and cost-effective one. By contrast, the calculated PI for the grid-tied EVCS is 0.80, which negates the viability of such a system.

B. COMPARATIVE ANALYSIS WITH OTHER EVCS SYSTEMS

The results obtained for the proposed stand-alone EVCS system were further compared with those of other EVCS systems that have appeared recently in the open literature. The locations, optimal configurations, and economical details for these systems are presented in Table 9. It is observed that the COE ranges between \$0.064/kWh and \$0.90/kWh, and the NPC varies between \$21,034 and \$6,958,162. It is evident from the comparative information that the proposed stand-alone EVCS system presented competitive values for both the COE and NPC, which indicates that the stand-alone EVCS project is economically in line with other previous studies concerning the design and optimization of electric vehicle charging stations. It can, therefore, be established that the optimal stand-alone EVCS project is a feasible alternative for the power supply of EVCS.

X. CONCLUSION, LIMITATION, AND FUTURE WORK

A. CONCLUSION

The adoption of EVs worldwide in dramatically increasing numbers strives to support the decarbonization of the

TABLE 9. Comparison of the optimized stand-alone EVCS with other previously studied EVCS designs.

Optimal system	Country	NPC	COE	Refs
PV/Biogas Gen/Battery	Bangladesh	$56,202	$0.1302/kWh	[48]
Diesel/PV/Battery	Canada	$0.835/0.945 M	$0.551/0.625/kWh	[19]
PV/Grid/battery	Vietnam	$97,227-113,785	$0.08-0.102/kWh	[49]
PV/Wind-based	India	$303,291.26	$0.072/kWh	[51]
Wind/CPV/FC/Bio-Gen/Bat.	Qatar	$2.53 M-$2.92 M	$0.285-$0.329/kWh	[43]
Wind/PV/battery	Turkey	$697,704	$0.064/kWh	[20]
PV/Battery	Romania	$ 135,524	$ 0.9//kWh	[59]
PV-based	China	$3,579,236	$0.098/kWh	[45]
PV-based	Bulgaria	$ 21,034	$0.111/kWh	[60]
PV/Wind/battery	China	$831,540	$0.294/kWh	[58]
PV/Wind/Fuel cell/battery	Delhi, India	$ 1,519,040	$0.264/kWh	[57]
PV/WT/Battery	Nigeria	$547,717	$0.211/kWh	[50]
PV/DG/ZnBr battery	Ethiopia	$2.7M-$3.0M	$0.18-0.2/kWh	[55]
PV/WT/Batteries/Grid	UAE	$1,513,066	$0.06743/kWh	[54]
V2G&RE-Integration	Brazil	$6,958,162	$0.12/kWh	[44]
PV/Battery	**Saudi Arabia**	**$ 255,997**	**$0.152/kWh**	**the present study**

environment and has started to constitute a new electric power demand for the utility grid network. The increasing trends for EV utilization and development in SA despite the existence of too few charging stations show the country still needs efficient, cost-effective, and eco-friendly alternatives for the power supply of EVCS. The bulk number of EV charging stations connected to the electricity distribution network can negatively influence the quality and reliability of the utility network's electric power supply. Therefore, we studied the techno-economic viability and the environmental benefits of a solar PV-wind-battery hybrid power configuration model for providing off-grid electrification to an EV charging station. Specifically, we utilized the HOMER Pro® software to investigate one such station, located in Al-Shumaisy, Saudi Arabia, and to model the hourly performance of each subunit of this station to ensure the optimal possible matching between the EV energy demand and supply. Different system design models are simulated to find the system configuration that meets the technical constraints and satisfies the EV charging demand at a low life-cycle cost. Three constraint-satisfying hybrid charging system models were designed and investigated to obtain the optimum technical and economic feasibility system. The optimized solution among these three models is based on the HCS model with the lowest NPC and COE values. The optimum stand-alone HCS is compared with the grid expansion option in terms of economic criteria factors and economic distance limit. The cost of laying a transmission line from an electrical distribution network point to the planned EVCS site, grid power purchase price, and the operation and maintenance cost were considered while the economical parameters of a grid connectivity option were computed. The following main results were obtained from the investigation carried out in the present study.

- The optimal hybrid charging station model comprises 116 kW of a photovoltaic system, a 59 kW inverter capacity, and a nominal battery capacity of 663 kWh.
- The hybrid energy system configuration produces yearly electricity of 191,221 kWh.
- The hybrid EVCS system operates for 15 h a day with a daily electric power production to charge at least 10 EVs.
- The PV panel supplies 100% of the energy generated at the selected EVCS location.
- The NPC and the Levelized COE of the optimized HCS for the planned EVCS site are $255,997 and $0.152/kWh, respectively.
- The break-even grid expansion distance beyond which an off-grid system configuration would be more cost-effective and viable is 1.00 km for the selected EVCS site.
- The payback period of the stand-alone solar-based EV charging station is 10.66 years, while that of the grid-connected EVCS is 12.51 years.
- The IRR and the ROI of the stand-alone EV charging station are 7.4% and 4.9%, respectively, whereas they are 6.1% and 3.9%, respectively, for the grid-connected EVCS system.
- The profitability index (PI) of the off-grid EVCS is greater than 1, while the calculated PI for the grid-tied EVCS is less than 1, which asserts the viability of the former system and the non-viability of the latter.
- As per the vast deposit of gas and oil reserves in SA, most of the total electricity supply is generated from burning fossil fuels. Therefore, the optimized stand-alone renewable energy-based solution would be more environmentally feasible than a solution based on grid extension.
- The proposed stand-alone system can improve EV users' travel experience while traveling far-distance and out-of-grid trips by providing off-grid energy access to recharge their EVs. The planned location of the proposed EVCS is close to the highway, so it will allow EV customers to recharge on the go quickly and efficiently.

Even though the proposed methodology and sizing analysis are performed for a Saudi Arabian case study, this approach and its outcomes can be implemented in other parts of the world by considering the site's geographical features and meteorological data (wind speed and solar radiation).

B. LIMITATIONS AND FUTURE WORK

The key limitation of the proposed system is the initial investment cost (on the high side) required to set up the proposed standalone renewable-energy-based EVCS. Although, with the recent technological breakthrough in RE technologies (RETs) coupled with other factors, the costs of RE have continued to fall dramatically. Moreover, the latest move by the SA government to increase the share of RE utilization across the country would mean that there will be a lot of structured programs, policies, incentives and initiatives to be implemented to provide direct and indirect support to facilitate RE and EV development. Future study can focus on harnessing other available alternative clean energy resources for sustainable and eco-friendly supply of EV charge demand in addition to evaluating the challenges, socio-economic outlook, opportunities associated with the utilization of EVCS in isolated and out-of-grid locations. The policies, programs, and incentive mechanisms that would support and facilitate the adoption of electric vehicles and its charging infrastructures on a large-scale in the country's transportation sector is another future research direction need that is expected to be extensively study as the country is fast moving towards the decarbonization of the environment and the economy (via the adoption of EVs).

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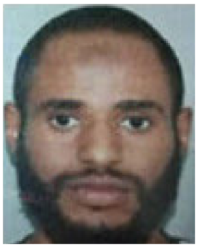

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