

**ASSESSMENT OF SOLAR AND WIND POTENTIALS IN
KINGDOM OF SAUDI ARABIA AND OPTIMIZATION
OF PERTINENT SYSTEMS**

BY

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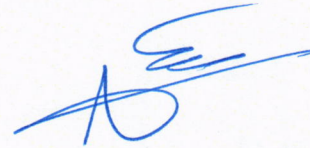
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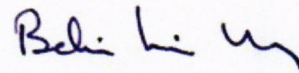
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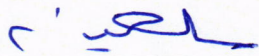
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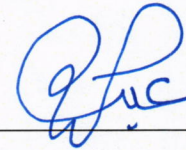
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| *Dedication*

To My Parents ...

To My Brothers and Sisters...

To My Family.... |

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I am thankful to Allah for providing me with the health and ability to carry out my mission.

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LIST OF ABBREVIATIONS

$C_{capital}$	Capital cost of the component (\$).
$C_{replacement}$	Replacement costs of the component (\$).
$C_{o\&m}$	Operation and maintenance costs of the component (\$).
C_{HT_min}	Minimum allowable capacity of the hydrogen tank (kg).
C_{HT_max}	Maximum allowable capacity of the hydrogen tank (kg).
$C_{HT}(t)$	Hydrogen tank capacity (kg).
CI	Coordination index (%).
$CO_{2,annual}$	Total annual CO ₂ emission in (kgCO ₂ /year).
EF_E	Energy emission factor in (kgCO ₂ /kWh).
E_{annual}	Total annual electricity served from fossil fuels (kWh/year).
DOD	Maximum allowable battery depth of discharge (%).
F_{PV}	PV module derating factor (%).

f	Project life (%).
G_{SC}	Solar constant (kW/m ²).
HHV_{H_2}	Higher heating value of hydrogen (kWh/kg).
$H_{loss}(t)$	Loss in hydrogen supply (kg/hr).
I_o	Hourly extraterrestrial radiation (kW).
I_T	Solar radiation on tilted surface (kW).
I_d	Diffused solar radiation (kW).
I_b	Beam solar radiation (kW).
I_{STC}	Solar radiation under standard test conditions (kW/m ²).
IR	Interest rate (%).
K_T	Clearness index.
$LCOE$	Levelized cost of electricity (\$/kWh).
$LCOH$	Levelized cost of hydrogen (\$/kg).
$LHSP$	Loss of hydrogen supply probability.
$LHSP_{required}$	Target value of LHSP.
$\dot{L}_{H_2}$	Hydrogen load (kg/hr).

$LPSP$	Loss of power supply probability.
$LPSP_{required}$	Targeted value of LPSP.
$\dot{m}_{H_2}$	Produced hydrogen flow rate per hour (kg/hr).
n	Day number.
NPC_{tot}	Total net present cost (\$)
$NPC_{component}$	Net present cost of the component (\$).
NPC_{PV}	Net present cost for the PV system (\$).
NPC_{WT}	Net present cost for the wind turbines (\$).
NPC_{conv}	Net present cost for the converter (\$).
NPC_{HT}	Net present cost for the hydrogen storage tank (\$).
NPC_{EZ}	Net present cost for the electrolyzer (\$).
N_{PV}	Number of PV modules.
N_{WT}	Number of wind turbines.
N_B	Number of batteries.
N_{HT}	Number of hydrogen storage tanks.
$P_T(t)$	Total DC generated power at hour (t) (kWh).

$P_{conv}(t)$	Power passed through system inverter to meet the demand (kWh).
$P_{PV}(t)$	PV model generated power at hour (t) (kWh).
$P_W(t)$	Wind turbine output power hour (t) (kWh).
$P_L(t)$	Load demand at hour (t) (kWh).
$P_{conv,rated}$	Rated converter power (kW).
$P_{L,peak}$	Peak load (kWh).
$P_{exc}(t)$	Excess in power production at any hour (kWh).
$P_{loss}(t)$	Loss in power production at any hour (kWh).
R_{PV}	Rated PV module power (kW).
R_b	Geometric factor.
RF	Renewable fraction (%).
SOC_B	Battery state of charge (kWh).
SOC_{Bmin}	Minimum battery state of charge (kWh)..
SOC_{Bmax}	Maximum battery state of charge (kWh).
$SOC_{nominal}$	Battery's nominal capacity (kW).
T_{PV}	Real-time temperature of PV module's cell (°C).

T_{STC} Temperature of PV module's cell at standard test conditions (°C).

T_a Ambient temperature (°C).

T_{NOCT} Nominal operating temperature (°C).

$T_{amb,NOCT}$ Ambient nominal operating temperature (°C).

v Wind speed (m/s).

v_{ci} Cut-in wind speed (m/s).

v_{co} Cut-off wind speed (m/s).

Greek Letters

σ Self-discharging rate of battery (%).

η_{BC} Battery charging efficiency (%).

η_{BD} Battery discharging efficiency (%).

η_{EZ} Electrolyzer efficiency (%).

η_{conv} Converter efficiency (%).

δ Deflection angle (Degrees).

ϕ Latitude angle (Degrees).

β Tilt angle (Degrees).

ω Hour angle (Degrees).

γ Power temperature coefficient (1/°C).

|

ABSTRACT

Full Name : Abdulrahman Salem Mubarak AL-Buraiki

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Major Field : Mechanical Engineering

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Kingdom of Saudi Arabia government has established several projects in line with Vision 2030 to increase the utilization of renewable energy (RE) resources while reducing the environmental impact of oil and gas conventional resources. In the present work, RE systems are considered for electricity and hydrogen productions via hybrid solar and wind systems under local weather conditions. In this case, techno-economic and environmental studies are carried out and MATLAB computer codes are developed to assess the performance of case studies incorporating solar/wind RE systems for different applications. In the first case study, a standalone hybrid PV/wind with battery storage system is developed to meet the electrical load requirements of a residential house

integrated with electric vehicle under different weather conditions at different locations in the Kingdom of Saudi Arabia, namely: Dammam, Riyadh, Jeddah, Buraydah, Tabouk and Sharurah. The results show considerable variations in the optimum system configurations at the considered locations due to different renewable energy potentials. In the second case study, a hybrid solar/wind system is developed for multigeneration of electricity and hydrogen to meet demands of residential house integrated with hydrogen vehicle. In this case study, to assess the performance of the hydrogen production, novel performance indicators are introduced, which include: deficiency in hydrogen supply, and loss of hydrogen supply probability (LHSP). This work is extended to assess the feasibility of introducing hydrogen refueling stations in the Kingdom of Saudi Arabia. As hydrogen refueling demand differs in various areas based on people behaviour, a third case study is conducted in the kingdom to evaluate the effect of people behaviour in various areas on the optimization results of hydrogen refueling station. Refueling data is collected in four areas: Industrial, Residential, Highway and Tourist area. Then, the performance of hydrogen refueling station powered by hybrid solar/wind renewable energy system is simulated via MATLAB software. The findings of this study show that, cheapest investment costs are found in the industrial areas. This effect of people behaviour on the optimization results has led to a novel idea of load coordination with solar potential. Therefore, a fourth case study is conducted to determine how load coordination with solar energy potential influences the system size and cost in off-grid renewable energy systems. A standalone photovoltaics PV array with battery storage system is considered and optimal size of the system is investigated under various types of load requirements with different load coordination levels with the solar energy availability, namely: street lighting, industrial, residential, and irrigation loads. The findings show that, fully coordinated load (irrigation) resulted in a remarkable reduction in the levelized cost of energy, which was reduced by 24%, while the storage system size was reduced by 39%. On the other hand, with no coordination opportunity for the street-lighting load has been identified, thus no reduction has been obtained.

ملخص الرسالة

الاسم الكامل: عبد الرحمن سالم مبارك البريكي

عنوان الرسالة: تقييم إمكانات الطاقة الشمسية وطاقة الرياح في المملكة العربية السعودية ودراسة تحسين الأنظمة ذات الصلة بتطبيقاتها.

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: مايو 2022

أنشأت حكومة المملكة العربية السعودية العديد من المشاريع بما يتماشى مع رؤية 2030 لزيادة استخدام موارد الطاقة المتجددة من أجل تقليل التأثير السلبي على البيئة بسبب استخدام موارد الطاقة التقليدية كالنفط والغاز. في هذه الأطروحة، تم تقديم دراسة جدوى حول إمكانية استخدام أنظمة الطاقة المتجددة الهجينة (الشمسية والرياح) في إنتاج الكهرباء والهيدروجين باستخدام البيانات الميترولوجية (الإشعاع الشمسي وسرعة الرياح) للمملكة العربية السعودية. من أجل ذلك، تم اعتبار عمل الأنظمة الهجينة في تغذية متطلبات الطاقة كأنظمة مستقلة وقائمة بذاتها في تغذية الأحمال بعيدا عن الشبكة الكهربائية ثم تم تطوير أكواد كمبيوتر (MATLAB) لمحاكاة هذه الأنظمة ومن خلال ذلك تم تقييم أداء هذه الأنظمة من تقنيا واقتصاديا وبينيا وذلك باعتبار تطبيقات مختلفة لاستخدام الطاقة في المملكة. في التطبيق الأول، تم تطوير نظام هجين قائم بذاته حيث يتكون من نظام هجين مع اعتبار البطاريات كنظام تخزين لتغذية الأحمال الكهربائية لمنزل سكني مع سيارة كهربائية في مواقع مختلفة في المملكة ذات اختلاف ملحوظ في كمية الإشعاع الشمسي وسرعة الرياح وهي: الدمام ، الرياض ، جدة ، بريدة ، تبوك وشرورة. أظهرت نتائج هذه الدراسة أن هناك اختلافات كبيرة في أحجام النظام الهجين في المواقع المدروسة بسبب اختلاف تلك الأماكن في كمية الإشعاع

الشمسي وسرعة الرياح. ثم في التطبيق الثاني، تم تطوير نظام هجين متعدد الإنتاجية حيث تم في هذه الحالة استخدام الطاقة المنتجة في تلبية متطلبات الطاقة الكهربائية لمنزل سكني ثم تحويل فائض الطاقة الى وقود الهيدروجين الذي يستخدم في توفير الوقود اللزم لسيارة هيدروجينية مرتبطة بالمنزل السكني. بالإضافة إلى ذلك، ولتقييم كفاءة النظام في إنتاج الهيدروجين، تم تطوير مؤشرات أداء جديدة وهي: كمية العجز في إمدادات الهيدروجين (LHS)، و مؤشر احتمالية العجز في إمدادات الهيدروجين (LHSP). امتد هذا العمل لعمل آخر تم فيه دراسة جدوى بناء محطات التزود بوقود الهيدروجين في المملكة العربية السعودية اعتمادا على الأنظمة الهجينة. ونظرًا لاختلاف عمليات التزود بالوقود بحسب اختلاف المناطق التي توجد فيها المحطات بناءً على سلوك الناس في تلك المناطق، تم القيام بدراسة جدوى لتقييم تأثير سلوك الناس في التزود بالوقود في المناطق المختلفة وتأثير ذلك على أحجام النظام الهجين الذي سيزود المحطات بالطاقة اللازمة لإنتاج الهيدروجين. ولأجل ذلك تم جمع بيانات التزود بالوقود في أربع مناطق ذات سلوك مختلف للناس وهذه المناطق تمثل: منطقة صناعية ومنطقة سكنية ومنطقة طرق سريعة ومنطقة سياحية. أظهرت نتائج هذه الدراسة أن أرخص تكاليف الاستثمار في بناء محطات الهيدروجين اعتمادا على الطاقة المتجددة وجدت في المناطق الصناعية وأغلاها في المناطق السياحية. هذا التأثير الكبير لسلوك الناس على أحجام الأنظمة المتجددة حفز إلى دراسة جديدة يتم من خلالها دراسة مواءمة الحمل الكهربائي مع وجود الطاقة الشمسية. لذلك، تم إجراء دراسة أخرى لتقييم تأثير تنسيق الحمل الكهربائي على حجم النظام وتكلفته في الأنظمة الشمسية القائمة بذاتها. ولأجل ذلك تم بناء نظام لإنتاج الطاقة المتجددة يتكون من خلايا الشمسية وبطاريات مع اعتبار أربعة أنواع مختلفة من الأحمال الكهربائية التي تتيح إمكانية مواءمة بين الحمل والإشعاع الشمسي بنسب مختلفة وهي: إنارة الشوارع، والأحمال الصناعية، والأحمال السكنية، وأحمال الري. أظهرت النتائج أن الحمل الذي يتيح فرص تنسيق ومواءمة كاملة (الري) أدى إلى انخفاض كبير ملحوظ في حجم النظام وتكلفته، حيث وجد أنه تم تخفيض التكلفة بنسبة 24%، بينما تم تقليل حجم نظام التخزين بنسبة 39%. وفي الجهة المقابلة، حيث لا توجد فرصة لإمكانية تنسيق الحمل مع الإشعاع الشمسي في حالة إنارة الشوارع، لم يتم الحصول على تخفيض في التكلفة ولا تنقيص للأحجام.

CHAPTER 1

Introduction

The overwhelming reliance on fossil fuels for energy generation in residential, transportation, commercial and industrial sectors has created serious environmental challenges. In response to this crisis, researchers are encouraged to offer sustainable solutions that enhance the exploitation of green energy resources while improving energy production and reducing the environmental impact [1]. Traditionally, efforts have been promoted on utilizing single-source renewable energy (RE) system like solar, wind, geothermal, etc. However, over-sizing issues are encountered due to the random behavior of the RE resources and lack of availability [2]. To overcome these issues, hybrid RE systems can meet energy demand requirements, ensure long period of sustainable production and reduce the negative environmental impacts [3–5]. Hybrid solar and wind RE systems are widely investigated in the literature as it guarantees continuous energy supply because solar system can supply the demand primarily during day hours whereas, at night and cloudy days, wind system can generate enough energy to meet the demand [6]. For off grid systems and in the absence of both solar and wind energies, incorporating energy storage system becomes essential to satisfy the load demand. In this case, battery storage units are coupled with the hybrid solar/wind systems to store part of the excess energy production for later use [7]. However, large amount of excess energy, which can exceed, in some cases, 60% of the total production [8], is often dumped due to the limited size of the battery storage units. In this regard, excess energy is utilized for hydrogen (H_2) production in many recent works [9]. Due to its high specific energy [10], H_2 is a valuable energy carrier and efficient storage medium [11,12]. Although H_2 can be obtained from different resources such

as coal, natural gas and biomass, its production from water by electrolysis method while using electricity produced by RE systems has shown great potential to reduce the environmental impact. Therefore, the incorporation of H₂ production subsystem is possible and offer a good solution to utilize the excess energy via incorporating an electrolyzer to produce green H₂ which can be stored in H₂ tanks for later use [13]

1.1 Literature Review

Numerous techno-economic and environmental studies were conducted to evaluate the feasibility of RE systems for electricity and H₂ production. It is observed that, to ensure efficient performance of the RE systems, optimal sizing is essential to minimize the cost while achieving specific reliability criteria [14]. The system economics were assessed in terms of many economic indicators that account for capital, operation and maintenance (O&M) and replacement costs such as total Net Present Cost (NPC), Annualized Cost (AC), Levelized Cost of Electricity (LCOE), Levelized Cost of Hydrogen (LCOH) [15]. In addition, the reliability assessment ensured that there is always enough supply to meet the demand. Although many indicators were used to perform the reliability assessment, the most commonly used indicator for this purpose is the Loss of Power Supply Probability (LPSP) which represents the unmet load fraction [16]. In this context, Abdin and Mérida [17] conducted a techno-economic analysis in which they investigated power generation and H₂ production from a hybrid solar/wind systems. The results of their study showed that to achieve a high reliable system with zero shortage (LPSP = 0%), the minimum LCOE was found to be 0.50 \$/kWh with LCOH of 17.6 \$/kg.

Moreover, environmental analysis were also included in the optimization to investigate the reduction in CO₂ emission and greenhouse gases [18]. For example, the Das et al. [19] developed a solar/H₂ system to supply energy to village longhouse. The results showed that, a renewable system with LCOE of 0.323 \$/kWh can meet the demand with a power shortage of 2% in the power supply and zero CO₂ emission, whereas a total CO₂ emission of 55,390 kg/year will be produced if a diesel generator is used to meet the demand.

The optimization studies regarding RE systems were conducted for different combinations of RE systems and for different applications. Therefore, in the following subsections, the optimization studies of RE systems that were conducted for electricity and H₂ production will be discussed for buildings electrification and for transportation sector.

1.1.1 Electricity and Hydrogen Productions via Using Renewable Energy System

In the literature, many research works were carried out to identify the outcomes of using standalone RE systems to meet residential electricity demand by accounting for various objective functions such as reducing total net present cost (NPC) and decreasing harmful carbon emissions [20]. For these purposes, some researchers investigated the feasibility of RE system that contains only single RE source. For instance, Tareq et al. [21] optimized a standalone solar system for the electricity demand of Khorfakkan city in United Arab Emirates and Gabra et al. [22] analysed the economic viability of a standalone wind system for rural

electrification goals in Africa. Because the single-source RE system used in both works was influenced by the variable behaviour of the renewable source, a back-up diesel generator was proposed in the optimal configuration. On the other hand, several researchers highlighted the promising advantages of using hybrid RE system for residential electrification. For example, Park and Kwon [23] explored the economic viability of a standalone system comprises of solar/wind developed to satisfy the electricity need of remote island. A hybrid solar/wind system was developed and optimized by Dahyun and Yong Jung [24] for electrification project in remote area in North Korea. In this study, two off-grid hybrid RE systems were evaluated with different types of batteries, then the total net present cost and energy cost were determined for the optimum configuration. Javed et al. [25] developed a mathematical model for off-grid hybrid solar/wind system with two different types of wind turbines and the optimal configuration was proposed to meet the electricity demand of remote island. A techno-economic study was presented by Akinyele [26] to assess the feasibility of developing a standalone hybrid RE system to supply electricity to five houses in a rural location in Nigeria. The study also investigated the increase in electricity demand in the future and evaluated its effect on the system size. The results of this research proved the feasibility of the hybrid RE systems for future electrification in rural areas.

In addition, a third RE source was investigated in other works. Li et al. [27] conducted a study to evaluate the feasibility of RE system comprises of solar/wind/biogas for remote village in West China. In this study, several alternatives of hybrid systems were assessed, and various load demands like residential, commercial, agricultural, and future possible industrial activities were investigated. Das et al. [28] studied the feasibility of a hybrid solar/wind/biogas system with battery storage that was developed to meet the energy demand of remote area in

Bangladesh by considering different load types. Duman and Güler [29] evaluated the feasibility of a standalone hybrid solar/wind/fuel cell system that was proposed to meet the residential electricity demand of second homes that are occupied in summer vacations and compared with the demand of regular occupied homes. The cost of energy was considered as the primary goal of this study, then several hybrid combinations were evaluated. The results of this study showed that the cost of energy was higher in the off-grid system, but it decreases yearly.

Recently, high attention is drawn to applications of H_2 in the RE systems. H_2 can be converted into electricity via fuel cell which works as a backup unit in RE systems to serve electric demands [30]. H_2 -based RE systems were widely used for electrification purposes in remote areas [31,32]. For instance, Kalinic et al. [33] developed a standalone hybrid system comprises of hybrid solar/wind system with H_2 storage for remote island in Turkey. The results of this work confirmed the superiority of using H_2 as a storage option in remote locations. Although, many papers were carried out for off-grid electrification, many research works have studied H_2 -based RE systems for on-grid applications. In this regard, Jahangiri et al. [34] integrated hybrid solar/wind system with electric grid to meet the daily electricity and H_2 demands of 14 kWh and 85 kg/day of a small residential home, respectively. A comparative study between on/off-grid systems was performed by Luta and Raji [35] to evaluate the H_2 -based RE solar/wind systems at remote area in South Africa. In addition, H_2 -based RE systems were also developed to serve non-residential demands. Singh et al. [36] performed a viability study to assess the performance of a standalone solar system to meet the electricity demand of a research building in India. Shabani and Andrews [37] evaluated the feasibility of a standalone hybrid solar/ H_2 system for fire-contingency networks in the southeastern of Australia. Moreover, H_2 -

based RE systems were also developed to serve other energy demands such as: auditorium of police station [38], hospital [39], small shopping center [40] and industrial park's demand [41].

1.1.2 Renewable Energy Utilization in the Transportation Sector

The increased number of automobiles on road has created severe environmental impacts due to CO₂ emissions generated by combustion of hydrocarbons. Nowadays, fossil fuels still meet about 94 % of vehicle's demand which makes transportation sector responsible for 24 % of total CO₂ emissions [42,43]. Furthermore, the rapid depletion of fossil fuels is another crucial issue threatens the transportation sector and necessitates replacing fossil fuels with a clean and sustainable fuel [44,45]. This led to a considerable transition towards harnessing green energy in the transportation and motivated the emergence of electric vehicle (EV). EV contributes significantly to the decarbonization of the transport sector since it operates on electricity and generates zero harmful gases. In addition, due to its high energy density, abundant availability on the planet and its oxidation does not emit CO₂ emissions, hydrogen is recognized as a promising transportation fuel that offers clean, reliable, safe, convenient, customer friendly, and affordable energy. Such characteristics make hydrogen an attractive alternative to fossil fuels for automotive industry [46–48].

Based on the United Nations Climate Change Conference (COP21) agreement which was conducted in Paris in 2015, many countries have declared laws regarding the ban of conventional vehicles utilization and have encouraged the transition to decarbonizing the transportation sector [49]. For instance, Denmark government has announced to stop the sales

of gasoline and diesel vehicles and planned to have one million zero-emission vehicles on road by 2030 whereas France and United Kingdom also have announced to stop sales of gasoline and diesel vehicles by 2040 [50]. China has planned to ban the production and sales of fossil fuel vehicles in the near future and to increase the penetration of the green mobility.

Moving away from internal combustion engine vehicles (ICEVs) production, vehicle manufacturers have intended to shift to the production of new and more environmental friendly vehicles [51]. In the last few decades, the green mobility technology has shown rapid growth accompanied with the emergence of Hybrid Electric Vehicle (HEV) which is driven by both electric motor and internal combustion engine. Although HEV can contribute to the reduction of environmental impact, it is not a zero-emission vehicle as it still uses internal combustion engine [52]. Battery electric vehicle (BEV) is another electric vehicle technology that is driven by solely electric motor supported by on-board battery, has been utilized widely as a zero-emission vehicle that can reduce CO₂ emissions dramatically [53,54]. Due to the limited electrical energy storage, BEV faces several limitations like battery degradation issues, low battery capacity, long recharging time, limited driving ranges, and high costs [55]. Alternatively, Fuel Cell electric Vehicle (FCEV), a new type of zero-emission electric vehicles, has attracted researchers and scientists attention [56]. FCEV is driven by electric motors supplied with electric power via on-board fuel cell that converts hydrogen fuel into electricity and generates zero-emissions at the tail-pipe [57]. FCEV has shown superiority over BEV because it mitigates the limitations of electrical energy storage faced in BEV. To explain, FCEV can provide similar utilization experience to ICEV as it can give higher driving ranges, lower refueling time and long term storage without degradation issues when compared to BEV [45]. Although first attempts to produce FCEV were early in 1960s [52], the commercial

FCEVs were produced in 2014 onwards by major cars manufacturer companies: Toyota, Hyundai and Honda [45,51,58]. In the last few years, considerable penetration of FCEVs in the market has been recorded. The sales of FCEVs in the light duty vehicle fleets are not expected to exceed 2 % of the annual vehicle sales in 2030. However, it is expected to jump to 10 % and 20 % by 2040 and 2050, respectively [59]. Although FCEVs are still in their early stages, FCEV will be cheaper, have longer range, higher preference status and estimated to become feasible in two coming decades and the years of 2025-2035 appear to be the years for FCEVs [60,61].

For more effective solutions to reduce the transportation sector dependence on fossil fuels, hybrid RE systems are recommended to be used in EV charging process [62]. In this context, several research papers were carried out to investigate the feasibility of employing renewable EV charging stations. For example, Ekren et al. [63] developed a methodology to optimize an off-grid hybrid solar/wind charging station to serve EVs in Turkey. Zhang and Cai [64] studied the feasibility of EV charging in a workplace using RE systems. Schetinger et al. [65] performed a techno-economic study to investigate the feasibility of three different EV charging scenarios depending on RE at a university campus. The results of this study confirmed the feasibility of renewable charging stations. With the extended use of EV in the last few years, investigating the feasibility of charging EV at home becomes essential. In this regard, Mazzeo [66] developed a solar system to meet residential electricity demand and EV charging demand. Kong and Sun [67] developed a multi-objective optimization study for home and EV charging demands by considering the minimization of electricity cost. Sadeghi et al. [68] studied the optimal sizing of a hybrid RE system developed to meet residential house demand in the presence of EV.

In addition, Fuel Cell Electric Vehicles (FCEV) is another type of electric vehicle which operate on H_2 fuel. FCEV have gained attention in the last few years as a promising alternative for the transportation because it experiences longer driving range, shorter refueling time and free carbon-emissions than other electric vehicles types [69]. In the literature, several research works were carried out to investigate the optimal size of H_2 refueling stations [70]. In this regard, Micena et al. [71] developed a solar powered H_2 refueling station to provide H_2 fuel for taxi-drivers in Brazil. Siyal et al. [72] developed a wind powered H_2 refueling station in three different cities in Sweden. Murat and Kale [73] assessed the viability of producing H_2 from hybrid solar/wind system to refuel H_2 vehicles in Turkey. In the Following section, the hydrogen refueling infrastructure will be reviewed.

1.1.3 Renewable Energy Systems for Hydrogen Based Transportation

Although fuel cell electric vehicles market is growing, the lack in hydrogen refueling infrastructures is the main obstacle that hinders the transition to hydrogen-based mobility [74–76]. An early hydrogen refueling station was built in California in January 2003 [77]. By 2013, a total of 58 hydrogen refueling stations were available in United States including private stations. However, the majority of these hydrogen refueling stations were developed to assist related research projects and to accelerate FCEV market. At the end of 2021 (Fig. 1.1), more than 680 hydrogen refueling station were in-operation worldwide with the majority of them are in the European Union [78].

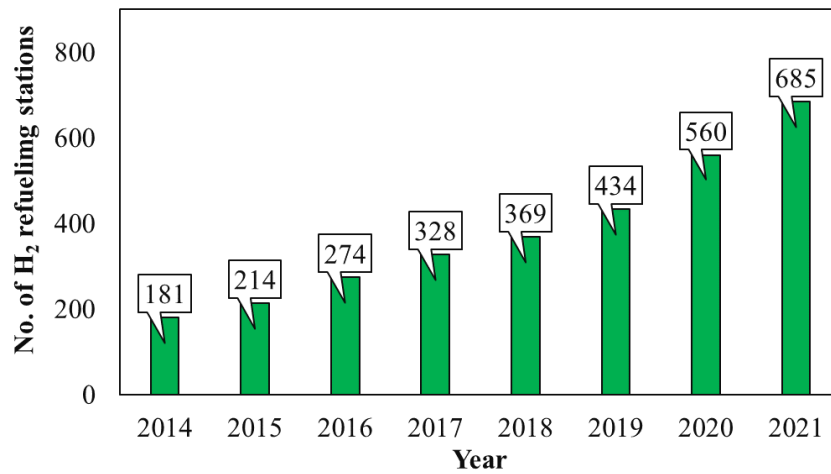


Figure 1.1 Development of H₂ refueling stations worldwide, adapted from [78].

Hydrogen infrastructure as defined by Apostolou and Xydis [51] is a supply chain that includes hydrogen production, storage, transportation and delivery to FCEV owners. Hence, hydrogen refueling station is mainly composed of the following components:

1. **Hydrogen production unit:** Currently, hydrogen is produced via various methods. However, about 96 % of the produced hydrogen is obtained from fossil fuels via steam reformation of natural gas (49 %), partial oxidation of liquid hydrocarbons (29 %) and coal gasification (18 %) [79–81]. The hydrogen produced through such processes is called Grey Hydrogen as CO₂ emissions are released during hydrogen production [82,83]. In some processes, released CO₂ emissions are reduced via CO₂ capturing, utilization and storage methods and the produced hydrogen through this process is called: Blue Hydrogen [82,84]. In addition, hydrogen can be produced in a 100 % carbon-free process from renewable energy resources via water electrolysis method and the hydrogen produced via this method is called: Green Hydrogen [82,84]. In hydrogen refueling stations, utilization of green

hydrogen is preferred than grey and blue hydrogen. Three technologies are available to perform water electrolysis: alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEME) and solid oxide electrolysis (SOE) [85].

2. **Hydrogen compression unit:** Hydrogen is produced via water electrolysis at typical pressures up to 5 MPa (50 bar) [86]. FCEVs are equipped with on-board hydrogen tanks that store hydrogen at pressure of 35 MPa or 70 MPa [87]. Therefore, a compression unit is incorporated in the hydrogen refueling station to increase hydrogen pressure to a higher level that is suitable for storage and refueling. Although various types of compressors are available, mechanical compressors are widely utilized in the hydrogen refueling stations such as: reciprocating compressors, linear compressors, diaphragm compressors, and liquid compressors [88].
3. **Hydrogen storage tanks:** Hydrogen storage equipment is one of the most significant components of the hydrogen refueling station as it crucially influences the hydrogen supply capacity. Hydrogen fuel can be stored as a compressed gas, cryogenic liquid, or metal hydride. In the transportation field, compressed gas storage method is more popular as it gives high reliability, acceptable efficiency and affordability [89]. Because hydrogen is stored on-board FCEV's tank at pressure of 35 MPa and 70 MPa, the nominal operating pressures of the hydrogen storage vessels in the hydrogen refueling station are 45 MPa and 87.5 MPa, respectively [85].
4. **Hydrogen dispensing and pre-cooling unit:** Fast refueling of compressed hydrogen raises hydrogen temperature due to the negative Joule-Thompson effect of hydrogen. Temperature increase more than 85 °C will lead to structural failure of vehicle's tank, the hydrogen dispensing system is equipped with a refrigeration unit that reduces hydrogen fuel temperature to a range of - 40 to -33 °C to ensure safely injection during the rapid filling process [90,91]. Then, the dispenser nozzle injects hydrogen fuel into vehicle's tank

with a maximum allowed hydrogen flow rate of 60 g/s and pressure of 35 or 70 MPa [92,93].

1.1.3.1 Classification of hydrogen refueling stations

Hydrogen refueling stations can be classified according to different criteria as shown in Fig. 1.2. To explain, based on the location where the hydrogen production occurs, the hydrogen refueling stations can be categorized into off-site and on-site hydrogen refueling stations [94]. In the case of off-site hydrogen refueling stations, hydrogen fuel is produced in central production units at industrial facilities whereas hydrogen is produced locally in the on-site hydrogen refueling stations [51]. In central production units, hydrogen is often produced in gaseous form at low pressures of 3 MPa. Then, it is delivered either through trucks or pipeline system. In the truck delivery scenario, the gaseous hydrogen is compressed to higher pressures of 18-20 MPa and stored in tube trailers which deliver hydrogen fuel to the refueling station site as compressed gas. On the other hand, the produced gaseous hydrogen can be compressed to a pressure of 7 MPa for the pipeline delivery scenario [95]. Alternatively, the produced gaseous hydrogen at industrial facilities can be liquefied at $-253\text{ }^{\circ}\text{C}$ and stored in low temperature and adiabatic vessels and delivered by liquid hydrogen tube trailers to the final destination [96].

According to the hydrogen storage status, hydrogen fuel can be compressed and stored in special storage vessels in gaseous form and dispensed to FCEVs as gaseous hydrogen. The hydrogen refueling stations in this case are called: gaseous hydrogen (CGH_2) stations [88,97]. However, hydrogen fuel can be also stored in liquid storage vessels, and it should be converted into the gaseous form before it is dispensed to vehicles. The hydrogen refueling stations in this case are called: liquid hydrogen (LH_2) stations [88,97]. CGH_2 storage is more appropriate and

recommended for transportation application since it can provide high reliability, acceptable efficiency, affordability and its technical simplicity than other storage methods [89].

In addition, the hydrogen refueling station can be categorized based on its daily hydrogen throughput. In this regard, five classes are defined: Very small, Small, Medium, Large and Very large. For maximum hydrogen throughput of 80 kg/day, the hydrogen refueling station in this case is categorized as very small class. However, for maximum daily hydrogen throughput of 212, 420 and 1000 kg, the hydrogen refueling station class is recognized as small, medium and large, respectively [98]. More than 1000 kg/day, the hydrogen refueling station is recognized as very large [85,99].

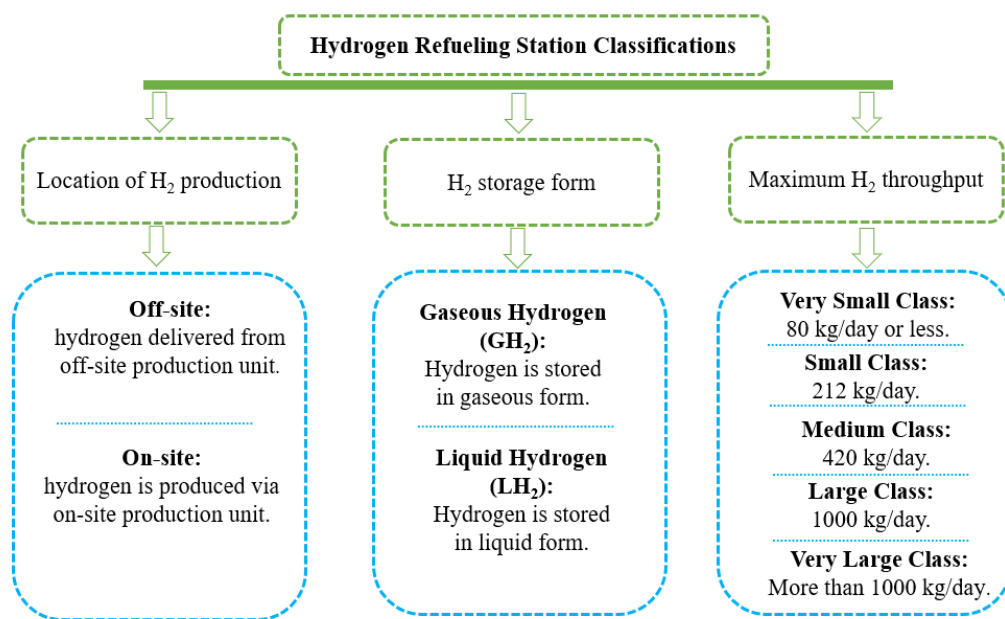


Figure 1.2 Classifications of hydrogen refueling stations

1.1.3.2 Public acceptance

The deployment of hydrogen as alternative fuel in the transportation sector is influenced by both public acceptance and opposition. Although hydrogen is a clean energy carrier, which does not damage environment through CO₂ emissions, public concerns are increased due to the accidents caused by hydrogen leaks [100]. In 2019, hydrogen tank of a hydrogen refuelling station exploded in Norway which created negative perceptions among people to use fuel cell electric vehicles [101]. Unlike public opposition, public acceptance accelerates the implementation of this new technology [102,103]. Public acceptance of hydrogen mobility is affected by several behaviour and psychological factors such as knowledge, and environmental awareness [104]. As addressed by [105,106], educated people are found to support the introduction of hydrogen mobility and individuals with more knowledge and information about hydrogen energy are positive about this technology implementation. In addition, environmental attitudes like concerns about air pollution and climate change are also significant factors behind the public positive support to this technology as reported in [107,108]. Furthermore, easy access to conventional resources made the acceptance to hydrogen technology in transportation very limited. Therefore, the development of regulation and policies to become essential accelerate the deployment of such new technology.

1.1.3.3 Risk assessment

Although hydrogen gas is non-toxic, safe, has low radiation level and less flammable than gasoline, it burns with invisible flame which makes hydrogen leaks more hazardous and requires special care as hydrogen leak can result in dispersion of hydrogen cloud which causes fire and explosion accidents when ignited [87,109]. Therefore, safety measures must be

guaranteed to reduce hazards associated with hydrogen leak accidents in hydrogen refueling stations [110].

Two kinds of community are exposed to risk hazards due to accidents of hydrogen refueling stations: customers inside the station and the nearby residents outside the station [111]. Potential risks to the work place of the station are defined as first party risks while risks to costumers and outside people are defined as second party and third party risks, respectively [111]. Hydrogen leaks from compressors and dispensers are considered main risk contributors to the first party and the second party [111].

Several research works in the literature were conducted to assess the potential risks and damages that might appear due to the implementation of hydrogen refueling stations [109,110,112,113]. For example, Li et al. [114] examined the harm effect distances of severe accidents like physical explosion and fires in gaseous hydrogen refueling stations. Based on the study results, several hazard mitigation measures are proposed. In order to avoid such hazards, the authors of [111] suggested to implement safety measures firstly on compressors and dispensers. Tsunemi et al. [115] assessed the risk inside the hydrogen refueling station and recommended that nearby residents and passersby should keep at least isolation of 6 m from the dispenser nozzle and isolation height of 3 m is fatal to the safety of workers and costumers inside the hydrogen refueling station.

1.1.3.4 Codes and Standards

Like other fuels, hydrogen is safe when its utilization is governed with appropriate standards and regulations [87]. Refueling protocol aims to ensure safe and fast refueling process by defining the rate at which dispenser refills the vehicle's tank, therefore, it provides the essential guidelines and instructions to guarantee process safety [93,94]. Several protocols are developed by the Society of Automotive Engineers (SAE) to ensure safety measures and standards. For example, SAE J2579 is developed to cover the safety requirements of the fuel cell electric vehicles while SAE J2600 is developed to cover the safety requirements of the hydrogen refueling process for all types of vehicles like light-duty vehicles (SAE J2601), heavy-duty vehicles (SAE J2602), Forklift vehicles (SAE J2603), etc [116,117]. As SAE J2601 and SAE J2799 are the most utilized hydrogen refueling standards worldwide, a brief review about each one will be discussed in the next subsections.

- **SAE J2061:**

For safe and publicly trusted hydrogen refueling station, the Society of Automotive Engineers (SAE) established the refueling protocol (J2601) for light duty vehicles to enable safe refueling of 5-7 kg of hydrogen within 3-5 minutes [48,93,118]. SAE J2601 defines process limits, technical specifications and guidelines for the refueling procedure which are developed via mathematical modeling and validated experimentally [48,117]. Fast dispensing raises the temperature of both the hydrogen fuel and the tank liner, therefore, for safe hydrogen refueling without overheating dispensing hose and vehicle's tank, according to SAE J2601, hydrogen must be cooled to a temperature of -40°C to avoid exceeding the operating temperature range, -40 to 85°C , associated with Type IV tanks of equipped in FCEVs to store hydrogen [93,94].

- **SAE J2799:**

It is a protocol developed by Society of Automotive Engineers (SAE) to govern the communication process between fuel cell electric vehicles to the hydrogen refueling stations and it is often used in conjunction with SAE J2601 refueling protocol [119]. It provides the vehicle's tank parameters like pressure and temperature to the station electrical interface. Although this process is optional, it can improve the refueling efficiency and give high state of charge [116,117].

1.1.3.5 Feasibility studies

It has been reported that the construction of hydrogen refueling station requires high investment costs due to the expensive costs of hydrogen technology [120]. Therefore, optimal sizing of renewable powered hydrogen refueling stations for FCEVs have attracted attention over the last decade and it has been addressed by many researchers. Several scientific research studies are summarized in Table 1.1. As can be observed from Table 2, majority of the studies were conducted in Europe. In addition, all hydrogen refueling station classes were included, however, very small class dominated the majority while very few of them considered the very large class. One significant result can be implied from this that that, cost of hydrogen is almost within the range of 3 – 15 \$/kg.

Table 1.1Summary of recent published scientific papers.

Authors	Location	Daily dispensing capacity	Station size class	Power source	Location of hydrogen production	Hydrogen source	LCOH (\$/kg)	Year
Zhao and Brouwer [69]	United States of America	24 kg/week	Very small	Solar/Wind	On-site	Water electrolysis	9.14 (solar-powered plant) 6.71 (wind powered)	2015
Turkdogan [121]	Turkey	1 kg/day (weekday) 1.5 kg/day (weekend day)	Very small	Solar/Wind	On-site	Water electrolysis	6.85	2020
Viktorsson et al. [122]	Belgium	65 kg/day	Very small	Solar/Wind/ Grid	On-site	Water electrolysis	11.36 (10.3 €/kg)	2017
Bansal et al. [123]	Denmark	40 kg/day	Very small	Wind/Grid	On-site	Water electrolysis	NA	2020

Grüger et al. [124]	Germany	53 kg/day	Very small	Wind/Grid	On-site	Water electrolysis	107.02 (97 €/kg) (fleet of 10 FCEVs) 25.37 (23 €/kg) (fleet of 50 FCEVs) 13.24 (12 €/kg) (fleet of 200 FCEVs)	2018
Minutillo et al. [125]	Italy	50, 100 and 200 kg/day	Very small and small	Solar/Grid	On-site	Water electrolysis	10.25 (9.29 €/kg) for system with 50 % grid penetration for capacity of 200 kg/day.	2021
Fragiacomo and Genovese [126]	Three Italian cities:	287 kg/day, 180 kg/day and 22 kg/day	Small and very small	Solar/Wind/geothermal/Grid	On-site	Water electrolysis	7.61-10.87 (6.9-9.85 €/kg.)	2020
Murat and Kale [127]	Turkey	125 kg/day	Small	Solar/Wind	On-site	Water electrolysis	8.92	2018

Murat and Kale [128]	Turkey	125 kg/day	Small	Solar/Wind	On-site	Water electrolysis	7.526	2018
Micena et al. [71]	Brazil	185.4 kg/day	Small	Solar/Grid	On-site	Water electrolysis	8.96	2020
Ayodele et al. [129]	South Africa	125 kg/day	Small	Wind	On-site	Water electrolysis	6.34	2021
Perna et al. [130]	Italy	200 kg/day	Small	NA	On-site	Ammonia cracking.	8.11 (7.35 €/kg)	2020
Barhoumi et al. [131]	Tunis	150 kg/day	Small	Solar	On-site	Water electrolysis	3.66 (3.32 €/kg)	2021
Caponi et al. [132]	5 different European locations: London, Rhooon, Versailles, Pau and Aalborg.	400 kg/day, 200 kg/day, 200 kg/day, 174 kg/day and 100 kg/day.	Medium and small	NA	On-site/ Off-site	Steam methane reformation (Blue hydrogen), water electrolysis (Green Hydrogen).	8.83-9.93 (8-9 €/kg) (off-site) 12.14-13.24 (11-12 €/kg) (on-site)	2021

Di Micco et al. [133]	South of Italy	450 kg/day	Medium	Solar/Grid	On-site	Water Electrolysis (Green Hydrogen)	11.82 (10.71 €/kg)	2022
Perna et al. [134]	Italy	450 kg/day	Large	Solar/Grid	On-site	Ammonia cracking, Biogas reforming and water electrolysis.	8.74 (7.92 €/kg) (electrolysis) 8.00 (7.25 €/kg) (Biogas) 6.93 (6.28 €/kg) (ammonia)	2022
Chen et al. [135]	China	500 kg/day	Large	Solar/Wind/ Grid	On-site/ Off-site	Water electrolysis	NA	2021
Gu et al. [136]	China	500 kg/day	Large	Solar	On-site/ Off-site	Coal gasification and Water electrolysis	NA	2020
Siyal et al. [72]	Sweden	1600 kg/day	Very large	Wind	On-site	Water electrolysis	5.18 \$/kg	2015

1.2 Scope of this Work and Research Gap

Kingdom of Saudi Arabia (KSA) is a large country with approximate area of more than 2 million km² [137]. In addition, KSA is a vigorous state that has recorded, recently, a considerable increase in population, industrialization and economic development. In KSA, energy need is estimated to increase from 3.4 million oil barrels per day (bbl/d) in 2010 to 8.3 million (bbl/d) in 2028 [138]. In addition, this energy demand is met with fossil fuels and the oil consumption is increasing with annual rate of 7% which makes KSA among the biggest five countries in oil consumption worldwide [139]. Consequentially, the CO₂ emission have shown dramatic increase with average annual rate of 5.85% and it is estimated to reach 614.6 million tons of CO₂ in 2019 [140]. In the last few years, KSA government has launched 2030 Vision in which it is aiming to accelerate the sustainable development and to reduce the dependence on fossil fuels. Several projects have been initiated to exploit the renewable resources and to reduce CO₂ emissions by 130 metric tons annually [141,142] such as King Abdullah City for Atomic and Renewable Energy (K.A.CARE) [143] and Saudi Energy Efficiency Centre [144]. In August 2020, KSA has announced the biggest \$5 billion H₂ plant which is powered by 4 GW solar/wind energy and produces 650 tons of green H₂ daily. H₂ production will allow KSA to become less reliant on oil while simultaneously providing a source of revenue from international purchasers [145].

KSA has a massive area enriched with various RE resources that can serve the energy demand. The solar and wind potentials in KSA are shown in Figs. 1.3 and 1.4. Daily solar radiation rates

in the Kingdom are considered as one of the highest solar rates in the world with average daily global radiation on horizontal surface of 5000-7000 Wh/m² (Fig. 1.3). The wind is low in KSA which is almost around 3 m/s in some. However, it can approach 7 m/s in some locations (Fig. 1.4).

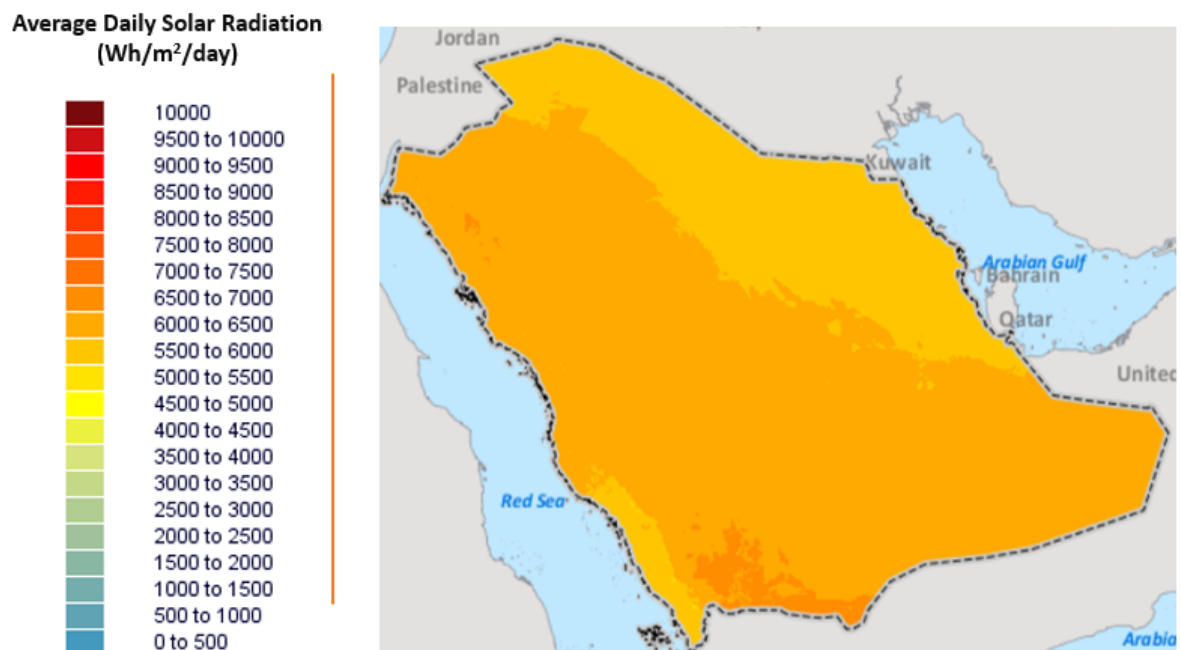


Figure 1.3 Average daily solar radiation in (Wh/m²/day) in KSA[146]

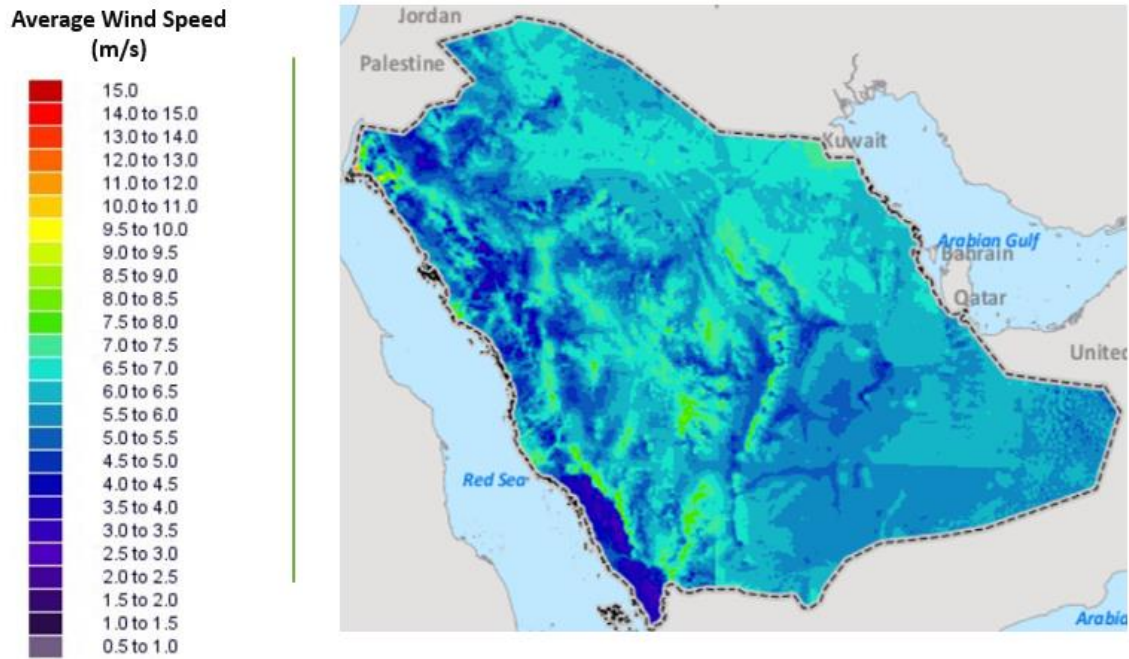


Figure 1.4 Average daily wind speed (m/s) in KSA [146]

The feasibility of RE systems in the KSA were investigated by several studies that conducted in different location among the Kingdom [147–150]. Al Garni et al. [142] developed a multicriteria decision making approach to examine the potentials of RE resources in KSA and found that solar and wind energy are the most favorable options for energy production than biomass and geothermal energy. Ramli et al. [149] explored the viability of a hybrid solar/wind system in the western coast of KSA with the purpose of increasing electricity production and reducing energy cost. The simulation results confirmed that solar system has higher potential than wind system in the studied location. Fathy et al. [151] proposed a hybrid solar/wind/diesel with battery storage system in remote area in the north of KSA. Recent optimization methodology was developed and utilized in this work. The results of this simulation proved the effectiveness of the proposed method in designing hybrid renewable systems. Rehman and El-Amin [152] presented a study to evaluate the potential of serving residential demands by

renewable systems for remote village near Arar in the north of the country. Baseer et al. [153] identified the feasibility of hybrid RE systems with battery storage for three residential compounds in Jubail Industrial City. Ramli et al. [154] utilized a multi-objective optimization method to account for the optimum size of a hybrid solar/wind with battery storage and diesel generator for the city of Yanbu. Hamanah et al. [155] evaluated the optimum size of a hybrid solar/wind system for power generation with the aim of minimizing total annual costs. Alsharafi et al. [156] proposed novel performance criterion to assess the performance of a hybrid system for power generation by considering economic and environmental analysis. In addition, Mokhiemer et al. [157] modelled and optimized a hybrid renewable solar/wind system to meet the demand of a desalination plant under weather conditions of Dhahran city. A brief summary of other published studies in the KSA is summarized in Table 1.2.

Recently, KSA has shown interest to become a leading player in the global hydrogen fuel market. Hydrogen production will allow KSA to become less reliant on oil while simultaneously providing a source of revenue from international purchasers [145]. In August 2020, KSA has announced that it is planning to build the biggest \$5 billion hydrogen plant which will be powered by 4 giga-watt solar/wind energy with daily throughput of 650 tons of green hydrogen fuel. Furthermore, the Saudi government has announced also that it will use a large portion of one of the biggest natural gas projects in the world, Jafurah plant, to produce blue hydrogen from natural gas were the production of blue hydrogen is expected to begin in 2024 [158]. In January 2022, Saudi Aramco has announced that it plans to produce hydrogen driven vehicles in the country to facilitate CO₂ reduction in the transportation sector [159]. In June 2019, Saudi Aramco has inaugurated the first and only hydrogen refueling station in the

KSA with cooperation with Air Products company. The station is developed to supply the hydrogen demand of small fleet of six fuel cell electric vehicles [160].

Taking into account the status of the energy production sector in the Kingdom of Saudi Arabia, the main objective of this thesis is to assess the viability of a system that uses hybrid solar/wind RE resources in the Kingdom of Saudi Arabia with the following specific objectives:

- 1) Assessing the performance of a hybrid solar/wind RE systems for a residential house integrated with electric/hydrogen vehicles.
- 2) Analysis of a hybrid solar/wind RE system for hydrogen refueling stations in different locations with different people behavior
- 3) Analyzing the performance of multigeneration power plants driven by RE systems.
- 4) Optimization of load requirements coordination with solar potential in the Kingdom of Saudi Arabia.

Table 1.2 Published studies on hybrid RE systems in KSA.

Key points: PV: Photovoltaics, WT: Wind turbine, FC: Fuel Cell, DG: Diesel Generator, BSS: Battery storage system, HSS: Hydrogen storage system, PHS: Pumped Hydro Storage, EZ: Electrolyzer, RF: Renewable Fraction, LPSP: Loss of Power Supply Probability, EI: Environmental Impact.				
Ref.	Location in Saudi Arabia	System	Objectives	Note
[153]	Jubail	PV/WT/DG/BSS PV/WT/ BSS	NPC, LCOE	Residential loads
[161]	Al-Sulaymania, Northern of Saudi	PV/Wind/DG/BSS	LCOE, RF, LPSP	Rural Electrification
[152]	Rawdhat Ben Habbas, Northern of Saudi	PV/WT/DG	LCOE, EI	Rural Electrification
[147]	Dhahran	PV/WT/BSS	NPC, LCOE	Residential loads
[157]	Dhahran	PV/WT/BSS	LPSP, LCOE	For reverse osmosis desalination system.

[154]	Yanbu	PV/WT/ DG/BSS	LCOE, RF, LPSP	Three cases studies involving differing house numbers.
[150]	Riyadh, Hafar Albatin, Sharurah, Yanbu	PV/WT/Grid	NPC, LCOE	Residential loads
[162]	Alrais, Western coastal of Saudi	PV/WT/BSS	NPC, LCOE	Electrical demand of mosque
[163]	Rawdhat Ben Habbas, Northern of Saudi	PV/DG/BSS	NPC, LCOE	Rural Electrification
[164]	Abha, Hofuf, Qurayat, Taif, Riyadh	PV/DG/BSS	NPC, LCOE, EI.	Residential loads
[165]	Yanbu	PV/Grid, PV/WT/Grid, PV/WT/EZ/HSS/FC /Grid	Life cycle cost	Residential loads
[155]	Dhahran	PV/WT/DG/BSS	Unmet load, LCOE.	Residential loads.

[166]	Dhahran, Riyadh, Jeddah, Abha and Yanbu.	PV/BSS, WT/BSS, PV/WT/BSS, PV/EZ/HSS/FC, WT/ EZ/HSS/FC, PV/WT/EZ/HSS/FC	LCOE, LCOH, LPSP, RF	Residential loads
[167]	Baha	PV/WT/EZ /FC/HSS/BSS, PV/ EZ/FC/HSS/BSS, WT/EZ/FC/HSS/BSS	NPC, LCOE, LPSP	Electrical demand of university building.
[168]	Sharurah	PV/DG/BSS, WT/DG/BSS, PV/WT/DG/BSS, PV/DG/EZ/FC/HSS, WT/DG/EZ/FC/HSS, PV/WT/DG/EZ/FC/HSS, PV/DG/PHS, WT/DG/PHS, PV/WT/DG/PHS,	NPC, LCOE, RF, Excess electricity, payback period, EI.	Electricity demand of a small community.
[169]	NEOM city	PV/EZ/FC/HSS/BSS, PV/BSS, PV/EZ/FC/HSS	NPC, LCOE	Energy demand of a desalination plant.

[170]	NEOM city	PV/EZ/FC/HSS/BSS	NPC, LCOE	Electricity demand of a small community.
[140]	NEOM city	PV/DG/EZ/HSS/Grid, WT/DG/EZ/HSS/Grid, PV/DG/EZ/HSS/BSS/Grid, WT/DG/EZ/HSS/BSS/Grid, PV/WT/DG/EZ/HSS /Grid, PV/WT/DG/EZ/HSS/BSS/Grid, PV/EZ/HSS/BSS/Grid,WT/EZ/HSS/BSS/Grid, PV/WT/ EZ/HSS/BSS/Grid,	LCOE, LCOH, EI, social impact.	Electricity and hydrogen demand for industrial applications.

CHAPTER 2

Mathematical Modelling

In response to the energy crisis, utilization of renewable energy systems such as solar and wind can mitigate the drawbacks of fossil fuels by meeting energy demand requirements, ensuring long period of sustainable production and reducing the negative environmental impacts. However, power supply fluctuation of renewable energy systems occurs due to random nature of the related weather conditions (solar radiation, wind speed, etc.). In this case, storage units (batteries, hydrogen, etc.) become essential which involved with high cost. To overcome these issues, the hybridization of more than one renewable energy source has recently received high attention. Hybrid solar and wind renewable energy systems are widely investigated in the literature as it guarantees continuous energy supply because solar system can supply the demand primarily during day hours whereas, at night and cloudy days, wind system can generate enough energy to meet the demand.

In this chapter, mathematical models govern the performance of hybrid renewable energy systems will be developed in section 2.1. In addition, performance and optimization criterions will be developed in section 2.2

2.1 Modelling Hybrid Renewable Energy System's Components

In this section, a detailed mathematical modelling of hybrid solar/wind system will be discussed. The studied hybrid renewable energy system in this work consists of power supply sources (solar photovoltaics and wind turbines), energy storage (battery storage, hydrogen storage), converters and hydrogen production units (electrolyzer). To predict the performance of such renewable energy system, the performance of each component needs to be modelled separately [171].

2.1.1 Solar Photovoltaics

The solar photovoltaics (PV) module performance is mathematically predicted by estimating the incident solar radiation on tilted surface, then, the PV output power is found. The incident solar radiation on tilted solar module can be calculated by the model proposed by Duffie and Beckmann [172]. This model requires defining several essential variables: latitude angle (ϕ) of the geographical location, tilt angle (β) of the PV panel, day number (n) and hours (h_1) and (h_2) between which the solar radiation on tilted surface (I_T) is desired. Then, the solar radiation on tilted surface is estimated in terms of the hourly extraterrestrial solar radiation which is given by:

$$I_o = \frac{12 \times 3600 \times G_{SC}}{\pi} \left(1 + 0.033 \cos \left(\frac{360n}{365} \right) \right) \left[\cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin \phi \sin \delta \right] \quad (2.1)$$

where (G_{SC}) is the solar constant which is equal to 1367 W/m² [172], (δ) is the deflection angle which is given by:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (2.2)$$

(ω_1) and (ω_2) are hour angles which are given by the following two relations:

$$\omega_1 = 15(h_1 - 12) \quad (2.3)$$

$$\omega_2 = 15(h_2 - 12) \quad (2.4)$$

After that, the clearness sky index is estimated and used in the calculations of beam, diffuse and ground reflected radiation. Clearness index (K_T) is given by:

$$K_T = \frac{I}{I_o} \quad (2.5)$$

where (I) is the hourly solar radiation on horizontal surface. Then, the hourly diffuse fraction of solar radiation is calculated:

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09K_T & K_T < 0.22 \\ 0.9511 - 0.1604K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 & 0.22 \leq K_T < 0.8 \\ 0.165 & K_T > 0.8 \end{cases} \quad (2.6)$$

where the diffused and beam solar radiations are given, respectively, by:

$$I_d = \frac{I_d}{I} \times I \quad (2.7)$$

$$I_b = I - I_d \quad (2.8)$$

then, the incident solar radiation can be found on the titled surface by:

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + I \rho_g \left(\frac{1 - \cos \beta}{2} \right) \quad (2.9)$$

where (β) is the tilt angle, (ρ_g) is the ground reflectance and (R_b) is the geometric factor which represents the ratio between the beam radiation on tilted surface and horizontal surface as given by:

$$R_b = \frac{\cos(\phi - \beta) \cos \delta \cos \omega + \sin(\phi - \beta) \sin \delta}{\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta} \quad (2.10)$$

Finally, the PV output power is predicted [20,173]:

$$P_{PV} = R_{PV} \times F_{PV} \times \frac{I_T}{I_{STC}} \times (1 + \gamma(T_{PV} - T_{STC})) \quad (2.11)$$

where (R_{PV}) is the PV module rated power, (F_{PV}) is the PV module derating factor, (I_{STC}) is the solar radiation under standard test conditions (1 kW/m^2), (γ) is the PV module temperature coefficient of power ($1/^\circ\text{C}$), (T_{STC}) is the cell temperature at standard test conditions (25°C) and (T_{PV}) is the real-time cell temperature which is given in terms of ambient temperature [20,173]:

$$T_{PV} = T_a + (T_{NOCT} - T_{amb,NOCT}) \times \frac{I_T}{I_{NOCT}} \quad (2.12)$$

where (T_a) is the ambient temperature, (T_{NOCT}) and ($T_{amb,NOCT}$) are reference and ambient temperature at nominal operating conditions, respectively and (I_{NOCT}) is the reference radiation at nominal operating conditions (0.8 kW/m²) [20].

2.1.2 Wind Turbine

Wind turbine converts wind energy into mechanical energy which is, thereafter, converted into electricity through electrical generator. The electricity output of a wind turbine is predicted in terms of wind speed at hub height which is given as:

$$\frac{v_h}{v_o} = \left(\frac{Z_h}{Z_o} \right)^{1/7} \quad (2.13)$$

where the subscript (o) refers to the anemometer height; location where measurements are taken and the subscript (h) refers to the height. Implementing cubic-spline interpolation method, the wind turbine power curve can be expressed as [174,175]:

$$P_W(t) = \begin{cases} 0 & v_h(t) < v_{ci} \\ a_1 v_h^3(t) + b_1 v_h^2(t) + c_1 v_h(t) + d_1 & v_{ci} \leq v_h(t) < v_1 \\ a_2 v_h^3(t) + b_2 v_h^2(t) + c_2 v_h(t) + d_2 & v_1 \leq v_h(t) < v_2 \\ a_3 v_h^3(t) + b_3 v_h^2(t) + c_3 v_h(t) + d_3 & v_2 \leq v_h(t) < v_{co} \\ 0 & v_h(t) > v_{co} \end{cases} \quad (2.14)$$

where $P_W(t)$ is the hourly electricity output of the wind turbine, (v_h) is the wind speed at hub height, (v_{ci}) is the wind turbine cut-in wind speed and (v_{co}) is the cut-off wind speed.

2.1.3 Converter

Power converters are required to adapt DC power into AC form to meet the AC load which can be represented in terms of converter efficiency [176] as given by:

$$P_{conv}(t) = \frac{P_L(t)}{\eta_{conv}} \quad (2.15)$$

where $P_{conv}(t)$ is the power passed through converter at hour (t) to meet demand, $P_L(t)$ is the load demand at hour (t) and (η_{conv}) is the converter efficiency. Converter size is calculated in terms of peak load as given by [177]:

$$P_{conv,rated} = \frac{P_{L,peak}}{\eta_{conv}} \quad (2.16)$$

where ($P_{conv,rated}$) is the converter's rated power and ($P_{L,peak}$) is the peak load.

2.1.4 Battery Storage

In the developed hybrid solar/wind system, the total hourly output power is a combination of PV and wind power:

$$P_T(t) = P_{PV}(t) + P_W(t) \quad (2.17)$$

where $P_T(t)$ is the total generated power at hour (t), $P_{PV}(t)$ and $P_W(t)$ are the hourly PV and wind turbine output power, respectively. The battery is charging when the total renewable production at any hour (t) is more than demand at that hour and the battery state of charge is given by [174,178]:

$$SOC_B(t) = SOC_B(t-1)(1-\sigma) + (P_T(t) - P_{conv}(t))\eta_{BC} \quad (2.18)$$

where $SOC_B(t)$ is the battery's state of charge, (σ) is the battery's self-discharging rate, and (η_{BC}) is the battery charging efficiency. However, when the produced energy by the renewable system is not sufficient to cover the demand, the battery is discharging at that hour according to the following relation [174,178]:

$$SOC_B(t) = SOC_B(t-1)(1-\sigma) - (P_{conv}(t) - P_T(t))\eta_{BD} \quad (2.19)$$

where (η_{BD}) represents the battery discharging efficiency. In addition, the battery charging and discharging hourly states are always kept between the following constraints:

$$SOC_{B_{min}} \leq SOC_B(t) \leq SOC_{B_{max}} \quad (2.20)$$

where $(SOC_{B_{min}})$ is the minimum allowable state of charge of the battery which is given as function of the battery nominal capacity $(SOC_{nominal})$ as given by:

$$SOC_{B_{min}} = DOD \times SOC_{nominal} \quad (2.21)$$

where (DOD) is the depth of discharge of the battery which is in the range of 30-50% [179].

In addition, the maximum allowable state of battery $(SOC_{B_{max}})$ is equal to the nominal capacity $(SOC_{nominal})$ as given by:

$$SOC_{B_{max}} = SOC_{nominal} \quad (2.22)$$

2.1.5 Electrolyzer

The electrolyzer is a device that consumes electrical energy to generate H_2 through some special chemical reactions. Electrolyzers are classified according to electrolyte and operation temperature into different types such as Polymer Electrolyte Membrane (PEM), Alkaline Electrolyzers (AE) and Solid Oxide Electrolyzers (SOE) [180]. To produce H_2 from water, an electric current is passed through water to decompose H_2 from oxygen as expressed by [181]:



Then, the separated H_2 is stored in special storage tanks for later use while the separated oxygen escapes. In this work, the required power to activate the electrolyzer is supplied from the developed hybrid solar/wind system. The mass flow rate of the produced H_2 ($\dot{m}_{H_2}$) is given by [182]:

$$\dot{m}_{H_2} = \frac{\eta_{EZ} P_{EZ}}{HHV_{H_2}} \quad (2.24)$$

where (η_{EZ}) is the electrolyzer efficiency, (HHV_{H_2}) is the higher heating value of H_2 ($HHV_{H_2} = 39.4$ kWh/kg [183]) and (P_{EZ}) is the input electrical power to the electrolyzer.

It can be implied from last formula that 1 kW electrolyzer with efficiency of 74% can generate 0.0187 kg/hr of H₂

2.1.6 Hydrogen Storage

The produced H₂ by electrolyzer is injected into H₂ storage tanks. The H₂ load is always met by the stored H₂ in the H₂ storage tanks. Therefore, the accumulated H₂ in the storage tanks at any hour (t) is equal to the difference between the produced H₂ and the H₂ load according to the following relation [184]:

$$C_{HT}(t) = C_{HT}(t - 1) + \dot{m}_{H_2}(t) - \dot{L}_{H_2}(t) \quad (2.25)$$

where $C_{HT}(t)$ is the H₂ tank capacity at hour (t) and $\dot{L}_{H_2}(t)$ is the H₂ load at hour (t). At any hour during operation time of the system, the H₂ tanks are subjected to following constraints [184]:

$$C_{HT_min} \leq C_{HT}(t) \leq C_{HT_max} \quad (2.26)$$

where (C_{HT_min}) is the minimum allowable capacity of the H₂ tank and (C_{HT_max}) is the maximum allowable limit.

2.2 Optimization Methodologies

The optimization of RE systems is performed by considering various indicators. In this work, criteria related to system reliability, cost and environmental assessments are considered.

2.2.1 System's Reliability

The concept of Loss of Power Supply Probability (LPSP) is often utilized to assess the reliability of RE systems. The LPSP is a probability function defined by a number between 0 and 1. A value of 1 means that the system fails to meet the load (loss of power supply is 100%). However, a value of 0 means that the load is always satisfied (loss of power supply is 0%). The LPSP is expressed by the following relation [6]:

$$LPSP = \frac{\sum_{t=1}^{8760} P_{loss}(t)}{\sum_{t=1}^{8760} P_L(t)} \quad (2.27)$$

where $(\sum_{t=1}^{8760} P_{loss}(t))$ is the summation of hourly power losses for one full year (given as the summation of 8760 hours) and $(\sum_{t=1}^{8760} P_L(t))$ is the summation of the electrical load for one full year. Loss of power supply can be expressed by:

$$P_{loss}(t) = P_L(t)\Delta t - (P_T(t)\Delta t + SOC(t-1) - SOC_{min})\eta_{conv} \quad (2.28)$$

where ($P_{loss}(t)$) is the loss of power supply. To achieve a reliable system, the following constraint should be satisfied:

$$LPSP \leq LPSP_{required} \quad (2.29)$$

where ($LPSP_{required}$) is the targeted value of LPSP and it is specified usually to a value of zero. And the excess energy percentage shows the percentage of excess as given by:

$$EXE = \frac{\sum_{t=1}^{8760} P_{exc}(t)}{\sum_{t=1}^{8760} P_T(t)\Delta t} \quad (2.30)$$

where $P_{exc}(t)$ is the wasted energy at hour (t).

$$P_{exc}(t) = P_T(t)\Delta t - \left(P_{conv}(t)\Delta t + \left(\frac{SOC_{max} - SOC(t-1)}{\eta_{BC}} \right) \right) \quad (2.31)$$

where (Δt) is the time step considered in the calculation (in this paper $\Delta t = 1$ hour). In addition, the Renewable Fraction (RF) is defined in terms of LPSP as given by:

$$RF = 1 - LPSP \quad (2.32)$$

It is also important to evaluate the reliability of H_2 supply. This can be ensured by introducing the Loss of Hydrogen Supply Probability (LHSP) to measure the percentage of unmet H_2 load. LHSP is defined by a number between 0 and 1 to indicate the loss of H_2 supply. To explain, a zero value of LHSP indicates that there are no losses in the H_2 supply and the H_2 load is always satisfied. However, the H_2 load is always unmet when LHSP is one. LHSP can be expressed as following:

$$LHSP = \frac{\sum_{t=1}^{8760} H_{loss}(t)}{\sum_{t=1}^{8760} L_{H_2}(t)} \quad (2.33)$$

where $(\sum_{t=1}^{8760} H_{loss}(t))$ is the summation of the hourly H_2 losses for one full year (given as the summation of 8760 hours) and $(\sum_{t=1}^{8760} L_{H_2}(t))$ is the summation of the hourly H_2 load for one full year. Loss in hydrogen supply is given by:

$$H_{loss}(t) = L_{H_2}(t)\Delta t - (m_{H_2}(t)\Delta t + C_{HT}(t - 1) - C_{HT_min}) \quad (2.34)$$

where $(\dot{L}_{H_2})$ is the hydrogen load in (kg/hr) and $(\dot{m}_{H_2})$ is the mass flow rate of hydrogen produced by electrolyzer in (kg/hr). Therefore, to achieve high reliable H_2 supply system, the following constraint should be always satisfied:

$$LHSP \leq LHSP_{required} \quad (2.35)$$

where $(LHSP_{required})$ is the target value of LHSP which is specified to a value of zero.

2.2.2 System's Economics

The cost of the hybrid system is evaluated by using the total net present cost (NPC) concept [129]. The net present cost is defined by:

$$NPC_{component} = C_{capital} + C_{replacement} + C_{o\&m} \quad (2.36)$$

where $(NPC_{component})$ is the total net present cost of the component, $(C_{capital})$ is the capital costs of the component (which includes the installation costs), $(C_{replacement})$ is the replacement costs of the component and $(C_{o\&m})$ is the operation and maintenance costs of the component.

Levelized cost of electricity (LCOE) is important tool that indicates the cost of one kWh of the produced energy by the developed system. It is defined by [185]:

$$LCOE = \frac{CRF \times NPC_{tot}}{\sum_{t=1}^{8760} P_L(t)} \quad (2.37)$$

where $(\sum_{t=1}^{8760} P_L(t))$ is the summation of hourly electric load for one full year hours (8760 hours) and (CRF) is the capital recovery factor which is defined by [174]:

$$CRF = \frac{IR(1 + IR)^f}{(1 + IR)^f - 1} \quad (2.38)$$

where (IR) is the interest rate and (f) represents the project life. Similarly, levelized cost of H₂ (LCOH) [125,185] is calculated by:

$$LCOH = \frac{CRF \times NPC_{tot}}{\sum_{t=1}^{8760} L_{H_2}(t)} \quad (2.39)$$

where $(\sum_{t=1}^{8760} L_{H_2}(t))$ is the summation of hourly H₂ load for one full year (8760 hours).

2.2.3 Environmental Impact

To investigate the amount of CO₂ production in (kgCO₂/year) that will be avoided if an off-grid RE system is developed to replace conventional energy system, working via utilizing conventional fossil fuels, is calculated by [66]:

$$CO_{2,annual} = EF_E \times E_{annual} \quad (2.40)$$

where $(CO_{2,annual})$ is the total annual CO₂ emission in (kg_{CO2}/year), (EF_E) is the energy emission factor in (kg_{CO2}/kWh) and (E_{annual}) is the total electric load served in (kWh/year) that is met by fossil fuel which is given by:

$$E_{annual} = \sum_{t=1}^{8760} P_L(t) \quad (2.41)$$

where $P_L(t)$ is the electric load at hour (t) .

CHAPTER 3

Hybrid Solar/Wind Systems for Residential House Integrated with Electric and Hydrogen Vehicles

In this chapter, the electricity demand of a residential house in the Kingdom of Saudi Arabia will be covered with a standalone hybrid solar/wind renewable energy system using weather conditions belonging to different locations in the kingdom. In addition, electric vehicle charging demand is also considered as the electric vehicle is assumed to leave home in the morning and return at night. Its daily charging demand is added to the demand of the residential house and the hybrid system is sized to meet all with no deficiency in the power supply. What's more, the electric vehicle is replaced with a hydrogen vehicle and another case study is conducted to size the system. In this case, hydrogen production and storage units are incorporated to the hybrid solar/wind system.

It should be noted that, this work has been published in two research papers:

1. Al-Buraiki, A. S., & Al-Sharafi, A. Technoeconomic analysis and optimization of hybrid solar/wind/battery systems for a standalone house integrated with electric vehicle in Saudi Arabia (2021) *Energy Conversion and Management*, 250, 114899.
2. Al-Buraiki, A. S., & Al-Sharafi, A. Hydrogen Production Via Using Excess Electric Energy of an Off-Grid Hybrid Solar/Wind System Based on a Novel Performance Indicator (2022) *Energy Conversion and Management*, 254, 115270.

3.1 Hybrid Solar/Wind System for Residential House Integrated with Electric Vehicles

In this section, the nocturnal charging of EV in a residential house operated by standalone hybrid PV/wind/battery-storage system will be studied in different locations with different climatic conditions in the Kingdom of Saudi Arabia. The schematic diagram of the studied system is shown in Fig. 3.1

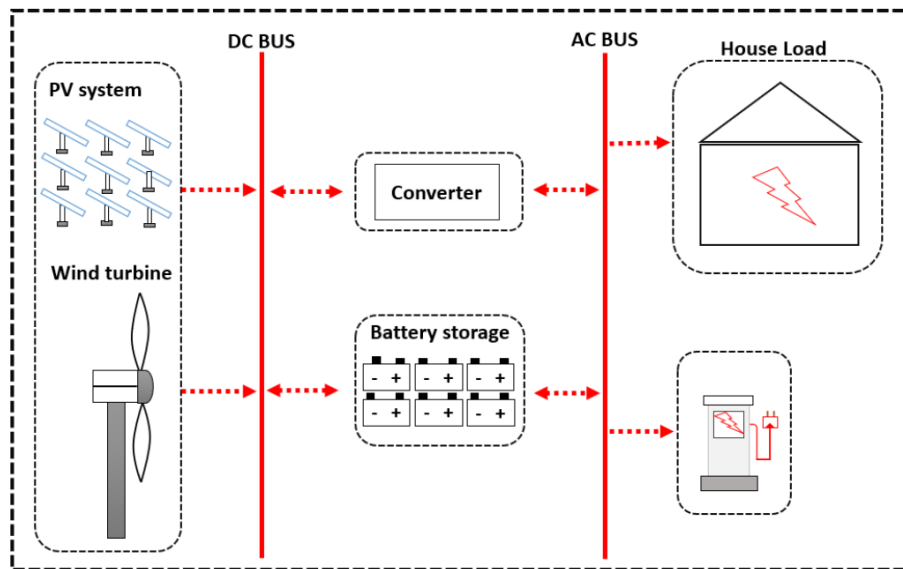


Figure 3.1 Schematic diagram shows the hybrid solar/wind/battery system.

The components of the hybrid renewable energy system are modelled according to the mathematical models described in chapter 3. In addition, Nissan Leaf EV with a 40 kWh

battery [186] is considered to perform the study since it has the highest market share among EV brands [187]. The charging capacity of the EV's battery at hour (t) can be modelled in terms its rated power as [188]:

$$SOC_{EV}(t) = SOC_{EV}(t - 1) + \frac{\eta_{EV}P_{EV}}{C_{EV,battery}} \times 100 \quad (3.1)$$

where $SOC_{EV}(t)$ is the state of charge of the EV's battery at hour (t), η_{EV} is the EV charging efficiency, P_{EV} is the EV charging rate and $C_{EV,battery}$ is the EV's battery capacity. In addition, EV's battery state of charge at each hour (t) is constrained by the following restriction:

$$SOC_{EV,min} \leq SOC_{EV}(t) \leq SOC_{EV,max} \quad (3.2)$$

where $SOC_{EV,min}$ and $SOC_{EV,max}$ are maximum and minimum EV battery allowable state of charge. The required charging hours for the EV to be fully charged is given by the following relation [189]:

$$C_{time} = \frac{EV_{demad}}{P_{EV}} \quad (3.3)$$

where C_{time} is the required charging time in hours and EV_{demad} is the daily EV energy demand in kWh.

3.1.1 System Energy Management

At any hour (t), the total power $P_T(t)$ produced by the hybrid system is given by Eq. (2.17) whereas the demand $P_{conv}(t)$ is calculated by Eq. (2.15). It should be noted that during the presence of the EV, the power demand required by the EV's battery is added to the house electrical demand $P_{conv}(t)$. Then several situations are considered during the operation of the system:

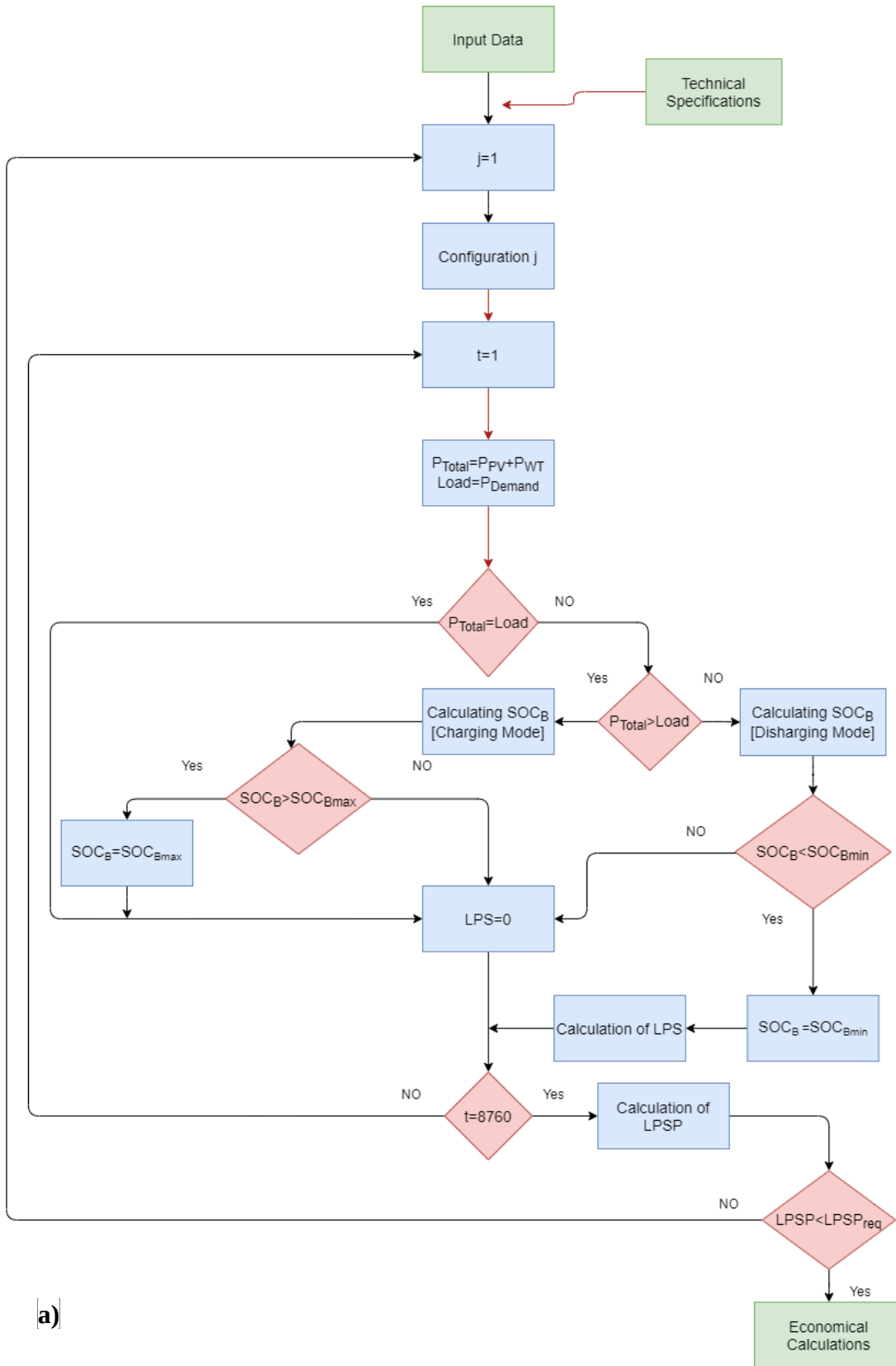
- i. If $P_T(t) > P_{conv}(t)$, two cases will appear:
1st case: when the battery state of charge in the previous hour is less than the maximum state of charge, then, the battery will be in charging mode until it reaches full capacity. After that, the remainder energy available will be considered as an excess energy which is expressed by Eq. (2.31).
2nd case: when the battery state of charge in the previous hour is equal to the maximum state of charge, then, the battery state of charge in this hour will be set to the maximum capacity and the surplus energy will be considered as excess energy according to the Eq. (2.31).
- ii. If $P_T = P_{conv}$ then, the battery state of charge in this hour will be set to previous hour state of charge.
- iii. If $P_T(t) < P_{conv}(t)$, two cases will appear:
1st case: when the battery state of charge in the previous hour is greater than the minimum state of charge, then, the battery will be in discharging mode until its state of

charge reaches the minimum limit, then the loss of power supply is calculated by Eq. (2.28).

2nd case: when the battery state of charge in the previous hour is equal to the minimum state of charge, then, the battery state of charge in this hour will be set to minimum limit and the loss of power supply is calculated by Eq. (2.28).

3.1.2 System Sizing Strategy

Two cases are considered. In the first case, the optimal system size is obtained to meet the electricity demand of a residential house only. In the second case, an EV is added to the house as a deterministic load at night hours (after 17:00) and it is assumed to be out of the house during day hours (08:00 – 17:00). Then, the system is sized and optimized again. In this regard, the loss of power supply probability (LPSP) combined with levelized cost of electricity (LCOE) are utilized to assess the system performance. It is important to note that only one wind turbine of rated power of 3 kW is considered in this study due to space limitations for a single house. The optimization is performed in MATLAB software by increasing the battery number and for each battery number the PV size is varied, therefore, several PV/wind/battery configurations are evaluated. The optimal system then is identified when the required LPSP is guaranteed and the lowest LCOE is achieved. The optimization process is represented in the flowchart shown in Fig. 3.2a and Fig. 3.2b for the first and the second cases, respectively.



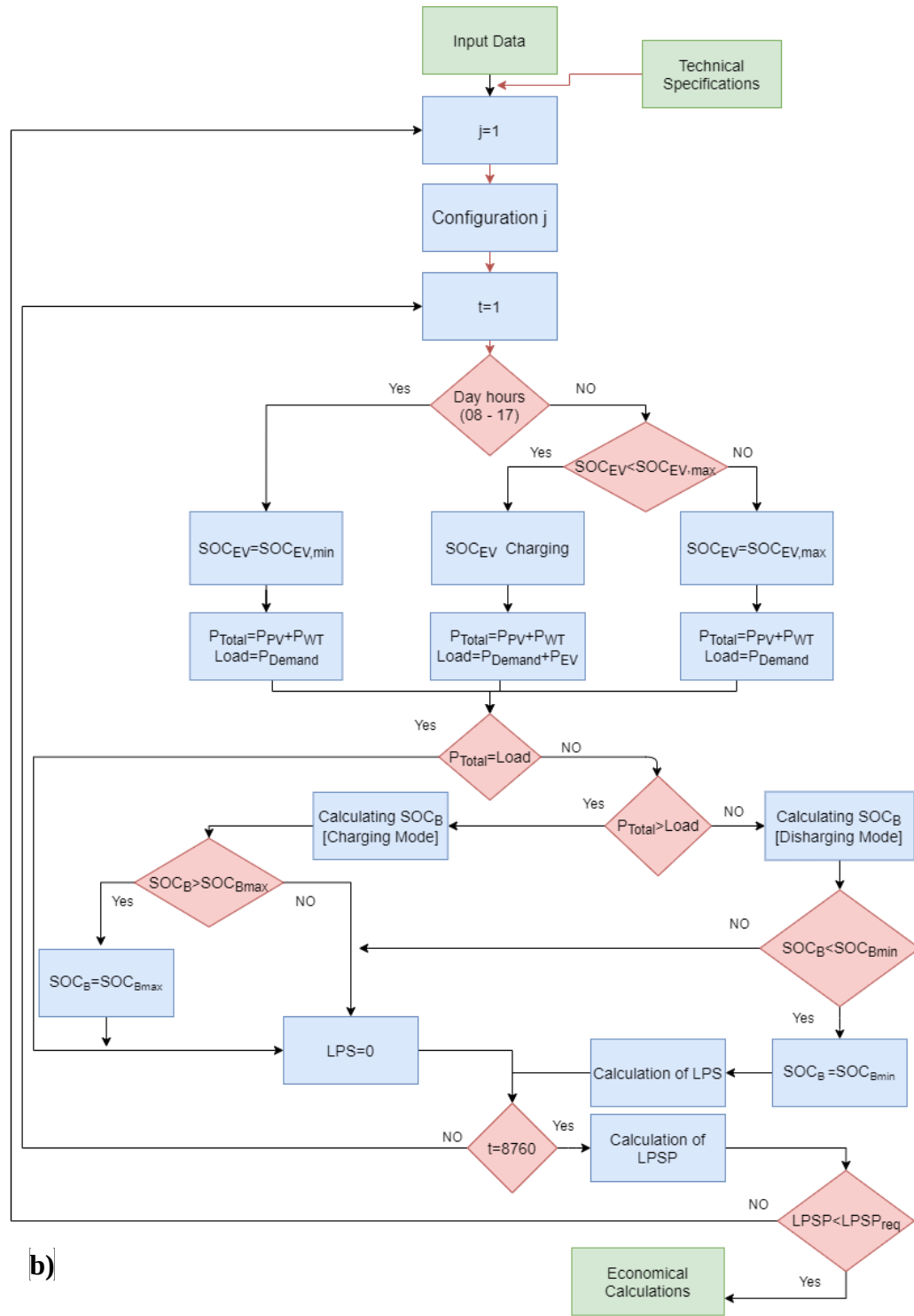


Figure 3.2 Optimization flowcharts for the hybrid PV/wind/battery system simulation a) Case 1: House without electric vehicle and b) Case 2: House with electric vehicle.

3.1.3 System Locations and Load Profile

To investigate the feasibility of proposed hybrid renewable energy systems, six different locations are considered namely: Dammam, Riyadh, Buraydah, Jeddah, Tabouk and Sharurah, as shown in Fig. 3.3. These locations have different climatic conditions and cover large geographical spectrum of the Kingdom of Saudi Arabia. The full year hourly weather data of the selected locations is provided by King Abdullah City for Atomic and Renewable Energy (K.A.CARE) [190].

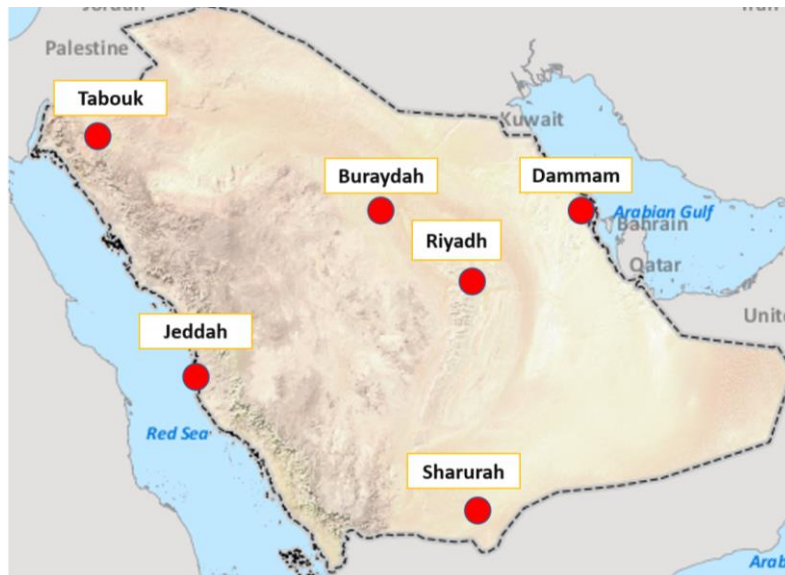


Figure 3.3 Saudi Arabia map illustrating cities under study [190].

To compare the variation in the renewable energy resource potentials of the selected locations, monthly average weather data is plotted in Fig. 3.4a which shows monthly average daily solar radiation. It can be observed that Tabouk (Latitude: 28° 23' N, Longitude: 36° 34' E) has the highest solar radiation with annual average of 6.22 kWh/m²/day while Sharurah (Latitude: 17° 30' N, Longitude: 47° 07' E) has the lowest solar radiation of 5.59 kWh/m²/day. Fig. 3.4b shows the monthly average values of wind speed with significant variation between the selected locations. In this case, Jeddah (Latitude: 21° 31' N, Longitude: 39° 12' E) has the highest wind energy potential with average annual wind speed of 3.79 m/s while Sharurah has the lowest potential in wind speed with average annual wind speed of 2.44 m/s. Fig. 3.4c depicts the variation in temperature in the studied locations. In Jeddah and Sharurah, the temperature variations are the lowest among the six locations with almost flattened temperature profiles during the whole year. Riyadh (Latitude: 24° 39' N, Longitude: 46° 42' E), Buraydah (Latitude: 26° 22' N, Longitude: 43° 57' E), Dammam (Latitude: 26° 23' N, Longitude: 49° 59' E) and Tabouk have considerable variations in the temperature profiles along the whole year.

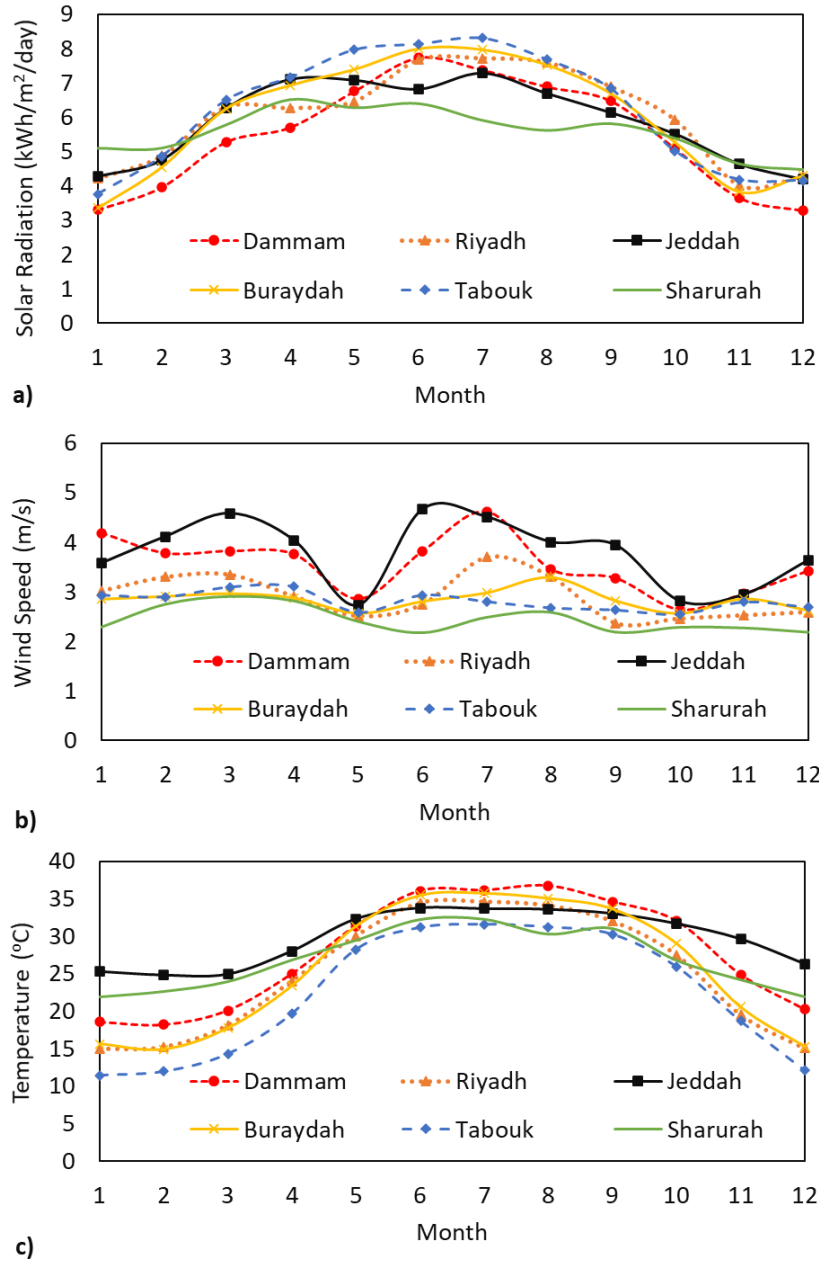


Figure 3.4 Monthly weather data for the selected locations a) Monthly average daily solar radiation, b) Monthly average wind speed and c) monthly average temperature.

It is important to notice that the simulation is performed in hourly basis. Therefore, as an example, the hourly weather data of Dammam city is illustrated in Fig. 3.5 and the

simulation results provided by the developed MATLAB code are presented in detail (section 5.1), then the results for the all locations are presented and compared. Fig. 3.5a, shows high potential in solar radiation which approaches 1000 Wh/m^2 in summer and reaches around 600 Wh/m^2 in winter. Fig. 3.5b represents the hourly wind speed and shows moderate wind potential with annual average wind speed of 3.64 m/s . In addition, Fig. 3.5c shows hourly temperature with an average of 20°C in winter and 40°C in summer.

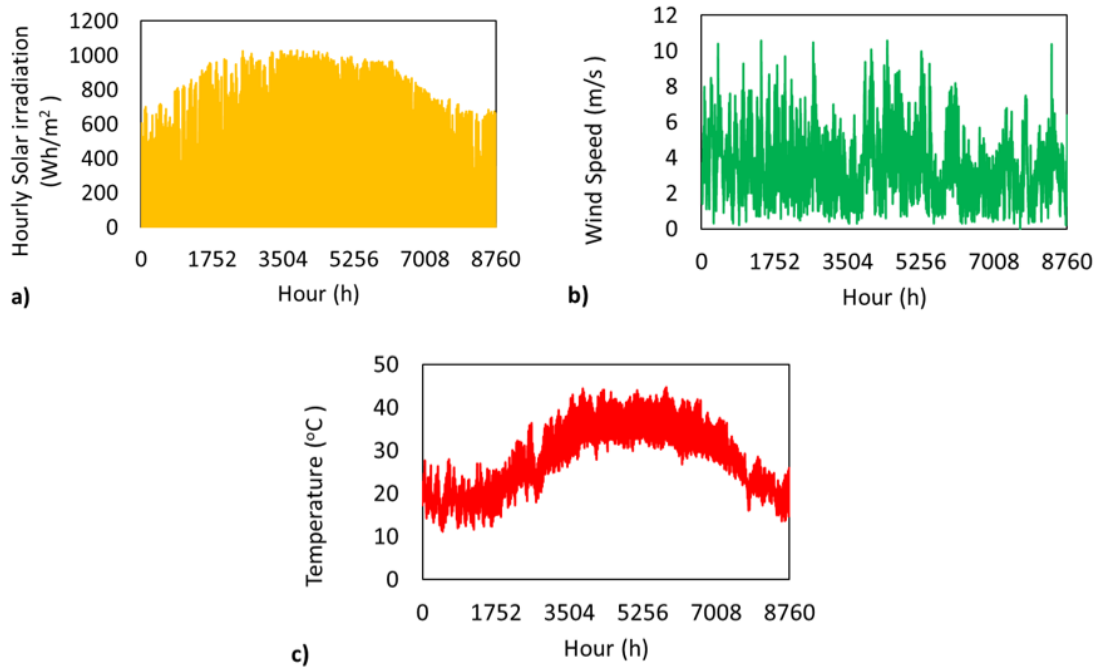


Figure 3.5 Weather data for Dammam (Latitude: $26^\circ 23' \text{ N}$, Longitude: $49^\circ 59' \text{ E}$). a) Hourly solar irradiation on horizontal surface, b) Wind speed at 10 m and c) Temperature.

Due to different levels of electrical energy consumption, monthly load variation influences the optimization results, cost, and system reliability. Therefore, actual monthly electrical

consumption for a typical house in the Kingdom of Saudi Arabia are provided by Saudi Electricity Company [191]. Then, the monthly dynamic load profiles are generated by using System Advisor Model software (SAM) [192] as shown in Fig. 3.6.

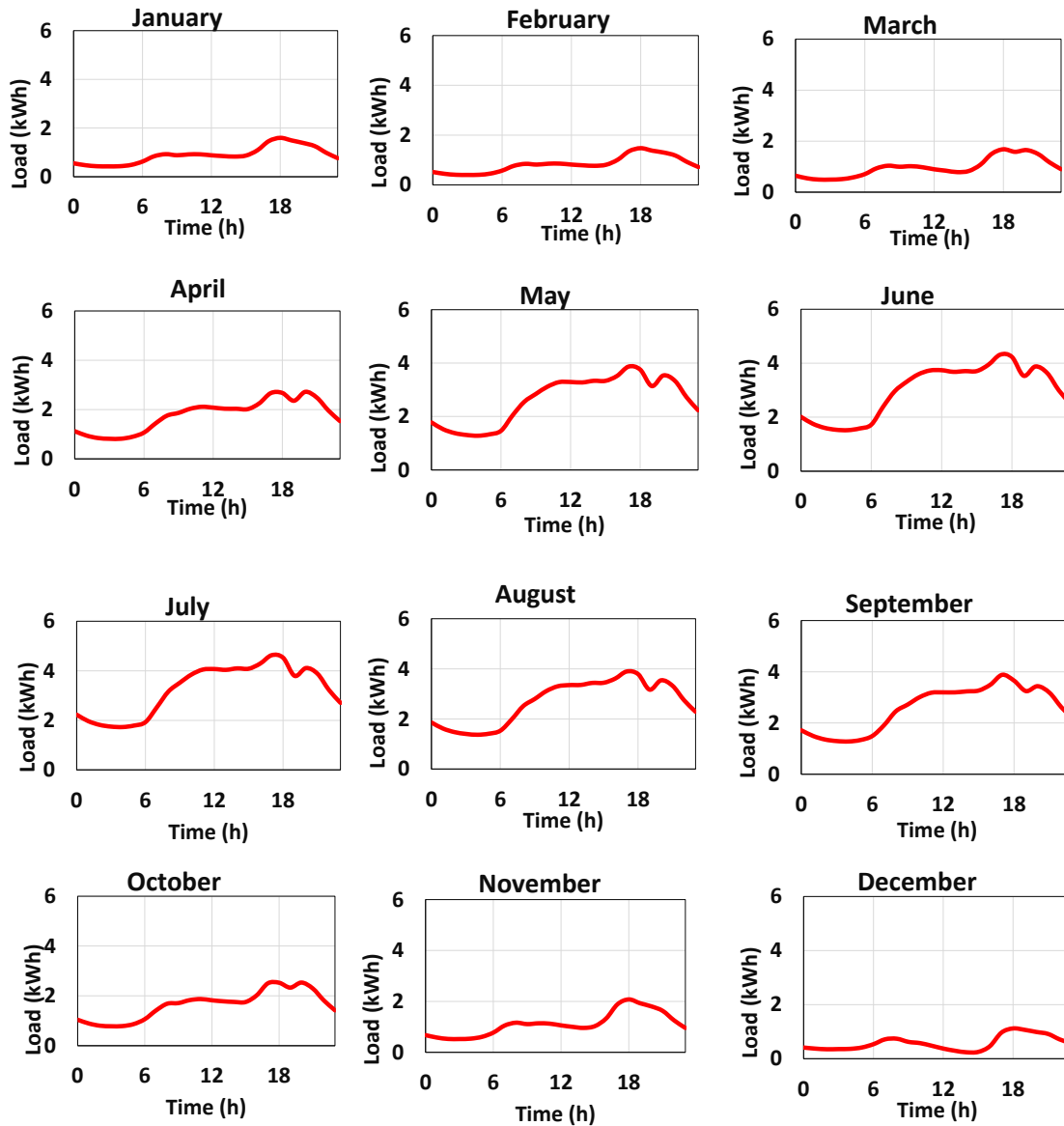


Figure 3.6 Daily load profiles for typical house for each month.

The technical specifications of the system components are provided in Table 5.1 below.

Table 3.1 System's components specifications.

Solar Photovoltaics [193]		
Reference efficiency	18.11	(%)
Power temperature coefficient	0.0037	(1/°C)
Module temperature at standard test conditions	25	(°C)
Nominal operating cell temperature	46	(°C)
Reference module temperature at nominal conditions	20	(°C)
Area of the module	2.209	(m ²)
Capital cost	1100	(\$/kW)
Replacement cost	1100	(\$/kW)
Operation and maintenance costs	100	(\$/year)
Lifetime	20	(years)
Wind turbine [194]		
Rated power	3	(kW)
Starting wind speed	3	(m/s)
Working wind Speed	3-25	(m/s)
Capital cost	5000	(\$)

Replacement cost	5000	(\$)
Operation and maintenance costs	100	(\$/year)
Lifetime	20	(years)
Battery [195]		
Type	Lead-Acid	
Voltage	12	(V)
Capacity	300	(Ah)
Capital cost	700	(\$)
Replacement	500	(\$/kW)
Lifetime	4	(years)
Converter [196]		
Efficiency	92	(%)
Capital cost	500	(\$/kW)
Replacement	500	(\$/kW)
Lifetime	15	(years)

3.1.4 Validation Against HOMER Software

To have flexibility in simulation to consider different applications, a MATLAB computer code is developed. In this case, it is important to compare the results provided by the

developed MATLAB computer code against another software to check the accuracy of the predictions. In this regard, many papers in the literature [25,197,198] compared their results with HOMER software (Hybrid Optimization Model for Electric Renewables) [41]. Hence, a validation study against HOMER is performed. Hourly based weather data for Dammam city (Fig. 3.5) and the technical specifications of the hybrid system components (Tables 2, 3 and 4) are used in both MATLAB code and HOMER software to meet the same electrical load requirements of a residential house (Fig .3.6). The schematic diagram of the hybrid PV/wind/battery system developed in HOMER and used for validation is shown in Fig. 3.7.

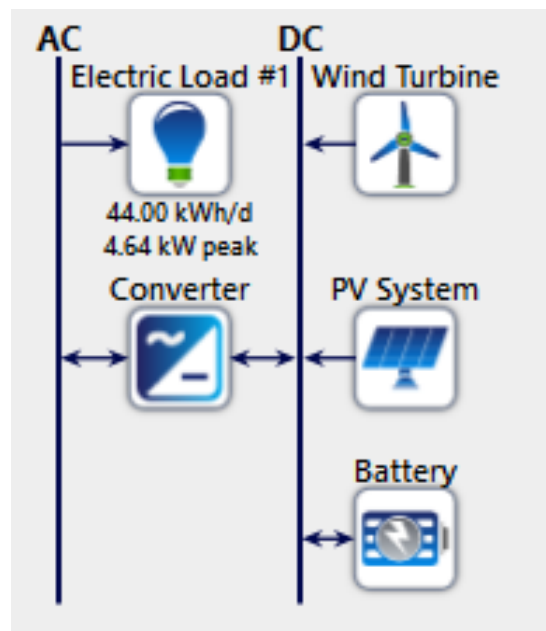


Figure 3.7 Developed hybrid PV/wind/battery in HOMER software.

Table 5.2 shows that the optimum configuration as given by HOMER comprises of 19 kW of PV panels size and 17 batteries with levelized cost of electricity of 0.458 \$/kWh. On the

other hand, the developed MATLAB code gives identical sizes for the hybrid system components which shows that both developed MATLAB computer code and HOMER software have excellent agreements.

Table 3.2 Comparison of MATLAB and HOMER simulation results.

Software	PV size (kW)	Wind turbine units	Number of batteries	Converter (kW)	NPC (\$)	LCOE (\$/kWh)	Renewable fraction
HOMER	19	1	17	6	85,051	0.458	1
MATLAB	19	1	17	6	85,045	0.457	0.9994
Difference	0	0	0	0	6	0.001	0.0006

3.1.5 Results and Discussion

The validated MATLAB code is used to evaluate the cost and reliability of a standalone PV/Wind/Battery hybrid system that is designed to supply electric energy to a residential house. Two cases are evaluated in this study according to the load type. In the first case,

the optimum size is determined for house electrical load without EV. However, in the second case, the system is sized for house electrical load with EV charging demand. The required LPSP is set to zero in all cases. However, a sensitivity analysis is carried out at the end of the discussion to investigate the effects of LPSP variation on the system cost. In the following sections, the results of the two considered cases will be discussed in detail.

3.1.5.1 Case 1: House without Electric Vehicle

An optimum hybrid PV/wind/battery system should be found with minimum cost and maximum level of reliability while meeting the residential load requirements. To achieve this goal, several combinations of the hybrid system components have been considered. In this case, the developed MATLAB code is executed to account for the required LPSP ($LPSP_{req} = 0$) by changing the number of batteries and PV modules. As a result of this process, a hybrid PV/wind/battery system that meets the house electrical load requirements with minimum cost is selected. Since the hybrid system is a standalone, 100 % renewable energy contribution is set to meet the load demand and the unmet load should be minimized as set by LPSP. The simulation results for case 1, given in Fig. 3.8, showed that the optimal configurations of the hybrid system with one wind turbine comprises of 19 kW PV panels and 17 batteries with LCOE of 0.457 \$/kWh and total NPC of 85,045 \$.

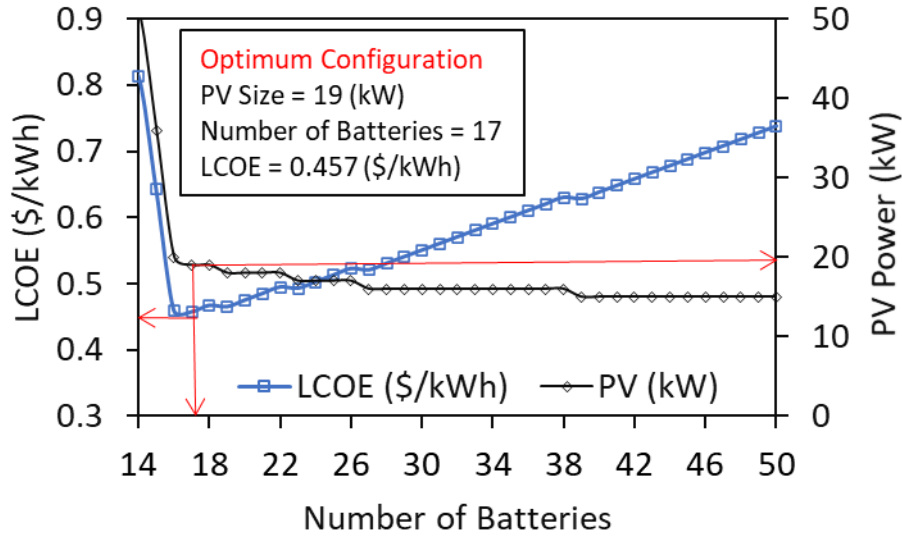


Figure 3.8 Optimal configurations for case 1: House without EV.

It can be observed from Fig. 3.8 that increasing the number of batteries reduces the PV size significantly until the optimum point is reached, then the reduction in PV size becomes small. This is due to the fact that with limited size of battery bank, larger size of PV array is needed to meet the load demand and achieving the reliability limit criterion. To illustrate the total monthly energy production by PV and wind, the optimum configuration for this case is considered and the results are shown in Fig. 3.9. To explain, the electric energy produced by the hybrid PV/wind system is plotted in Fig. 3.9a. To meet the demand of this case, 85 % of the produced electric energy is generated by the PV system whereas 15 % is produced by the wind system. For typical winter and summer days (17th of January and 17th of July [172]), the energy production by both PV and wind turbine, load requirements and batteries state of charge are shown in Fig. 3.9b and Fig. 3.9c, respectively. It can be noticed from Fig. 3.9b that, in winter, the battery state of charge is always kept with enough

amount of the stored energy to supply the demand due to the small demand in the winter. However, in summer, the demand is high which causes a considerable consumption from the stored energy in the battery as shown in Fig. 3.9c.

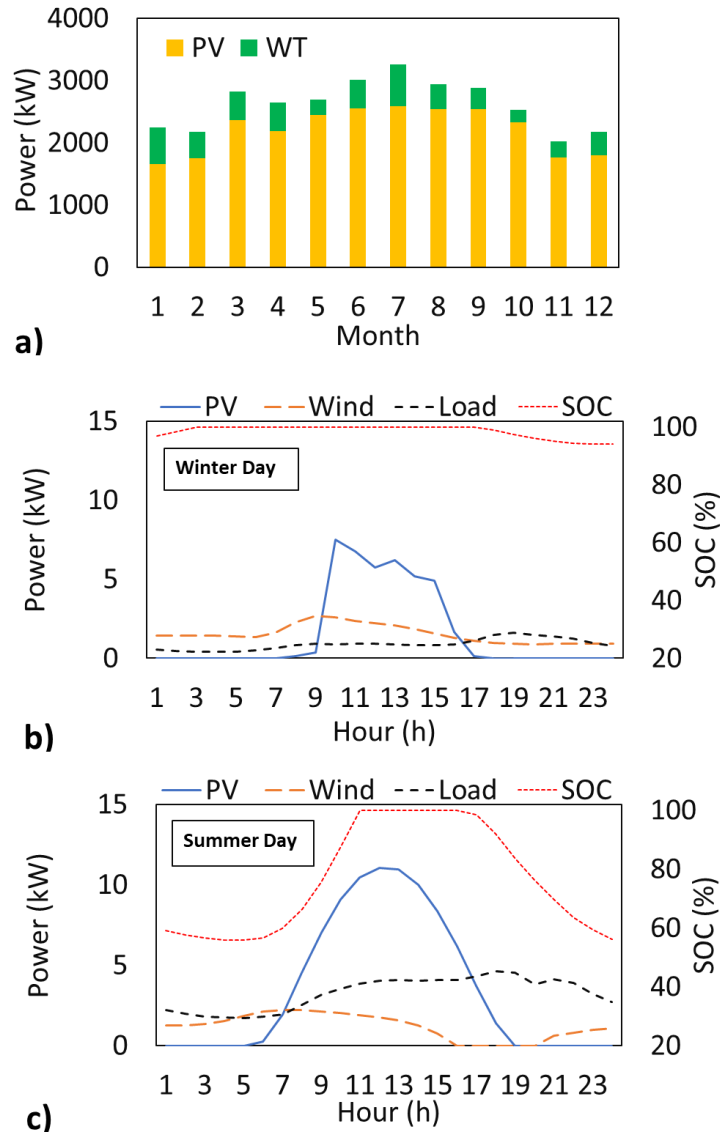


Figure 3.9 a) Monthly PV and wind productions for Case 1: House without EV, b) Energy production by both PV and wind turbine, load requirements and batteries state of charge for typical winter day, and c) Energy production by both PV and wind turbine, load requirements and batteries state of charge for typical summer days

3.1.5.2 Case 2: House with Electric Vehicle

In this case, an EV is added to the system as a deterministic load which means that the EV arrives and departs the house with a specified battery capacity. To perform this simulation, the EV is assumed to leave home at 8:00 in the morning with fully charged battery and arrives back later at 17:00 with a lower capacity depending on the daily distance travelled by the vehicle. In this study, Nissan Leaf electric vehicle is used to perform the study in which the electric consumption is given as 0.1419 kWh/km according to the Spritmonitor Database [199]. In this database, different EV drivers worldwide introduce their daily consumptions which are utilized by Spritmonitor Database to provide the averaged consumption. In addition, an average daily travelled distance by the EV is required to determine the daily electricity demand. Therefore, an average daily travelling distance in Dammam city is assumed to be 25 km/day and, therefore, the daily electricity demand of the EV is 3.54 kW. In this case, the required power by the EV is added to the house load after its arrival at 17:00. When the daily demand of the EV is supplied, it is then disconnected. The developed MATLAB code is used to find optimum configuration and the results are shown in Fig. 3.10. In this case, the optimal configuration with one wind turbine is corresponding to 20 kW PV and 19 batteries with LCOE = 0.449 \$/kWh and total NPC = 91,006 \$.

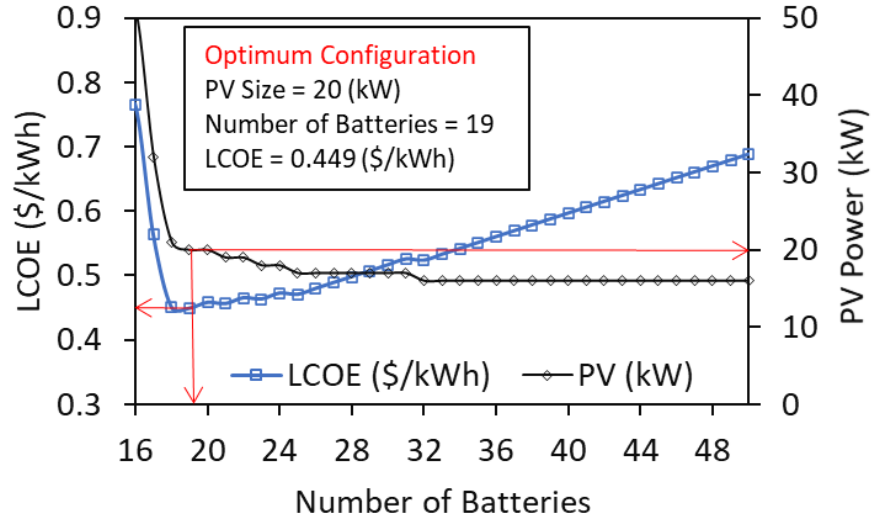


Figure 3.10 Optimal configurations for case 2: House with EV.

It can be observed from Fig. 3.10 that adding the EV to the house as an extra load and sizing the system to be 100 % powered by renewable energy has resulted in high cost due to the significant increase in batteries and PV size. In this case, Fig. 3.11 illustrates the energy consumption of the house in the presence of the EV for winter and summer days (17th of January and 17th of July [172]). In the left part of Fig. 3.11 (for winter typical day), the state of charge of the EV battery has started to increase at 17:00 by a charging rate of 1.5 kWh until it reached maximum capacity after 2.5 hours of charging according to Eq. (3.3). Simultaneously, the state of charge of the system battery has decreased due to the increased load demand. However, the state of charge of the house battery in right part of Fig. 3.11 (for the summer typical day) has decreased significantly due to the high house load in summer in addition to the EV demand. For hours after midnight, 01:00 to 8:00, the EV state of charge is constant because its capacity is fully charged, and it remains in the

house until 8:00, then it departs. The daytime hours 8:00 until 17:00, the EV is out of the house and its capacity is represented here by its minimum limit.

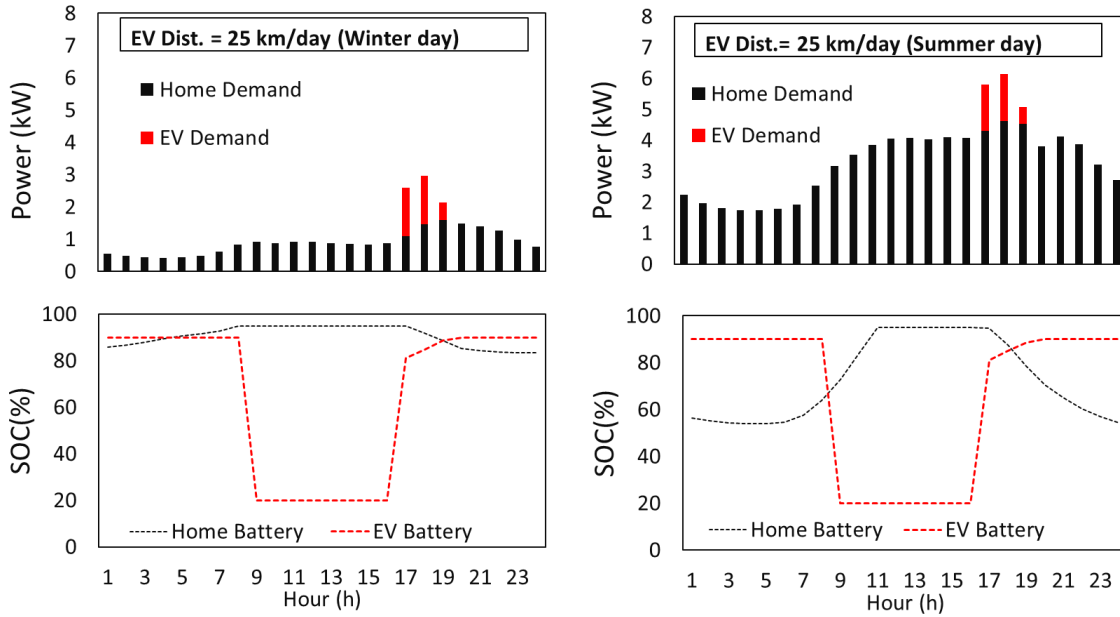


Figure 3.11 Energy demand for home and EV in winter (to the left) and in summer (to the right) days for a daily distance travelled of 25 km/day.

The state of charge of the system's battery is shown in Fig. 3.12a for all hours of one full year. Fig. 3.12b illustrates the state of charge of the system battery for January which is represented by hours 1 to 720 of the year and Fig. 3.12c shows the state of charge in July which starts at hour 4345 of the year. In Fig. 3.12b, it is clear that, through month of January days, the battery state of charge fluctuates between 60% and 90% of its capacity due to small loads that is always covered by the renewable production. However, during summer days, the electrical loads are much high, consequently, the stored power in the

battery is exploited extensively and its state of charge approaches the lower limit as shown in Fig. 3.12c for July in which the system's battery state of charge is fluctuating between 30% and 90%.

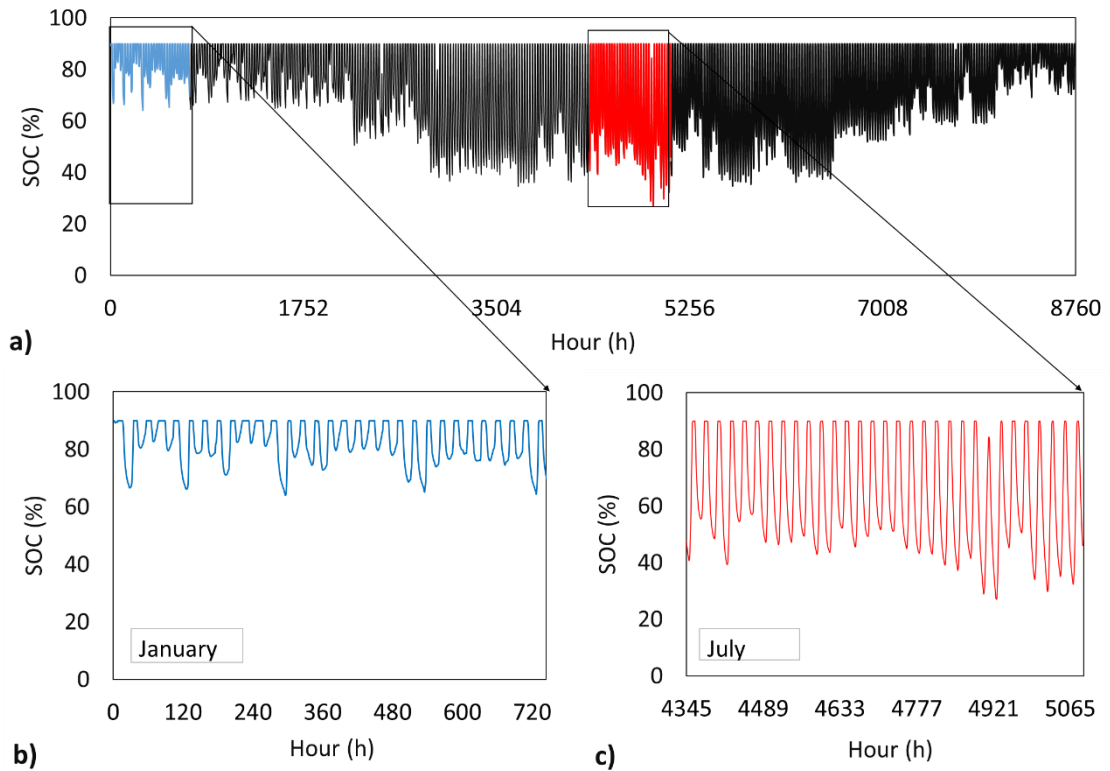


Figure 3.12 System's battery state of charge: a) for one full year b) for January c) for July

3.1.5.3 Different Daily Distances Travelled by the Electric Vehicle

In this section, the hybrid system is sized and optimized for different EV daily travelled distances. For this purpose, the daily travelled distance is considered to vary from 25 to 100 km/day with an increment of 5 km/day. The summary of the optimization results is listed in Table 5.3. It is observed that as the travelled distance increases, the total net present cost (NPC) increases slightly. However, it should be noted that the levelized cost of electricity as defined by Eq. $(LCOE = NPC_{tot} \times CRF / P_{yearly})$ is sensitive to the total served electrical load (P_{yearly}) which is increasing while increasing the travelled distance. It is observed that as the daily distance increases, the load increases and consequently, the system size is increased to meet the demand with 100 % renewable contribution.

Table 3.3 . Optimal system size and costs for different daily distances for Dammam.

Scenario	Distance (km)	PV size (kW)	Batteries	NPC (\$)	LCOE (\$/kWh)
I	25	20	19	91,007	0.4488
	30	19	21	92,470	0.4514

	35	20	20	92,862	0.4487
	40	21	19	93,254	0.4417
	45	20	21	94,717	0.4442
II	50	21	20	95,109	0.4417
	55	20	22	96,572	0.4420
	60	21	21	96,964	0.4375
	65	22	20	97,356	0.4352
	70	21	22	98,819	0.4377
III	75	22	22	101,066	0.4316
	80	21	24	102,529	0.4321
	85	22	23	102,921	0.4319
	90	23	22	103,313	0.4260

	95	22	24	104,776	0.4284
IV	100	23	23	105,168	0.4263

To investigate the energy consumption details of each distance, only four daily distances are selected as scenario-I, scenario-II, scenario-III and scenario-IV correspond for 25 50, 75, 100 km/day as highlighted in blue in Table 5.2. For daily travelled distance of 25 km, Figs. 3.13a and 3.13b depicts the home and EV daily energy demands for winter and summer days, respectively. According to EV consumption of 0.1419 kWh/km [199], the EV demand of 3.54 kW requires two hours and half of charging to be met. In Figs 3.13c and 3.13d, the second scenario of 50 km/day is shown.

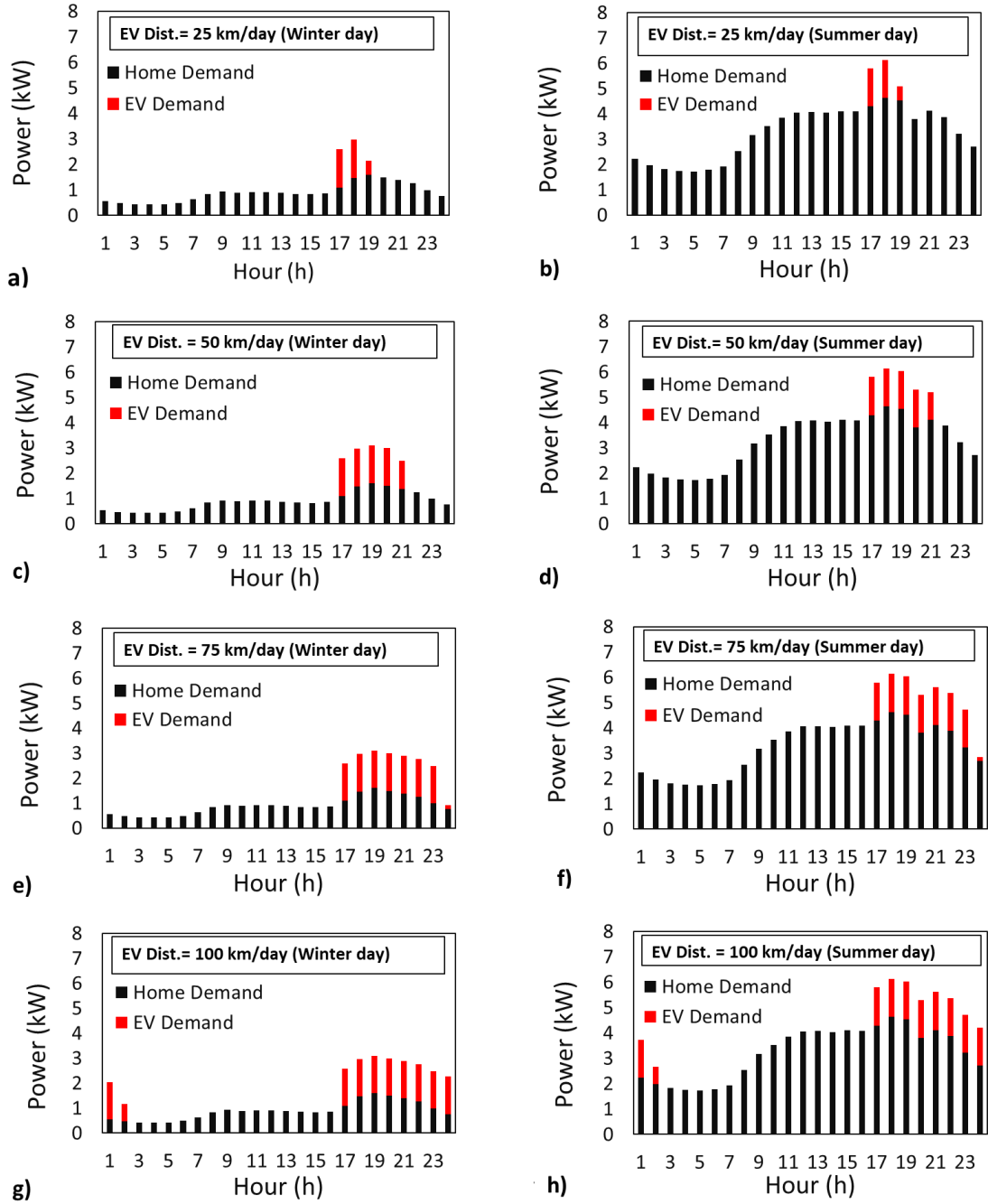


Figure 3.13 Electrical energy demand for residential house and EV nocturnal charging.

To meet this distance demand, the EV consumes 7.1 kW of its battery power and requires 5 hours of charging at night according to Eq. (3.3). When the daily travelled distance increased to 75 km/day, the EV battery demand increases. In this scenario, the EV daily demand of 10.64 kW requires 7.1 hours as shown in Figs. 3.13e and 3.13f for winter and summer day, respectively. The EV starts charging at 17:00 until 24:00. Finally, Figs 3.13g and 3.13h represent, for winter and summer days, the power demand required by the system and EV's battery for daily travelled distance of 100 km/day. For this specified distance, the EV consumes 14.19 kW per day. When the EV arrives home, it starts charging at 17:00 and its demand is met at 2:00 in the morning. Since the EV load is met by the system's battery, it is important to highlight the effects of different daily travelling distances on the system's battery state of charge. For winter typical day (17th of January [172]), the system's battery state of charge is illustrated in (Fig. 3.14a) for the four scenarios: 25, 50, 75 and 100 km/day. For daily travelled distance of 25 km/day, (scenario-I), the EV load is met during the period 17:00 – 19:00 (Figs. 3.13a and 3.13b). The electricity supplied to the EV battery is drained from the system's battery which leads to reduction in their state of charge during this period. In the early morning hours 01:00-07:00, the house load decreases, and the EV load is zero whereas only wind energy is available which contributes to cover the small house load and increases the system's battery state of charge slightly as shown in (Fig 3.14a). After sunrise, the solar energy contributes significantly to meet the demand and charge the system's battery which reaches its maximum limit quickly. For 50 km daily distance, the EV load is met in the period 17:00-21:00 (Figs 3.13c and 3.13d). As a result of that, most of the energy supplied to EV is extracted from the system's battery during these hours. It is shown in (Fig. 3.14a), for 50 km daily distance (scenario-II) the state of

charge of the system's battery takes more time than the time taken by scenario-I to reach its maximum state of charge. When the daily distance is 75 km/day (scenario-III), the EV charging process takes longer time than the previous scenarios (Figs. 3.13e and 3.13f). Therefore, the state of charge of system's battery in this scenario approaches 80% after midnight (Fig. 3.14a). What's more, when the daily travelled distance is 100 km/day (scenario-IV), the EV charging time starts at 17:00 and ends at 2:00 (Figs 3.13g and 3.13h). The state of charge of the system's battery in this scenario is shown in a decreasing behavior between 17:00 and 2:00. Then, the available wind energy at night contributes to increase the system's battery state of charge slightly. In this scenario, the system's battery reaches its maximum state of charge after sunrise at 10:00 (Fig. 3.14a). For typical summer day (17th of July), the system's battery state of charge is shown in (Fig. 3.14b) for all four scenarios as well as with the case of house load only as a reference case. Due to high residential loads in summer, the four scenarios of EV charging record almost similar effects on the system's battery state of charge. It is noticeable that, in the scenarios of daily travelled distance of 25 and 50 km/day, the system's battery minimum state of charge fluctuates around 60 % while in the worst cases of 75 and 100 km/day the minimum state of charge approaches 50 %.

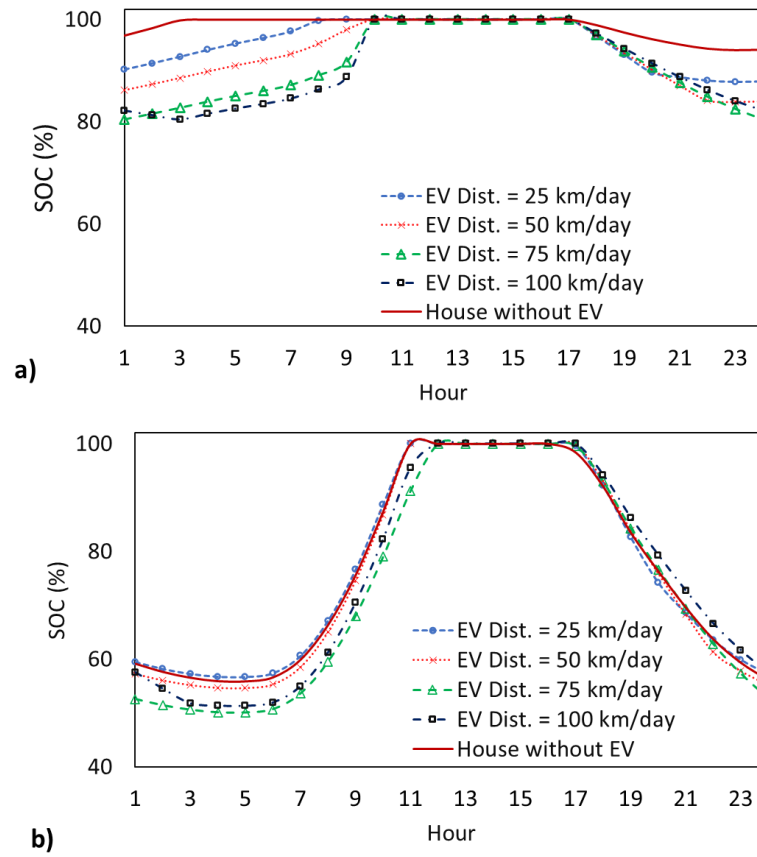


Figure 3.14 State of charge of the hybrid system's battery for all cases for a) winter typical day, and b) summer typical day

3.1.5.4 Different Locations in the Kingdom of Saudi Arabia

In this section, the results provided by the developed MATLAB code for all studied six locations in the Kingdom of Saudi Arabia (Fig. 3.3) will be discussed and compared to investigate the effects of different climatic conditions on the hybrid system optimization. The four scenarios selected in the previous sections are considered and the developed

MATLAB is executed to account for the optimum configuration in each location. The same objectives are also considered which are minimizing the total costs and ensuring LPSP = 0%. Since the number of wind turbines is fixed to only one wind turbine, the system size will be different in the PV array size and the number of batteries. In Table 3.4, the optimization results for all four scenarios are summarized in terms of PV size, batteries number, net present costs (NPC) and levelized cost of electricity (LCOE).

Table 3.4 Optimum sizes for all cities and all four scenarios.

Location	Scenario	PV Size (kW)	Batteries Number	NPC (\$)	LCOE (\$/kWh)
Dammam	I	20	19	91,007	0.4488
	II	21	20	95,109	0.4417
	III	22	22	101,066	0.4316
	IV	23	23	105,168	0.4263
Riyadh	I	23	20	99,603	0.4912
	II	23	23	105,168	0.4884
	III	24	25	111,125	0.4746
	IV	25	27	117,082	0.4746

Jeddah	I	22	22	101,066	0.4984
	II	21	26	106,239	0.4934
	III	23	27	112,588	0.4808
	IV	25	27	117,082	0.4746
Buraydah	I	19	19	88,760	0.4377
	II	19	22	94,325	0.4381
	III	21	23	100,674	0.4300
	IV	21	26	106,239	0.4307
Tabouk	I	17	25	95,396	0.4705
	II	17	29	102,816	0.4775
	III	18	32	110,628	0.4725
	IV	19	34	116,585	0.4726
Sharurah	I	26	25	115,619	0.5702
	II	27	27	121,576	0.5646
	III	29	29	129,780	0.5543

IV	30	30	133,882	0.5427
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It is observed from Table 5.3 that, Tabouk records the lowest size in the PV system in all scenarios. This result confirms the highest solar potential in Tabouk as represented also in Fig. 3.4a. The high solar radiation in Tabouk allows the PV system to generate large amount of electricity that is sufficient to cover electric loads. However, the low potential in wind energy in Tabouk enforces the hybrid system to store as much of solar energy as possible, hence, Tabouk records the highest number of battery storage units in all scenarios. Buraydah comes next in terms of PV sizes but with considerable difference in the size of the storage units. On the other hand, Sharurah records the largest PV system size among the six locations. In addition, the storage units are also high in Sharurah. To clarify, Sharurah has the lowest solar and wind potentials among these cities, which resulted in large sizes of the hybrid system. Also, in Sharurah, the temperature profile during the whole year (Fig. 3.4c) is more flattened than other cities which reduces the efficiency of the PV modules and affects their production negatively. Jeddah has low solar potential as shown in Fig. 3.4a, but it has the highest potential in wind energy (Fig. 3.4b), therefore, the hybrid system size in Jeddah is not large as Sharurah. Finally, Dammam and Riyadh have moderate sizes for both PV system and storage units.

To investigate the economic aspects of the hybrid renewable energy system in these different locations, the total NPC is plotted for all four scenarios as shown in Fig. 3.15. It can be implied from Fig. 3.15, constructing hybrid system with 100% renewable

contribution (RC) in Sharurah is very expensive due to its low potential in both wind and solar and it has high temperature during the whole year which affects the efficiency of PV production negatively. Jeddah, Riyadh and Tabouk have medium costs for installing hybrid renewable systems because Jeddah has high wind potential and Riyadh and Tabouk have high solar potential. In addition, In Riyadh and Tabouk, the temperature profiles are curved (Fig. 3.4c) which means that the temperature is high in the summer and low in winter and this behavior does not affect the PV modules efficiency. Finally, Dammam and Buraydah are the most economical cities among the studied six locations for installing hybrid renewable energy systems. Dammam has relatively high solar and wind potentials with curved temperature profiles. Buraydah also has high solar energy potential with curved temperature profiles during the whole year. These conditions give Dammam and Buraydah economical choices to construct hybrid renewable energy systems.

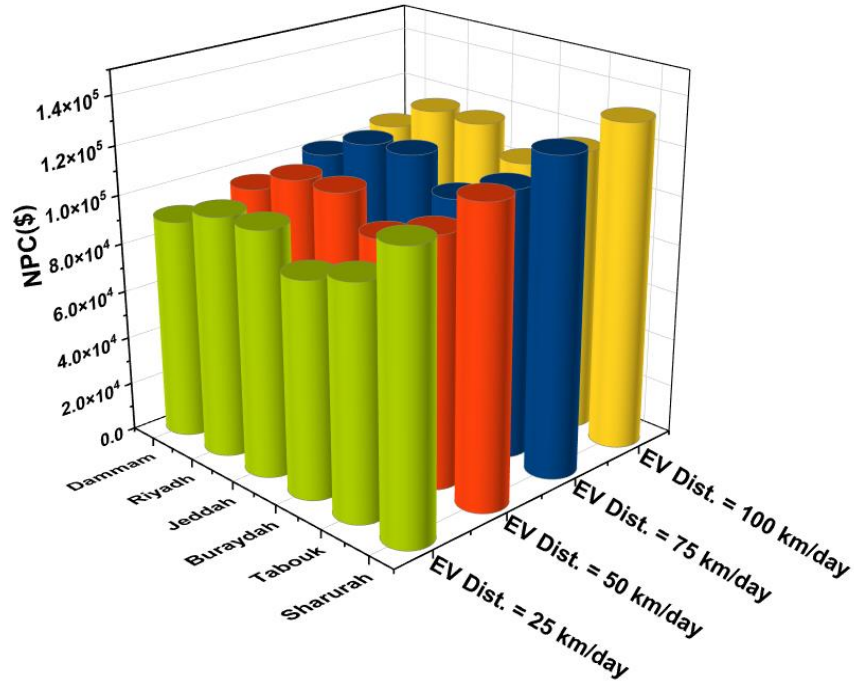
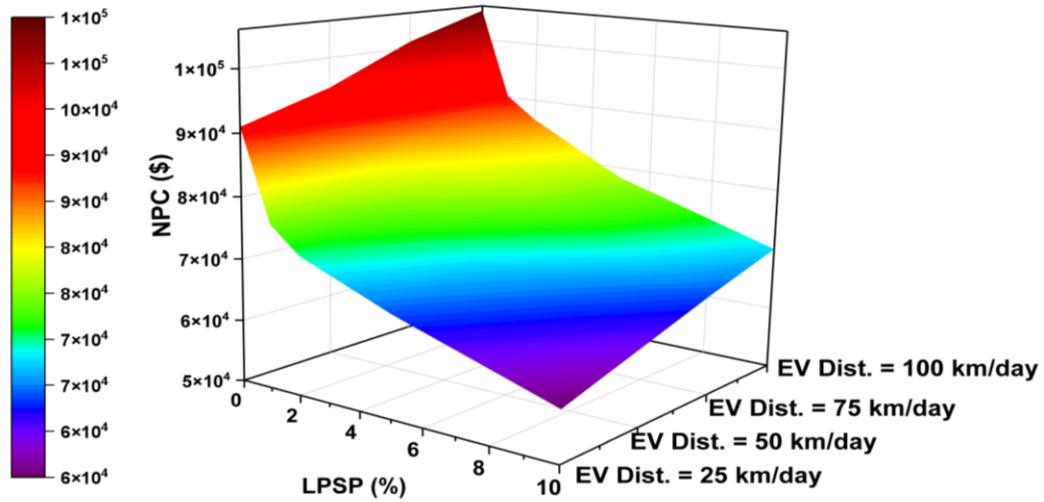


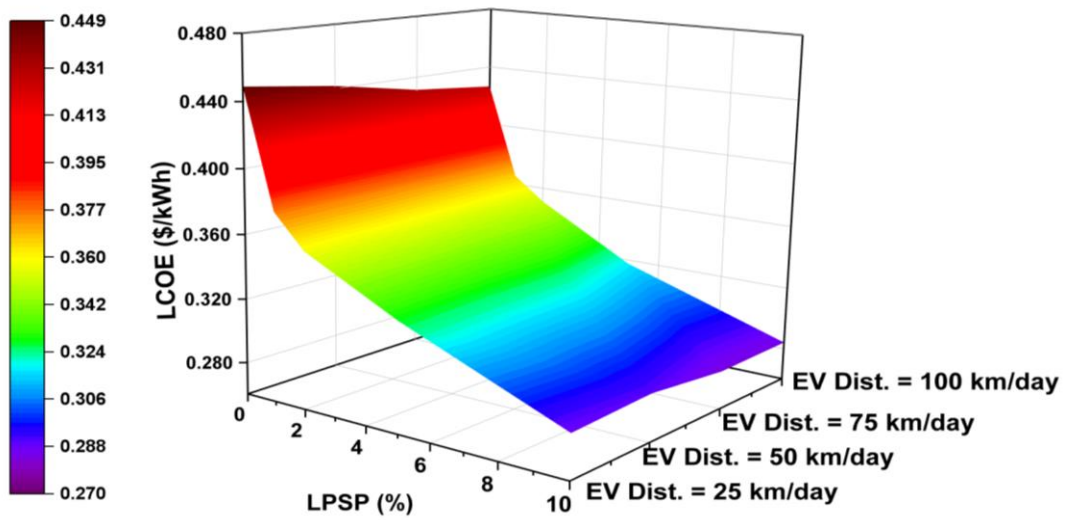
Figure 3.15 NPC of all four scenarios for all six locations under study

3.1.5.5 Sensitivity Analysis

It is significant in the hybrid renewable energy system to evaluate the effects of the variation in the sensitive input variables such as the loss of power supply probability (LPSP) on the optimization objective function which are net present cost (NPC) and levelized cost of electricity (LCOE). For this purpose (for the scenarios: I, II, III, IV for the daily travelled distances: 25, 50, 75 and 100 km), the hybrid system located in Dammam location is considered. The variations of NPC and LCOE for different levels of LPSP are shown in Figs. 3.16a and 3.16b, respectively.



a)

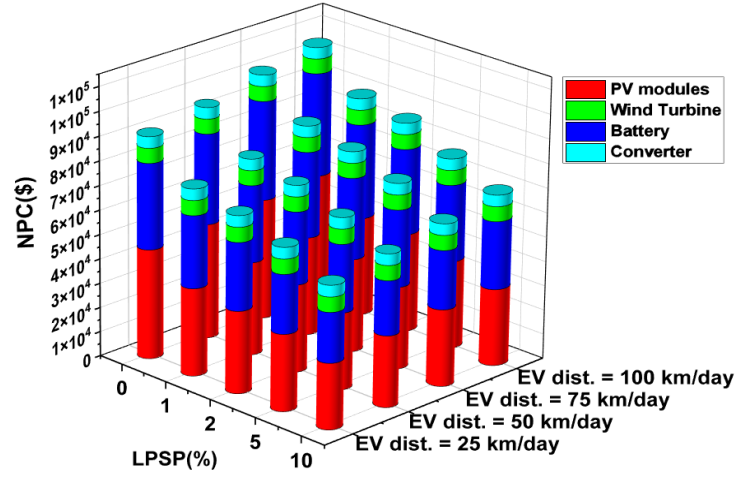


b)

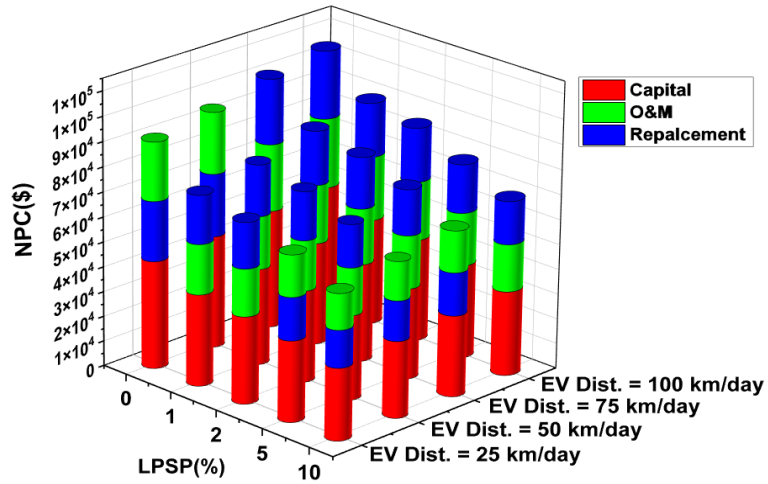
Figure 3.16 Effect of LPSP variation on a) NPC of hybrid system for the four scenarios., and b) LCOE of hybrid system for the four scenarios.

For scenario-I, for high reliable system with 100% renewable contribution and LPSP = 0%, the total NPC of the optimum configuration is 91,006 \$ with LCOE of 0.449 \$/kWh. As LPSP increased to 1, 2 until 10%, the system reliability is reduced and, consequently, renewable contribution (RC) is dropped to 99, 98 until 90%, respectively. In addition, at LPSP = 10% the total NPC and LCOE of the system are reduced to 58,190 \$ and 0.287 \$/kWh, respectively. For scenario-II, as the LPSP varied from 0% to 10%, the RC is changed from 100% to 90% and the total NPC is decreased from 95,109 \$ to 62,292 \$, whereas the LCOE is also decreased from 0.442 \$/kWh to 0.290 \$/kWh. Similarly, for scenario-III and scenario-IV, the variation in LPSP leads to considerable reduction in the total NPC and LCOE of the system as shown in Fig. 3.16a and Fig. 3.16b, respectively. Because the total NPC allows to demonstrate the cost shared by each component in the hybrid system, the total NPC is represented, in Fig. 3.17a, in terms of the cost shared by each component for different values of LPSP. To explain, for LPSP = 0% and scenario-I, the total NPC of the system is 91,006 \$ which is distributed among system components as 44,939 \$ for the PV system, 6,246 \$ for the wind turbine, 35245 \$ for the battery system and 6146 \$ for the converter. Similarly, the NPC of other scenarios are depicted in similar manner. It can be implied from Fig. 3.17a that, PV system costs dominate the components' cost because PV system is main component in the hybrid system which is responsible for providing most of the required energy. However, battery storage units come next in terms of cost due to their limited lifetime which requires them to be replaced each four years. Wind turbine and converter system share small amounts of the total NPC. In Fig. 3.17b,

the total NPC of the hybrid systems is illustrated in terms of capital, O&M and replacement costs for all scenarios with different values of LPSP. It is clearly shown that, capital costs share the highest fraction of the total NPC. Although O&M and replacement costs have comparable values, O&M costs share more in the total NPC than replacement costs in most of the considered scenarios.



a)



b)

Figure 3.17 Effect of LPSP: a) on the cost of each component of hybrid system for the four scenarios and b) on the Capital, O&M and Replacement costs for the four scenarios.

3.2 Hybrid System Power and Hydrogen Multigeneration for Residential House Integrated with Hydrogen Vehicles

In this section, the electricity and hydrogen demand of a residential house integrated with hydrogen vehicle operated by standalone hybrid solar/wind with battery and hydrogen storages will be investigated as shown in Fig. 3.18

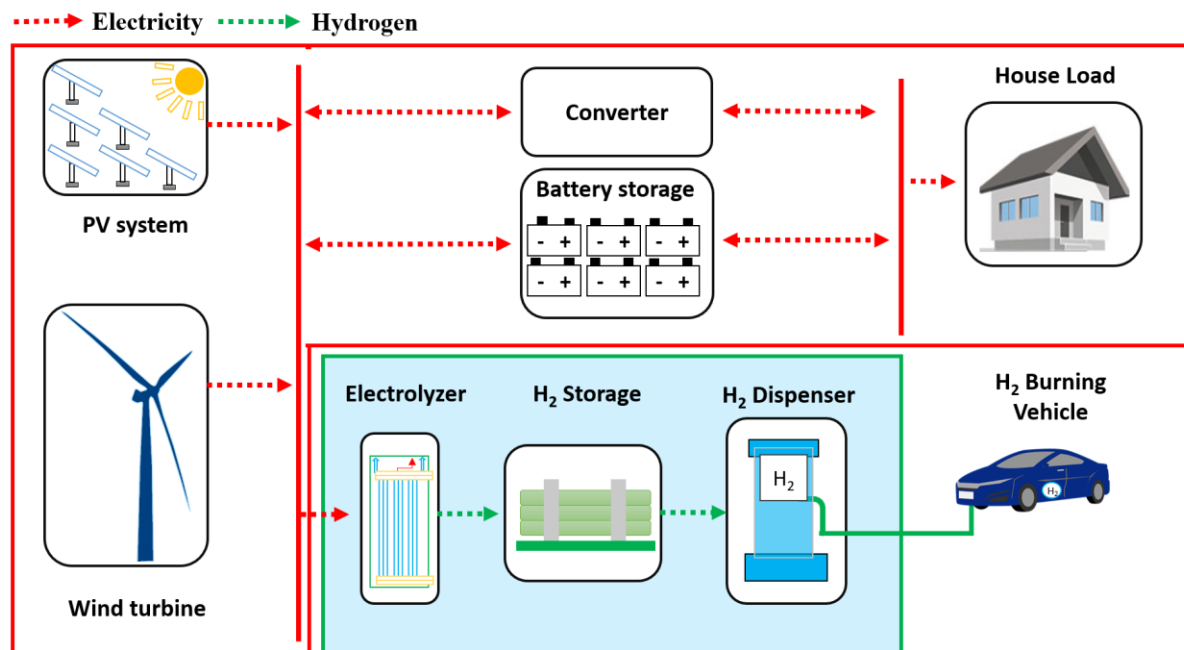


Figure 3.18 Schematic diagram of solar/wind hybrid system for electricity and hydrogen production

Due to the random behavior of the weather conditions including solar radiation and wind speed, renewable energy systems suffer from fluctuation in the energy production.

Furthermore, the sun is unavailable at nights or in case of cloudy weather. On the other hand, the local wind speed may fall below the cut-in wind speed of the selected wind turbine. In this case, utilizing a single energy resource (solar or wind) results in larger system components sizes which involves with higher cost. Therefore, the integration of both resources in a hybrid system that comprises solar panels and wind turbines leads to minimize the components sizes and the cost of energy production. In this paper, two demands are planned to be met totally by a hybrid solar/wind system. The first demand is the daily electrical load of a residential house while the second demand is the hydrogen fuel demand of hydrogen vehicle. The proposed hybrid renewable system (Fig. 3.18) is used to meet the electricity demand. When the energy generated by the hybrid system is more than load requirements and battery banks reach their maximum allowable capacity, the excess energy is used to operate electrolyzer to produce hydrogen. The hydrogen produced by the electrolyzer is stored in special hydrogen storage tanks. Finally, the hydrogen vehicle demand is always supplied from the stored hydrogen.

3.2.1 System Locations and Load Profile

The study is performed in Dhahran city, eastern province, Kingdom of Saudi Arabia which is located at 26° 17' N 50° 09' E. The hourly weather data for one full year in Dhahran is provided by King Abdullah City for Atomic and Renewable Energy (K.A.CARE) as shown in Fig. 3.19. It can be noticed that the monthly average daily solar radiation in Dhahran is

within a range of 3.62-7.8 (kW/m²/day) in winter and summer, respectively. It is also shown that wind speed is low in Dhahran with average annual speed of 3.54 (m/s) whereas temperature is low in winter and high in summer with average temperature of 20 and 35 (°C), respectively.

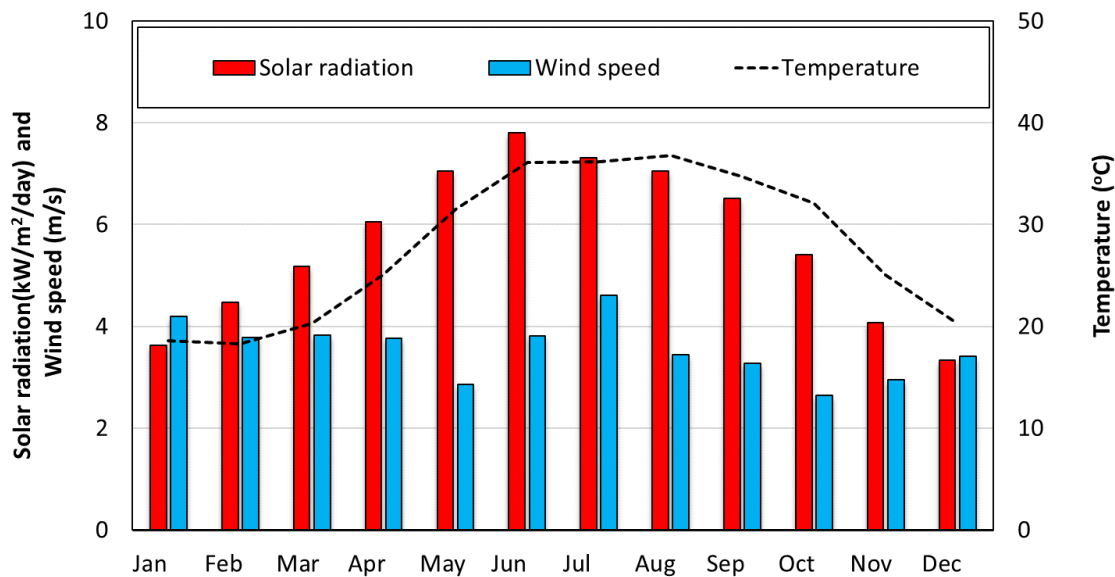


Figure 3.19 Weather data of Dhahran (Latitude: 26° 17' N Longitude: 50° 09' E).

Monthly electric bills provided by Saudi Electricity Company [191] are used to generate and plot the monthly electric load profiles which is shown in Fig. 3.20 as D-map. It is implied from Fig. 3.20 that, small electric loads in winter days are shown while in summer, the electric loads are increased due to the extensive use of air conditioning systems in Dhahran during the hot climatic conditions.

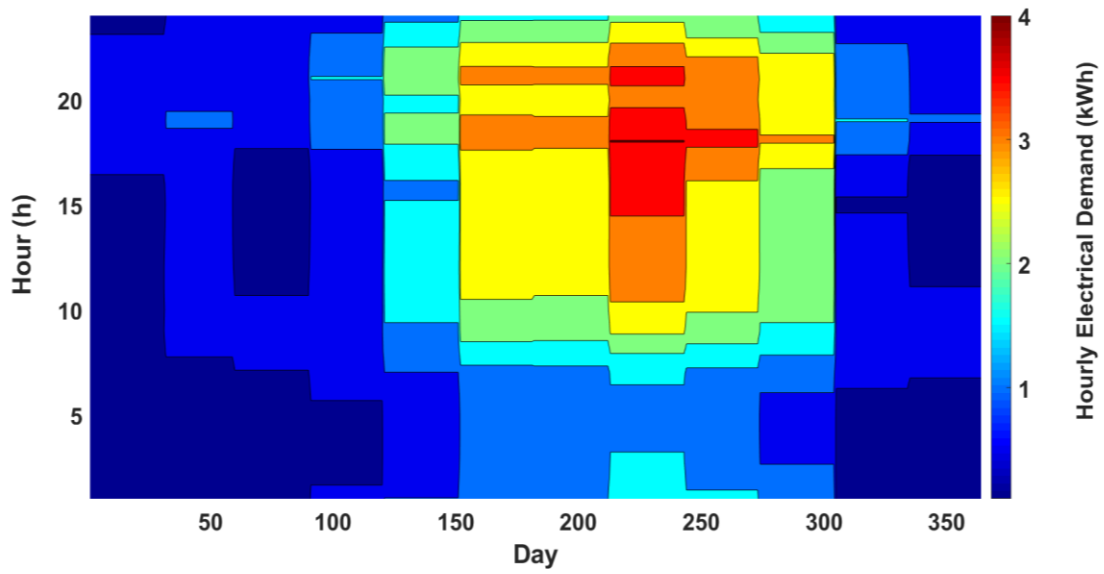


Figure 3.20 Hourly based load profiles for one full year for a typical house in the Kingdom of Saudi Arabia.

The technical specifications of the hybrid system components are proved the same as given in Table 3.1 for PV, wind turbine, battery and converter. However, the specifications of the hydrogen system are provided in Table 3.6 below.

Table 3.5 System's components specifications.

Electrolyzer [200]			
Rated power	3	(kW)	
Efficiency	74	(%)	
Capital cost	2500	(\$)	
Replacement cost	2500	(\$)	
Lifetime	10	(years)	
Hydrogen Tank [200]			
Initial tank level	10	(%)	
Storage pressure	700	(bar)	
Capital cost	1000	(\$/kg)	
Replacement cost	1000	(\$/kg)	
Lifetime	20	(years)	

3.2.2 System Energy Management

During the operation of the system, the renewable energy production of the hybrid solar/wind system is managed as following:

- a) When the total energy generated is greater than electrical load, the load is supplied directly from the renewable production and the surplus energy is stored in the batteries. In this case, the battery is charging until its maximum capacity is reached. After that, the remained surplus energy is considered as an excess energy ($P_{exc}(t)$) which is given by Eq. (2.31).
- b) When the total energy generated is less than electrical load, the load is supplied from the stored energy in the battery bank. In this case, the battery is discharging according to Eq. (18) until its minimum limit is reached. After that, the remained unmet load is considered as a loss of power supply which is given by Eq. (2.28).

When there is an excess energy available, it is utilized to operate the electrolyzer for hydrogen production which is injected into hydrogen tanks and used to meet the hydrogen load. The electrolyzer operation is governed by the availability of excess energy as well as the hydrogen level in the hydrogen tanks, therefore, two cases for the electrolyzer appear:

- a) When there is an excess energy available and the hydrogen level in the tank is less than its maximum limit, the electrolyzer is run and the produced hydrogen is stored in the tank until the maximum tank limit is reached, then the electrolyzer is turned off.
- b) When there is no excess energy available, the electrolyzer is switched off. However, the hydrogen load is met by the stored hydrogen in hydrogen tanks. In this case, hydrogen tank is discharging until its minimum limit is reached, then, the remained unmet hydrogen load is considered as a loss of hydrogen supply which is expressed by Eq. (2.34).

The energy management strategies described above are represented in the flowchart shown in Fig 3.21.

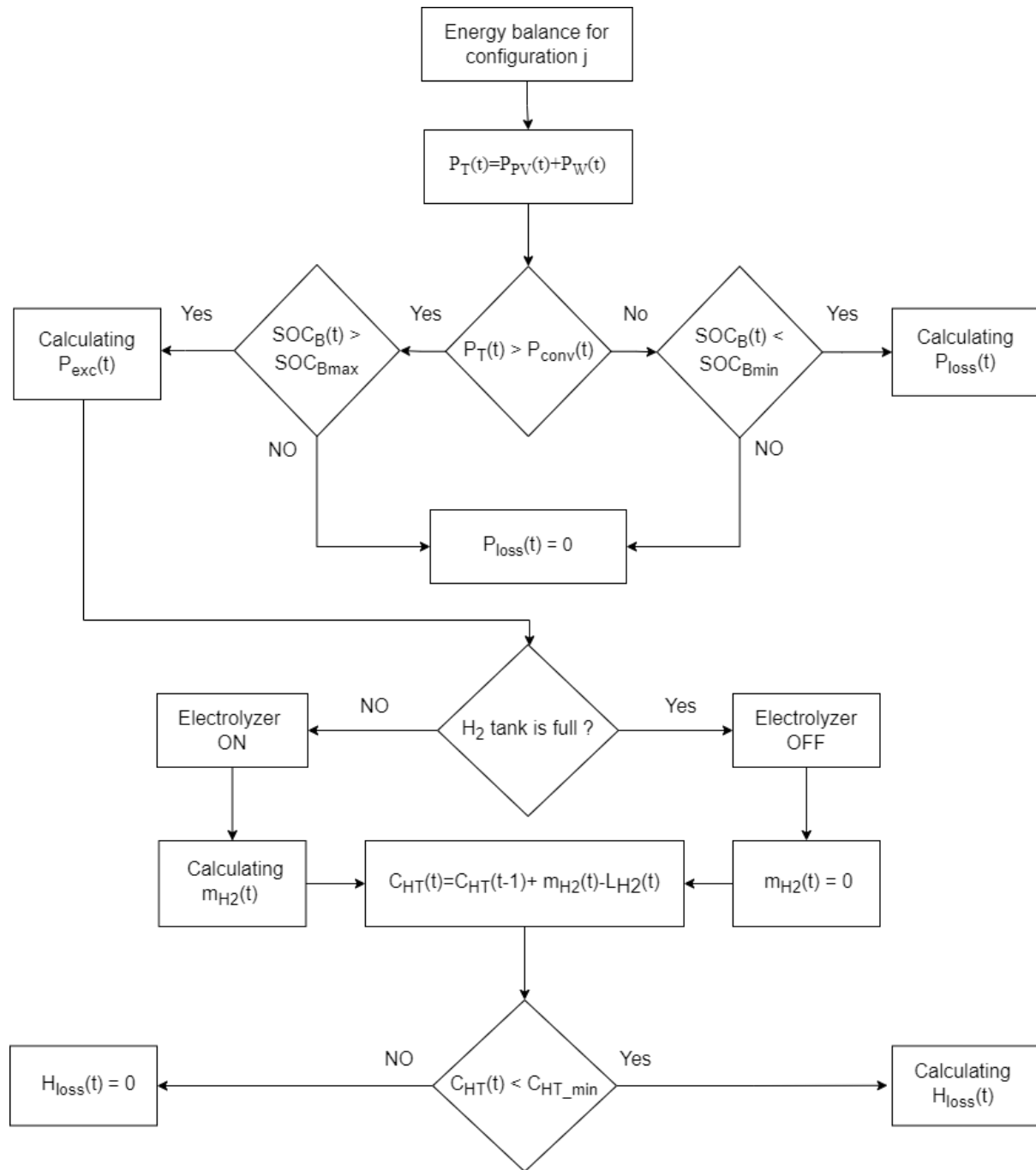


Figure 3.21 Energy management flowchart

3.2.3 System Sizing Strategy

A techno-economic and environmental optimization is conducted in this work to determine the optimum size of the hybrid solar/wind system for electricity generation and hydrogen production. The optimization is subjected to the following constraints:

$$0 \leq N_{PV} \leq N_{PV_max} \quad (6.4)$$

$$0 \leq N_W \leq N_{W_max} \quad (6.5)$$

$$0 \leq N_B \leq N_{B_max} \quad (6.6)$$

$$0 \leq N_{HT} \leq N_{HT_max} \quad (6.7)$$

where the N_{PV} is the number of PV modules, N_W is the number of wind turbines, N_B is the number of batteries and N_{HT} is the number of hydrogen tanks. The right side of the inequalities represents the maximum allowable limit of each component size. In addition, the capacity of the battery and hydrogen storages are subjected to their minimum and maximum allowable limits as given by (Eq. 3.20) and (Eq. 3.26), respectively.

The developed mathematical models described above are utilized and a MATLAB computer code is developed to perform the optimization. The optimization is conducted firstly by satisfying the electrical load. In this regard, several solar/wind/battery configurations are evaluated until the required LPSP is achieved. Then, the configuration with the lowest LCOE is selected as the optimum size that meets the electric load. Then,

the excess energy is utilized to optimize a hydrogen unit by increasing the hydrogen tank size until the required LHSP is achieved with the lowest possible LCOH. Finally, the reduction of environmental impact is calculated. The optimization flowchart is shown in Fig. 3.22 below.

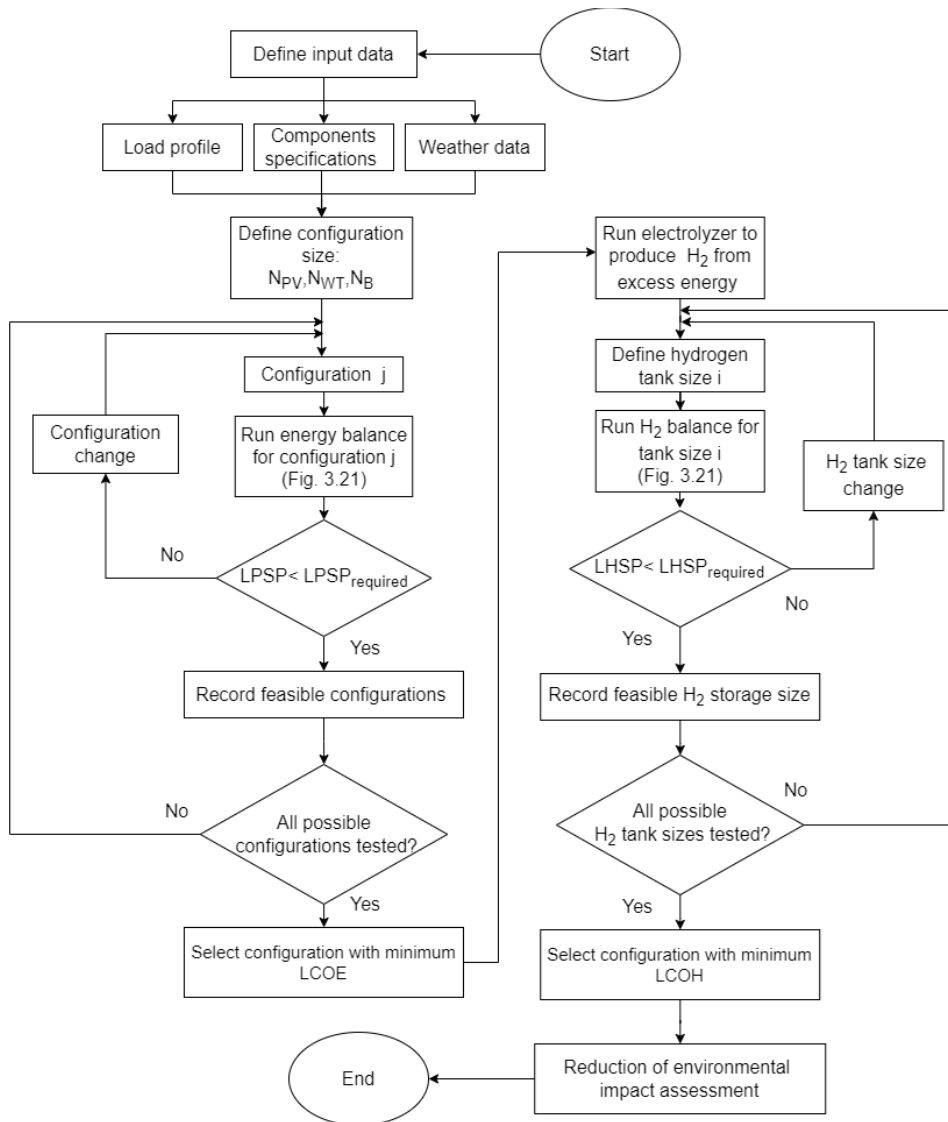


Figure 3.22 Optimization strategy flowchart.

3.2.4 Results and discussion

An off-grid hybrid renewable energy system is simulated and optimized using the developed mathematical models in MATLAB software based on hourly weather data for one full year in Dhahran city. The simulation was carried out firstly for the solar/wind/battery system to obtain the optimal size that meets the electrical load requirements of a residential house. Then, the excess energy remained was utilized and another simulation was conducted to obtain the optimal size of a hydrogen unit that meets the hydrogen fuel demand of a hydrogen vehicle integrated with the residential house.

3.2.4.1 Optimization Results of Electricity Production Subsystem

In the first stage of optimization, several combinations of PV/wind/battery are evaluated. To ensure 100 % renewable energy fraction ($RF = 100\%$ and $LPSP = 0\%$), wind turbines number is, firstly, set to zero ($N_w = 0$) and the size of PV array and batteries are varied until the desired reliability is achieved ($LPSP = 0\%$ and $RF = 100\%$) and the corresponding LCOE is observed. Then the wind turbine number is increased to ($N_w = 1, 2, 3$ and 4) and the sizes of PV array and batteries are varied again until the desired reliability is achieved, and the cost is recorded. The results are plotted in Fig. 3.23 for different number of wind

turbine units. For system without wind turbine, the optimum size is achieved with LCOE of 0.663 \$/kWh. For system with one wind turbine unit, a considerable reduction in the LCOE is found which becomes 0.625 \$/kWh. By increasing wind turbine units to 2, 3 and 4, the LCOE of the optimal size is found to be 0.593, 0.605 and 0.647 \$/kWh, respectively. It can be inferred from this results that, the cost of the hybrid system has started with high value when there is no wind turbine. However, when the wind turbine units are added, the cost has decreased until the wind turbine units become two, then the cost has increased again. Therefore, the optimum size of the renewable energy system is achieved with two wind turbine units, 18 kW PV size and 14 batteries with LCOE of 0.593 \$/kWh. It can be observed from Fig. 3.24 that, by increasing wind turbine units, considerable reduction in the PV system size is achieved. For example, without wind turbine, the renewable system is comprising of 28 kW PV array and 14 batteries. By the addition of one and two wind turbine units, PV array size has decreased to 23 and 18 kW, respectively which shows the superiority of hybrid source system over single source system in reducing the total size and, therefore, reducing total cost.

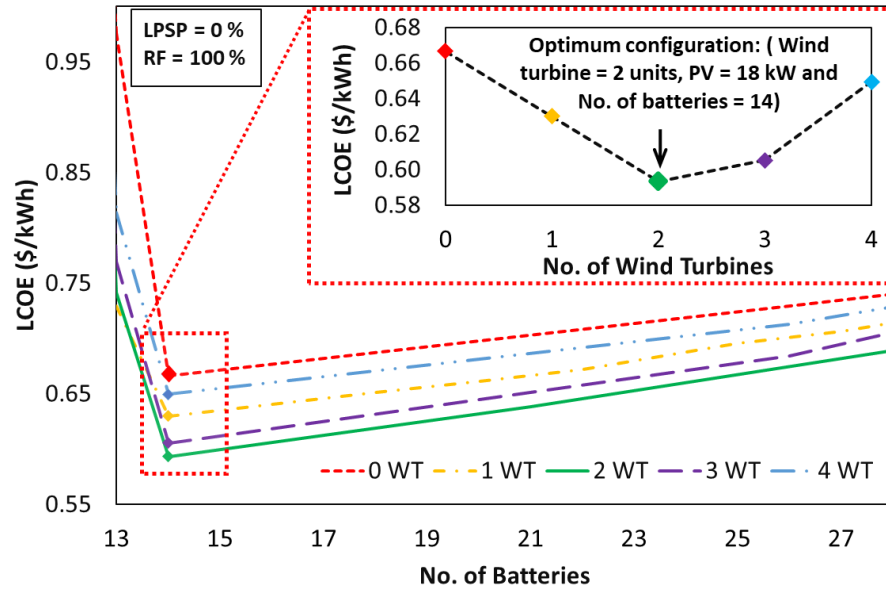


Figure 3.23 Optimization results for the hybrid system with different wind turbine units.

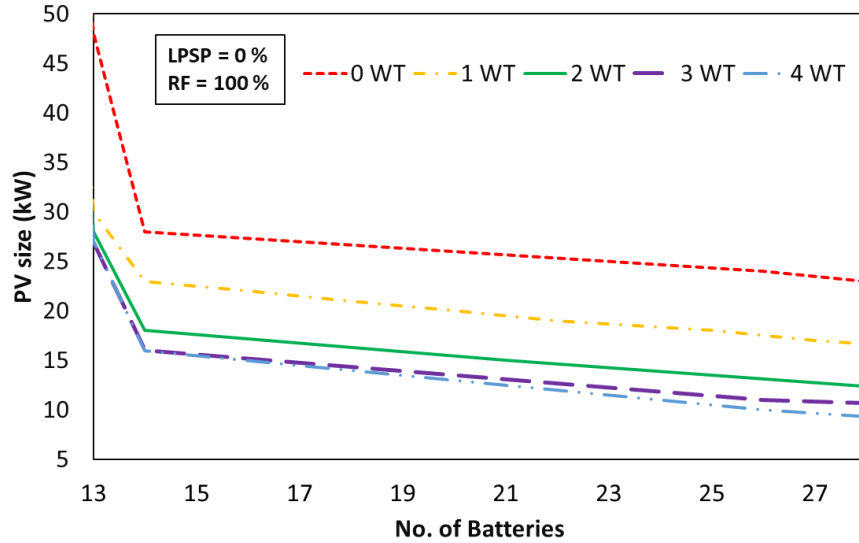


Figure 3.24 PV array sizes corresponding to the number of wind turbine units.

Fig. 3.25 shows the total annual PV array production, wind turbines production, electrical load and the excess energy. The optimum hybrid system which comprises two wind turbines, 18 kW PV array and 14 batteries, produces a total power of 37.84 MW. The PV array produces 27.97 MW/year, ($\frac{27.97}{37.84} \times 100 = 74\%$ of the total renewable production) while the wind turbines produce 9.87 MW/year, ($\frac{9.87}{37.84} \times 100 = 26\%$ of the total renewable production). On the other hand, the total annual electrical load is 12.14 MW; hence, the hybrid system produces an excess energy of 24.32 MW/year which represents high portion of the total hybrid system production and this is expected for an off-grid system with zero level of LPSP [8,174]. Fig. 3.26 shows the energy production and consumption in hourly basis. In Fig. 3.26a, the PV and wind production for one full year is presented for 8760 hours. Energy production and consumption are shown in Fig. 3.26b for low consumption period (first week of January) and in Fig. 3.26c for high consumption period (first week of August). It can be noticed that, in low demand days, the small electricity demand is always met by the renewable production and the stored energy in the batteries experience small contribution. However, in the days of high electricity demand, the stored energy in the batteries contributes more to meet the demand. In Fig. 3.27, the system's battery state of charge is represented as a D-map for one full year for the optimum size (2 wind turbines, 18 kW PV array and 14 batteries). It can be noted clearly that, during low demand period, the battery state of charge is almost around its maximum capacity. However, in high demand period, there is a notable variation in the battery state of charge which approaches the minimum limit. It is also obvious that, in the early-morning hours and late-night hours, the stored power in battery is utilized to meet the demand due to low

renewable production in these hours. However, during the period that contains hours 10-17, the renewable production becomes high enough to meet the demand and store the surplus production in the batteries which shows full capacity in this period.

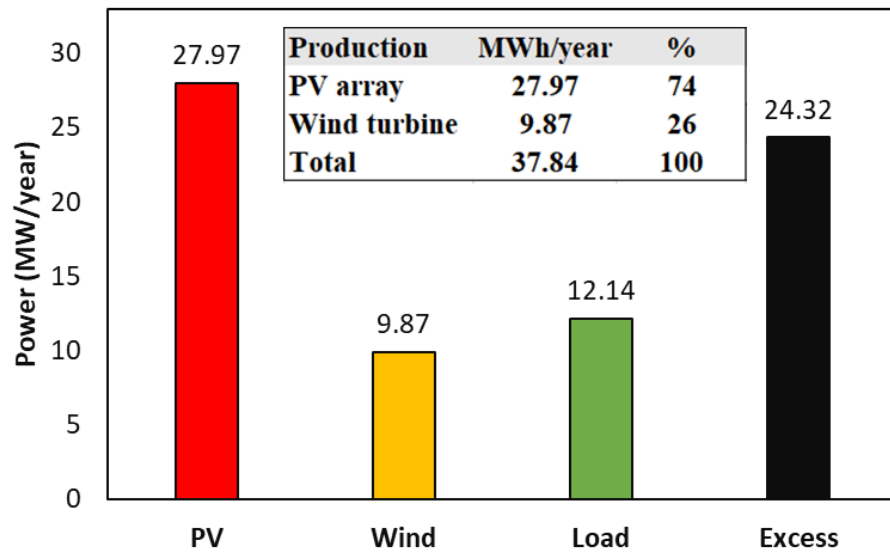


Figure 3.25 PV and wind turbines production, load requirement and excess energy of the optimum configuration of the hybrid system (two wind turbines, 18 kW PV array and 14 batteries).

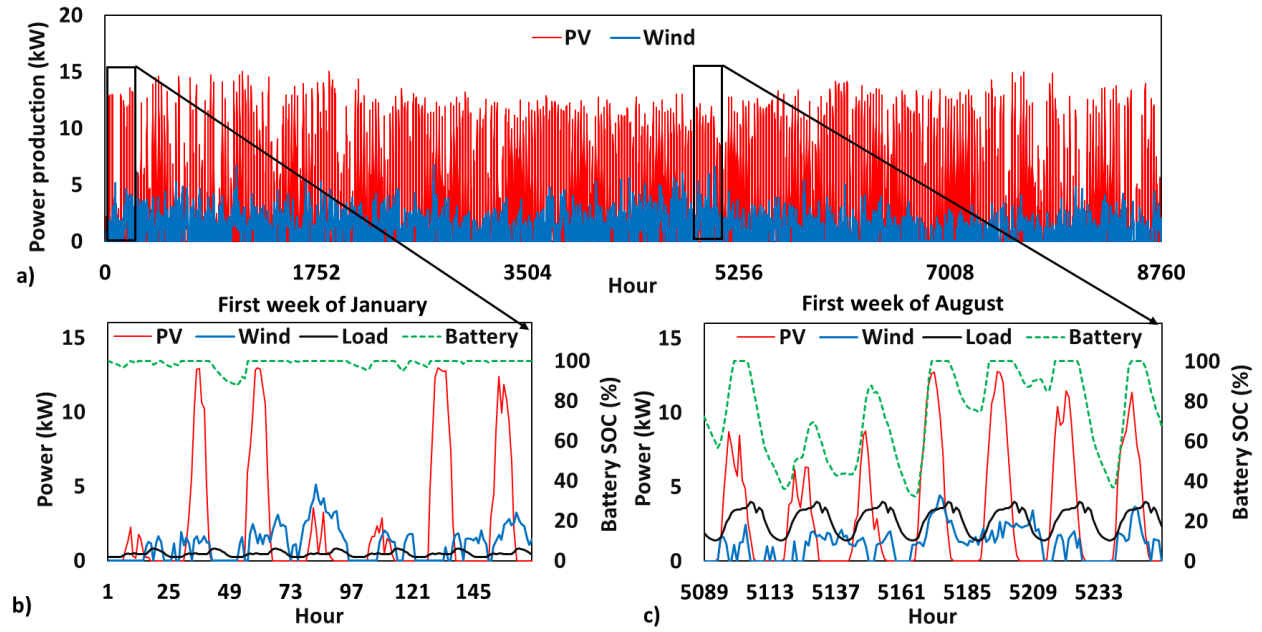


Figure 3.26 Energy production and consumption in hourly basis for a) full year, b) one week of low electricity demand and c) one week of high electricity demand.

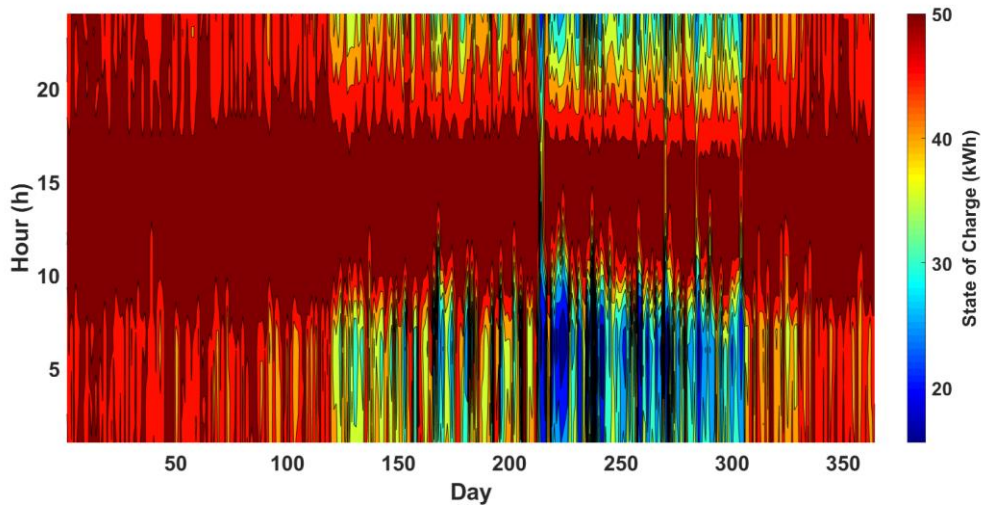


Figure 3.27 D-Map of the state of charge of the battery bank for the optimum configuration (two wind turbines, 18 kW PV array and 14 batteries).

3.2.4.2 Optimization Results of Hydrogen Production Subsystem

Due to the large amount of excess energy generated by the hybrid renewable system and instead of throwing it off, it can be used to produce hydrogen which can be then used for different applications. In this work, the excess energy is used to operate electrolysis unit to produce hydrogen. The produced hydrogen is stored in hydrogen storage tanks, and it is utilized later to refuel hydrogen burning vehicles. It is important to size the hydrogen system in an optimal way such that it can provide hydrogen fuel whenever required. Two electrolyzers (each electrolyzer has a rated power of 3 kW with conversion efficiency of 74 %) are utilized to perform the hydrogen production. The two specified electrolyzers can produce 0.1127 kg/hr of hydrogen when they are fed by their rated power as describe in (section 2.3.5). In addition, hydrogen storage tanks (each unit has capacity of 1 kg) are optimized to ensure high reliable hydrogen supply system. For this purpose, the loss of hydrogen supply (H_{loss}) and loss of hydrogen supply probability (LHSP) are developed in this work (Eqs. (4.8) and (4.7)) and utilized in this section as an indicator to assess the hydrogen system reliability. To perform this study, it is required firstly to specify the hydrogen load required by the hydrogen vehicle. Toyota Mirai hydrogen vehicle is utilized in this paper to perform the study. This hydrogen vehicle is equipped with a 5 kg hydrogen storage tank that stores hydrogen at a pressure of 70 MPa [10]. The vehicle converts the hydrogen fuel into electricity by using solid polymer electrolyte fuel cell. In addition, the average hydrogen consumed by the vehicle is about 0.0076 kg/km [201] which means that 5 kg of hydrogen enables the vehicle to travel a distance of 658 km. In this work, the

Toyota Mirai vehicle is assumed to travel this distance weekly. To study the effect of refueling scenario on the optimization results, three refueling scenarios are assumed as shown in Fig. 3.28. To explain, (Scenario-I) is shown in (Fig. 3.28a), the 5 kg demand of hydrogen is distributed among the seven days of the week such that 0.8 kg/day of hydrogen is fed into the vehicle in days 1 to 5 while in the weekend days the hydrogen demand is reduced to 0.5 kg/day. In Fig. 3.28b (Scenario-II), the weekly demand of hydrogen (5 kg) is supplied into the vehicle every other day with a load of 1.5 kg/day in days 1, 3 and 5 whereas in the weekend the load is reduced to 0.5 kg/day. However, in Fig. 3.28c (Scenario-III), the total weekly hydrogen demand (5 kg) is supplied into the vehicle in one day.

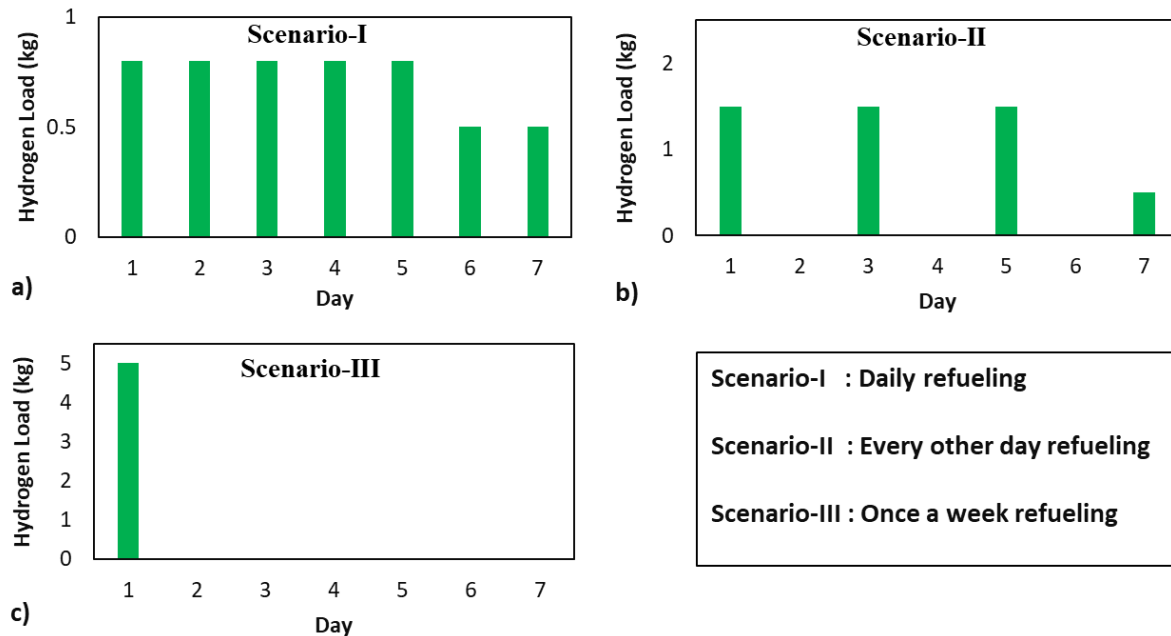


Figure 3.28 Hydrogen vehicle refueling scenarios: a) Everyday refueling, b) Every other day refueling and c) Once a week refueling.

To conduct the optimization study, the size of the electrolyzer system is fixed (6 kW) and the size of hydrogen tanks is varied. For each tank size, the LHSP is recorded as an indicator to assess the hydrogen system reliability. Fig. 3.29a, the hydrogen tank size is varied from 1 to 20 kg for the three refueling scenarios described above and the LHSP and LCOH are observed. For scenario-I (daily refueling), tank capacity of 1 kg leads to LHSP is 0.087. As capacity increases to 2 and 3 kg the LHSP drop to 0.056 and 0.051, respectively, and it continues decreasing until it becomes zero at tank capacity of 14 kg which means there is no shortage in hydrogen supply during the whole year. For scenario-II (every other day refueling), the LHSP is about 0.48 when the tank capacity is 1 kg which indicates that, the hydrogen load is not met during 48 % of the whole year hours. By increasing the tank capacity to 2 kg, a dramatic drop in the LHSP is provided and it becomes 0.065 which means that only 6.5 % deficit hours occur during the year. Keep increasing the tank capacity to 15 kg, the LHSP keeps decreasing until it reaches 0. For scenario-III (once a week refueling), the LHSP starts with value of 0.86 at 1 kg tank capacity and it decreases slightly as the capacity increases to 5 kg. Then the LHSP drops to 0.048 at tank size of 6 kg and it continues dropping until it reaches a minimum value of 0 at capacity of 17 kg.

The considerable variation in the LHSP described above can be understood by studying the hydrogen production by the electrolyzer for the three refueling scenarios. Since the weekly demand of hydrogen is 5 kg, the total annual demand of hydrogen is 260 kg. To meet this need, the electrolyzer produces hydrogen when the hydrogen tank is not full.

Therefore, the tank capacity affects the electrolyzer output directly. Fig. 3.29b represents the electrolyzer output in versus hydrogen tank size. For scenario-I, the daily refueling scenario consumes small amount of the stored hydrogen which allows the electrolyzer to produce hydrogen most of the time. As a result of that, the produced hydrogen starts with annual production of 250.50 kg when tank size is 1 kg. As tank size increases to 20 kg, the annual hydrogen production becomes 264.33 kg. For scenario-II, when the tank size is 1 kg, the electrolyzer produces 172.0 kg/year and the production reaches 261.17 kg/year when the tank size is 20 kg. Low hydrogen production is recorded for scenario-III with 1, 2, 3, 4 and 5 kg tank sizes. The maximum production is about 257.67 kg annually when the tank size is 20 kg. In Fig. 3.29c, the effect of different refueling scenarios on reducing the excess energy fraction is demonstrated. For scenario-I, using hydrogen storage tank of 1 kg, excess energy percentage is reduced from 64 % to 29.02 % which means that half of the excess energy is reused again. As tank size increases, slight reduction in excess energy percentage is noticed which approaches 27.07 % with tank capacity of 20 kg. For scenario-II, the percentage of excess energy is reduced to 40.07 % with tank size of 1 kg, then it becomes 27.51 % with tank size of 20 kg. The reduction in excess energy becomes insignificant with scenario-III. To explain, the excess energy percentage is reduced from 64 % to 57.36 % when the tank size is 1 kg. Moreover, when the tank size increases, excess energy percentage becomes 28.01 % with tank capacity of 20 kg.

Levelized cost of hydrogen (LCOH) is an important tool that indicates the cost of one kg of the produced hydrogen by the developed hybrid system. Fig. 3.29d shows that, minimum value of LCOH, for scenario-I, of 33.80 \$/kg is identified with tank size of 2 kg. Then, as

tank size increases, the hydrogen production becomes expensive. For scenario-II, the LCOH starts with high value (49.23 \$/kg) at 1 kg tank size, and it decreases to a smaller value (34.04 \$/kg) at 2 kg tank size, then it increases again to a maximum value of 38.77 \$/kg at tank size of 20 kg. For scenario-III, the cost of hydrogen (LCOH) starts with high value of (172.49 \$/kg) and it decreases to a value of (35.76 \$/kg) with tank size of 6 kg. After that, the hydrogen production becomes expensive again.

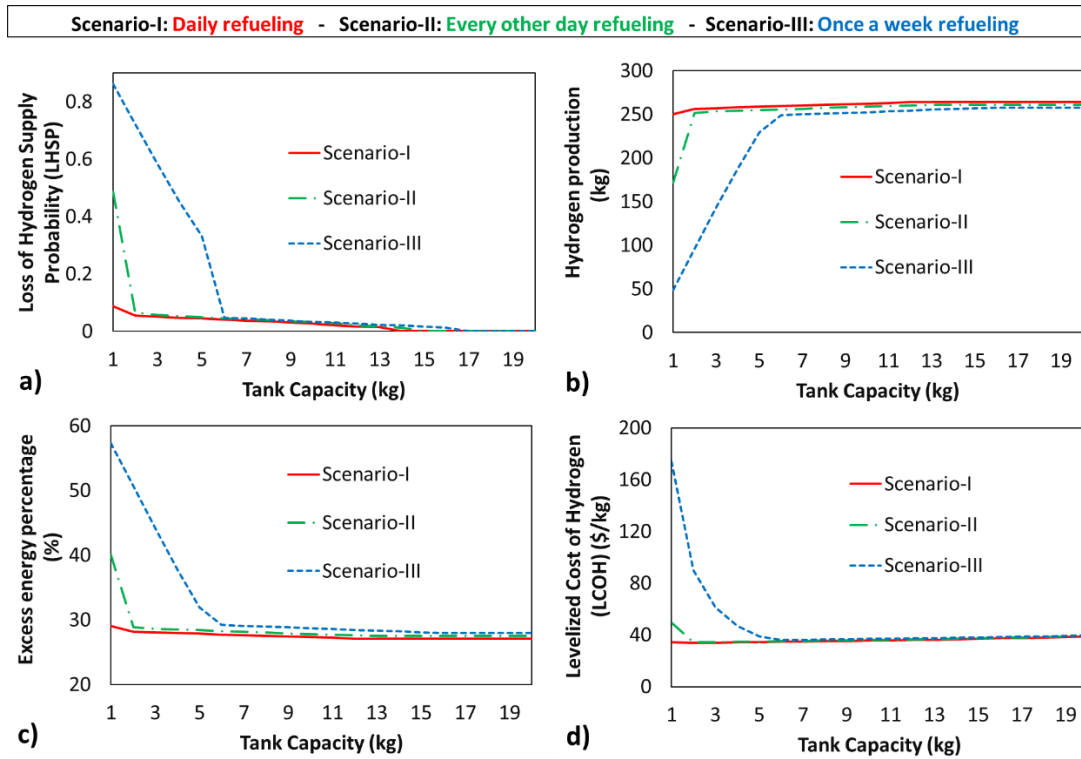
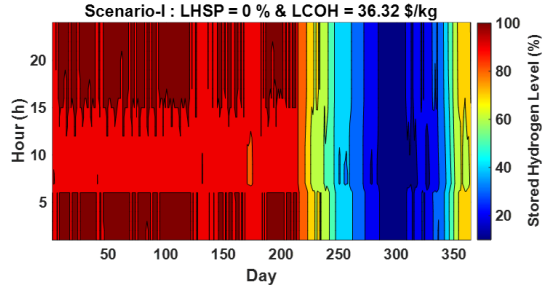
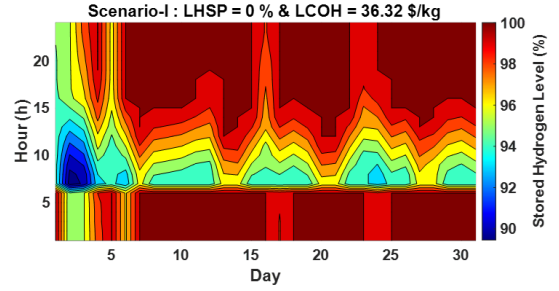


Figure 3.29 System performance criteria and economics for different hydrogen vehicle refueling scenarios: a) Loss of hydrogen supply probability versus tank size, b) Amount of hydrogen produced in terms of tank size, c) Reduction in excess power versus tank size and d) Levelized Cost of hydrogen in terms of tank size.

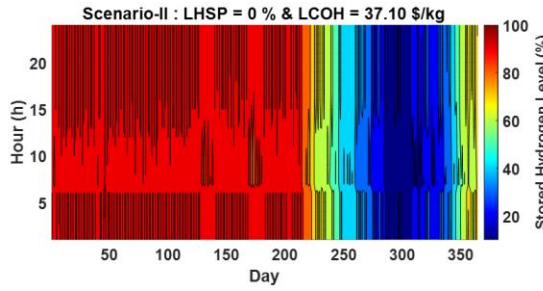
In addition, to compare the three refueling scenarios, the hydrogen accumulation level in the storage tanks is investigated for the size that gives LHSP of zero. In Fig. 3.30a, the stored hydrogen in 14 kg tank (which gives LHSP=0) for scenario-I is plotted as a D-map. Since the refueling process occurs at 7 AM in the morning, there is an obvious reduction in hydrogen level at this hour. Later during hours 15-24 the produced hydrogen by the electrolyzer refills the tank and it remains full until 7 AM of the other day. It is also clear that, during summer days the stored hydrogen level approaches the minimum tank limit. In Fig. 3.30b, the D-map of the storage tank is shown for one month (January). It is implied that, scenario-I gives the storage tank flexibility to be refilled in few hours during the day. In Fig. 3.30c, the D-map of storage tank for scenario-II is shown for the size that gives (LHSP = 0). To illustrate the detail of this scenario, the D-map is shown in Fig. 3.30d for one month (January). It is clearly shown that in this scenario the storage tank remains not totally filled during some days of the month. This behavior becomes significant for scenario-III which is shown in Fig. 3.30e for one full year. During the month of January (Fig. 3.30f) for scenario-III, a dramatic reduction in hydrogen level occurs during the refueling day, then the tank takes 4 to 5 days to be refilled again to its maximum level. It can be deduced from this behavior that, scenario-I gives the hydrogen tank flexibility to be refilled in in few hours and allows to meet the hydrogen demand most of the time. It can be concluded from this discussion that, refueling behavior in scenario-I is the most promising refueling behavior that allows to get the cheapest cost of hydrogen with high reliable hydrogen supply system as well as useful utilization of excess energy. Since scenario-I is the preferable scenario for the refueling behavior, it is important to investigate the details of hydrogen production in this scenario.



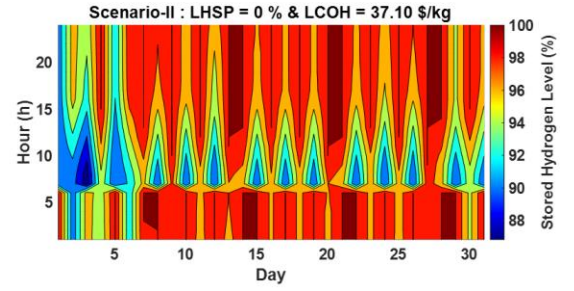
a) Scenario-I (Full year)



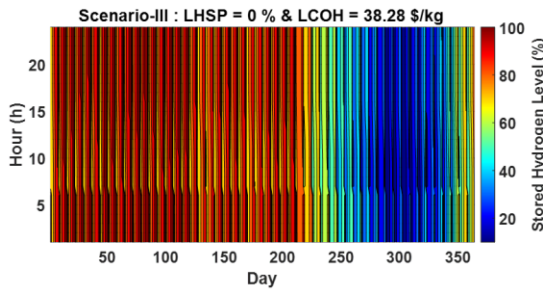
b) Scenario-I (January)



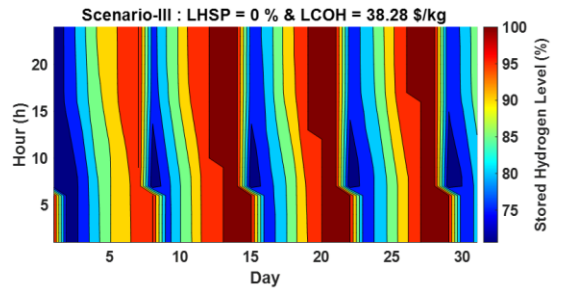
c) Scenario-II (Full year)



d) Scenario-II (January)



e) Scenario-III (Full year)



f) Scenario-III (January)

Figure 3.30 D-maps of the state of charge of the zero level of loss of hydrogen supply probability (LHSP) for: a) Scenario-I (Full year), b) Scenario-I (January), c) Scenario-II (Full year), d) Scenario-II (January), e) Scenario-III (Full year), f) Scenario-III (January)

To meet total annual hydrogen load of 260 kg with daily refueling process, the hydrogen produced by 6 kW electrolyzer system is depicted in Fig. 3.31 per month for tank size of 14 kg since it gives LHSP of zero. It is clearly shown that, the monthly produced hydrogen is around 22 kg from January until July then it becomes below 20 in August, September and October. This behavior can be understood by noticing the relation between electrical load and excess energy which is also shown in the same figure. To explain, in the months of August, September and October, the electrical load is high such that most of the generated renewable energy is used to meet the electrical demand, therefore, significant reduction in excess energy occurs. As a result of that, the hydrogen production is decreased also in these months because hydrogen production is influenced directly by any fluctuations in the amount of excess energy.

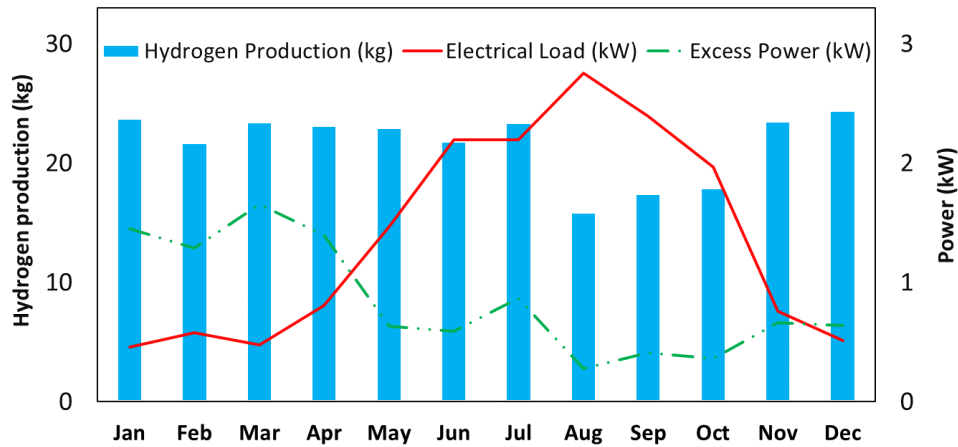


Figure 3.31 Hydrogen production in kg/month for one full year and the relation between electrical load and excess power.

It is also important to investigate the effect of hydrogen tank size on the loss of hydrogen supply probability and cost of hydrogen for scenario-I. In Fig. 3.32a, hydrogen accumulation in 1 kg storage tank is shown. It is clearly shown that hydrogen level in the tank fluctuates between the maximum and the minimum limits during the year. This behavior can be justified by noticing that the LHSP is 0.087% for 1 kg tank size which means that the hydrogen reaches the minimum tank level during 8.7% of the whole year hours. In addition, since the tank size is only 1 kg and the hydrogen daily demand for this scenario is 0.8 kg/day, most of the stored hydrogen is utilized and the tank is refilled every day. For 2 kg tank size (Fig. 3.32b), the hydrogen accumulation level is mostly between 60-100 %. However, during high electrical load month (August, September and October), the hydrogen level in the tank approaches the minimum tank limit which is indicated by the LHSP of 5.6 %. For tank size of 5 and 10 kg (Figs. 3.32c and 3.32d), the LHSP is reduced to 4.5 and 2.7 % which indicates significant reduction in the loss of supplying the hydrogen load.

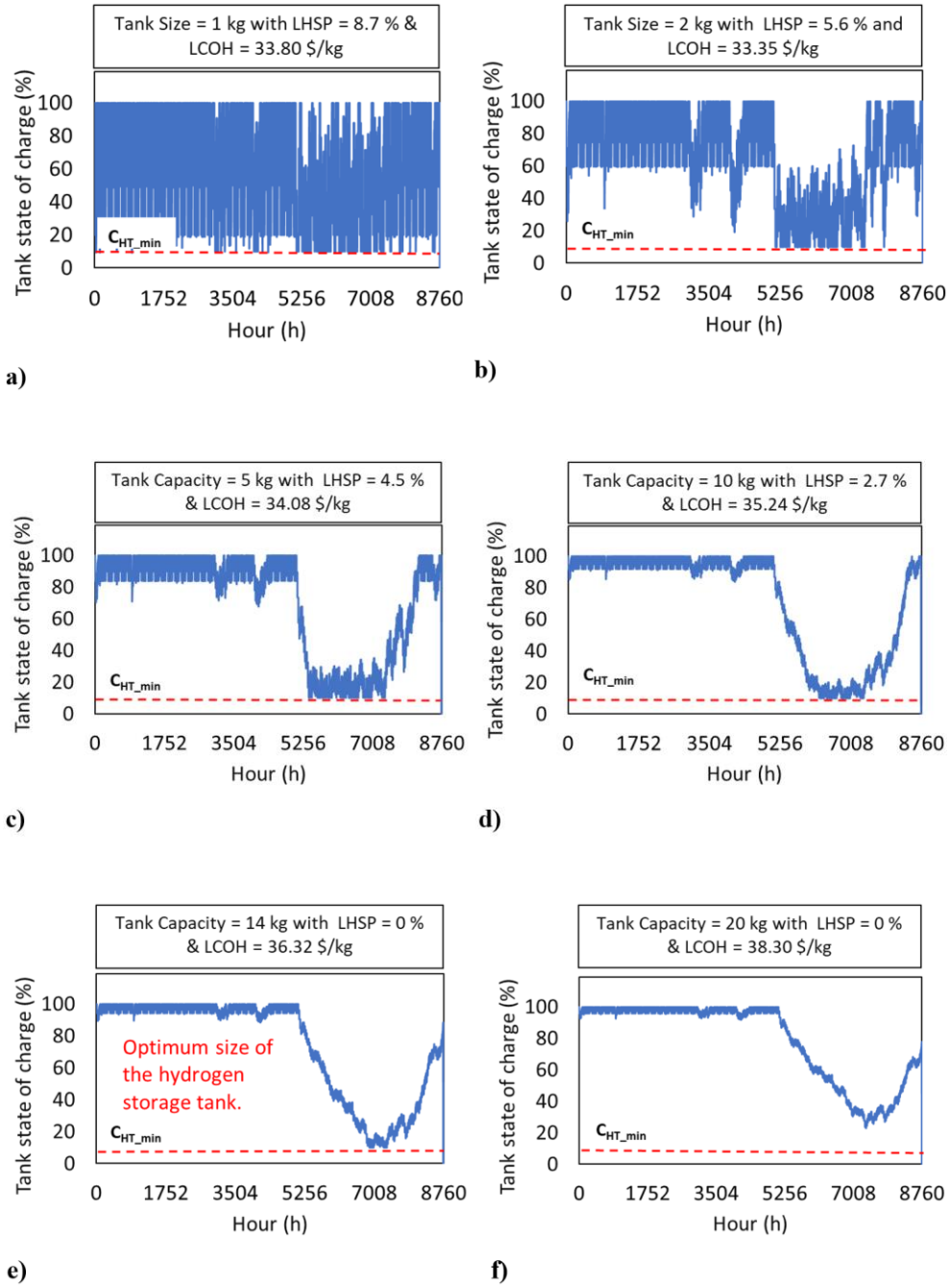


Figure 3.32 Scenario-I for different tank sizes and the corresponding loss of hydrogen supply probability (LHSP) and hydrogen cost.

However, levelized cost of hydrogen is increased to 33.80 and 33.35 \$/kg for these two sizes, respectively. Keep increasing tank size, LHSP is observed to reach 0 with tank size of 14 kg and onwards. In Fig. 3.32e, the hydrogen level is barely above the minimum limit of the tank which gives acceptable results in terms of LHSP and LCOH. However, in Fig. 3.32f, the tanks size of 20 kg shows acceptable LHSP value but with higher cost of (LCOH = 38.30 \$/kg).

To demonstrate the environmental effect, the integrated residential house with hydrogen vehicle involved with zero-emission. The electricity demand is totally met by the hybrid solar/wind system and the hydrogen fuel is produced by electrolyzer by utilizing the hybrid system excess energy. In the Kingdom of Saudi Arabia, the conventional energy system emission factor is 0.7956 (kgCO₂/kWh) [202]. Therefore, for a residential house consumes 12140 kWh/year, the total annual CO₂ emission is 9.66 (Tons/year) which will be avoided using the proposed system.

3.2.4.3 Comparison with Results Presented in the Literature

In this section, the findings of the current research work are compared with the results published in related research studies [17,19,140,166] in terms of cost, reliability and environmental impact. Due to the variation in the hybrid system components and load requirements, the related total costs are different. However, Levelized cost of electricity (LCOE) and levelized cost of hydrogen (LCOH) are appropriate criterions for comparison.

In these related research works, it is observed that LCOE ranges between 0.3 to 1.2 \$/kWh, whereas LCOH ranges between 36 to 99 \$/kg. The costs of the current study (LCOE = 0.593 \$/kWh and LCOH = 36.32 \$/kg) shows significant alignment with the other research works. In addition, the reliability is studied in terms of loss of power supply probability (LPSP) in [17,166] and in terms of power capacity shortage (CS) in [19,140]. In the current study, the power supply reliability is guaranteed in terms of LPSP. However, additional novel indicator is developed to guarantee the reliability of hydrogen supply which is loss of hydrogen supply probability (LHSP). The environmental analysis shows that, using off-grid hybrid renewable energy system produces zero CO₂ emission. However, in some papers [19], there is a CO₂ emission released when diesel generator is used. The system developed in the current study is a zero-emission system. In addition, 9.66 Ton/year of CO₂ will be avoided by the developed system. Based on the comparison, the findings of the current study shed light on the system's viability.

CHAPTER 4

Hybrid Solar/Wind Systems for Hydrogen Refueling Stations

In the Kingdom of Saudi Arabia (KSA), the energy demand is met with fossil fuels and oil consumption is increasing with annual rate of 7 % which makes KSA among the biggest five countries in oil consumption worldwide [139]. As a result, CO₂ emissions have experienced dramatic increase with average annual rate of 5.85 % which makes KSA as one of the leading CO₂ emitters [140,203]. It was reported by [204] that, the prime cause behind such a substantial increase in energy consumption is thought to be the rapid increase in the number of automobiles. Transportation sector's CO₂ emissions in Saudi Arabia are quite high when compared to emissions from other sectors. In the Arabian Gulf region, the transportation sector is strongly dependent on fossil fuels and accounts for 32 % of the total energy demand which heavily contributes to the air pollution which necessitates the electrification of the transport sector [205,206].

To accelerate the sustainable development in the country, the government has launched 2030 Vision through which it has initiated several projects to exploit the renewable resources and established research centers to support the renewable energy studies in the country [142]. According to the KSA 2030 Vision, the government aimed to increase the share of renewable energy in power generation to 50 % by 2030 [207] and to reduce CO₂ emissions by 130 metric tons annually to achieve net-zero carbon emissions by 2060 [141].

Recently, KSA has shown interest to become a leading player in the global hydrogen fuel market. Hydrogen production will allow KSA to become less reliant on oil while simultaneously providing a source of revenue from international purchasers [145]. In August 2020, KSA has announced that it is planning to build the biggest \$5 billion hydrogen plant which will be powered by 4 giga-watt solar/wind energy with daily throughput of 650 tons of green hydrogen fuel. Furthermore, the Saudi government has announced also that it will use a large portion of one of the biggest natural gas projects in the world, Jafurah plant, to produce blue hydrogen from natural gas where the production of blue hydrogen is expected to begin in 2024 [158]. In January 2022, Saudi Aramco has announced that it plans to produce hydrogen driven vehicles in the country to facilitate CO₂ reduction in the transportation sector [159]. In June 2019, Saudi Aramco has inaugurated the first and only hydrogen refueling station in the KSA with cooperation with Air Products company. The station is developed to supply the hydrogen demand of small fleet of six FCEVs [160].

Based on the literature review, it is notable that, no research work has considered the variation in hydrogen refueling demand based on people behaviour in different areas. In the Saudi context, no research work study has investigated the viability of developing hydrogen refueling station in the country. Taking into account both of these points, in this paper, a techno-economic and environmental study is carried out to investigate the feasibility of introducing on-site hydrogen refueling stations in the Kingdom of Saudi Arabia. The novelty of this research work comes from the consideration of hydrogen refueling demand in different areas with different human activities and its effects on the optimum size of the hydrogen refueling station.

In this chapter, a detailed mathematical modelling of an on-site hydrogen refueling station will be discussed. The schematic diagram of the hydrogen refueling station as given in Fig. 4.1 shows that it consists of power supply sources (solar photovoltaics and wind turbines), electrolyzer, compressor, hydrogen tanks and cooling and dispensing unit. To predict the performance of such renewable energy system, the performance of each component needs to be modelled separately [171].

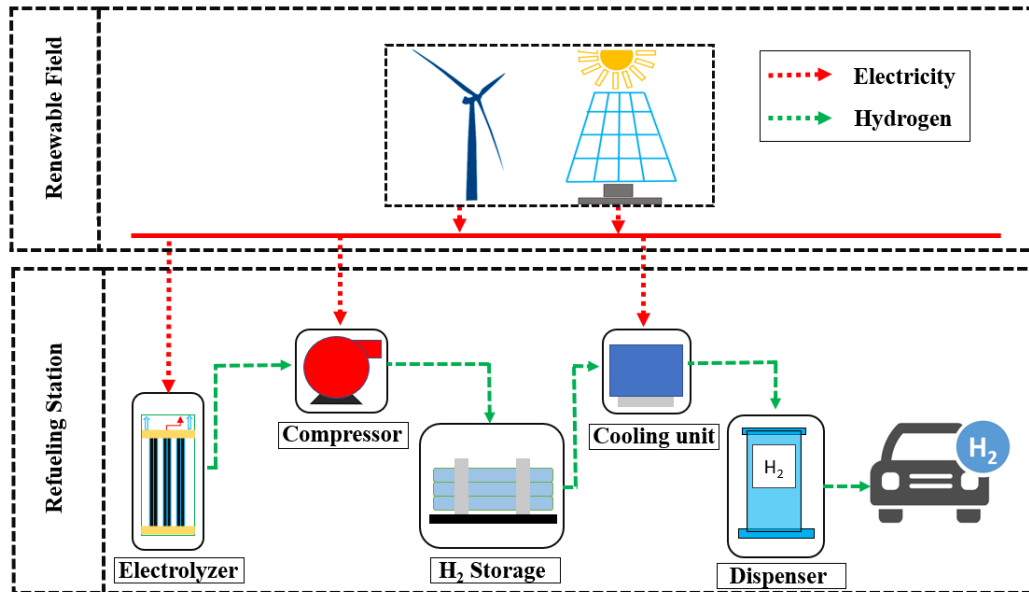


Figure 4.1 Schematic diagram of the proposed refueling station

Mathematical models of the PV array, wind turbine, electrolyzer and hydrogen storage are as provided in chapter 3. However, models of compressor, cooling unit and dispenser will be discussed in the following paragraphs.

Hydrogen fuel cell vehicles are equipped with on-board hydrogen tanks that store hydrogen at 35 MPa or 70 MPa [87] while hydrogen is produced via PEM electrolyzer at 1.4 MPa [128]. Therefore, a compressor is needed to increase hydrogen pressure to a higher level that is suitable for storage and refueling [135]. The power consumption by a hydrogen compressor is calculated by [125,208][209]:

$$P_{comp}(t) = \frac{k}{k-1} \times \frac{R_{H_2} \times T_{inlet}}{\eta_c} \times \left(\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right) \times \frac{\dot{H}_{EZ}(t)}{3600} \quad (4.1)$$

where (P_{comp}) is the compressor electricity consumption, (k) is the ratio of specific heats (1.4), (R_{H_2}) is the hydrogen gas constant (4.12 kJ/kgK), (T_{inlet}) is the hydrogen temperature at the inlet of the compressor (298 K), (P_1) and (P_2) are pressures of the gaseous hydrogen entering and leaving the compressor and (η_c) is the compressor efficiency.

A dispenser unit is used to inject the compressed gaseous hydrogen fuel into vehicle's tank through 35 or 70 MPa nozzles [92][93]. Because fast hydrogen filling increases hydrogen temperature, SAE J2601 refueling protocol suggested to chill hydrogen temperature before dispensing to -40 °C to avoid overheating of the dispensing hose and the vehicle's tank [93,94]. Based on experimental data, the power consumed via hydrogen cooling can be expressed as [209,210]:

$$P_{cooling}(t) = 0.33 \times H_{FCEV}(t) \quad (4.2)$$

where $P_{cooling}$ represents the pre-cooling unit power consumption.

4.1 Study Area and Load Profile

In this work, hydrogen refueling profiles of FCEVs in Saudi Arabia is developed according to current refueling profiles of conventional gasoline refueling vehicles. The gasoline refueling data is collected in four various locations under different human behavior which are as shown in Fig. 4.2 include: industrial area, residential area, highway area and tourist area. Because people availability in these areas differ, refueling events differ as well. To develop hydrogen refueling profiles, the number of vehicles visiting each refueling station is observed hourly for one full week, and the daily profile for each station is developed in terms of number of vehicles per hour. Then, the station's occupancy fraction is obtained for each hour by dividing the number of vehicles visiting the station that hour by the maximum number of vehicles. The average occupancy profiles per working days and weekend days are developed as shown in Fig. 4.3.



Figure 4.2 Map of Saudi Arabia shows the location under study.

Station 1 is located in industrial area where the peak hour occurs around hour 10 in the morning, then, the number of vehicles visiting the station in this area decreases. However, in weekend days, only few vehicles visit the refueling station with peak hour in the early morning. In average, in the industrial area, one peak occurs in the morning. Station 2 is located in residential area. In working days, people usually visit the refueling stations in the morning when they are going to work and at night during their return. In the weekend days, the number of vehicles visiting the refueling station becomes small in the morning. In average, in the residential areas, two peaks occur during the whole day. One peak occurs in the morning around hour 9 and the second peak is shown at night around hour 19. Station 3 is located near highway. In this area, peak hours are mainly at night. However, there is a small peak in the morning around 10. In average, two peaks are shown in the highway area with the morning peak disappears in the weekends. Unlike residential area, morning peak

in the highway area is lower than residential area in the working days while in the weekend days the night peak in the highway is higher than residential area. Station 4 is located in a costal tourist area which shows high occupancy profiles during workdays and weekend days because this area is always busy with visitors with peak hours at night.

Weather data of the studied location is shown in Fig. 4.4 It is observed that, the studied area is rich with renewable energy resources. To explain, solar radiation (Fig. 4.5a) is varying from 3.33 kWh/m²/day in January and December (winter) to 7.8 kWh/m²/day in June and July (summer) with annual average of 5.66 kWh/m²/day and average annual clearness index of 0.62. As shown in Fig. 4.5b, the monthly average values of wind speed vary within the range of 2.6 – 4.6 m/s measured at anemometer height (10 m). Highest wind speed values are observed in January and July while the lowest values are in May and October with annual average of 3.55 m/s. In Fig. 4.5c, the average monthly temperature values vary within the range of 18 – 25 °C in winter months while in summer months it varies around 35 °C.

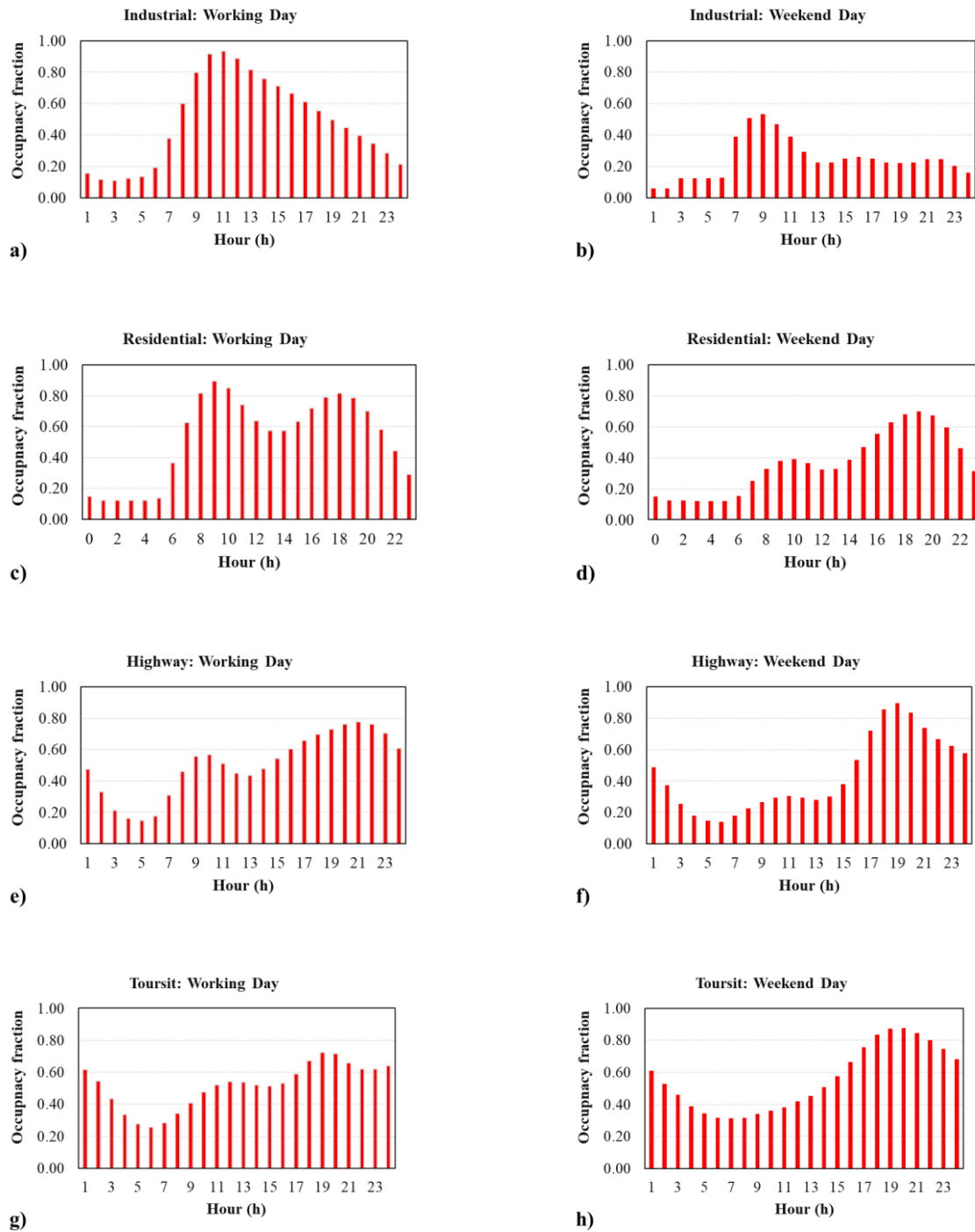


Figure 4.3 Station's occupancy profiles in working days for a-b) Industrial area, c-d) Residential area, e-f) Highway area and g-h) Tourist area.

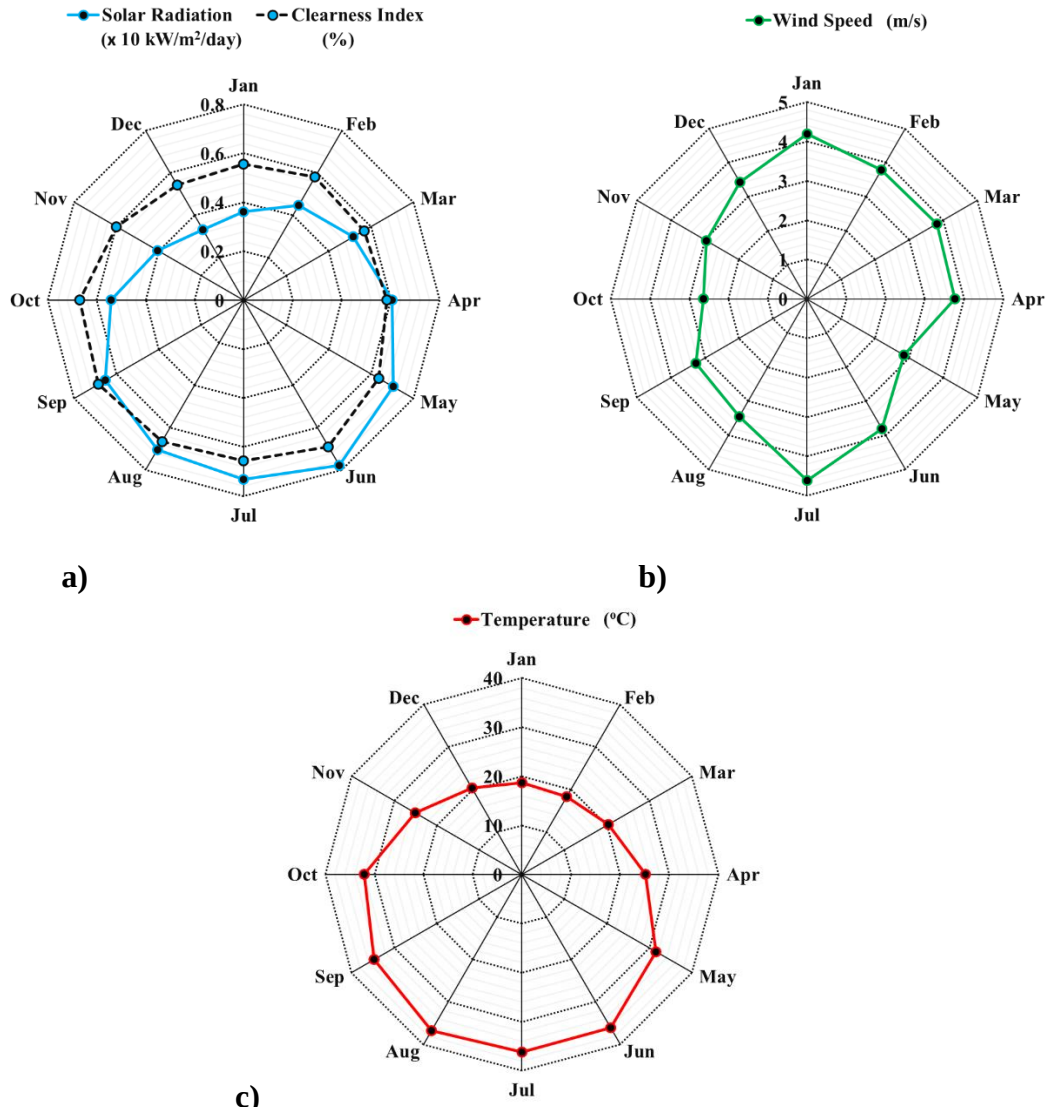


Figure 4.4 Weather data of the studied location. a) Monthly average daily solar radiation in (kW/m²/day), b) Monthly average wind speed at hub height in (m/s) and c) Monthly average temperature in (°C).

4.2 System Sizing Strategy

The main goal of this study is to determine the optimum size of hydrogen refueling station. The feasible configurations that satisfy hydrogen demand will be sorted and ranked based on the minimization of NPC and the configuration with the lowest NPC will be considered as the optimum size.

The system performance is subjected to several constraints such as: allowable components' sizes, minimum and maximum limits of storage tanks, electricity and hydrogen balance, excess energy fraction and renewable energy fraction. The components sizes are restricted between the allowable minimum and maximum size of the component as expressed by:

$$N_{i_{min}} \leq N_i \leq N_{i_{max}} \quad (4.3)$$

where N_i refers to number of units of component i , $N_{i_{min}}$ is the minimum allowable capacity of component i and $N_{i_{max}}$ is the maximum allowable capacity.

The hourly state of charge of hydrogen tanks is governed by the following constraints:

$$HT_{min} \leq HT(t) \leq HT_{max} \quad (4.4)$$

where the subscripts min and max refers to minimum and maximum limits of the hydrogen tanks, respectively. During hours of low renewable production, hydrogen tanks are discharged to meet the demand. If hydrogen tanks reach the minimum allowable limit, the

system fails to meet the demand and the hourly deficiency in hydrogen is given by Eq. (2.34) with slight modification as expressed by [211]:

$$H_{loss}(t) = H_{FCEV}(t)\Delta t - (H_{EZ}(t)\Delta t + HT(t - 1) - HT_{min}) \quad (4.5)$$

where $H_{shortage}(t)$ represents the hourly shortage in hydrogen supply. In this case, hydrogen supply reliability constraint is expressed in terms of Loss of Hydrogen Supply Probability (LHSP) which given as [211]:

$$LHSP = \frac{\sum_{t=1}^{8760} H_{loss}(t)}{\sum_{t=1}^{8760} H_{FCEV}(t)} \quad (4.6)$$

The LHSP is set to zero, in this paper, to ensure high reliability in the hydrogen supply.

4.3 Results and Discussion

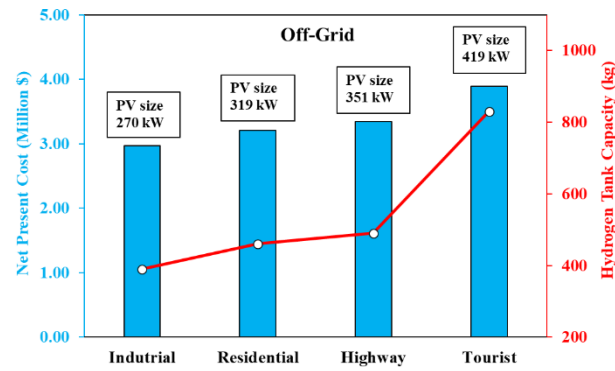
In this study, the optimum configuration of a hydrogen refueling station powered by a hybrid solar/wind renewable energy system is determined and the station's performance is simulated via MATLAB software. The station is designed to meet the hydrogen fuel demand in four different areas: industrial, residential, highway and tourist area. Two renewable energy fractions are considered: (1) RF = 100%, which means that the hydroegn refeuling station is totally powered by the hybrid solar/wind renewable energy system and (2) RF = 75 % and grid penetration of 25 % in cosnidered in this case. Ahe beginning of the optimization process, only two units of wind turbines are used (each with capacity of 300 kW) due to space limitations, electrolyzer size is fixed to 240 kW. Then, sizes of the

PV array and hydrogen tanks are varied. The configurations that satisfy the demand with (LHSP = 0) are sorted based on the total NPC.

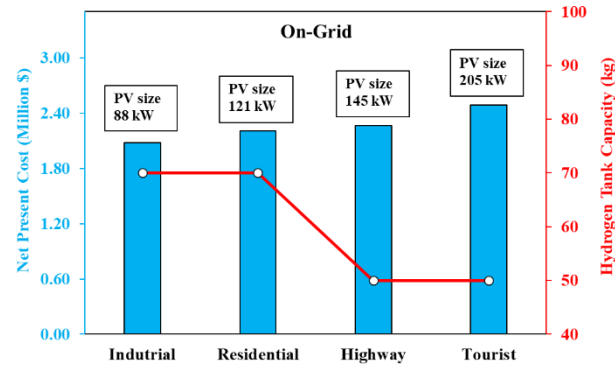
4.3.1 Energy Conversion Results

The optimization results are shown in Figs. 4.5a and 4.5b for off-grid and on-grid cases, respectively. In off-grid case, the total NPC of the feasible configurations is 2.973, 3.203, 3.345 and 3.895 M\$ for the industrial, residential, highway and tourist area, respectively, whereas in the on-grid case, NPC becomes 2.080, 2.203, 2.266 and 2.487 M\$ for the industrial, residential, highway and tourist area, respectively. It can be implied from Fig. 4.5 that; the industrial area gives the minimum sizes (Off-grid: PV= 270 kW and HT= 390 kg, On-grid: PV= 88 kW and HT= 70 kg) among the four areas. This can be understood by noticing that most refueling events in the industrial area occur during daytime hours (Fig. 4.3). This refueling behaviour in the industrial area results in small sizes of the PV array and hydrogen tanks because the demand is met directly during the availability of solar energy. On the other hand, the largest sizes of the PV array and hydrogen tanks are recorded in the tourist area's station (Off-grid: PV= 419 kW and HT= 830 kg, On-grid: PV= 205 kW and HT= 50 kg). In this area, high refueling demand is shown during both daytime hours and night hours which requires large PV size as well as large hydrogen tank size to store sufficient hydrogen to meet the demand when there is low production. In the residential and highway areas, the refueling events are almost close to each other. Unlike

highway area, it is observed that, in the residential area, few refueling events occur after midnight which reduces the demand. As a result of that, the size of the refueling station in the highway area (Off-grid: PV= 351 kW and HT= 490 kg, On-grid: PV= 145 kW and HT= 50 kg) is larger than residential area (Off-grid: PV= 319 kW and HT= 460 kg, On-grid: PV= 121 kW and HT= 70 kg).



a)



b)

Figure 4.5 Optimization results for a) Off-grid system and b) On-grid system.

Fig. 4.6 shows the contribution of solar and wind to the total energy production for each location. It should be noted that, two wind turbines are used, therefore, the contribution of wind turbines will differ according to the solar array size in each location. Smallest solar contribution of 47.82 % is shown in the industrial area because the peak demand occurs during daytime hours and the production of PV array can cover the demand directly while the wind turbines contribute with 52.18 %. In contrast, due to the high demand in the tourist area, the largest PV contribution is shown for this area with 58.71 % while the wind is the smallest with 41.29 %. In the residential area, the PV and wind contributions are 51.98 % and 48.02 %, respectively whereas in the highway area the PV array contributes with 54.36 % and wind turbines contributes with 45.64 % to the total renewable energy production. In the grid-connect case, as shown in Fig. 4.7, considerable reduction in PV array contribution is noticed which reach 19.12, 24.14, 27.35 and 34.01 % for the industrial, residential, highway and tourist areas, respectively. Grid contribution is between 16.85 and 17.10 % while wind shares the highest in all stations.

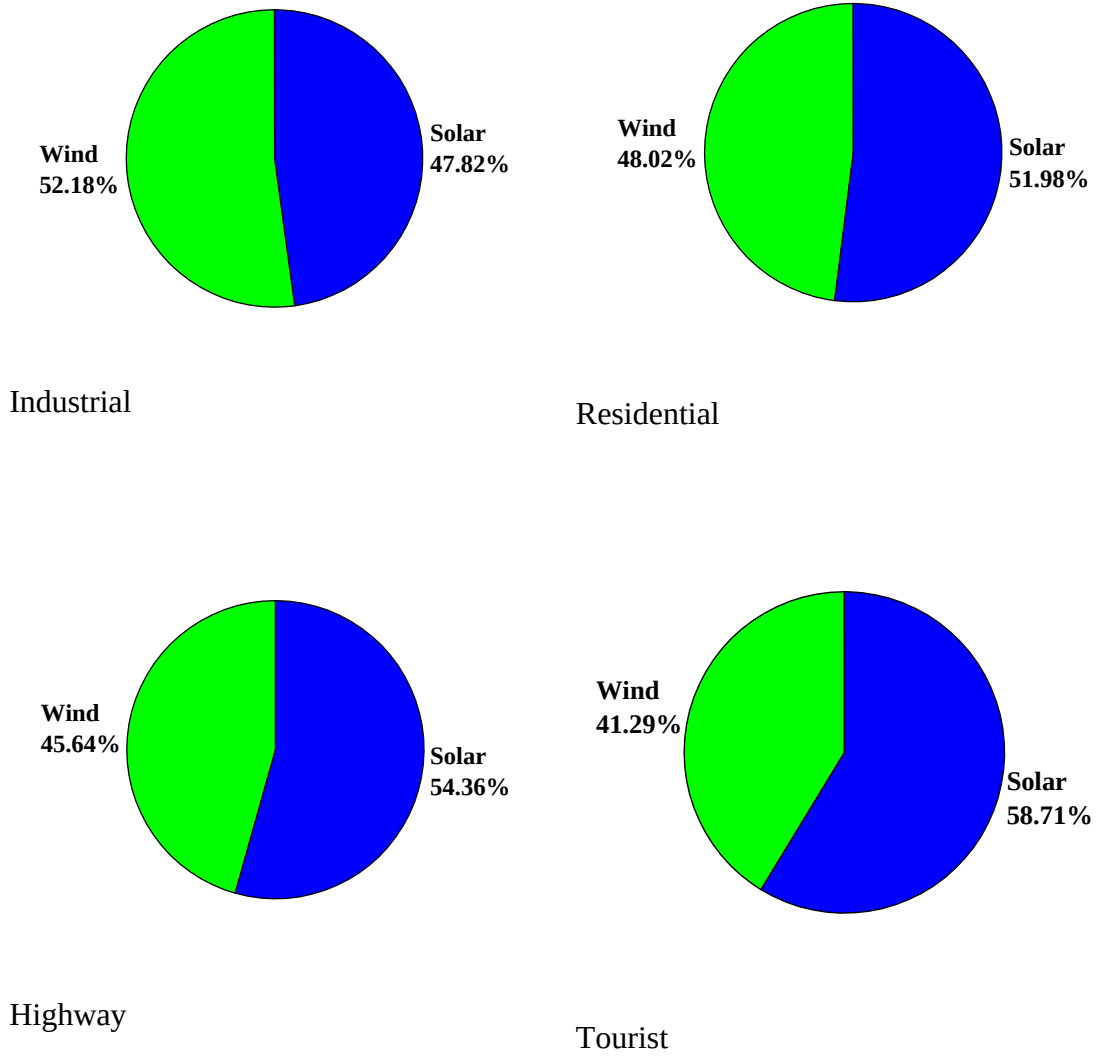


Figure 4.6 Contribution of solar and wind to the total renewable energy production (Off-grid).

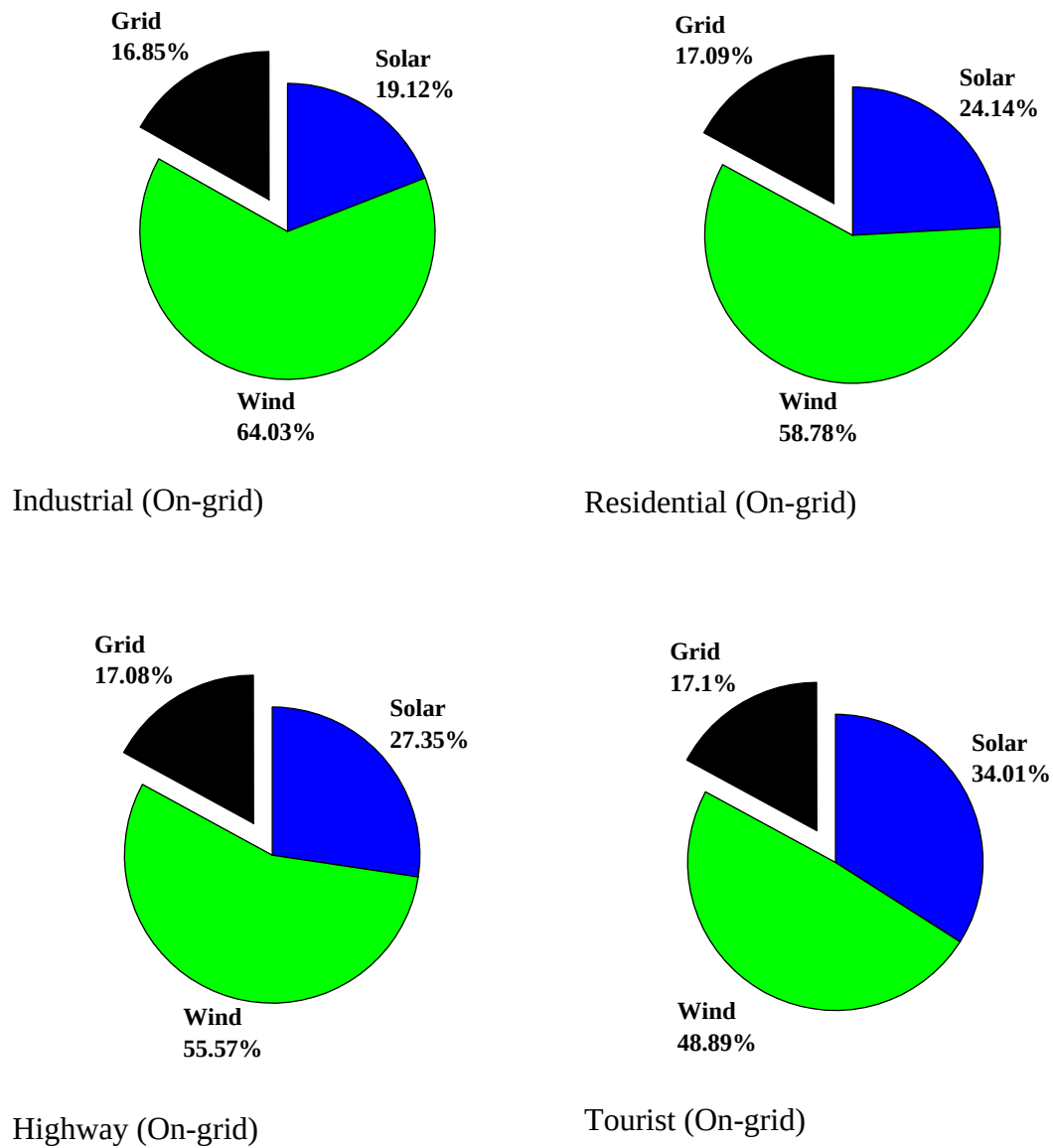
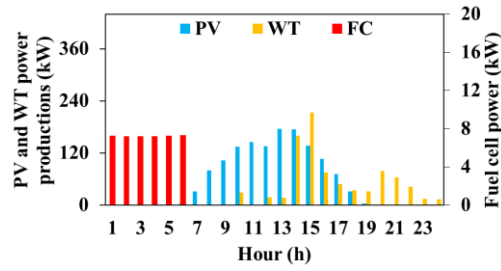


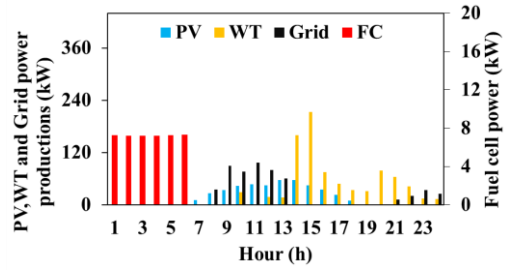
Figure 4.7 Contribution of solar and wind to the total renewable energy production (On-grid).

Fig. 4.8 shows power production in all four stations for both off-grid and on-grid cases in the summer solstice day (21st of June). In off-grid case, the PV array production, wind

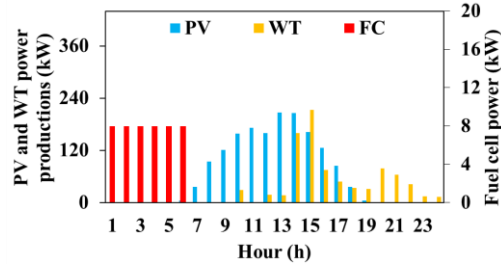
turbine production and fuel cells production have almost similar profiles in all four stations. However, PV production increases from industrial to tourist areas slightly due to variation in PV sizes. In the case of grid-connected system, a significant reduction in the PV production is observed and the energy shortage is compensated via grid electricity. Fuel cells also operate in this case to run the electric load during early morning hours. In the industrial area (Fig. 4.8b), electricity is drawn from grid during daytime hours while small amount of grid power is drawn at night. In the residential and industrial areas (Figs. 4.8d and 4.8e), grid energy is drawn during morning and at night as well. It is important to notice that, in the tourist area (Fig. 4.8h) solar and wind production are enough on this day to satisfy the demand and no grid power is needed.



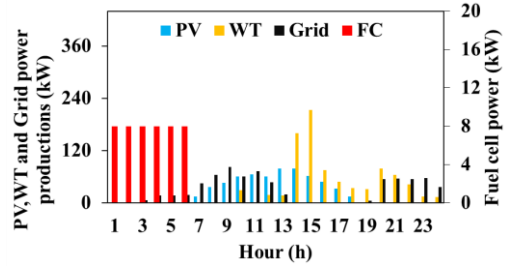
a) Industrial area (Off-grid)



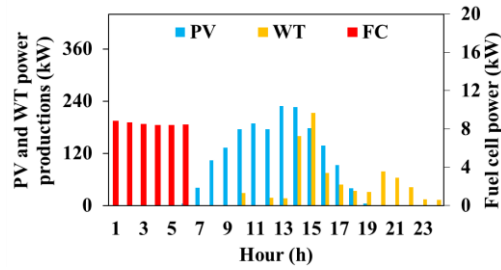
b) Industrial area (On-grid)



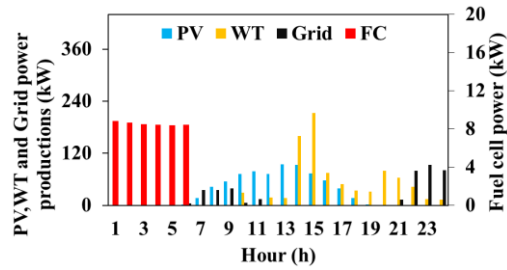
c) Residential area (Off-grid)



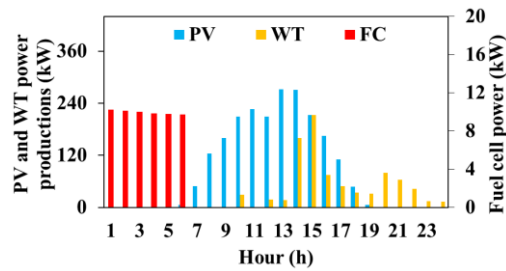
d) Residential area (On-grid)



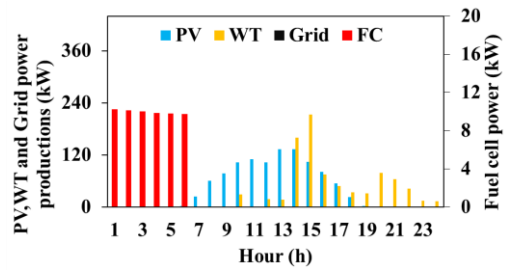
e) Highway area (Off-grid)



f) Highway area (On-grid)



g) Tourist area (Off-grid)

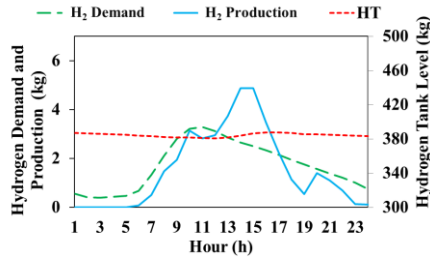


h) Tourist area (On-grid)

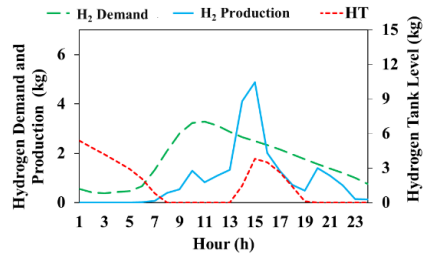
Figure 4.8 Hourly energy production in the summer solstice day (21st of June) in the four locations for Off/On-grid system.

The hydrogen demand, production and storage are shown in Fig. 4.9 for the summer solstice day (21st of June).

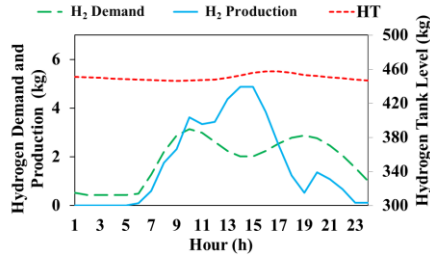
The effects of people refueling behaviour in different locations are reflected obviously in this figure. In off-grid cases, (Figs. 4.9a and 4.9c, 4.9e and 4.9g), all stations are always maintained with high storage capacity to ensure zero value of hydrogen supply probability. It is significant to note that in off-grid cases, hydrogen production profiles follow the hydrogen demand profiles as well as the profiles of solar and wind availability as previously shown in Figs. 4.8. However, in the on-grid cases (Figs. 4.9b and 4.9d, 4.9f and 4.9h), the hydrogen storage capacity reach the minimum tank's level in all stations because the loss of hydrogen supply probability is not zero and grid power is allowed to cover the power shortage.



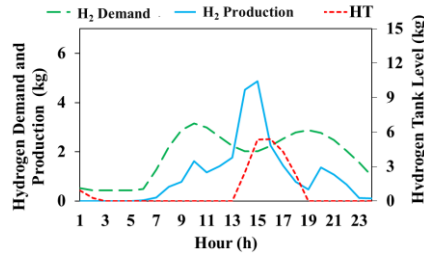
a) Industrial area (Off-grid)



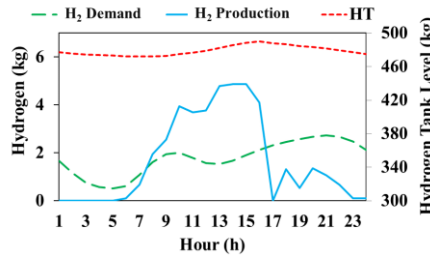
b) Industrial area (On-grid)



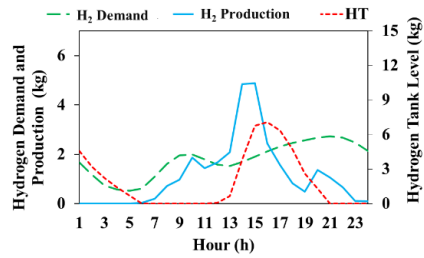
c) Residential area (Off-grid)



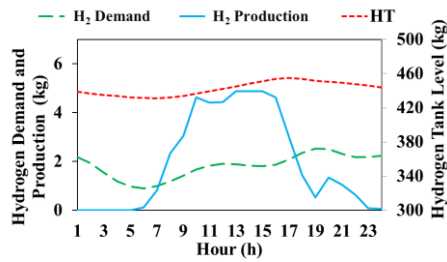
d) Residential area (On-grid)



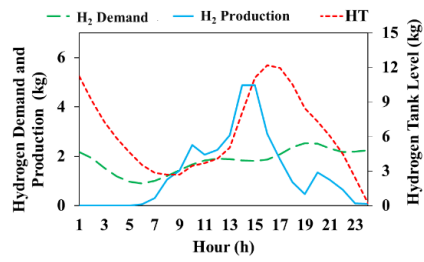
e) Highway area (Off-grid)



f) Highway area (On-grid)



g) Tourist area (Off-grid)



h) Tourist area (On-grid)

Figure 4.9 Hourly hydrogen demand and production in the winter solstice day (21st of June) in the four locations for Off/On-grid system.

4.3.2 System Economical Results

The levelized cost of hydrogen (LCOH) of the optimized hydrogen refueling stations in the four studied areas are shown in Fig. 4.10. It is observed that, highest LCOH is observed in the off-grid case in the tourist area with a value of 9.90 \$/kg while it is the lowest in on-grid case with a value of 7.81 \$/kg because in the on-grid case the storage size is reduced dramatically, hence, the costs as well. In on-grid cases, LCOH is the highest in the industrial area with a value of 8.16 \$/kW while in the off-grid it has a middle value of 9.62 \$/kg. Middle LCOH values are shown in the residential and highway areas.

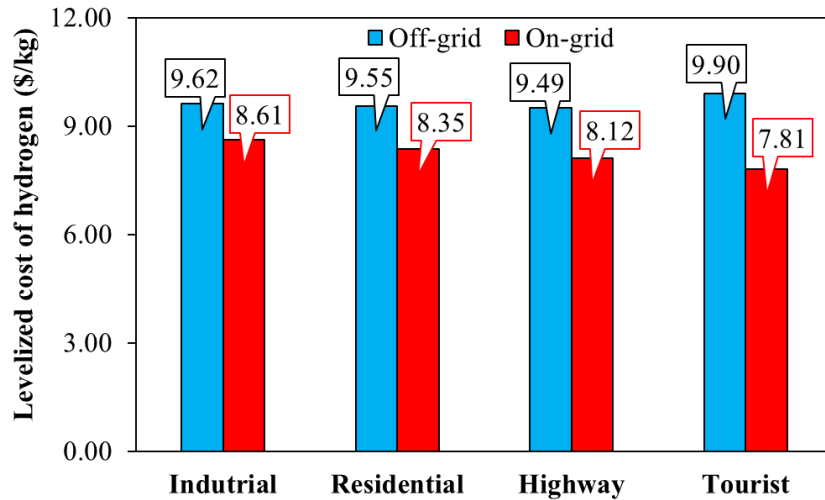
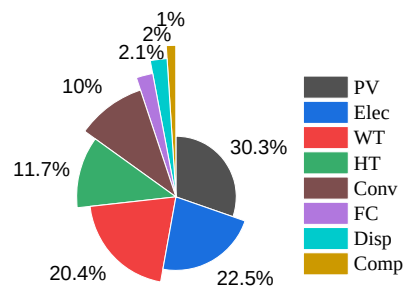
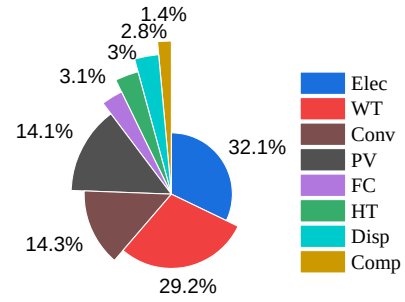


Figure 4.10 levelized cost of hydrogen of the optimum configurations.

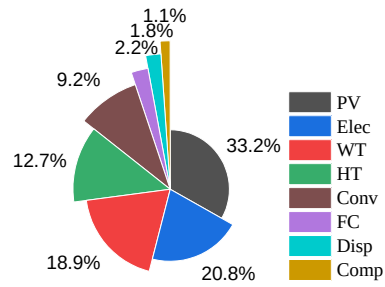
Fig. 4.11 shows the contribution of each component on the total NPC of the system. In off-grid cases, Figs. 4.11a, 4.11c, 4.11e and 4.11g, it is observed that, the highest three contributors to the total cost are the PV array, the electrolyzer and the wind turbine, in the industrial, residential and highway areas. However, hydrogen tanks contribute more than electrolyzer and wind turbines in the tourist. In the on-grid cases, (Figs. 4.11b, 4.11d and 4.11f and 4.11h), electrolyzer costs dominate the total NPC costs in the industrial, residential and highway areas while the PV array dominates the NPC costs in the tourist area.



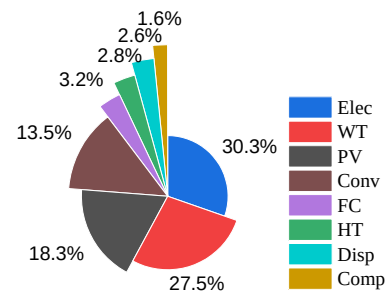
a) Industrial (Off-grid)



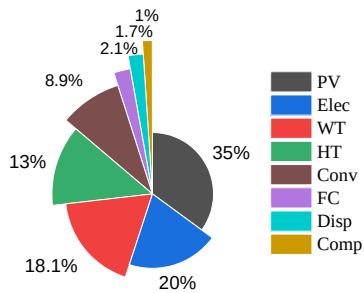
b) Industrial (On-grid)



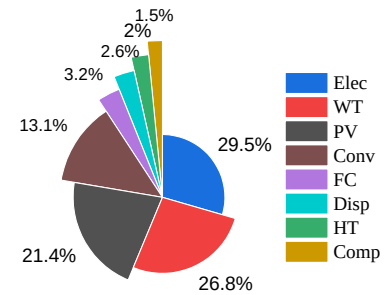
c) Residential (Off-grid)



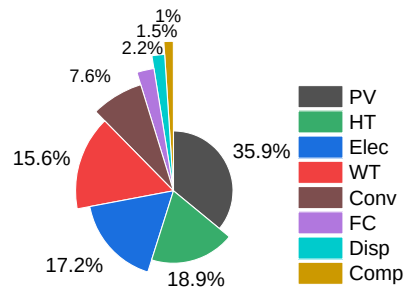
d) Residential (On-grid)



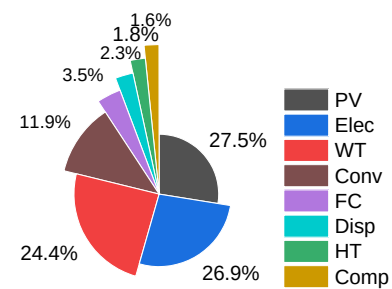
e) Highway (Off-grid)



f) Highway (On-grid)



g) Tourist (Off-grid)



h) Tourist (On-grid)

Figure 4.11 Share of each component from the total NPC.

4.3.3 System Environmental Results

The utilization of hydrogen as a clean fuel in the transportation sector gives significant environmental benefits. Replacing gasoline with hydrogen leads to save large amounts of CO₂ emissions as the utilization of hydrogen as fuel in vehicles produce water as a by production. In this case, the amount of saved CO₂ emissions is determined by Eq. (2.40) with slight modification. Hence, Eq. (2.40) becomes [129,212]:

$$CO_{2_{annual}} = M_{gasoline} \times EF_{CO_2} \quad (4.7)$$

where $CO_{2_{annual}}$ represents the saved amount of CO₂ emissions in (kgCO₂/year), $EF_{gasoline}$ is the CO₂ emission factor of gasoline fuel in (2.3 kgCO₂/kg-gasoline [129]), and $M_{gasoline}$ is the amount of gasoline fuel that would be replaced by hydrogen fuel (kg-gasoline) which can be expressed as:

$$M_{gasoline} = \frac{H_{ANN} \times LHV_{H_2}}{LHV_{gasoline}} \quad (4.8)$$

where H_{ANN} is the total annual mass of hydrogen produced by the hydrogen refueling station in (kg/year), LHV_{H_2} is the lower heating value of hydrogen (120 MJ/kg [183]) and $LHV_{gasoline}$ is the lower heating value of gasoline (43.4 MJ/kg [10]).

Because the refueling events are different according to people behaviour in the various locations, consequentially, amounts of saved CO₂ emission are different as well. The high amount of saved CO₂ is found to be in the tourist area which in this study (Fig. 4.12) is about 111.73 Tons/year while the lowest amount is about 87.76 Tons/year in the industrial area. In the residential and highway areas, the saved CO₂ amounts are found to be 95.52 and 100.08 Tons/year, respectively.

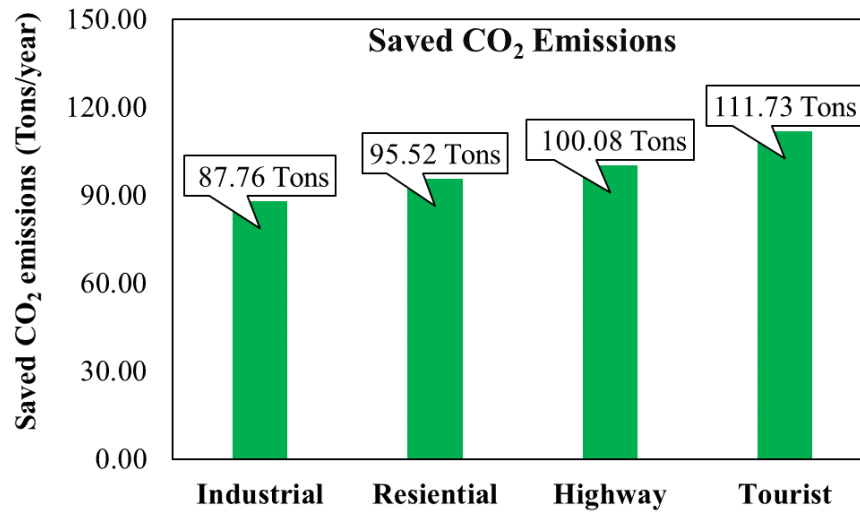


Figure 4.12 Saved CO₂ emission in off-grid cases.

CHAPTER 5

Solar Energy Potential and Load Requirements

Coordination

Environmental concerns have been increased due to the massive usage of fossil fuel in power generation as huge amounts of carbon dioxide are emitted which contributes to increase global warming [213,214]. Exploitation of renewable energy in power generation systems has shown an obvious reduction in the harmful carbon emissions and represented significant energy supply option for current and future usage [149,154]. The transition to clean energy systems that rely heavily on renewable energy resources has raised the challenge of finding adequate solutions to the mismatch between inflexible supply and inelastic consumption [215]. The stochastic renewable energy supply is often mitigated by the inclusion of auxiliary units to balance the gap between the supply and demand such as battery storage, fuel cell generators, diesel generator or grid connection. However, such solution is still a challenging due to high costs of the auxiliary units [7,216,217]. As we move away from renewable energy supply difficulties, energy consumption management becomes increasingly important in order to maximize renewable energy utilization and minimize supply issues [218–220].

Solar photovoltaic (PV) arrays are the primary source of power generation in off-grid solar-based renewable energy systems. In such a system, power is generated during the daylight hours when sunlight is available. The surplus power generation during daytime hours is stored in energy storage system such as batteries and utilized during the absent of sun to meet the night demand of electricity [221]. In the residential buildings, load peaks are observed to occur during nighttime where the normal production profiles of solar PV array do not match such load profiles. In this context, efficient energy management techniques are critical for reducing supply and demand variances [222]. There are two fundamental techniques to manage energy consumption: lowering or coordinating energy demand [223]. Furthermore, in order to overcome such issue, future electricity demand is recommended to be more closely aligned with the solar production profile. As a result, one of the primary goals to enhance solar energy utilization is to coordinate the demand with renewable generation which will be accomplished through increasing subscriber awareness of the importance of more attentive consumption patterns as well as the construction of more energy efficient buildings [224,225].

To achieve efficient coordination in off-grid solar systems, users can manage their energy consumption according to the availability of renewable energy production. Although several methods can be used to manage loads, coordinating load profiles with the production profiles of PV array production is the better choice [226]. Peak load coordination is a method of smoothing the load profile by restricting peak loads or moving certain loads to lower demand times [227]. Several benefits are secured due the utilization of this method include rescheduling demand away from crucial and daily demand peaks,

reducing total energy consumption, reducing the future demand for new power plants, reducing system cost as well as addressing the oversizing problems [228,229].

Managing energy consumption has become a key priority in grid-connected systems to avoid high peak prices. In this context, in several research studies, the applications of solar based renewable energy systems have been investigated with an emphasis on the optimal load management. Alquthami et al. [230] evaluated the load demand management of a residential house by taking into consideration the customer convenience. Yadagani et al. [231] proposed an energy management model for a residential load covered by solar PV system integrated with electric grid in order to reduce the load peak. The proposed model aims to efficiently utilizing the available solar energy generation to meet load as well as to encourage consumers to shift loads to off-peaks hours when grid prices are low. The results showed that successful load management leads to significant cost reduction. Seyed and Arezoo [232] defined an energy exchange method between smart buildings in the case of off-grid mode. The results of this showed that significant reduction in cost is achieved when lighting load is managed.

Many research studies have focused on the benefits of managing the demand of residential homes. In this sector, it is vital to identify and categorize domestic appliances in order to manage them because the varied appliances used in homes have different priorities and roles. The impact of home appliance coordination on home energy management is studied by Zhai et al. [233]. Several research works have evaluated, on the other hand, the benefits of managing other load types. For instance, Peltokorpi et al. [234] developed a new framework to manage various loads including heating and cooling. Sun et al. [235] applied

demand management techniques to a combined manufacturing and heating/cooling system. Moreover, Wang and Li [236] evaluated the feasibility of applying demand management methods on a sustainable industrial load.

Several literature surveys [237–239] showed that; the published load management related studies have focused on managing the load side with respect to grid prices with the aim of reducing electric bills. There is an obvious shortage in the research studies that focused on the load side management with respect to solar energy potential in off-grid PV systems. In this context, Kingdom of Saudi Arabia has a massive area enriched with solar resources that can serve the energy demand efficiently [163]. Because KSA is located within equatorial sunbelt, daily solar radiation rates in the kingdom are considered as one of the highest solar rates in the world for both direct solar radiation (DSR) as well as direct normal irradiance (DNI). Fig. 5.1 shows the significant solar potential in KSA which possesses average daily global radiation on horizontal surface of 5.6 to 6.6 kWh m⁻² [240–243]. Therefore, the current study aims to bridge this gap by determining the optimal size of standalone PV/battery system. Four different types of loads will be evaluated to investigate load coordination possibilities of loads with different coordination options.

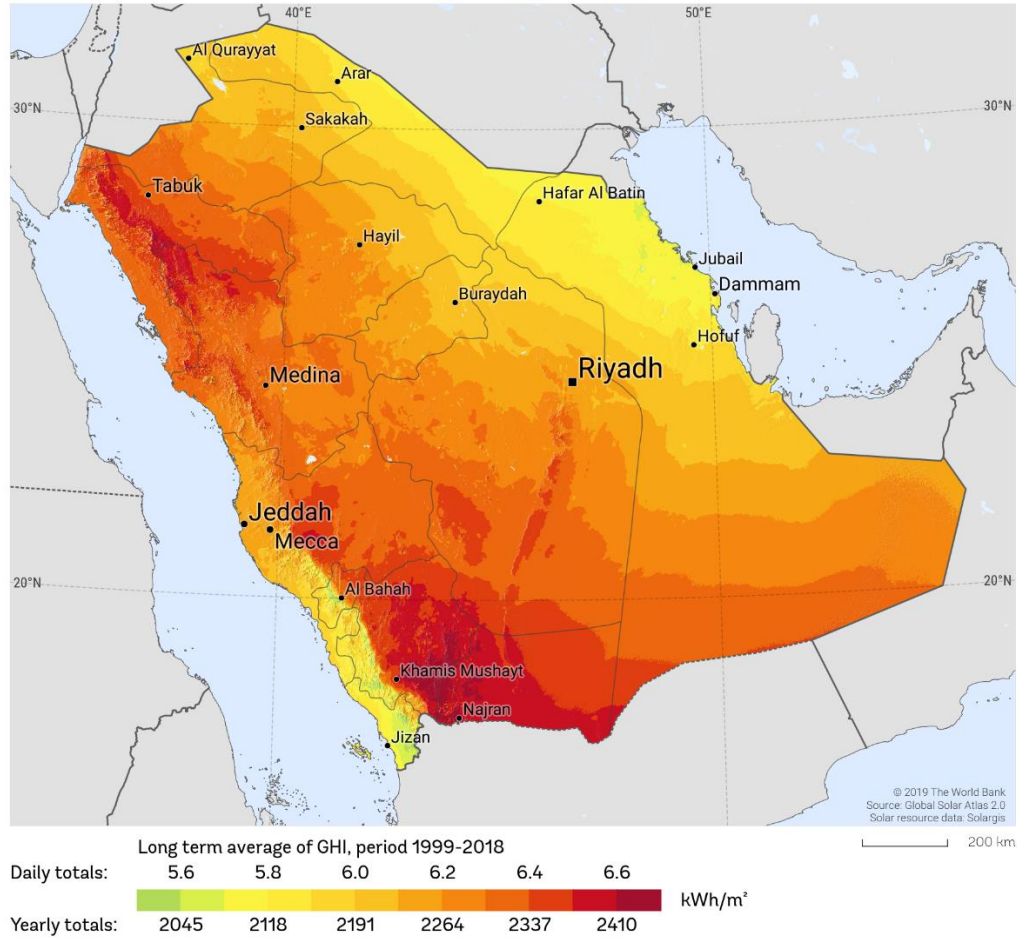


Figure 5.1 Solar energy potential in the Kingdom of Saudi Arabia [243].

These loads include street-lighting, residential, industrial and irrigation which represents non-coordinated, partially coordinated and fully coordinated loads. The reduction in cost and storage system size will be reported and compared. In this research work, techno-economic optimization study is conducted to assess the required solar energy conversion to meet the demand of different loads such as irrigation, residential, industrial, and street-lighting with load management considerations. Fig. 5.2 illustrates the schematic diagram of the studied solar system. Solar photovoltaics (PV) array is the main source of energy in

this off-grid system. The DC production of the PV array is converted into AC to satisfy the AC load via converter which is connected between DC and AC buses. Battery storage units are also incorporated to store the surplus energy production and it is discharged during low production periods to meet the demand.

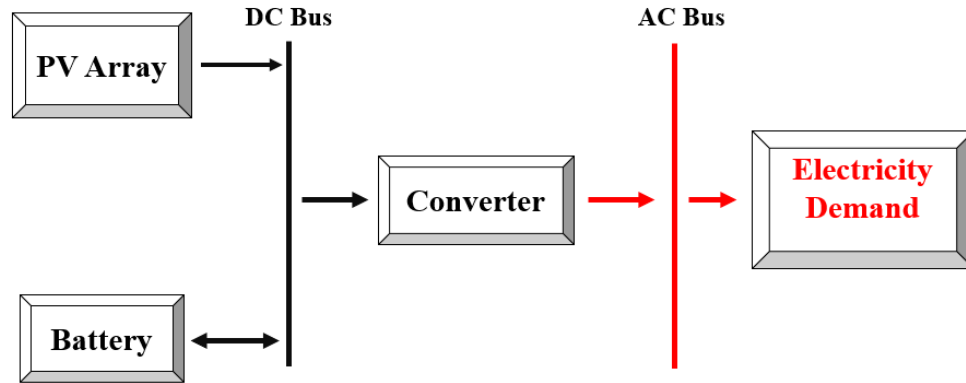


Figure 5.2 Schematic diagram of the solar and battery system.

5.1 System Location and Load Profile

Kingdom of Saudi Arabia is one of the top countries that acquires high solar energy potential. This study considers Dammam city, which is located in the eastern province of the Kingdom of Saudi Arabia (Fig. 5.1). The city is located at a latitude and longitude of $26^{\circ} 23' N$ and $49^{\circ} 59' E$, respectively. The studied area is blessed with plentiful solar radiation. The hourly solar radiation on the horizontal surface is shown in Fig. 5.3a for one full year as provided by King Abdullah city for Atomic and Renewable Energy [143]. The

average solar radiation in Dammam is 5.66 kWh/m²/day which reflects the excellent sunshine potential in this area with high solar radiation in summer months with average of 7.17 kWh/m²/day. However, in winter months, average solar radiation in Dammam becomes 3.81 kWh/m²/day. The studied area has an average clearness index of 0.620 with high value in summer that approaches 0.671 and slightly lower value in winter equal to 0.560. Temperature in Dammam is shown in Fig. 5.3b with hourly time step for one year. The area experience high temperature values in June, July, August and September with average temperature of 36 °C while in December, January, February and March temperature average drops to 19 °C.

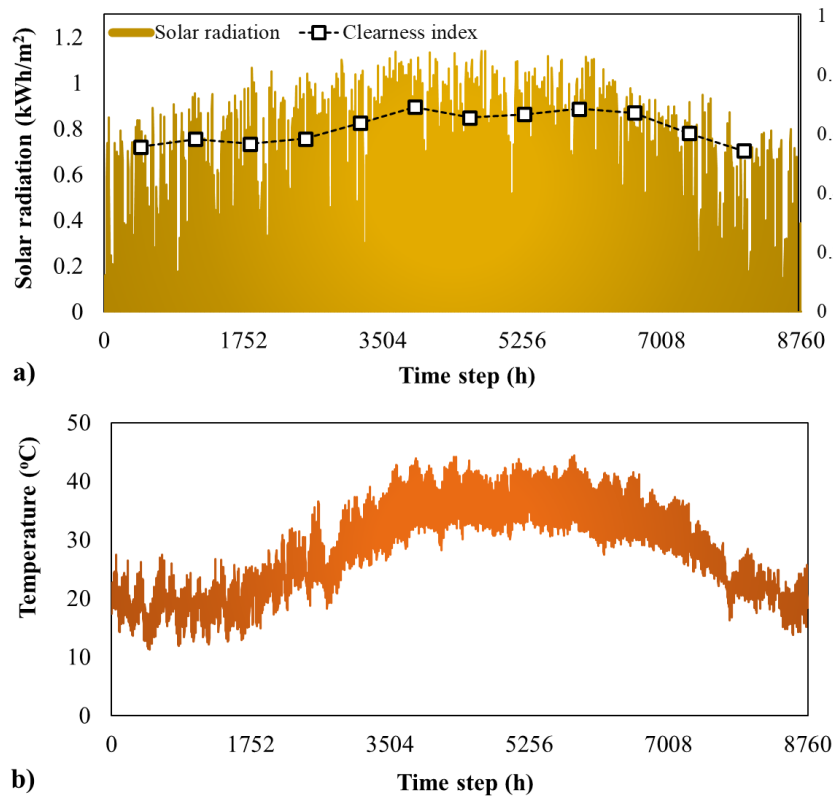


Figure 5.3 Annual solar radiation and wind speed in Saudi Arabia in hourly basis.

The present study aims to evaluate the load demand management for off-grid solar powered system and addresses the effects of such management on the system size and cost. To achieve this goal, four different load types are studied and assessed in this paper. The loads are classified as: non-coordinated load, partially coordinated load, and fully coordinated load. Table 1 shows the description of these loads in terms of appliances and devices power and classification. The energy demand is calculated as the summation of the rated power of device P_i multiplied by its operation time t_i as given by Eq. (1) [244]:

$$E_{Demand} = \sum_{i=1}^n P_i \times t_i \quad (5.1)$$

where E_{Demand} represents the total energy demand. For non-coordinated load, a street-lighting load is selected to represent this type of load profile. In street-lighting load, the lights operate only during night while it is switched off during daytime hours. For partially coordinated load, residential load is selected to represent this type of loads. For residential load, many appliances constitute the load profile as depicted in Table 5.1. These appliances are divided into two categories. Some appliances such as AC, lights, fridge and water heater are assumed as non-coordinated loads which means that, the power required by these devices should be supplied in the required time given in the table and their operation times cannot be changed to other times. However, the power demand by other devices such as washing machine, clothes iron, dish washer and vacuum cleaner can be coordinated, and their operation time can be shifted and coordinated with solar potential. Similarity, industrial load is also considered as a partially coordinated load but with larger fraction being coordinated than the residential load. For fully coordinated load, irrigation load is

considered as a fully coordinated because all irrigation can be shifted to the desired time. Fig. 5.4 represents the coordination percentage as per these four loads. It is shown that, street lightning has 0 % coordination chance while residential and industrial loads are partially coordinated with 50 and 65 %. Irrigation load is 100 % coordinated load type.

Table 5.1 Estimation of daily load demand in terms of appliances.

Load	Appliances	Power (W)	No. of appliances	Load type
Street lighting	Lights	150	20	Non- coordinated
Residential	Lights	20	20	Non- coordinated
	AC	650	1	Non- coordinated
	Fridge	240	1	Non- coordinated

	Water heater	1500	1	Non-coordinated
	Washing machine	500	1	Coordinated
	Clothes iron	2000	1	Coordinated
	Clothes dryer	1500	1	Coordinated
	Dishwasher	300	1	Coordinated
	Vacuum cleaner	1600	1	Coordinated
	Water pump	180	1	Coordinated
Cartoon and Packing Factory	Machine 1	600	2	Coordinated
	Machine 2	500	2	Coordinated
	Machine 3	250	4	Coordinated
	Machine 4	150	4	Coordinated

	Alarm unit	100	2	Non-coordinated
	Cooling unit	200	2	Non-coordinated
Irrigation	Irrigation pump	1000	4	Coordinated
	Cleaning fans	25	2	Coordinated
	Cooling fans	375	2	Coordinated
	Lawn mover	700	4	Coordinated

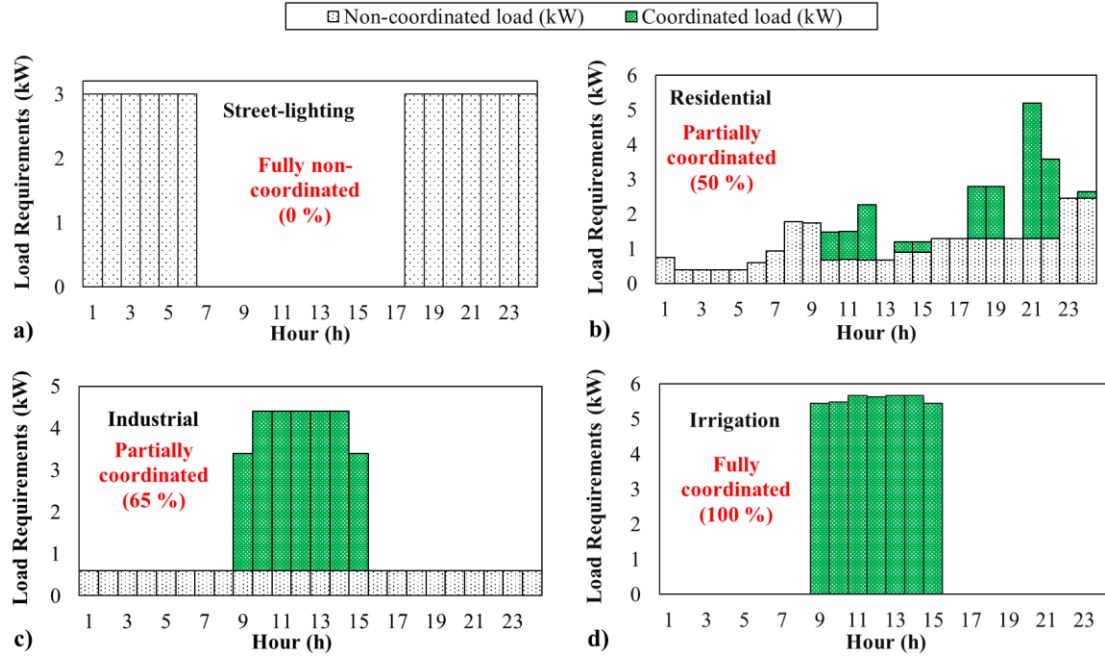


Figure 5.4 Types of loads used in this study and their corresponding coordination percentage.

5.2 Load Coordination

The main objective of this study is to investigate the effect of load coordination with solar potential on the system optimal size as well as on the system total cost. The loads are classified into non-coordinated, partially coordinated and fully coordinated load. Average length of sunshine period in Dammam is shown in Fig. 5.5a for each month. Solar energy is available during daytime hours, on average, within the period between hours 7 and 17 in studied area (Fig. 5.5b). However, the period within 9 to 15 is selected for the coordination purpose as solar intensity is high during this time interval.

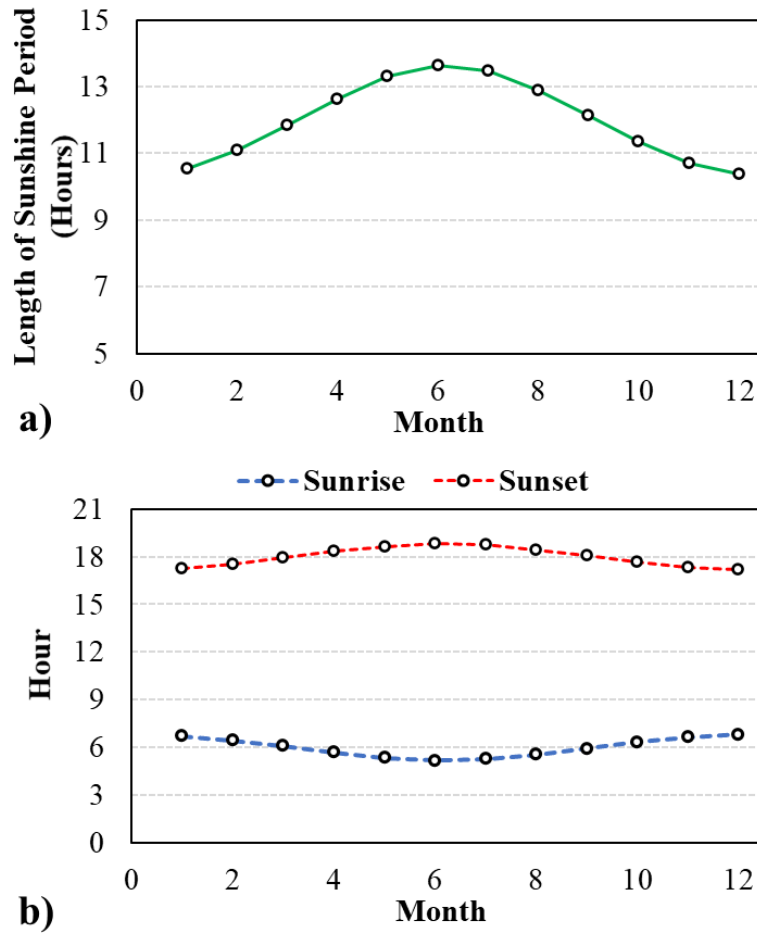


Figure 5.5 a) Length of sunshine period in Dammam and b) Sunrise and sunset hours in Dammam.

In the present study, the load is coordinated in two steps within this period. In the first step, the number of load coordination hours is evaluated, and the optimum number of coordination hours is selected for the second step. To explain, all coordinated load (in the fully coordinated case) and the partially coordinated load (in the partially coordinated case) are gathered in two, three, four, five, six and seven hours during the period of hours 9 to 15. The optimum number of coordination hours is selected. In the second step, the

coordinated load with specified coordination hours is shifted through 24 hours and the optimum load coordination center is selected. In this context, Load Coordination Center (LCC) is defined as the center of the coordinated load that is used to represent load shifting through 24 hours. Another important parameter is the Coordination Index (CI) which is defined in this study as the ratio of the coordinated load that are in the sunshine area. The CI can be expressed as:

$$CI = \frac{\text{No. of load coordinated hours that are in the sunshine period}}{\text{Length of sunshine period}} \quad (5.2)$$

where the length of sunshine period is set to 7 hours as discussed above.

5.3 System Energy Management

The energy management strategy used in this study is depicted in Fig. 5.6 below. It is observed that, during daytime hours two scenarios exist between the load demand and solar energy production:

1. When there is a sufficient solar production, the generated solar energy is directed to satisfy the load requirements. When the load is satisfied and there is an excess energy production, the batteries are charged until they reach their maximum constraint. If there is still some energy production, it is considered as a dumped load.

2. On the other hand, if the solar production is lower than load requirements, batteries are discharged, and the load is satisfied. If batteries are discharged and their minimum constraint is reached, the remained unsatisfied load is considered and energy shortage.

During nighttime hours, the load is met by the stored energy in the batteries. Therefore, batteries are discharged to satisfy the load requirements. If batteries are discharged and their minimum limit is reached, the remained unmet load is considered as energy shortage.

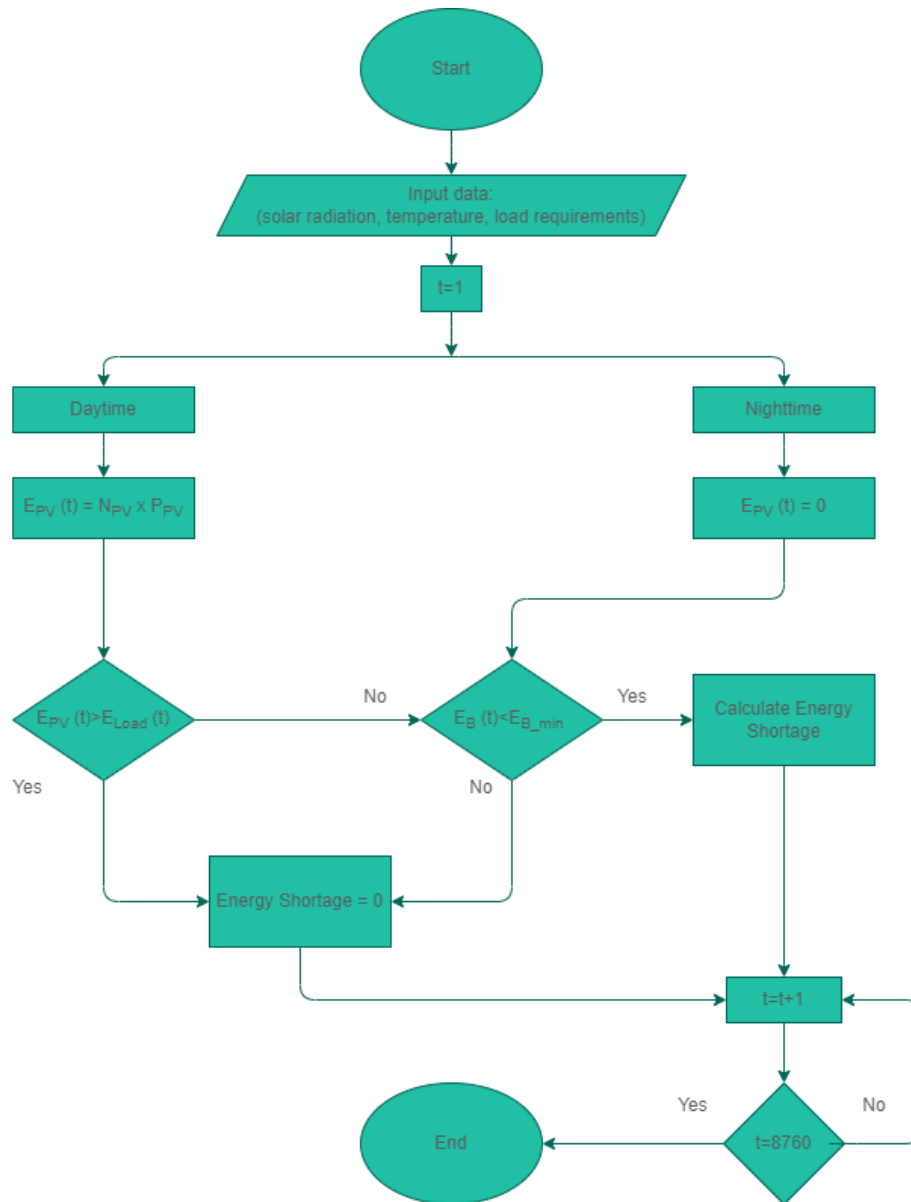


Figure 5.6 Flowchart denotes the energy management strategy.

5.4 Optimization Strategy

The goal of this study is to investigate the effect of load coordination on the system size and cost. The objective function of this optimization study and its constraints will be discussed in the following subsections. Minimization of system cost is considered as the objective of this study; therefore, the cost of the developed standalone system is evaluated in terms of the Levelized Cost of Energy (LCOE) which is defined by Eq. (2.37). Different design constraints are considered including ranges of decision variables, storage limitations and reliability requirements. Decision variables constraints represent the number of PV modules and the number of battery units which are expressed by:

$$N_{PV_min} \leq N_{PV} \leq N_{PV_max} \quad (5.3)$$

$$N_{B_min} \leq N_B \leq N_{B_max} \quad (5.4)$$

where the subscript min denotes the minimum number of each component while subscript max denotes the maximum number.

In addition, the battery storage system is subjected to the following constraint:

$$E_{B_min} \leq E_B(t) \leq E_{B_max} \quad (5.5)$$

where E_{B_min} is the minimum allowed battery state of charge and E_{B_max} is the maximum allowed battery state of charge.

Furthermore, the reliability requirements is evaluated, in this study, in terms of Loss of Power Supply Probability (LPSP) which is defined by Eq. (2.27).

The abovementioned optimization strategy is represented in Fig. 5.7 as a flowchart.

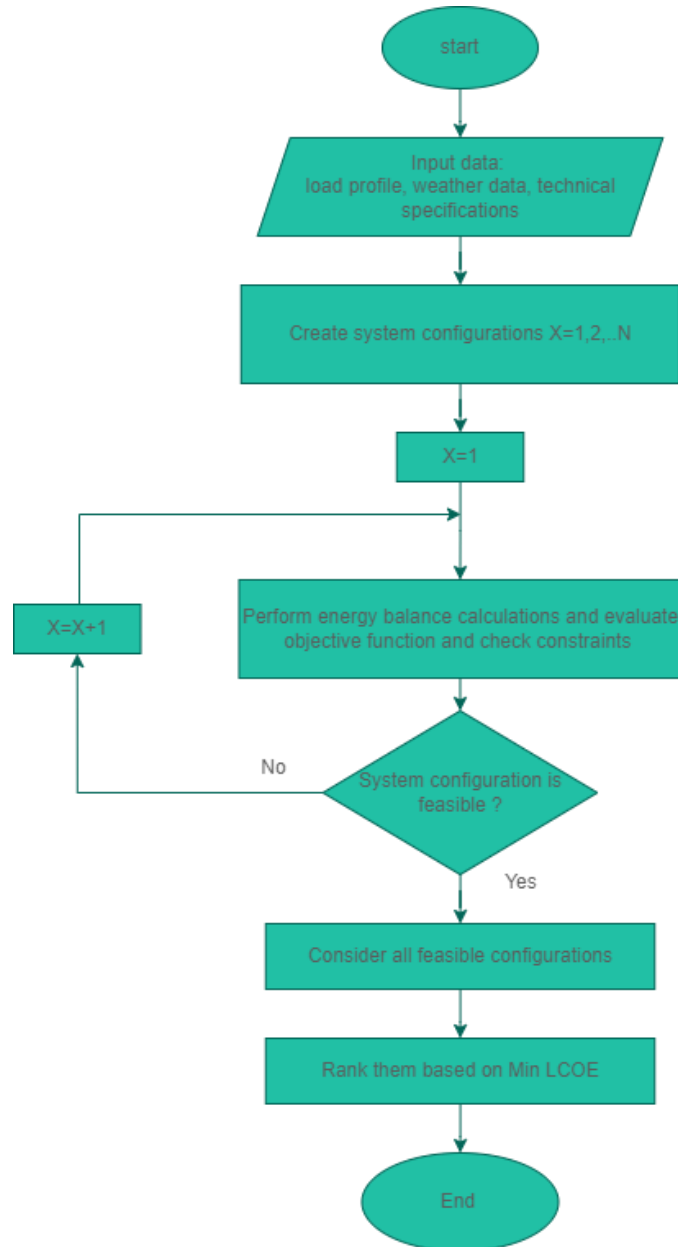


Figure 5.7 Optimization strategy flowchart

5.5 Results and Discussion

The current study assesses the optimal size problem of a standalone solar system designed to meet the energy demand of a variety of loads while taking into account the impact of load control on the optimization. The load management scenarios as well as optimization results will be discussed in the following subsections. Because this study considers four different types of loads, the residential load will be explored first. The four load categories will next be compared, emphasizing the need of load coordination.

5.5.1 Coordination Results for the Residential Load

The residential load is considered in this study as a partially coordinated load as shown in Fig. 5.4b. To explain, the residential load consists of the power consumption of various electrical appliances and machines used in homes in which some of these appliances can be used at any time (which is named in this study as coordinated appliances) while others cannot and should be operated in specified times. To investigate the effect of load coordination and management, the operation hours of the coordinated appliances can be shifted and aligned with solar energy availability.

The optimization process of the coordinated residential load can be performed in two steps. In this first step, the coordinated load will be managed such that the coordinated load will

be distributed in two, three, four, five, six and seven hours, then the optimum number of coordination hours will be selected for the second optimization step. Fig. 5.8 shows the distribution of the coordinated load for different number of coordination hours. In Fig. 5.8a, the coordinated load is coordinated in two hours. The number of coordination hours is also increased to 3 until 7 as shown in Fig. 5.8b to Fig. 5.8f. The optimization result of this step of coordination is shown in Fig. 5.9 **Error! Reference source not found.** in terms of leveled cost of energy as well as total net present cost. The result shows that, shifting the coordinated load in two hours has led to high cost because putting the coordinated load in two hours leads to increase the load peak, therefore, increasing the system size and the system cost as well. As number of coordination hours increases, the load is distributed more which resulted in reducing the load peak. As a results of that, the required PV size decreases and the cost as well. It can be implied form Fig. 5.9 that, when the number of coordination hours equal to 7, small system size is required, and low cost is achieved. Hence, for the residential used in this study, the number of coordination hours of 7 is selected for the second optimization step.

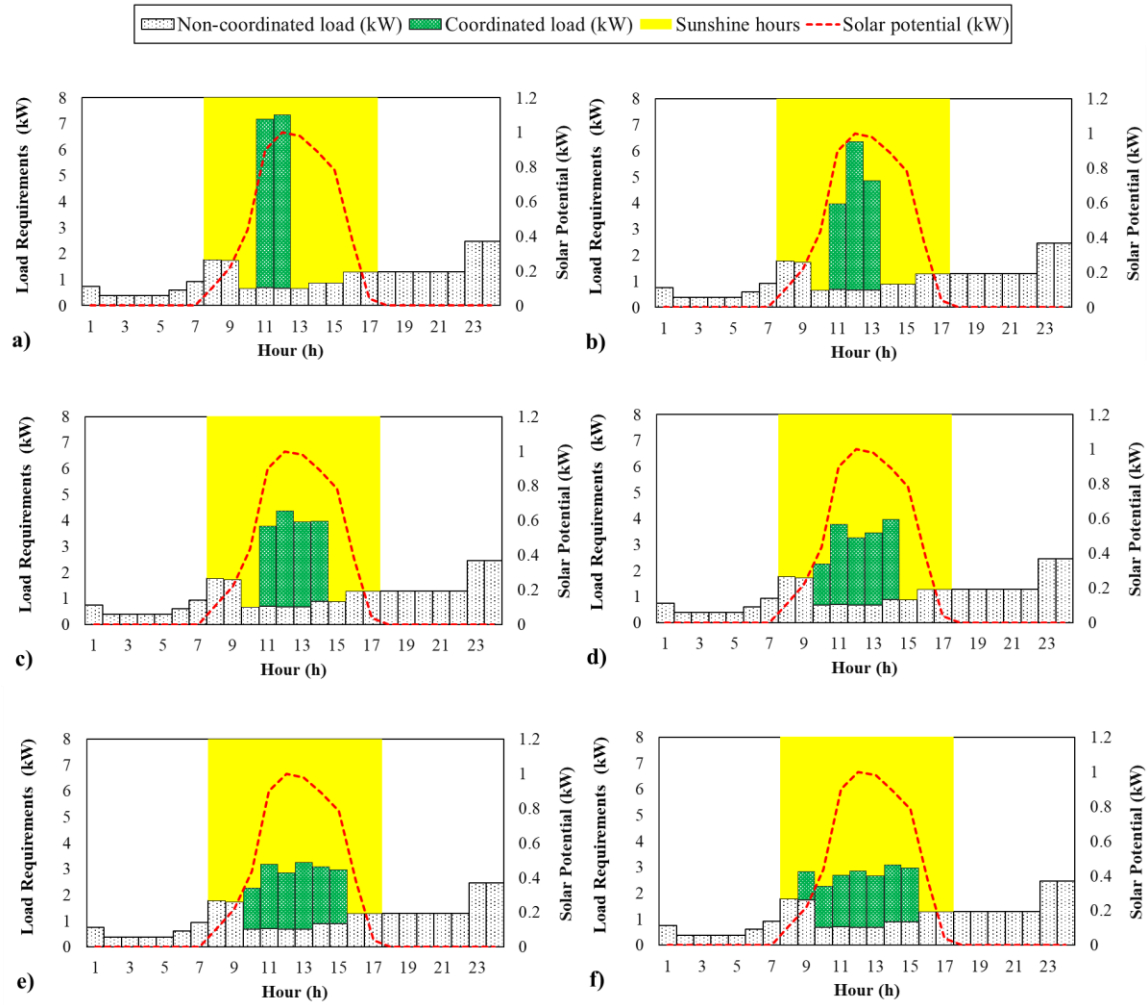


Figure 5.8 Different scenarios for the first step of the optimization for the residential load.

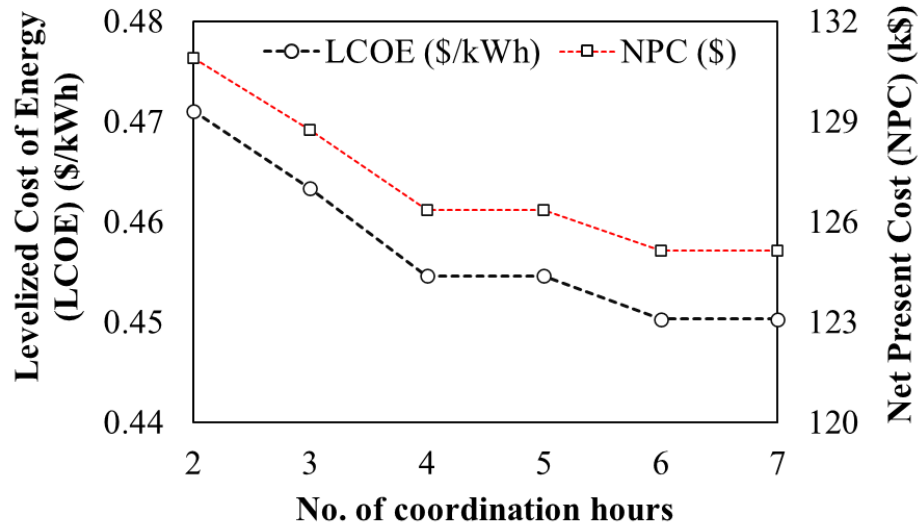


Figure 5.9 Optimization results of number of coordination hours.

To perform the second step of the load coordination, the residential load with 7 coordination hours is optimized by shifting its center through 24 hours and observing the variation in the performance indicators. Fig. 5.10 shows selected examples of load coordination through 24 hours. For example, Fig. 10a denotes that the load coordination center (LCC) is at 1 in the early morning with coordination index (CI) of zero. As load is shifted into right, the LCC center increases and CI still equal to zero. Fig. 5.10c shows that when LCC equal to 6, CI starts increasing to 0.14 until it reached its highest value of 1 at LCC equal to 12 (Fig. 5.10e). Then CI decreases as LCC moves right until it approaches value of zero at LCC equal to 19 onwards.

Fig. 5.11 shows that the optimum configuration for the specified residential load in this study comprises of 19 kW PV array, batteries with levelized cost of energy of 0.450 \$/kWh.

The battery storage size is quite high because there is a large part of the residential demand cannot be coordinated and should be supplied during the absence of solar energy.

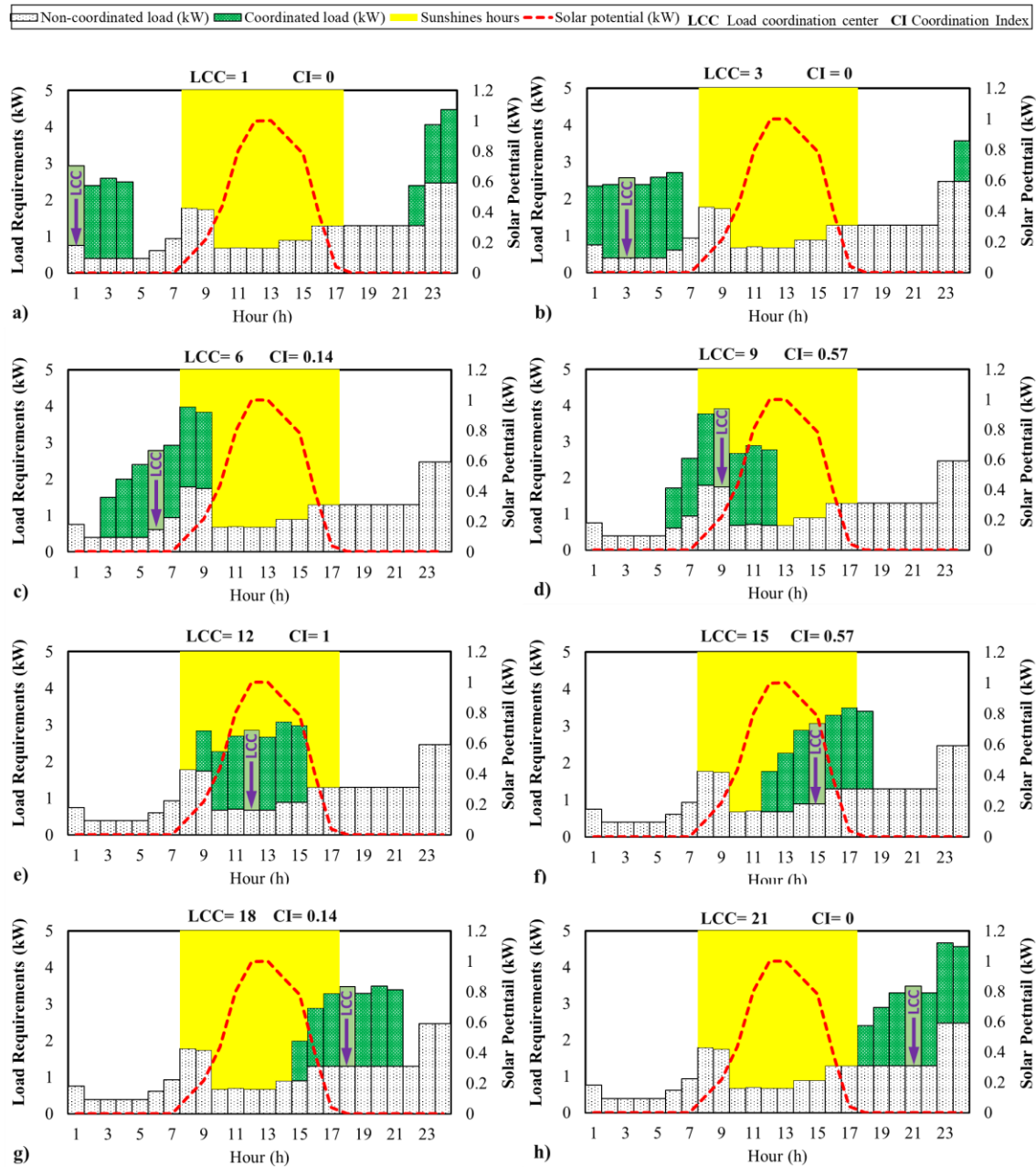


Figure 5.10 Different coordination centers for the load center.

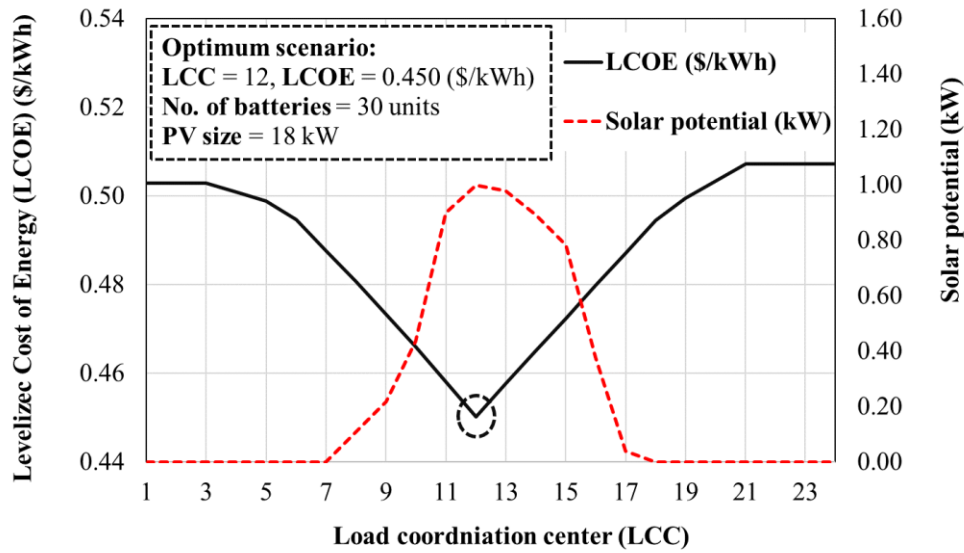


Figure 5.11 Optimization results for residential load demand.

Fig. 5.12 depicts the optimization results in terms of LCC and CI. It is noticed that the CI is zero when LCC = 1 until it becomes = 5, then it increases and reaches the maximum point at 12 and it returns to zero at 17 onwards. In Fig. 5.12a, and in Fig. 5.12b, cost indicator (LCOE) and storage size indicator (number of batteries) starts with high value and decreases as CI increases. The optimum values are observed when the CI reached its highest value with LCC of 12. Fig. 5.12**Error! Reference source not found.**c shows the percentage of cost reduction which approaches 11 % with CI of 1 and LCC of 12. This significant cost reduction is due to that large portion of the load is met with solar energy with high CI which reduces the size of the storage system. Fig. 5.12d denotes that, a total reduction in the storage size of 14 % is

achieved with CI of 1 and LCC of 12 and this result proves the significant outcomes of load coordination and management in standalone renewable energy systems.

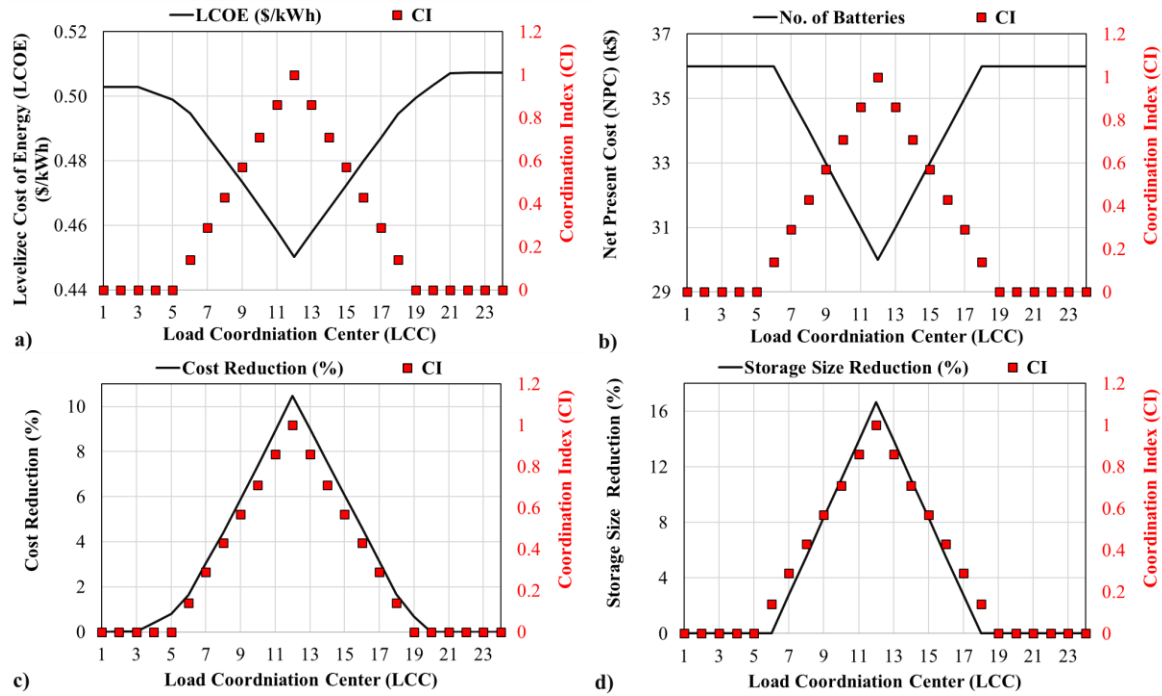


Figure 5.12 Effect of load coordination center and coordination index on a) Levelized cost of energy, b) Net present cost, c) Cost reduction and d) Storage system size reduction.

5.5.2 Comparing the Coordination Results of the Four Loads

In the previous subsection, detailed discussion is provided which showed the optimization results regarding the load coordination for a residential load. The same process is followed for the other loads. However, the street-lighting load is a fully non-coordinated load which means there is no chance exist to shift the load coordination center with respect to coordination index. Therefore, two optimization steps, discussed above, are not applicable for this load type. The optimum PV/battery system size that meets the demand of the studied street-lighting load is discussed separately. Then, the optimization results of the industrial and irrigation loads are analyzed and compared. Street-lighting load represent the electricity consumed by streetlights during nighttime where electricity is needed only during all night hours. Therefore, there is no chance to shift or coordinate this type of load to another time when solar energy is available. When the load requirements are met with standalone PV system, sufficient storage system should be designed to ensure covering the demand of the street-lighting in the absence of sunlight and solar energy. As discussed in Table 1, the street-lighting load requirements consists of lights demand only. The electricity demand is zero during daytime hours. After sunset, the load appears with constant demand of 3 kW until sunrise. The optimization results show that, this type of load is satisfied totally with renewable energy system comprises of 19 kW PV array, 41 batteries. This optimum configuration is found to have levelized cost of energy LCOE of 0.535 \$/kWh and net present cost NPC of \$ 148,787.

The optimization results of residential, industrial and irrigation are shown in Fig. 5.13. The optimization is conducted by increasing batteries and for each battery the PV size is increased until energy shortage becomes zero at which the code converges. It is observed that, the optimum configurations for all load types are obtained when the load coordination center (LCC) is between 10 and 14 which is the period of the high solar intensity. Due to variation in coordination percentage of in each load, the optimum configurations come with different number of batteries. For residential load (load coordination percentage of 50 %), the optimum configuration is shown with 30 batteries, 18 kW PV array and LCOE of 0.450 \$/kWh (Fig. 5.13a). As load coordination percentage increases to 65 and 100 % for the industrial and irrigation loads, the optimum configurations are obtained as shown in Figs. 5.13b and 5.13c with (28 batteries, 18 kW PV array and LCOE = 0.433 \$/kWh) and (25 batteries, 18 kW PV array and LCOE = 0.419 \$/kWh), respectively.

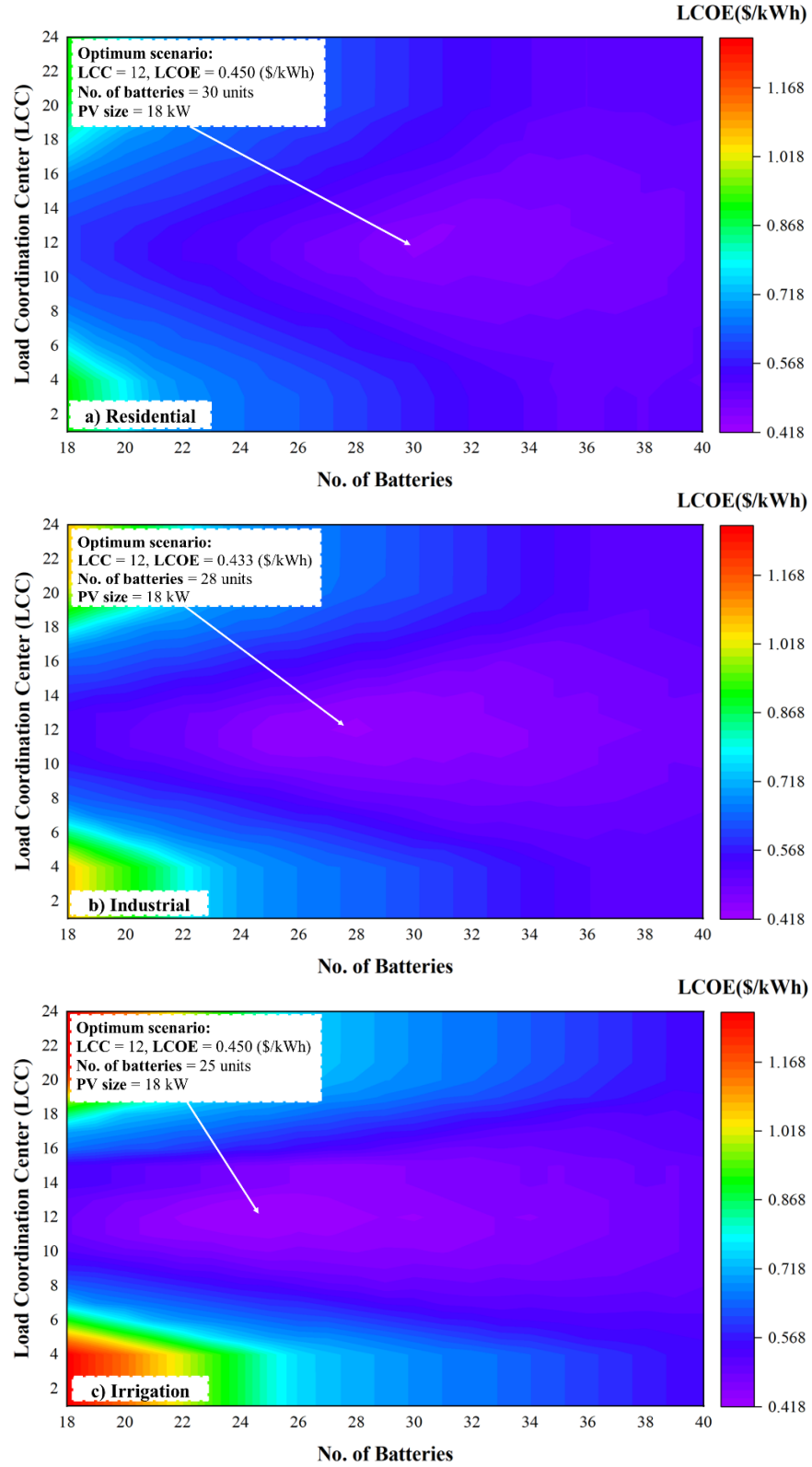
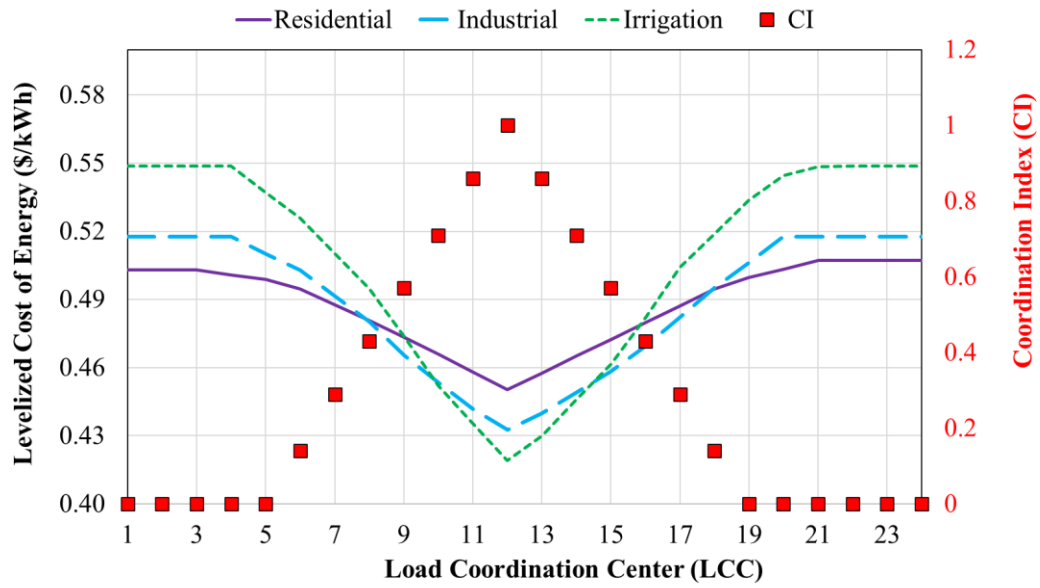


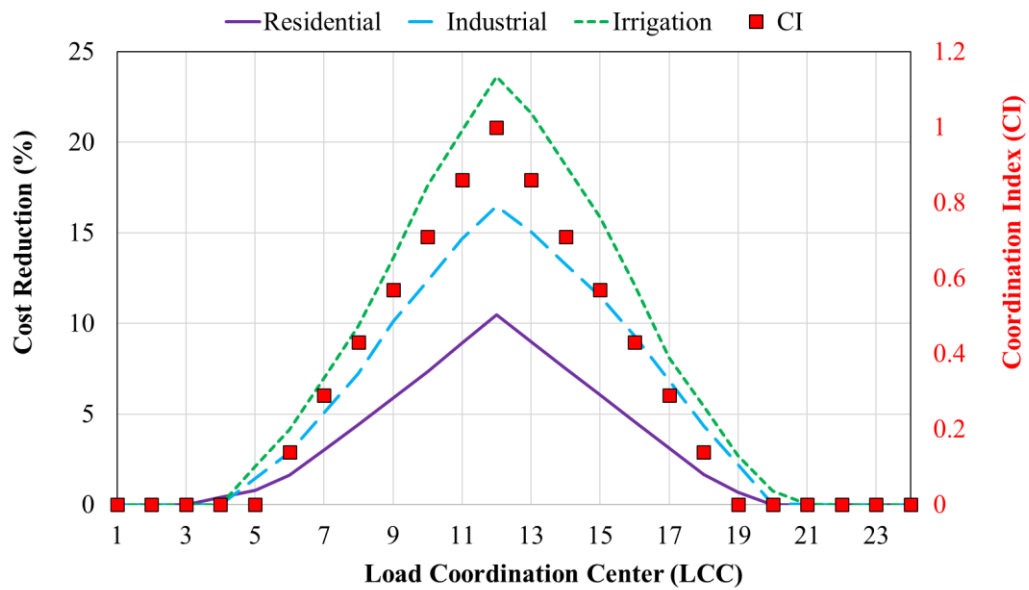
Figure 5.13 Optimization results of load coordination for a) residential, b) industrial and c) irrigation loads.

The shifting of load coordination center (LCC) through 24 hours affects the optimization result. As LCC moves from 1 to 24, different values of coordination index (CI) are obtained. In Figure 5.14 Fig. 14a, x-axis represents position of LCC which is shifted through 24 hours. Left y-axis denotes the levelized cost of energy while the right y-axis represents the values of the coordination index. The levelized cost of energy is plotted for the residential, industrial and irrigation loads in the same figure for comparison. It is shown that, the levelized cost of energy starts with high value. As LCC is shifted to right, CI starts to increase whereas the levelized cost of energy decreases. The lowest cost is observed when the highest value of CI is reached, then the cost starts to increase again. Residential load case starts with lower cost than industrial, and irrigation load cases because the amount of coordinated load in the residential case is smaller than the industrial and irrigation cases. For $CI = 1$ and $LCC = 12$, all cases reach their minimum cost. However, irrigation load case is the lowest among them. To explain, the irrigation load is a fully coordinated load, which means that for $CI=1$, the whole irrigation load is within the high solar potential period. As a result, the PV production goes directly to meet the irrigation demand and, consequentially, small storage system size is required in this case to cover the load during low production times. For $CI=0$, the whole irrigation becomes out of the solar potential period which requires higher storage system size and that is why the irrigation load case comes with the highest costs with CI of zero. In addition, because there is a 65 % of the industrial load is coordinated, all of this portion is met with direct solar production when $CI = 1$ which results in smaller system size and cost as well. However, the levelized energy

cost in the industrial case comes between the irrigation and residential cases because the load coordination percentage in this case is between them. Fig. 5.14b shows the cost reduction in terms of LCC and CI. As CI starts to increase, useful cost reduction exists. In the studied cases, the irrigation case experienced the highest cost reduction followed by industrial and residential, respectively. It can be concluded from this figure that, As the percentage of load coordination increases, maximum reduction in the levelized cost of energy is observed with $CI = 1$ while minimum reduction exists with $CI = \text{zero}$.



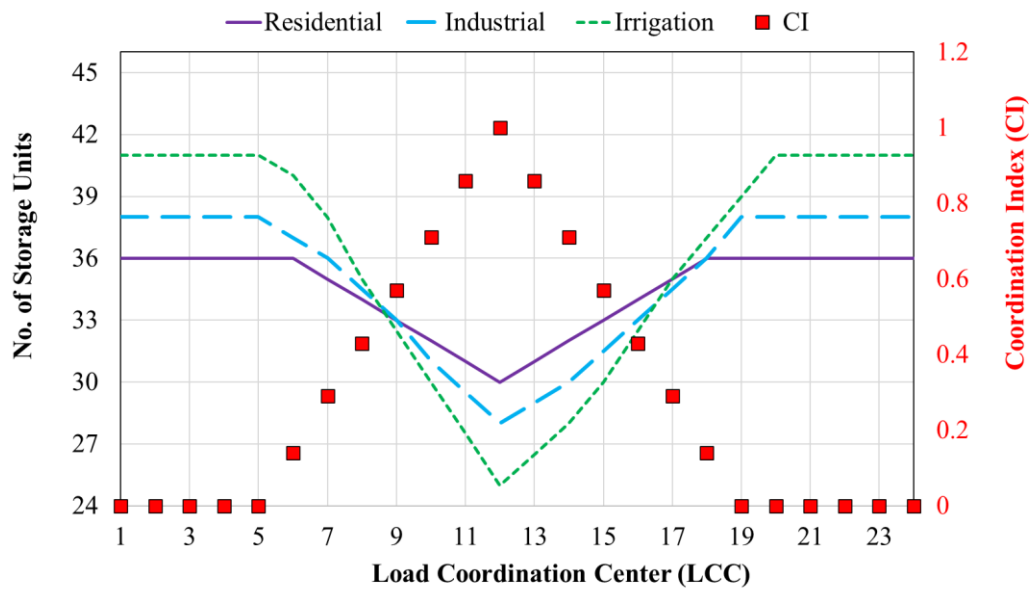
a)



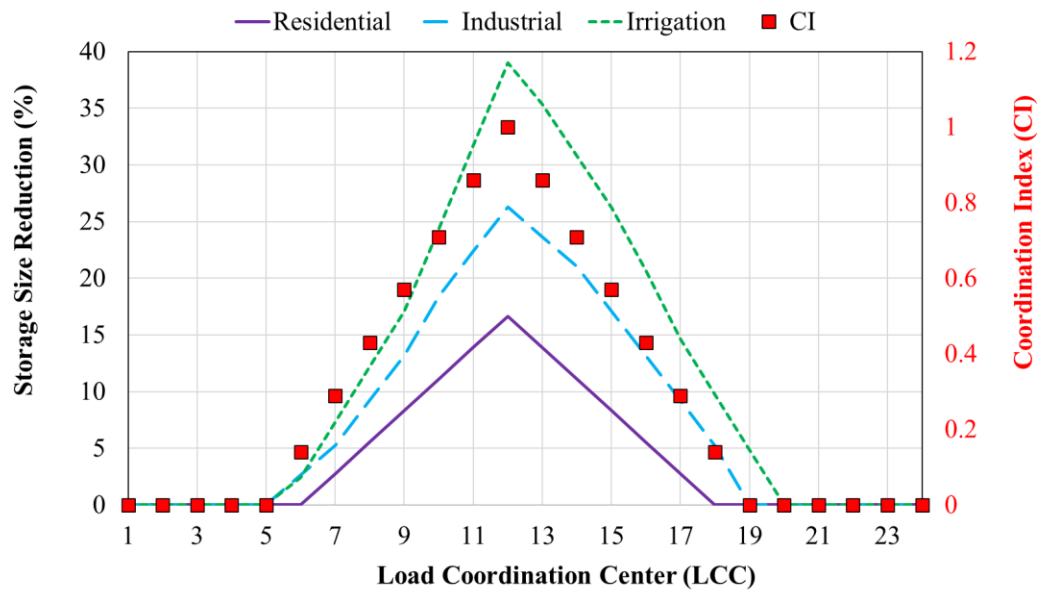
b)

Figure 5.14 Comparing the change in the levelized cost of energy for the residential, industrial and irrigation loads with respect to the coordination index.

Similar behavior to the levelized cost of energy is observed for the size of the storage system as shown in Fig. 5.15a. For fully non-coordinated scenarios ($CI = \text{zero}$ & LCC is out of interval 5 to 19), residential case comes with the lowest number of batteries because 50 % of the residential load is coordinated and 50 % in non-coordinated. For $CI = \text{zero}$, significant portion of the non-coordinated residential load is still met with the available solar energy whereas the 50 % coordinated as well as portion of the non-coordinated is met with batteries. For the irrigation load case with $CI = \text{zero}$, the whole load is met with batteries because the whole load is coordinated and $CI = \text{zero}$ means that the whole load is out of the sunlight period which requires large number of batteries. In addition, since 65 % of the industrial load is coordinated, larger portion than residential load and lower portion than irrigation load of the industrial load is met with batteries for $CI = \text{zero}$ which resulted in medium size of the storage system. On the other hand, for fully coordinated scenarios ($CI = 1$ & $LCC = 12$), dramatic reduction in the number of batteries is observed in the irrigation case as the whole load is available in the sunlight period. Because large portion of the residential load is non-coordinated, only small reduction in batteries is noticed in this case. Medium reduction in batteries is shown in the case of the industrial load. Fig. 5.15b denotes that, significant reduction in the storage system size is provided when the LCC is coordinated between 5 and 19. The highest reduction is found with $LCC=12$ and $CI = 1$. It can be implied from this figure that, As the chance of load coordination increases, (which is 50 %, 65 % and 100 % for the residential, industrial and irrigation, respectively) high reduction in the storage system size can be obtained.



a)



b)

Figure 5.15 Comparing the change in the storage system size for the residential, industrial and irrigation loads with respect to the coordination index.

Fig. 5.16a represents the cost reduction in all four load types in the fully non-coordinated (CI = zero) and fully coordinated cases (CI = zero), respectively. It is observed that, the most cost reduction is achieved in the case of irrigation load with a total cost reduction of 24 % while in the street-lighting load no reduction is found because the load is fully non-coordinated and there is no chance to coordinate or shift this type of load. Industrial and residential load cases have shown cost reduction of 14 and 11 %, respectively. In Fig. 5.16b, the reduction in the storage system size is shown. It is observed that about, for fully coordinated irrigation case, 39 % of the storage system size is obtained. Unlike irrigation load, zero reduction is obtained in the street-lighting load because there is no chance to coordinate the street-lighting load. In addition, 22 and 14 % reduction in the number of batteries are found due to the coordination of industrial and residential, respectively.

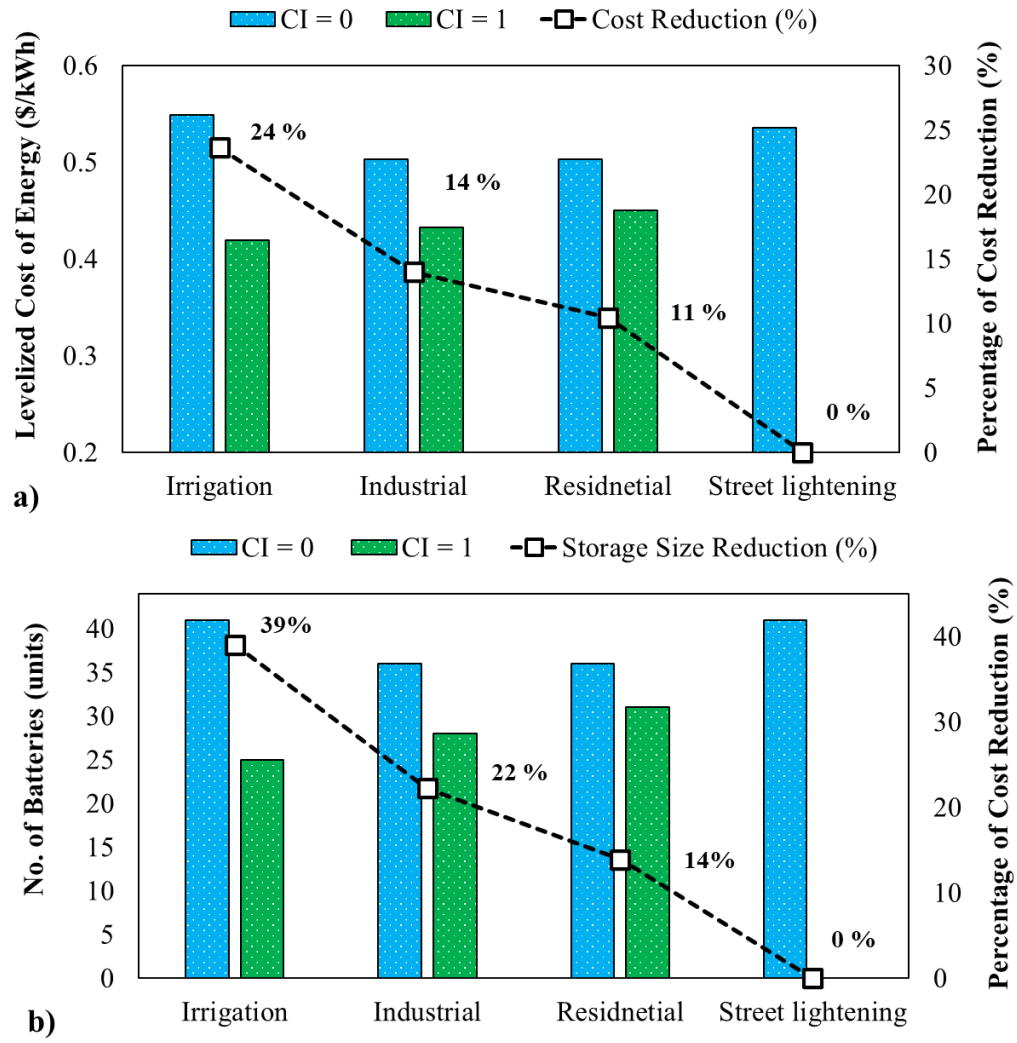


Figure 5.16 Comparing coordination scenarios of the four load types with coordination index of zero and one.

CHAPTER 6

Conclusions and Recommendations

In this thesis, techno-economic and environmental optimization studies were carried out to investigate viability of hybrid solar/wind renewable energy systems for electricity and hydrogen production in the kingdom of Saudi Arabia. Several case studies were considered to evaluate the feasibility of such system; therefore, conclusions are provided under the following subsections.

6.1 Residential House Integrated with Electric Vehicle

In this case study, an optimal size of a standalone hybrid PV/wind/battery system was obtained, and the effect of electric vehicle (EV) presence was investigated at different locations with different weather conditions in the Kingdom of Saudi Arabia, namely: Dammam, Riyadh, Jeddah, Buraydah, Tabouk and Sharurah. Two cases were considered to conduct the study. In the first case, the optimum size of hybrid PV/wind/battery system was found to meet a specified residential electricity demand while in the second case an EV was incorporated into the house for nocturnal charging, and the optimum size of the hybrid system was evaluated by considering different scenarios of the EV daily travelled distance (25 to 100 km/day with increment of 5 km/day). Mathematical models of the hybrid system components and a MATLAB computer code were developed. Then, the

predictions of the developed MATLAB computer code were validated against HOMER software and both results showed excellent agreement. Hourly based optimization study was conducted in MATLAB with the aim of minimizing total costs and maintaining high reliability. The following points are summarised for an average daily EV travelled distance of 50 km/day; however, similar trends of the optimization results are observed for all considered EV travelled distances:

- In the locations where both solar radiation and wind speed are high in the Kingdom of Saudi Arabia, smaller hybrid system components sizes were needed as observed in Buraydah ((Latitude: 26° 22' N, Longitude: 43° 57' E)) and Dammam (Latitude: 26° 23' N, Longitude: 49° 59' E). In this case, the results showed that, in Buraydah, the optimum hybrid system comprised 19 kW PV, one wind turbine and 22 batteries with NPC = 94,325 \$ and LCOE = 0.4381 \$/kWh; whereas, in Dammam, the optimum configuration comprised of 21 kW PV, one wind turbine and 20 batteries with NPC = 95,109 \$ and LCOE = 0.4417 \$/kWh.
- In the location where low potentials in both solar and wind, more expensive costs and larger hybrid system components sizes were needed as observed in Sharurah (Latitude: 17° 30' N, Longitude: 47° 07' E) where the total NPC of the optimum configuration was 121,576 \$ with LCOE = 0.5646 \$/kWh.
- In the locations where the potential of one of the renewable resources is high and the other is low, as observed in Tabouk (Latitude: 28° 23' N, Longitude: 36° 34' E), Riyadh (Latitude: 24° 39' N, Longitude: 46° 42' E) and Jeddah (Latitude: 21° 31' N, Longitude: 39° 12' E), moderate sizes and costs were found. For example, the costs of installing hybrid PV/wind/battery systems in Tabouk, Riyadh and Jeddah were found to be (NPC = 102,816 \$, LCOE = 0.4775 \$/kWh), (NPC = 105,186 \$, LCOE = 0.4884 \$/kWh), (NPC = 106,239 \$, LCOE = 0.4934 \$/kWh), respectively.

It was also observed in all scenarios that, as the daily travelled distance increases from 25 to 100 km/day, the hybrid system sizes and costs increased as well. Finally, a sensitivity

analysis was conducted and the effects of LPSP variations on the total NPC and LCOE were highlighted.

6.2 Residential House Integrated with Hydrogen Vehicle

In this case study, a techno-economic and environmental study of a standalone hybrid solar/wind system with battery and hydrogen storage is developed for electricity generation and hydrogen production based on hourly weather data of Dhahran city, Kingdom of Saudi Arabia. The hybrid system components are modelled mathematically, and MATLAB computer codes are developed to determine the optimal size of the hybrid system components meet the electricity and hydrogen demands with minimum cost of electricity and zero losses in the power and hydrogen supply. To account for these goals, the cost is modelled in terms of total net present costs (NPC), levelized cost of electricity (LCOE) and levelized cost of hydrogen (LCOH) whereas the reliability is modelled in terms of loss of power supply probability (LPSP) and loss of hydrogen supply probability (LHSP) which is introduced as the novelty of this paper. The results of this study are summarized in the following points:

- To meet electricity demand of 12140 kWh/year of a residential house, an optimum hybrid solar/wind system with 0% LPSP and 100% RF is found to consist of two wind turbines, 18 kW PV and 14 batteries with LCOE of 0.593 \$/kWh.

- After satisfying the electricity demand, 24320 kWh/year of the produced renewable energy is remained unused which is utilized to produce hydrogen to meet the hydrogen fuel demand of hydrogen vehicle integrated with the residential house.
- A hydrogen fuel demand of 5 kg/week (260 kg/year) of a Toyota Mirai hydrogen vehicle is utilized. Then, to investigate the effects of refueling behaviour on the optimization results, three different refueling scenarios are assumed: daily refueling (scenario-I), every other day refueling (scenario-II) and once a week refueling (scenario-III).
- To meet hydrogen fuel demand with 0% LHSP and minimum LCOH, a hydrogen production unit consists of 6 kW electrolyzer is selected and the size of hydrogen storage tanks is optimized and the size that fulfils the LHSP criterion with the lowest LCOH is selected.
- The results showed that the hydrogen load can be met totally (LHSP = 0) with hydrogen tank size of 14 kg in scenario-I, 15 kg in scenario-II and 17 kg in scenario-III while the corresponding LCOH is 36.32, 37.10 and 38.38 \$/kg for scenario-I, scenario-II and scenario-III, respectively.
- The results showed that, hydrogen refueling with scenario-I (daily refueling) is recommended as it allows to get the cheapest cost of hydrogen with high reliable hydrogen supply system.
- An environmental analysis showed that, the developed hybrid renewable energy system contributes to reduce CO₂ emission with value of 9658.58 (kgCO₂/year).

This study is conducted under weather conditions of Dhahran city only. In addition, it is assumed that there are no losses in hydrogen lines. However, in the future, a detailed hydrogen refueling unit will be investigated and intelligent optimization techniques will be utilized. Moreover, the study will be conducted by considering several locations in the Kingdom of Saudi Arabia.

6.3 Hybrid Solar/Wind System for Hydrogen Refueling Station

In this case study, a literature review was conducted about the development, classification, safety standards and feasibility studies of hydrogen refueling stations. However, it was observed that, no study in the literature has investigated the effect of people behaviour in different areas on the optimum size of the hydrogen refueling station. Therefore, a case study was developed to examine the optimum size of hydrogen refueling station in four different areas belongs to various human activities which are industrial, residential, highway and tourist area. People are visiting refueling stations in these areas at different times due to nature of their availability in these areas which lead to obvious variation in the refueling events and refueling demand as well. Based on this idea, refueling demand data was collected from gasoline refueling stations in the four areas in the eastern province, Kingdom of Saudi Arabia. The data was analysed and used to estimate hydrogen refueling demand. Then a techno-economic and environmental optimization study was conducted to determine the optimum configuration under different refueling behaviour. The findings of this study can be summarized in the following points:

- The optimization results showed that the NPC ranges from 2.973 to 3.895 M\$ in the off-grid cases while in the on-grid cases it ranges from 2.080 to 2.487 M\$. In addition, the LCOH is within the range 9.49 – 9.90 \$/kg in the off-grid cases and within the range 7.80 – 8.61 \$/kg.
- The cheapest economic results are observed in industrial area (NPC = 2.973 M\$ in the off-grid and 2.080 M\$ in the on-grid) because the majority of refueling events

in the industrial occur during daytime hours which is met by small PV array size and requires small storage capacity to cover night demands.

- The highest costs are shown in the tourist area (NPC = 3.895 M\$ in the off-grid and 2.487 M\$ in the on-grid) because the refueling events are high during all day hours in both working days and weekend days which resulted in large sizes of the PV array and hydrogen tank.
- The residential and highway areas show medium costs between the industrial and tourist areas with NPC of 3.211 and 3.345 M\$ in the off-grid cases, respectively while in the on-grid cases, the NPC becomes 2.203, 2.266 M\$ for the residential and highway respectively. These medium costs in the residential and highway areas are due to the fact that, number of hydrogen refueling events in these two areas are not high as tourist area while they are higher than industrial area.
- The costs of PV array, wind turbines and electrolyzer dominates the total costs in the industrial, residential and highway areas while in the tourist areas the PV array and hydrogen tank costs were the highest because of the need for high storage tanks in the tourist area.
- It was expected by this study that, the saved CO₂ emissions will be 87.76, 95.52, 100.08 and 111.73 Tons/year in the industrial, residential, highway and tourist areas, respectively which means that replacing gasoline fuel with hydrogen fuel will offer significant environmental benefits as huge amounts of CO₂ emissions will be saved.
- Based on this study, building hydrogen refueling stations in industrial areas requires small investment costs because people availability in that area is coincident with

availability of sun which results in small system sizes. In contrary, investing in tourist areas requires high capital costs due to high demands during whole day hours.

- From environmental point of view, installing hydrogen refueling station leads to dramatic reduction in CO₂ emissions and huge amounts of CO₂ emissions were saved in the tourist area. Therefore, governments are encouraged to support investments in these areas to save more CO₂.

6.4 Solar Energy Potential and Load Coordination

Enhancing the use of renewable energy systems is an essential aspect that will help to avoid the drawbacks of fossil fuels while also promoting sustainable development. Load management is a powerful technique for aligning demand with solar energy supply in order to maximize energy utilization efficiency. The major goal of this research is to see how load management affects the optimal system size and cost in off-grid renewable energy systems. For this purpose, a standalone solar PV array with battery storage is developed, and four types of load coordination scenarios are considered, including street lighting (non-coordinated 0%), industrial (partially coordinated (65%)), residential (partially coordinated (50%)), and irrigation (fully coordinated (100%)). The study is simulated via MATLAB software by using the meteorological data of Dammam city, in the Kingdom of Saudi Arabia. The findings of this study are summarized in following points:

- Street-lighting load is a non-coordinated load which is turned on during nighttime only where solar energy is not available. The results showed that, a solar PV array with high storage size is required to meet this type which is, in this case, comprised of 19 kW, 41 batteries with a levelized cost of energy LCOE = 0.535 \$/kWh.
- Residential load is a type of partial coordinated with 50 % of the load coordinated and 50 % is non-coordinated. To meet this demand with coordinating 50 % of it, the results showed that, a solar PV system consists of 18 kW with 30 batteries and LCOE = 0.450 \$/kWh.
- Industrial load is coordinated with percentage of 65 %. The results showed that, this load is satisfied with PV size of 18 kW and 28 batteries while the levelized cost of energy is LCOE = 0.433 \$/kWh.
- The irrigation load is a 100 % coordinated load which resulted in the smallest renewable energy system size (PV = 18 kW, batteries = 25 units and LCOE = 0.419 \$/kWh).
- The results showed that the highest reduction in the system size and cost is achieved with a coordination index of one (CI=1) which means that the load is fully aligned solar potential.
- Finally, as coordination percentage increase, the reduction in cost as well as in storage system size is found to increase also.

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Vitae

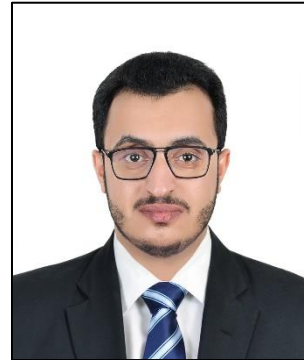
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Publications

1. **Al-Buraiki, A. S., & Al-Sharafi, A.** Technoeconomic analysis and optimization of hybrid solar/wind/battery systems for a standalone house integrated with electric vehicle in Saudi Arabia (2021) Energy Conversion and Management, 250, 114899.
2. **Al-Buraiki, A. S., & Al-Sharafi, A.** Hydrogen Production Via Using Excess Electric Energy of an Off-Grid Hybrid Solar/Wind System Based on a Novel Performance Indicator (2022) Energy Conversion and Management, 254, 115270.