

Unlocking the Potential of Electric Vehicles to Enhance Large-Scale Photovoltaic Solar Energy Integration into Grid Systems - A Case for Saudi Arabia

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Abstract

Traditionally, the Kingdom of Saudi Arabia (KSA) has relied heavily on fossil fuels to meet its energy demands. However, due to environmental concerns and economic incentives, the Kingdom is planning to escalate renewable energy generation, notably from Solar Photovoltaic (PV), and to promote the widespread adoption of electric vehicles (EVs). One of the issues associated with solar energy is its intermittent nature, and its large-scale integration could pose a challenge to the grid system; therefore strategies to alleviate this problem are required. This thesis investigates the potential of EVs to support the country's renewable energy aspirations by enhancing large-scale PV energy integration into the Saudi grid.

This study begins by considering the current energy situation in KSA, the development of solar PV in the country, and the challenges associated with large-scale solar PV integration into the grid. It then reviews the state-of-the-art in EVs, their related charging infrastructure, and Vehicle-to-Grid (V2G) technology, which enables EVs to feed energy back to the grid when demand is high. This is a particularly useful feature in the Saudi context, where demand for electricity fluctuates heavily between summers and winters (and between day-time and night-time) due to the need for air conditioning during the excessive summer heat. The study goes on to explore the current status of EVs in Saudi Arabia and the factors that are most likely to affect their widespread adoption in the country. It finds that battery-driven electric vehicles (BEVs) are more likely to find acceptance than other EV types in KSA due to their zero emissions, better safety levels, and the fact that owners can benefit financially by exporting their excess energy via V2G.

The study then considers the opinions of Saudi citizens to determine the factors and features that they deem important in EVs, which were gathered via a survey conducted for this purpose. Responses from 1012 potential EV drivers were analysed in order to identify and rank their preferences, leading to the identification of the features most likely to influence Saudi citizens' adoption of EVs. The main barriers identified related to infrastructure, performance, financial, social, and policy, but the most important were the lack of charging infrastructure and the additional load placed on the grid. Concerns about the safety and performance of EV batteries in high temperatures and

EVs ability to perform in desert conditions emerged as novel concerns related to the Saudi context. These findings were validated in a workshop conducted by the Saudi Standards, Metrology, and Quality Organization (SASO) via a focus group of EV users who shared their experience of using EVs in KSA. Their responses were in line with the earlier survey, and three major themes emerged related to EV infrastructure, battery performance, and lack of effective policy.

The study then assesses the viability of implementing a solar-powered system to support EVs in major Saudi cities. After analysing several cities in terms of their potential to generate electricity using solar PV and expected increases in the numbers of EVs by 2030, Riyadh was identified as the most suitable location for a case study to test the viability of three models through simulation. These included Model 1 (PV Plant Only), Model 2 (PV Plant and Charging Stations), and Model 3 (PV, Charging Stations and V2G). Techno-economic analysis of these models in low, medium and high EV uptake scenarios (LUS, MUS and HUS) revealed that Model 1 (PV Only) would be the cheapest option at around $1 billion in LUS. However, Model 3 (PV plant, charging stations and V2G) has the best Internal Rate of Return (IRR) (around 28.2% in HUS) and would reduce emissions most significantly (by around 5.5 mtCO_2 in HUS).

The study concludes that EVs have considerable potential to enhance large-scale PV energy integration into the Saudi grid and proposes the construction of solar PV plants together with charging stations and V2G technology as a cost-effective alternative to PV plants alone. It also recommends that EV manufacturers demonstrate that their vehicles are safe and effective in hot desert climates if they wish to penetrate the Saudi market. In order to promote a widespread EV implementation, the government and all other authorities should develop policies to support EV adoption, including by providing subsidies or other incentives to EV users.

The data gathered for this study and the research findings will be of interest to policymakers, EV manufacturers, entities charged with providing EV infrastructure, solar PV and EV businesses, and any sector working towards the Vision 2030 goals.

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Main Publications

1. **S. Alotaibi**, S. Omer, S. Aljarallah, W. Altheyab, S. Alsamdani, and A. Alzaidan, "Challenges and Concerns in Developing Confidence among Electric Vehicle (EV) Users in Saudi Arabia," *in Proceedings of International Conference and Exhibition for Science (ICES2023)*, Riyadh, Saudi Arabia. February 6-8, 2023.
2. **S. Alotaibi,** S. Omer, and Y. Su, "Identification of Potential Barriers to Electric Vehicle Adoption in Oil-Producing Nations—The Case of Saudi Arabia," *MDPI Electricity*, vol. 3, pp. 365-395, Aug. 2022.
3. **S. Alotaibi,** S. Omer, S. Aljarallah, and Y. Su, "Potential implementation of EVs–Features, Challenges and User perspective," *in Proceedings of 2021 IEEE Green Energy and Smart Systems Conference (IGESSC)*, pp. 1-10, Nov. 2021.
4. **S. Alotaibi,** S. Omer, and Y. Su, "A review on the potential of electric vehicles in reducing world CO2 footprints," *International Journal of Transport and Vehicle Engineering*, vol. 14, pp. 570–578, 2020.

Other Publications

5. A. Alshahrani, S. Omer, Y. Su, E. Mohamed, and **S. Alotaibi,** "The technical challenges facing the integration of small-scale and large-scale PV systems into the grid: A critical review," *Electronics*, vol. 8, no. 12, p.1443, 2019.

List of Abbreviations

AVC	Automatic Voltage Controller
ANOVA	Analysis of Variance
BCR	Benefit Cost Ratio
BEV	Battery-driven Electric Vehicles
BP	British Petroleum
BLDC	Brushless Direct Current Motor
CCS	Combined Charging System
CHAdeMO	Charge de Move
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
DEWA	Dubai Electricity and Water Authority
DHC	Daily Hourly Charge
DoD	Depth of Discharge
DSO	Distribution System Operator
EEER	Electricity Export Escalation Rate
EEG	Electricity Exported to Grid
EER	Energy Efficiency Ratio
EFA	Exploratory Factor Analysis
ELCC	Effective Load Carrying Capability
EPC	Energy Production Cost
ESS	Energy Storage Systems
ESU	Energy Storage Unit
ETAP	Electrical Transient Analyzer Program

EV	Electric Vehicle
EVM	Electric Vehicle Meter
EVSE	Electric Vehicle Supply Equipment
FCEV	Fuel Cell Electric Vehicle
FCM	Final Customer Meter
FCV	Fuel Cell Vehicles
FLC	Fuzzy Logic Control
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Green House Gases
GHI	Global Horizontal Irradiance
GIS	Geographical Information System
GW	Gigawatt
HEV	Hybrid Electric Vehicles
HFCV	Hydrogen Fuel Cell Vehicles
HUS	High Uptake Scenario
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicles
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IRR	Internal Rate of Return
KAPSRC	King Abdullah Petroleum Studies and Research Centre
KEM	KAPSRC Energy Model
KSA	Kingdom of Saudi Arabia

LIB	Lithium-ion Batteries
LMP	Locational Marginal Price
LUS	Low Uptake Scenario
MoE	Mall of Emirates
MPPT	Maximum Power Point Tracker
MSRP	Manufacturer's Suggested Retail Price
$MtCO_2$	Million Tonnes of Carbon Dioxide
Mtpa	Million Tonnes per Annum
MUS	Medium Uptake Scenario
NiMH	Nickel-Metal Hydride
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NREP	National Renewable Energy Program
O&M	Operation and Maintenance
OPEC	Organization of Petroleum Exporting Countries
PEV	Personal Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicles
POA	Plane of Array
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
REPDO	Renewable Energy Project Development Office
RETS	Renewable Energy Technologies
SAR	Saudi Arabian Riyal
SASO	Standards, Metrology, and Quality Organization

SEC	Saudi Electric Company
SGI	Saudi Green Initiative
SOC	State of Charge
T&D	Transmission and Distribution
THD	Total Harmonic Distortion
UAE	United Arab Emirates
UK	United Kingdom
US	United States
USD	US Dollar
UV	Ultraviolet
V2G	Vehicle-to-Grid

Chapter 1
Introduction

1.1 Introduction

The Kingdom of Saudi Arabia (KSA) has vast reserves of fossil fuels, especially oil, which have enabled the country to meet its energy needs and provide subsidized energy to domestic consumers [1]. These reserves also generate substantial revenues, as KSA sells its surplus oil products on the international market. However, the Kingdom also has one of the highest per capita energy consumption rates in the world [2], and oil supplies are forecast to last for only another 30 to 40 years at current consumption rates [3]. As a result, KSA is now transitioning to renewable energy sources to meet domestic demand, both as a way to reduce greenhouse gas (GHG) emissions [4] and to increase the oil available for export [5]. The country has set itself an ambitious target of producing 60 GW of electricity from renewable sources, with around 40 GW of this from solar Photovoltaic (PV), as part of its national strategic plan by 2030 [6], and large-scale solar PV projects are now being established in the country [7].

In tandem with this, the Saudi government is also seeking to promote the adoption of electric vehicles (EVs) as part of the Saudi Green Initiative (SGI), a key element of Vision 2030, which aims to reduce GHG emissions by more than 278 Mtpa by 2030 and achieve net-zero emissions by 2060 [8]. Powering these EVs through solar PV has multiple potential benefits for Saudi Arabia, it can reduce GHG emissions, free up more oil for export, and slow down the depletion of its oil reserves. However, solar energy is intermittent in nature, and its large-scale integration could pose a challenge to the grid system [9], especially in a hot country like Saudi Arabia, where demand fluctuates significantly between day-time and night-time due to the need for air conditioning, especially in the summer [10]. Recent developments in the field of EVs, notably Vehicle-to-Grid (V2G) technology, which enables EVs to feed energy back to the grid when demand is high, may provide a solution. As a result, this thesis explores the potential of EVs to support the Kingdom’s renewable energy aspirations by enhancing large-scale PV solar energy integration into the national grid.

This chapter explains the motivation for conducting this research and provides background information about the study. It then sets out the aims and objectives and the research questions. It goes on to present an overview of the methodology used to conduct this investigation and then outlines the novelties and contributions of the work. The chapter concludes by presenting an outline of the thesis structure.

1.2 Motivation for the Research

As the transportation sector is a major contributor of GHG emissions in Saudi Arabia [11], the country needs to switch to more environmentally-friendly alternatives, notably EVs, in order to achieve its reduction targets [12]. However, at present, EVs are unavailable for purchase in the Kingdom and must be imported individually. This situation will change dramatically over the next few years. In May 2022, Lucid Motors, a US EV manufacturer, announced that it will begin constructing manufacturing facilities with a capacity of 155,000 EVs in KSA, with the Saudi government committing to purchase 100,000 vehicles over a ten-year period [13]. The year 2022 also saw the establishment of the first Saudi EV brand "Ceer", which aims to have vehicles that have been designed and manufactured in KSA on the roads in 2025. [14]. As a result of this progress, there is an urgent need to understand how potential users in the country view EVs and the strategies required to support their widespread adoption. In addition, given that the 2030 deadline for GHG emissions is now only seven years away, there is an increasingly urgent need to assess the viability of using EVs as energy carriers for electricity generation using solar PV, both as a way to reduce emissions and to take full advantage of the new solar energy supplies.

1.3 Background to the Study

Given the plentiful oil supply in Saudi Arabia, most vehicles have petrol or diesel engines, and most electricity is generated using fossil fuels [15]. However, this generates high levels of CO_2 emissions, and there is a need to find alternative sources of electricity to power the large volume of traffic in the country [11]. Amongst the various renewable energy sources (solar, wind, geothermal, hydroelectric, ocean, and biomass), wind and solar PV are the two major candidates for electric grid integration due to their capacity for large-scale electricity generation [16]. However, there are

challenges associated with the nature, generation and storage of the energy from renewable sources as set out below.

1.3.1 The Challenge of Intermittency

The integration of renewable energy into the Saudi national grid would substantially reduce the country's reliance on fossil fuels, enabling it to achieve de-carbonization targets while meeting the rising energy demand, improving energy access, and increasing energy security [17]. Given its hot arid climate, KSA has considerable potential to benefit from solar PV technology in particular [18]; however, renewable energy sources are not without problems. Firstly, most renewable sources are intermittent in nature (i.e., they are not available all the time) [9]; and secondly, they cannot adapt quickly to meet fluctuating demand (i.e., it is difficult to alter the grid power quickly based on a surge in demand) [19]. While energy sources such as oil, natural gas, nuclear, and coal are 'dispatchable', meaning they can be accessed as required, intermittent renewable energy sources, such as solar, wind and tidal energy, are 'non-dispatchable', so a balance of both forms of energy is required.

1.3.2 Generating and Storing Solar Energy

Solar PV is the primary method for harnessing thermal energy from the sun, as this converts it directly into useable electricity [20]. Currently, solar panels are installed either in large-scale solar parks/farms, in smaller-scale solar car parks, or on building rooftops, to generate electricity from sunlight. Generated electricity is fed into the grid and then supplied to industries, houses, or other sites where there is a demand for electricity. This process is noise and pollution free, and there is no generation of harmful carbon based by-products [21]. However, as solar energy is non-dispatchable and the level of demand varies, imbalances may occur between supply and demand; these are neither safe for the grid nor for the supply source, and they can lead to loss of load or loss of generation [22]. Therefore, there is a need for effective storage of electricity from renewables to ensure a consistent supply during peak demand and when solar generation is low. This storage can be either 'centralised' or 'decentralised'. Figure 1.1 illustrates the process of transferring solar energy from the PV cells to the end users or to storage.

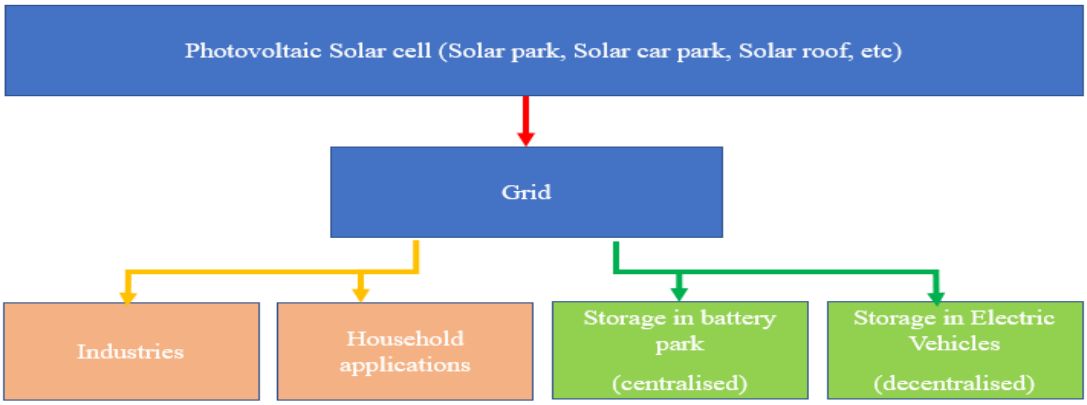


Figure 1.1 An illustration of the process of electricity generation from PV, showing possible centralized and decentralized storage (created by the author).

Storage of electricity in battery parks (large areas with thousands of batteries to store electricity), often referred to as 'centralized' storage and would solve some of the problems associated with excess production of electricity [23]. However, there are some significant risks associated with them. For example, if there is a malfunction of the battery systems or a Lithium-ion battery is damaged, it could lead to explosions and may damage the entire battery park [24]. In addition, large-scale electrical batteries are still very expensive and need regular replacement due to their limited life span [25]. Therefore, 'decentralized' storage is also required, for example in individual vehicles [26].

Decentralised storage in EVs offers several advantages, including the reduction of risk, the distribution of the investment and maintenance required to many end users, and the ability to respond to fluctuating demand more effectively. The development of Vehicle-to-Grid (V2G) allows electricity stored in EVs to be transferred back to the grid during high network-demand times, while during low network-demand times, unused power in the grid can be stored in EVs [27,28]. Figure 1.2 depicts this scenario, with the EV using V2G technology to transfer energy to and from the grid, thereby acting as a buffer between the solar PV cells and the grid.

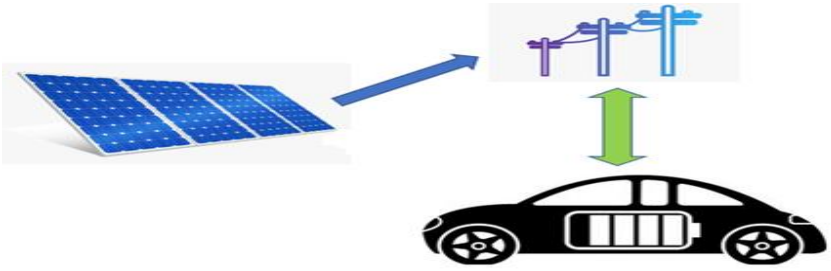


Figure 1.2 A scenario depicting the integration of large-scale PV, grid and EVs (created by the author).

1.4 Research Aims & Objectives

Exploiting solar PV to power EVs would support Saudi Arabia's renewable energy and GHG emissions aspirations, and could potentially lead to economic growth. The Saudi government has taken significant steps forward in terms of constructing solar powered plants and concluding the deal with Lucid Motors to manufacture EVs locally. However, further attention needs to be paid to developing effective ways to promote the adoption of EVs, to provide the energy and infrastructure they require, and to enhance the large-scale integration of solar energy into the electricity grid.

As a result, this study investigates the current status of EVs in Saudi Arabia, the barriers to their widespread adoption, and their potential as an energy-carrier strategy for large-scale photovoltaic solar energy integration into the grid system. It aims to identify the key consumer barriers within the Saudi context and to propose a cost-effective and environmentally-sustainable model for the application of solar-powered EVs in a typical Saudi city, based on low, medium, and high-uptake scenarios.

The main objectives of the research are, therefore:

1. To review the state-of-the-art of EV technologies (e.g., fuel economies, GHG emissions, costs, charging technologies etc.) and the potential impact of the integration of large-scale solar PV into the grid system.
2. To identify recent trends in EV usage and the features which are most significant for end users in Saudi Arabia.
3. To identify the barriers to the widespread adoption of EVs in Saudi Arabia, among both potential and current EV users.
4. To identify and evaluate potential locations in Saudi Arabia for a utility-scale PV system to support EVs at the city level, and to identify the most suitable location for a case study.
5. To propose different models to support EV usage in a major Saudi city, based on the case study location identified in Objective 4.
6. To perform a techno-economic analysis to identify the most effective model for implementation in the case study city, from a financial and environmental perspective.

1.5 Research Questions

In order to achieve the aims and objectives set out above, the study aims to answer the following questions:

1. What are the barriers to widespread EV adoption in Saudi Arabia, among both potential and current EV users?
2. What is the potential of solar PV to meet the increased need for electricity to power EVs, and what effect would this have on the national grid?
3. What is the most cost-effective and environmentally beneficial model to adopt when introducing solar PV into the Saudi grid to support EVs at the city level?

1.6 Research Methodology

This study used a mixed methods approach, including both quantitative and qualitative methods. Both primary and secondary sources of information were used to collect data for this study. While primary data was obtained from a number of sources, including production data from an existing Saudi solar PV plant and a questionnaire distributed to EV users, experts, and the general public. Secondary data was collected with the help of a focus group of EV users and a literature review of the state-of-the-art in EV technologies, grid integration strategies etc. Another source of secondary data were official Saudi government documents and other information collected from different ministries and organization in Saudi Arabia. NVivo and SPSS software were used for data analysis, while RETScreen software was used mainly for carrying out techno-economic simulations [29,30,31].

1.7 Novelties and Anticipated Contributions of the Thesis

This thesis is expected to contribute to knowledge and to society in the following ways:

1. It takes Saudi Arabia as a case study and analyses the barriers to the adoption of EVs among current and prospective users. To the best of the author's knowledge, this is the first study conducted to identify barriers to EV adoption in the context of a major oil-producing and an extremely hot country.

2. It identifies current trends in EV usage in Saudi Arabia and their features which are most important for end users. This was achieved in part by conducting a focus group with current EV users as part of a workshop organised in collaboration with the Saudi Standards, Metrology, and Quality Organization (SASO). This was the first workshop of its kind conducted in Saudi Arabia to assess the experience of Saudi EV users, and the findings of this focus group can be applied beyond this study to devise policies for EV users in Saudi Arabia. Therefore, it can play an important part in promoting the use of EVs in the country.

3. It assesses six different locations in Saudi Arabia for their suitability as potential sites for utility-scale PV systems in line with EVs application in these cities. The assessment is based on factors such as installation and generation costs, emissions reduction potential, payback period etc. This is a unique study, and the findings will provide the Saudi government and policymakers with data about the cost and potential impact of implementing solar PV plants in different parts of the country.

4. Three models are developed, and analysis is performed for each model: Model 1 (PV Plant), Model 2 (PV Plant + EV Charging Stations), and Model 3 (PV Plant + EV Charging Stations + Vehicle-to-Grid). Cost, finances, emissions, and sensitivity analysis are evaluated and discussed for each model. A comparison of the three models is then presented. To the best of the author's knowledge, this is the first study is combined the three clean energy models, in which EVs are powered by solar PV plant and a certain amount of EVs can be feeding back the national grid by V2G. The viability of such an application is then evaluated for various beneficiaries, including a government, users and grid.

5. Finally, the thesis provides a detailed techno-economic analysis of three scenarios (Low, Medium and High EVs uptake) to support solar-powered EV application in a major Saudi city. Financial, emissions, cost, and sensitivity analysis are performed, and the most effective strategy is identified, based on its financial and environmental impact in low, medium and high uptake scenarios. To the best of the author's knowledge, these models have not been envisaged in the context of KSA, nor has their relative viability within the Kingdom have been assessed.

1.8 Outline of the Thesis

The rest of the thesis is organized as follows:

Chapter 2 provides the literature review and is presented in different sections. The first offers an overview of the energy outlook of Saudi Arabia, in terms of consumption, generation and distribution. The second explores the status of solar PV in the country, and then reviewing the challenges of large-scale solar PV, also the potential impact of its large-scale integration into the grid. Then explores the state-of-the-art in EV technologies are presented, identifying the different types of EVSs, their key components, and exploring recent trends in their usage and development. V2G technology is also introduced. The final section considers the factors which are most likely to affect EV adoption, both globally and in the context of Saudi Arabia.

Chapter 3 details the methodology used in this research.

Chapter 4 analyses the findings of a survey of potential EV users in Saudi Arabia "Electric Vehicles Future in KSA" and identifies the barriers to widespread EV adoption from their perspectives. Both quantitative and qualitative methods are used to find the most important barriers and those which are specific to the Saudi context. Finally, a combined barriers framework is proposed.

Chapter 5 examines the outcomes of a focus group of current EV owners held as part of a workshop organised by SASO to evaluate the user experience of EV drivers in Saudi Arabia. Qualitative and quantitative findings are presented and discussed and key takeaways from the focus group and workshop are identified. This focus group is also used to validate the findings from the questionnaire in Chapter 4.

Chapter 6 assesses the potential of six different major Saudi cities to support the adoption of EVs powered by solar PV. The assessment is based on the projected number of EVs in 2030, the potential for electricity generation through solar PV (in terms of solar irradiation levels), and the estimated load requirements in each location. Consideration is also given to the need to attract investment to develop the necessary infrastructure. The chapter concludes by selecting the most suitable city for further detailed analysis.

Chapter 7 provides a techno-economic assessment of the feasibility of three models to support PV grid integration in the selected city, based on the findings in Chapter 6.

Each model is assessed in three EV uptake scenarios: low, medium, and high. The three models are compared, and the most economically and environmentally beneficial model is proposed for implementation in major Saudi cities.

Chapter 8 provides the conclusions of the research. The research questions are answered, and the contributions of the thesis are explained. The limitations of the current work are identified and possible directions for future work are proposed.

1.9 Conclusion

This chapter has introduced the study, explained the rationale for the research, set out the research objectives and research questions, and provided an overview of the research methods. It has also identified the novelty of the research. The next chapter provides an in-depth review of the literature appropriate to this study.

Chapter 2
Literature Review

2.1 Introduction

Widespread adoption of Electric Vehicles (EVs) has important economic and environmental implications for Saudi Arabia. However, as EVs are powered by electricity, the existing Saudi electric power infrastructure may not be sufficient to power EVs. Solar PV energy may be used to generate the additional electricity required to power EVs, however, large-scale solar PV integration as its own challenges. Moreover, there may be additional barriers to adoption of EVs, in general, and in the Saudi context, in particular, where the extremely hot climate and arid terrain can pose additional challenges to EV adoption. Therefore, in this chapter, a detailed literature review, encompassing these issues, is presented. First, a detailed energy outlook of Saudi Arabia is presented, followed by solar PV applications in Saudi Arabia. Challenges of large-scale solar PV integration and its potential impact are discussed next. This is followed by a discussion of the state-of-the-art in EV technologies and trends. Common barriers to EV adoption, as observed globally, are presented next. Finally, EV adoption in Saudi Arabia, potential barriers, benefits, and standards body are discussed towards the end of this chapter.

2.2 Saudi Arabia's Energy Outlook

In order to understand the potential of EVs and Photovoltaic (PV) solar energy to reduce Saudi Arabia's reliance on fossil fuels, it is important to examine the current energy situation in the country. This section, therefore, presents an overview of the energy supply and consumption situation in Saudi Arabia.

2.2.1 Energy Consumption

Historically, Saudi Arabia has been a small consumer of energy compared to most of the countries in Europe, Asia, and North America [32]. Hence, it used to export a large amount of its fossil fuel production. However, as shown in Figure 2.1, this trend has changed in the last couple of decades [32]. Some of the reasons for this change are rapid economic growth, energy-intensive industrialization, a growing population, high living standards, and high incomes. The increase in domestic energy consumption presents two main challenges: how to meet the domestic energy demands without compromising future oil export revenues and how to manage the country's carbon footprint.

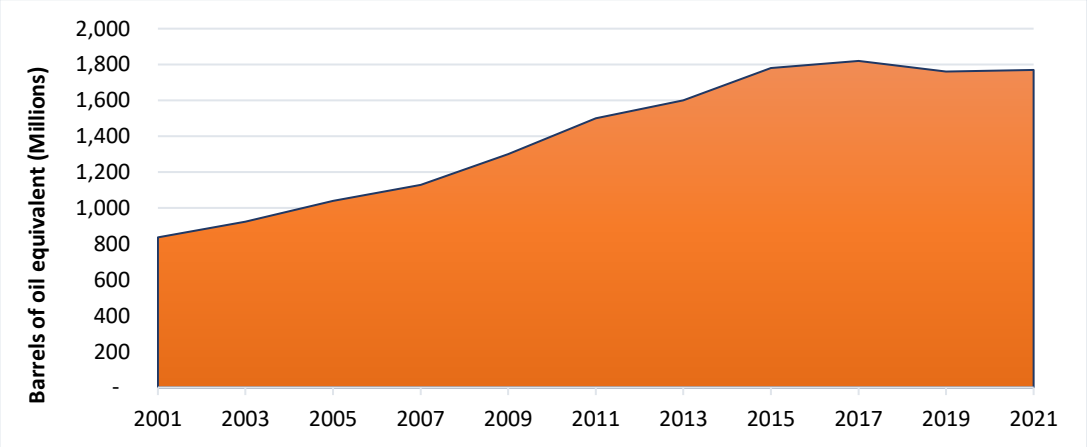


Figure 2.1 Primary energy consumption (barrels of oil equivalent) in KSA in the last two decades [32].

2.2.1.1 Oil consumption

Figure 2.2 shows the final energy consumption in Saudi Arabia by source between 1990 and 2020. It clearly demonstrates that the major source of energy is oil products (such as petrol, diesel fuel, lubricating oil), which are commonly used in the transportation sector. This presents an opportunity for the adoption of EVs in place of Internal Combustion Engine Vehicles (ICEVs), as they will reduce domestic oil

consumption, making more oil available for export to the international market, and can be fuelled by electricity generated by cheaper and cleaner sources, such as solar PV.

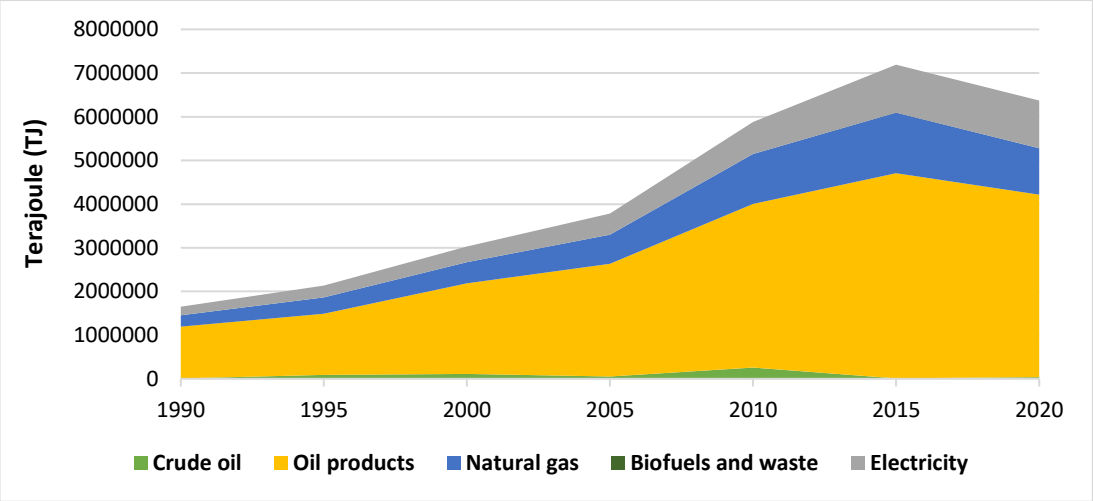


Figure 2.2 Total final energy consumption by source in KSA between 1990 – 2020 [33].

Saudi Arabia is not only one of the largest producers of oil but also the sixth largest consumer and shared 3% of the world total consumption in 2021, as shown in Table 2.1 [34]. Primary energy consumption in the country has been growing at a rate of 5% in recent years [35], and per capita consumption is now the highest in the world [36]. At the current pace, energy consumption could reach up to 8 million barrels per day of oil equivalent by 2030 [35], and existing rates of both production and consumption are not sustainable: in short, if consumption continues at this rate, the country may run out of oil in a relatively short period [37].

Table 2.1 The ten top oil consumers and their share of total global consumption in 2021 [34].

Country	Million barrels per day	Share of world total
US	19.89	21%
China	14.76	15%
India	4.79	5%
Russia	3.67	4%
Japan	3.41	4%
Saudi Arabia	**3.35**	**3%**
Brazil	2.96	3%
South Korea	2.58	3%
Canada	2.26	2%
Germany	2.13	2%
Total top 10	59.8	62%
World total	96.66	

2.2.1.2 Electricity Consumption

Saudi Arabia is also among the highest consumers of electricity in the world, and consumption has been increasing over the last few decades (See Figure 2.3 and Figure 2.4). During the last two decades, residential electricity consumption has grown at an average annual rate of 6% [38]. Consumption is four times greater than the U.S (whose population is 10 times larger), five times greater than South Korea (with a 60% larger population), and eight times greater than Japan (whose population is almost 4 times larger) [39,40].

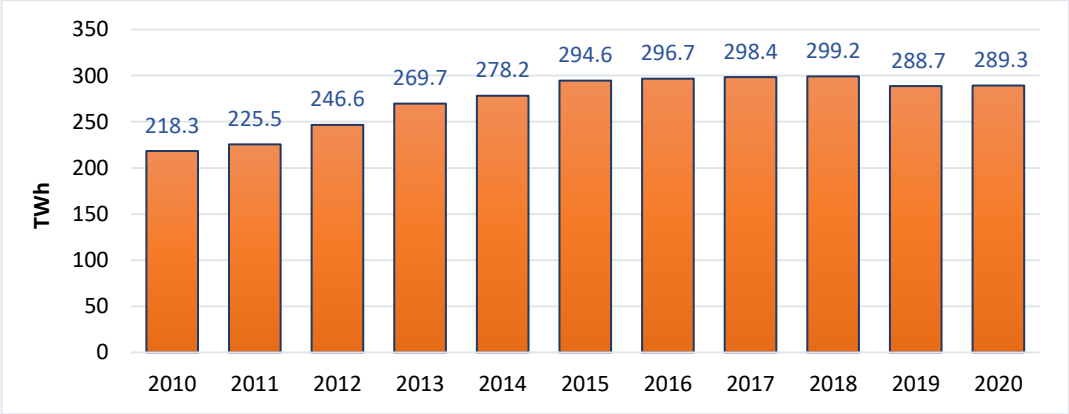


Figure 2.3. Total electricity consumption in KSA [41].

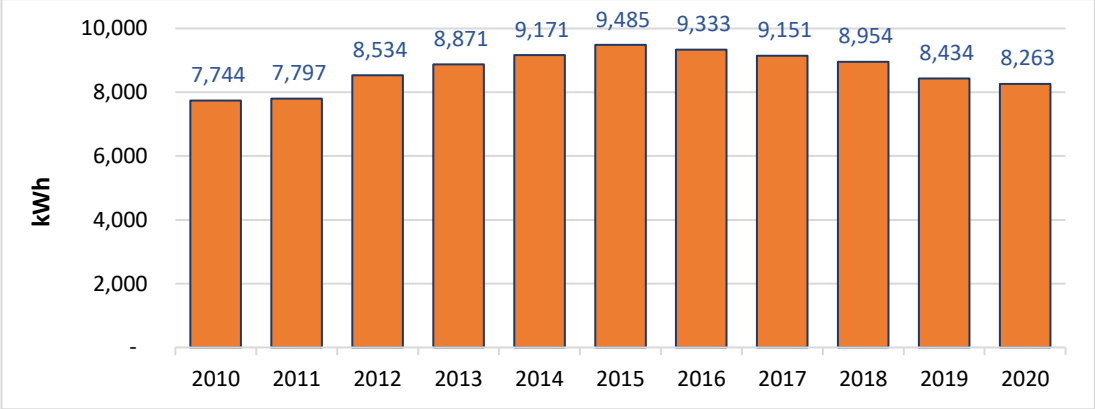


Figure 2.4. Electricity consumption per capita in KSA [41].

Figure 2.5 shows the amount of the electricity consumed by each sector in KSA. The residential sector consumes 142,484 GWh of electricity, followed by the industrial and sector which consumes 58,704 GWh electricity. The agriculture industry is the sector with the lowest electricity consumption, at 5,655 GWh. At present, no electricity is consumed by the transport sector, so the load on the grid will increase significantly

once EV adoption is widespread. Currently, most of the electricity in KSA is generated using fossil fuels, of which it has vast resources. KSA uses these fossil fuels for both domestic consumption, at subsidised rates, and internationally, at competitive prices. However, subsidies put financial burden on the economy, and therefore, are being gradually lifted. For example, Saudi citizens now pay much more for home electricity (+260%) since subsidies were reduced [42]. If KSA can generate electricity using renewable resources (such as solar PV), more of its fossil fuel reserves can be made available for sale in the international market and a lot of money can be saved.

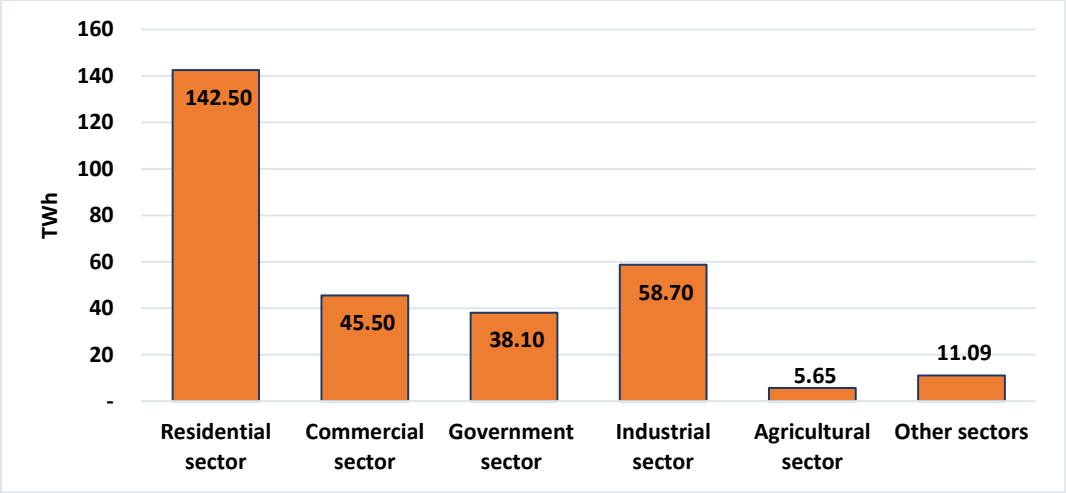


Figure 2.5. Electricity consumption in KSA in 2021, by sectors [41].

KSA has a mainly desert terrain. Deserts can get very hot in summers and very cold in winters. Similarly, the temperature fluctuates highly between day and night. Therefore, Saudi Arabia has a highly fluctuating demand for electricity at different times of the year and at different times of the day. For example, during the summers, air-conditioning is heavily used which increases the demand for electricity. Therefore, there is a need to manage fluctuating demand. The typical daily electricity load curves for Saudi Arabia during the summers and winters are shown in Figure 2.6 and Figure 2.7 respectively. The figures show that electricity consumption is highest on Fridays, on average, approximately 2 GW more than on weekdays. It is to be noted that, in Saudi Arabia, the weekdays are Sunday – Thursday. During the summers, both the average daily consumption and the peak electricity consumption almost doubles. For example, during the summers, the peak energy consumption is around 55 GW between 1:00 pm – 3:00 pm. On the other hand, during the winters, the peak consumption is around 32 GW between 6:00 pm – 7:00 pm.

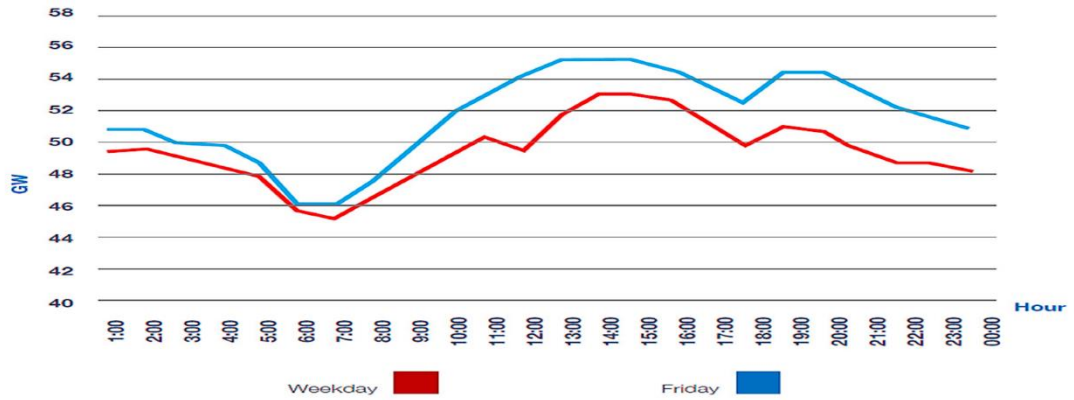


Figure 2.6. Typical summer daily electricity load curves for Saudi Arabia. The results are shown for Weekdays and Fridays [43].

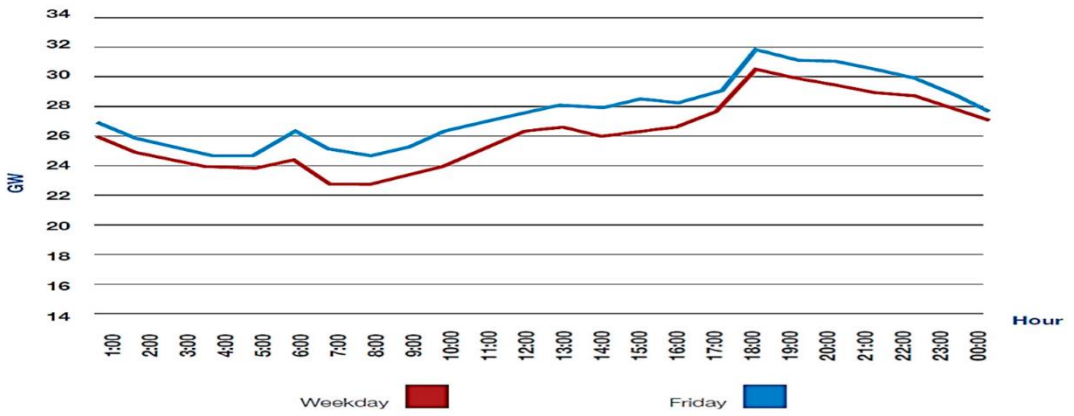


Figure 2.7. Typical winter daily electricity load curves for Saudi Arabia. The results are shown for Weekdays and Fridays [43].

2.2.2 Energy Production and Distribution

In order to identify and evaluate the potential locations for utility-scale PV systems in Saudi Arabia, it is important to understand the existing energy supply and distribution situation in Saudi Arabia and its renewable energy production goals for the future. Therefore, in this section, the energy supply situation in Saudi Arabia is presented first, followed by an overview of the Saudi national grid. Finally, renewable energy production targets of Saudi Arabia are outlined.

2.2.2.1 Total Primary Energy Supply

In 2021, Saudi Arabia had around 76 GW of installed power generation capacity [44]. Most electricity in Saudi Arabia is currently generated by burning natural gas (60.7%) and oil (39%), with only 0.3% from solar (See Figure 2.8). This results in high levels of GHG emissions, making the country one of the top emitters of GHG gases (notably CO_2) (See Figure 2.9).

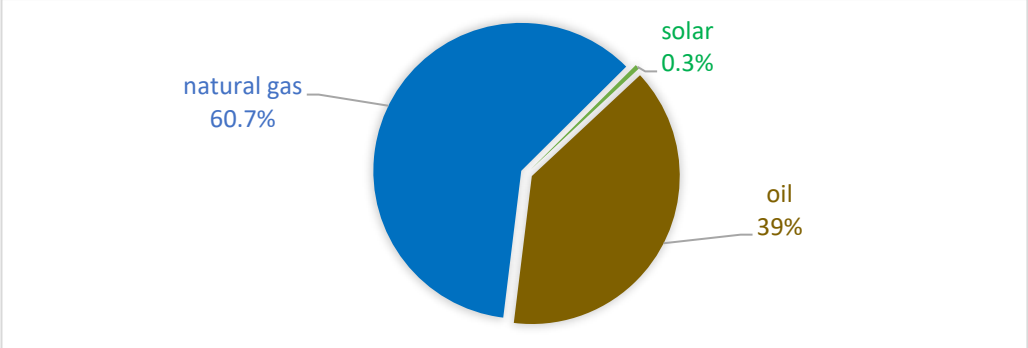


Figure 2.8. Electricity consumption in Saudi Arabia by fuel type [44].

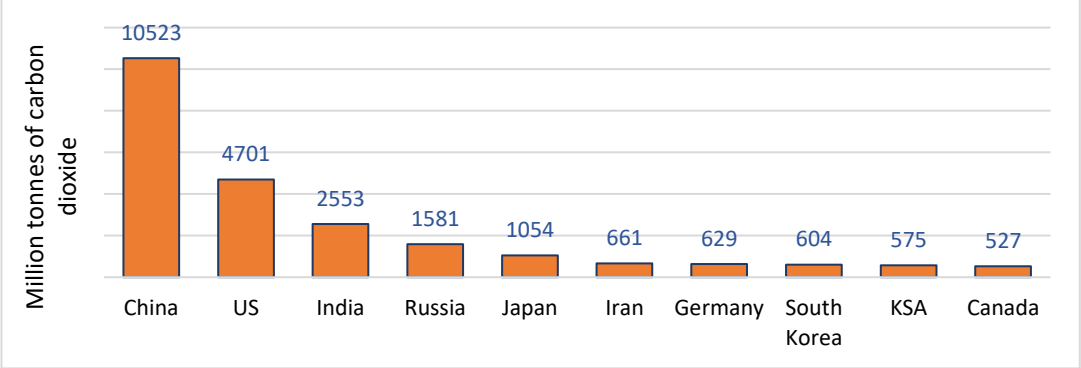


Figure 2.9. Top Carbon Dioxide (CO_2) emitting countries in the world in 2021. With 575 million tonnes of CO_2 emissions in 2021, KSA was the 9th largest emitter of CO_2 in the world [32].

Furthermore, Oil and natural gas are the two most important sources of energy in Saudi Arabia. In nearly three decades, Saudi Arabia's oil supply has increased around 300% (from approx. 1,600,000 TJ in 1990 to around 6,250,000 TJ in 2020) and its natural gas supply has increased around 600% (from approx. 815,000 TJ in 1990 to approx. 5,700,000 in 2020) [33] (See Figure 2.10). From 2015 to 2020 in Figure 2.10, the oil decreased as the main source of energy, in the KSA has a long-term goal to increase its natural gas supply to enable it replace oil in electricity production and free up more oil to sale it in the international market [45].

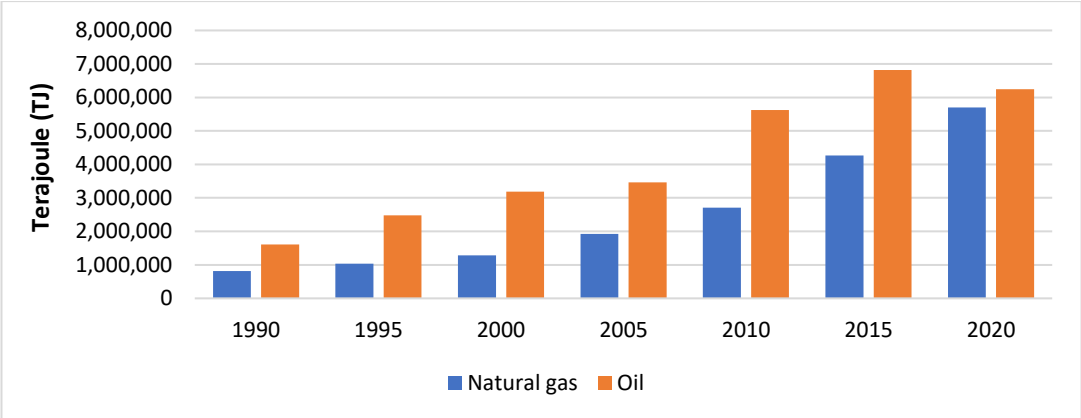


Figure 2.10 Total oil and natural gas supplies in Saudi Arabia between 1990 – 2020 [33].

2.2.2.2 Saudi National Grid

Saudi Electricity Company (SEC) is an independent electric energy company which is responsible for the generation, transmission, and distribution of electricity in the country. National Grid Saudi Arabia, a subsidiary of SEC, is responsible for planning, designing, developing, operating, and maintaining the transmission network in KSA [46]. The electricity transmission network covers over 13,000 cities and villages. It consists of 91,533 circular kilometres of transmission lines, 1,190 substations, and 3,785 transformers [46]. In terms of operations, the country has been divided into four regions central, eastern, southern and western operating regions as shown in **Error! Reference source not found.**.



Figure 2.11 Electrical operation regions of the KSA [47].

The Eastern and Western regions have the largest licensed capacities [43]. From 2016 – 2020, the capacity of the eastern region has remained almost the same, that of the southern and eastern regions has increased by around 1.8 GW each, and that of the central region has decreased by around 1.6 GW (See Figure 2.12).

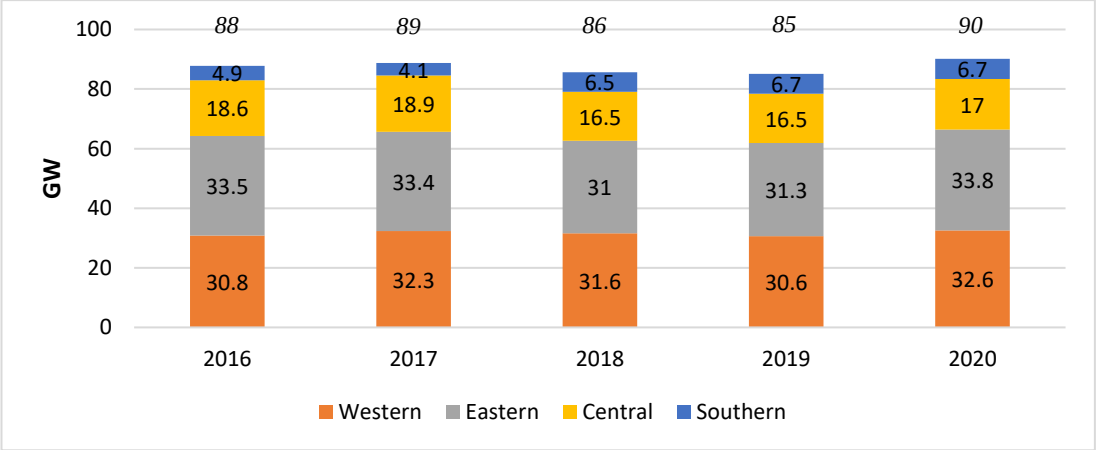


Figure 2.12. Licensed capacity by region and year [43].

The peak load of each region is shown in Figure 2.13. As can be seen, the peak load in the different regions has not seen a significant change over the last few years.

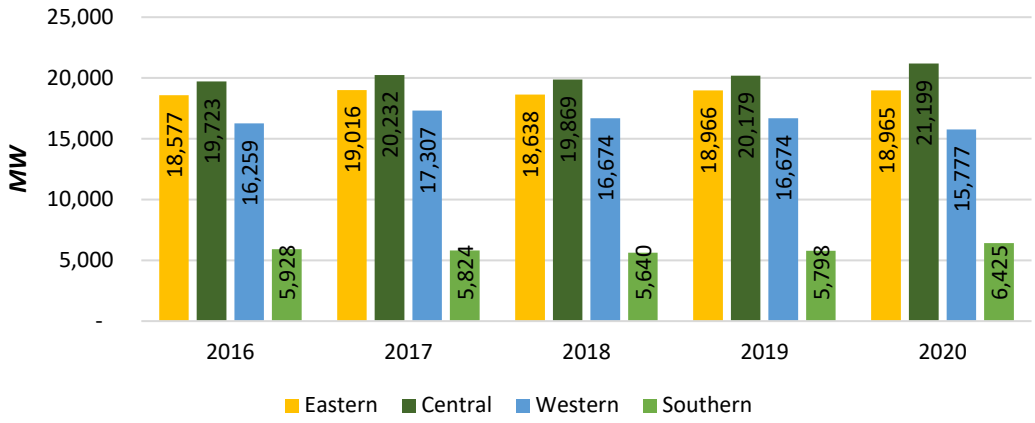


Figure 2.13 Peak load of each region, by year [43].

The length of the transmission and distribution lines in each region are shown in Figure 2.14. The central and western regions have the longest distribution lines (over 225,000 circular kilometres (ckm)). Similarly, the western and central regions also have the longest transmission lines of 28,206 ckm and 25,710 ckm respectively. The southern region has the smallest distribution and transmission lines networks at 124,641 ckm and 14,109 ckm respectively.

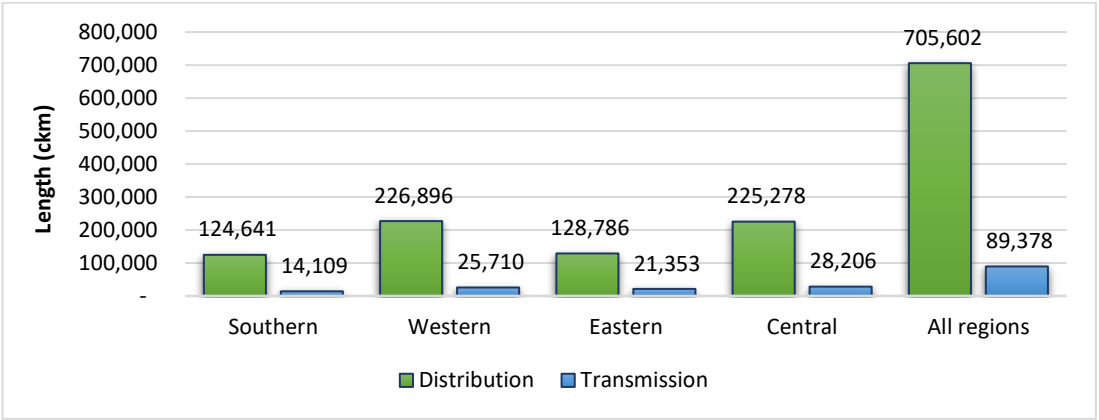


Figure 2.14 Length of transmission and distribution lines in each region [43].

Five different types of transmission lines are used in the KSA: 110 kV, 115 kV, 132 kV, 230 kV, and 380 kV. The length of each type of transmission line is shown in Figure 2.15. It can also be seen that most of the transmission lines are overhead lines of 380 kV followed by 132 kV and 115 kV lines. Among the underground lines, most of them are either 110 kV or 132 kV. 230 kV lines are used sparingly for underground and overhead transmission, since an underground 230 kV line may cost at least 10 to

15 times the cost of an overhead line, and overhead transmission lines are relatively simple to maintain [48].

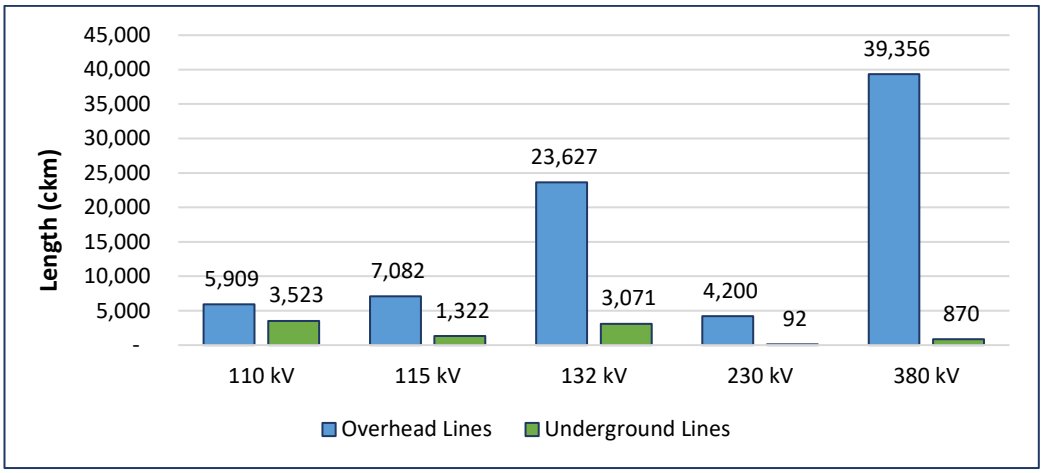


Figure 2.15 Length of transmission lines by voltage [43].

2.2.2.3 Renewable Energy Production Targets

Currently, the Saudi economy is tied to its production of crude oil. However, as part of plans to diversify its economy, the country is now seeking to exploit other sources of energy – especially renewable sources. As a result, a number of initiatives related to the promotion of Renewable Energy Technologies (RETs) have been developed as part of Vision 2030. Under Vision 2030, it is envisaged that the Kingdom will generate 27.3 GW of electricity through renewable energy resources by the year 2023 and 58.7 GW by the year 2030 [49]. This will be done by exploiting wind, solar PV, and waste-to-energy [49]. The renewable energy generation and efficiency targets set in order to achieve this are summarized in Table 2.2.

Table 2.2. Renewable energy generation targets in KSA [49].

Generation Targets	Year
27.3 GW (mix of wind, solar PV, CSP solar, and waste-to-energy)	2023
58.7 GW (40 GW - solar PV; 16 GW - wind; 2.7 GW - other renewable sources)	2030

Over the next 10 years, the country plans to generate around 30% of its electricity from solar energy, and install PV capacity of more than 41 GW by as part of a $50 billion investment in renewable energy [50]. Given the significance of solar in the country's future energy mix, the next section examines the potential and challenges involved in developing solar PV and integrating it into the Saudi grid.

2.3 Solar Photovoltaics Applications in Saudi Arabia

Saudi Arabia's geographical location in the 'sun-belt' of the world means it is ideally placed to generate solar energy. It receives many hours of sunshine per day, and its solar radiation intensity is among the highest in the world [51]. Levels of solar radiation (insolation) in the three major cities, Jeddah, Riyadh, and Dammam, average 5.78 kWh/m^2/day, far exceeding the global average of 1.36 kWh/m^2/day [52], and these high levels combined with the long sunshine hours are key indicators of solar potential [53,54]. The Saudi terrain of widespread desert and its climate of year-round clear skies also makes it a suitable destination for large-scale solar PV production [55], and the country now has many solar PV power projects in development as part of the Saudi National Renewable Energy Program (NREP) [49].

2.3.1 Saudi National Renewable Energy Program

The NREP is a long term, strategic initiative, which aims to diversify Saudi Arabia's domestic power supply. It forms part of the country's Vision 2030 and is overseen by the Renewable Energy Project Development Office (REPDO) [49]. Overall, the programme plans to generate around 4.5 GW of electricity from new solar PV projects in the country, starting with the 300 MW Sakaka solar PV power plant, which was connected into national grid in 2019. Table 2.3 shows the main solar PV projects in Saudi Arabia currently underway, and the reduction in CO_2 emissions and fossil fuel consumption they are expected to generate [49].

Table 2.3 List of Key Solar PV projects in Saudi Arabia.

Round	Project	Size (MW)	CO_2 reduction (tCO_2/year)	Reduction of expected fossil fuels consumption (Million oil-equivalent barrels per day)	Expected Completion Year
1	Sakaka	300	605,932	4.07	2019
2	Jeddah	300	606,444	4.07	2022
	Madinah	50	108,063	0.73	2022
	Sudair	1,500	2,900,000	20.37	2023
	Shuaibah (Al-Faisaliah)	600	1,125,426	7.65	2023
	Rabigh (Makkah)	300	582,215	3.91	2023

	Rafha	50	106,565	0.29	2023
	Qurrayat	200	399,328	2.68	2024
3	Ar Rass	700	1,414,959	9.50	2024
	Layla	80	161,710	1.09	2024
	Wadi Ad Dawasir	120	242,564	1.63	2024/25
	Saad	300	606,411	4.07	2025
	Total	**4,500**	**8,859,617**	**60.06**	

2.3.2 Identifying Suitable Locations for Utility-Scale PV Systems

Although the NREP will create more solar energy to feed into the grid, the adoption of EVs will significantly increase electricity demand. As a result, further utility-scale PV systems will be required. Global Horizontal Irradiance (GHI) is a popular metric used to determine the suitability of a place for PV installations, with higher values of GHI representing greater suitability. The GHI map of the KSA shows that the south, central, and north-western regions have the highest incidence of solar irradiance (See Figure 2.16) [56]. The level of solar irradiance is high throughout the year, but it is particularly high during the summer season at 760 W/m^2 compared to 660 W/m^2 in the winter. In both seasons, the level of irradiance is the highest between 12:00 (noon) and 2:00 pm [57].

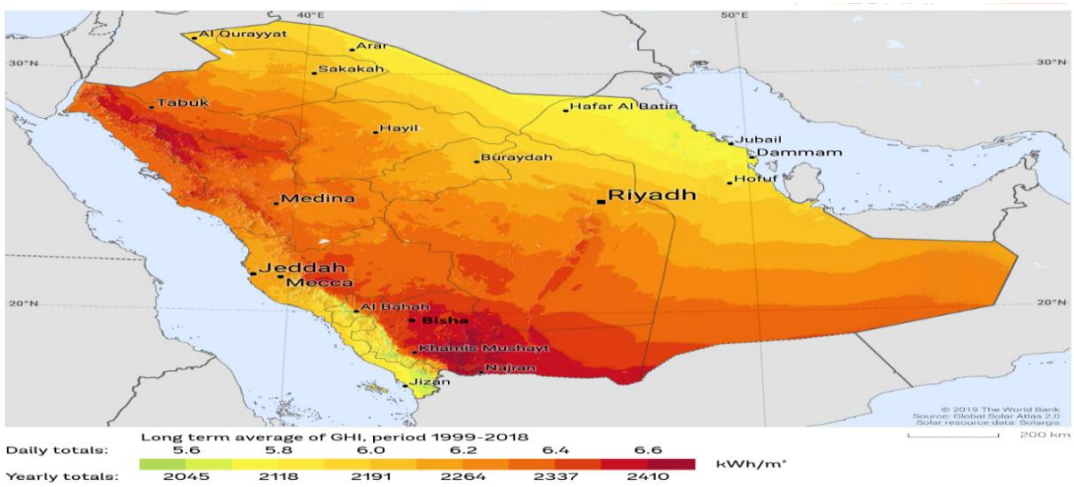


Figure 2.16 Global horizontal irradiation (kWh/m^2/year) in KSA [56].

The suitability analysis map for solar PV in the Kingdom is shown in Figure 2.17. It combines factors such as population density, land cover, topography, protected areas and distance from the grid to measure the suitability of an area for the development of

a solar PV project [58]. The map shows that the central, eastern, and western regions of the KSA are highly suitable for developing solar PV projects.

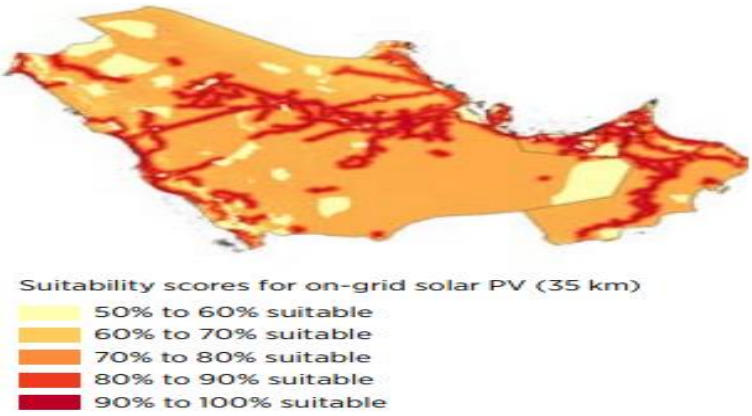


Figure 2.17 Suitability analysis results for on-grid PV [58].

2.4 Challenges of Large-scale Solar PV Integration into Grid System

Wind and solar photovoltaic (PV) are the two major contributors for electric grid integration due to their capability to produce large quantities of electricity. However, both these technologies face similar technical integration challenges due to their intermittent nature. In the case of harnessing wind energy, it is always difficult to forecast availability and to predict the variability of the wind, whereas solar energy is easy to predict, especially in a hot dry country such as Saudi Arabia. However, both are characterised by partial unpredictability, non-controllable variability, and location dependence, which impact operation and performance and affect integration into the grid. Partial unpredictability refers to the inability to predict the exact available energy production of energy sources on a time scale of an hour or a day from the present time [59]. Non-controllable variability relates to the fact that although customer demand is predictable, it is not controllable, adding a level of variability. Location dependence reflects the fact that renewable energy sources are often situated in remote locations. Solutions include forecast technologies to predict the weather and generation output of intermittent sources to schedule and dispatch energy more effectively and the creation of solar energy generation capacity close to the power demand centres [59]. As the transmission of renewable energy to the market is crucial and complex, distributed systems are typically used instead of central energy generation systems,

with microgrids offering the potential to significantly reduce the cost of transmission line loses [60].

However, the integration of small-scale PV based renewable energy micro-grids into the electricity grid involves technical, commercial, and regulatory challenges [61]. The technical challenges relate to voltage regulation, power quality, harmonics, and protection [62]. Climatic change, the variation between the sunshine and clouds, can create periods of voltage fluctuation or an imbalance in the voltage profile which may lead to the malfunction of voltage regulation equipment and power quality systems which are required for the safe operation of that equipment. Harmonic distortion is also associated with the current conversion from DC to AC via an inverter which plays an important role in dispersing harmonic distortion into the distribution system [63].

Grid codes and standards were established to ensure the grids' security, stability, and reliability [59]. The dependence on renewable energy to produce electricity at large scale was initially very low; however, with the development of grid codes for wind and solar power plants, the situation has changed drastically. The main purpose of the grid codes are to enable operation close to that of conventional power plants by supporting the regulation of voltage, frequency, reactive power, and active power, and grid operators now claim that integrated renewable power plants have similar operational behaviour to conventional power plants [59]. This integrated system should provide frequency support to the grid by controlling the active power and should control the reactive power to provide the voltage support to the grid. However, the failure to control these parameters can create further challenges in grid balancing, which can lead to a mismatch of frequency in the grid between the supply and demand [59]. However, when the supply of renewables is higher than the demand, the excess energy produced can only be offset by a reduction in energy production from the conventional baseload generators. By contrast, when demand is higher than the renewable supply, the extra demand can be met by the conventional generators.

A recent study [64] performed load analysis to demonstrate the change in load pattern effect and ramping requirements caused by the increase in large-scale PV penetration into Riyadh's electrical grid. They found that the PV over-generation phenomena occurs when the net load falls below the baseload point set. This allowed them to determine the most appropriate penetration level for the PV system to facilitate grid

integration without stability issues. They also used the net load to analyse the impact of integrating largescale PV into the grid, and found that, in certain circumstances, ramping up the grid's conventional generation system, while ramping down the renewable (and vice versa), could cause severe net load ramp events that exceeded the grid's technical capability. They concluded that an increase in the penetration level of the PV system would dramatically increase the ramping requirement of the grid's conventional generation system.

2.5 Application of Renewable Resources: Solar Energy for Electric Vehicles

Charging EVs using renewable sources such as PV offers a number of environmental, technical, and economic opportunities. The problems related to GHG emissions can be reduced by combining emissions-free EV with low carbon PV power generation. Implementation of EV charging system with PV can reduce some of the problems associated with grid integration. PV systems are relatively maintenance free with no fuel and little labour involved, by comparison with conventional electricity generation. During the daytime, many EVs are parked in car parks which are in direct sunlight, paving the way for charging them using of 'charging-while-parking' technology. By lining the roofs of car parks with PVs, EVs can be conveniently charged while their drivers are engaged with other activities. Several charging methods to accommodate this have been proposed [65], and these are discussed in more detail below.

2.5.1 Standalone - PV to EVs

As the name suggests, standalone technology uses only the PV as the energy source, without the involvement of the grid. This method is more efficient due to fewer power conversion stages; however, the PV arrays should be sufficiently large to fulfil the changing needs of the required number of vehicles. There are two main approaches to achieving the charging goal: direct PV to EV connections and PV-EV connection with an intermediate ESU (Energy Storage Unit). As inadequacy and intermittency are one of the main disadvantages of the direct PV-EV charging system, when PV power is unavailable, or it does not meet the power demand, the ESU enables utilization of the stored excess energy to continuously support the charging system (See Figure 2.18).

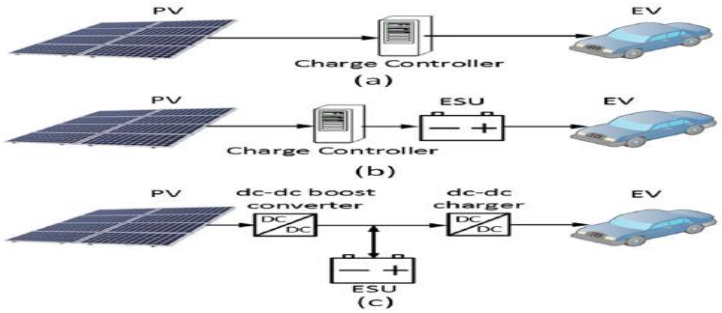


Figure 2.18 (a) PV-standalone system without ESU. (b) with ESU, and (c) with ESU, dc-dc boost converter and dc-dc charger [65].

Another PV-standalone charging system combines the EV battery with a hydrogen fuel cell systems (See Figure 2.19).

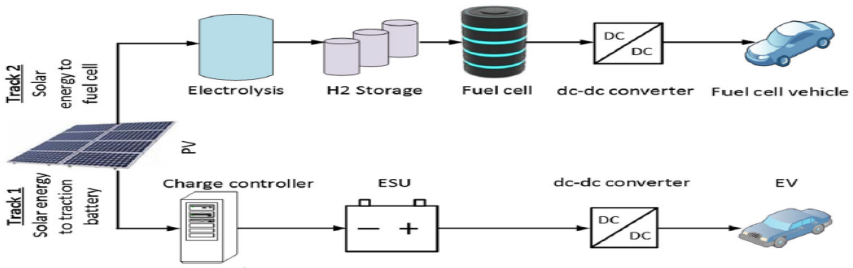


Figure 2.19 PV-standalone system with EV battery and fuel cell system [65].

2.5.1.1 Comparative Costs (fuel powered and solar powered vehicles)

By switching to an electric-powered vehicle, the driver can save an annual average of $2,000 in fuel cost [66]. Table 2.4 shows the comparative fuel cost of gasoline powered, utility electricity powered (solar panel to grid to car), and solar electricity powered (solar panels to car) vehicles [66]. As the table demonstrates, charging EVs with direct solar power has significant cost benefits, with an average rate of $0.06 per mile to fuel a typical EV compared to $0.2 per mile for a typical fuel-powered vehicle. This suggests that the use of EV and additional installation of solar powered charging systems in homes and workplaces could yield cost savings of around 40% [66].

Table 2.4 Comparative cost involved in using gas-powered and solar-powered vehicles (assuming the vehicles travel 40 miles on average per day) [66].

Cost	Gasoline powered	Utility electricity powered	Solar electricity powered
Cost per day ($)	8.00	2.51	1.48
Cost per month ($)	243.20	76.30	44.99
Cost per year ($)	2,918.40	915.6	539.90
Average cost per mile ($)	0.20	0.06	0.04

Note: assuming $4 per gallon of petrol and $0.20 average electricity rate.

2.5.2 Photovoltaics – Solar panel to Grid

The main issues associated with charging EVs relate to the charging costs and the additional load imposed on the grid, which can be very large, especially for fast charging. Generally, if charging takes place during peak time, energy tariffs are high, with owners paying a premium for the additional load. To overcome this issue, a PV-grid charging system is proposed in [65] which combines PV power and grid power. The availability of the PV system improves the grid stability and reduces the amount of unused capacity which needs to be held in reserve, known as the 'spinning reserve' capacity. The main components in PV-grid system are a Maximum Power Point Tracker (MPPT) dc-dc converter, a bidirectional inverter, and a bidirectional dc charger. The bidirectional converter can act as an inverter or a rectifier, behaving as a buck converter for inversion and as a boost converter for rectification [65]. Figure 2.20 shows a typical setup for the PV-grid charging system.

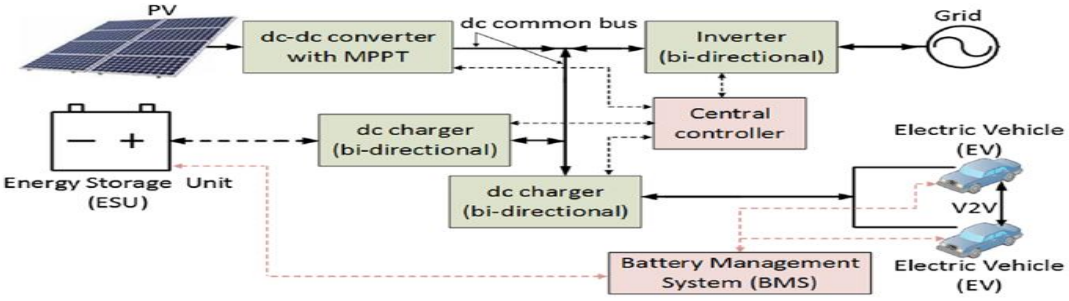


Figure 2.20 A typical setup for the PV-grid EVs charging system [65].

2.6 Potential Impact of Large-Scale Solar PV Integration into the Saudi Power Grid

Saudi Arabia aims to install around 57 GW of renewable energy generation capacity by 2030, with 40 GW (around 70%) generated by solar PV alone [67]. With such a significant power capacity addition, it is important to consider the impact that this intermittent source of energy will have on the Saudi power grid. Therefore, this section examines the potential for meeting peak load demands, the economic implications, and the voltage regulation issues associated with integrating solar power into the grid in Saudi Arabia.

2.6.1 The Potential Benefit of Solar PV for the Power Grid in Saudi Arabia

Solar PV has the potential to reduce peak load demands in the Saudi grid and is therefore considered as a valuable resource in the region [55]. A recent study by Elshurafa & Muhsen [67] assessed the potential of solar PV to reduce peak load demands by developing a site potential analysis in the Saudi capital, Riyadh. Using Geographical Information System (GIS), they developed an energy and capacity estimation analysis of rooftop PV systems in multiple buildings in the city, at the residential, commercial and institutional levels. Their findings indicate that a theoretical upper limit capacity of 4.34 GW could be installed in the city to provide 8.14TWh annually, assuming a 15% module efficiency, an aggregate loss factor of 15% and a capacity factor of 21.4% for the PV systems. The peak load of the power grid in the Central region, in which Riyadh is located, is 20 GW and this is partially covered by 16 GW of available generation capacity in the region [67]. However, the remaining 4G W needs to be provided by available generation capacity in the Eastern region. If this theoretical capacity were realised, it would provide nearly 9% (around 1.8 GW) of the energy needs in the Central region (20 GW) and reduce energy demands during peak load scenarios for the power grid.

2.6.2 The Economic Impact of Solar PV in the Saudi Power Grid

Despite the potential grid relief that could be obtained by adding PV capacity, as described in the Riyadh study [67], there are deep concerns relating to the cost benefit of such integration. Markus & Alexandre [68] addressed this topic in two case studies on KSA – one in Sharourah in the Southern Operating Region and the other in Al Ula in the Western Operating Region. Markus & Alexandre [68] developed a static and security-constrained linear optimal power flow for both sites. The analysis contemplated shares of PV, wind, concentrated solar power, and thermal generation mixtures to assess the economic dispatch and reliability of the system, while at the same time calculating the Effective Load Carrying Capability (ELCC) of each technology under different peak demand scenarios. The average production costs for each location and technology mix were also evaluated.

An important result for PV was that, in both locations, adding a large amount of PV capacity (assuming 150% of peak demand) turned out to be more economical than the conventional thermal generation alone. Meanwhile, wind power could be added up to

120% of peak demand before the average production cost became higher than the conventional solution in both cases. Overall, according to the study [67], the most economical solution was a mixture of thermal generation and Renewable Energy Sources (RES) if the share of RES was below 20% for PV and about 40% for wind. With this mixture, the overall system cost would reduce.

The study also found that the correct decision for short and medium-term planning of the RES mix was extremely site dependent. For Sharourah, adding PV alone was very beneficial, but adding PV and wind was a better decision for Al Ulla. In addition, the authors found that if available capacity already satisfied the next year's capacity, then adding PV was always the best way to reduce average production costs in the system.

Despite the in-depth analysis carried out by [68], an important limitation of the study was that the intermittency cost associated with PV was not considered. These include the costs associated with ramping up existing power plants and operating up-spinning reserves to compensate for times of reduced power output during cloudy days, as well as the cost of building transmission capacity for the integration of solar PV, which form the main cost of integrating solar PV into the power grid. However, Elshurafa & Matar [69] did analyse the costs of solar PV intermittency in the power utilities of Saudi Arabia. They developed an energy-economic model using the King Abdullah Petroleum Studies and Research Centre (KAPSRC) Energy Model (KEM), the first publicly available large-scale energy policy model for Saudi Arabia, to examine the integration of 20 GW of solar PV capacity (representing 25% share of the power mix) into the grid. The study tested small increments of 1 GW under different case scenarios where the total capacity was distributed across different regions in Saudi Arabia, with the model calibrated to 2015. The results pointed to a cost of intermittency equivalent to $0.013/kWh for each unit generated by PV or as little as $0.002/kWh if shared by all customers. Elshurafa & Matar [69] also stated that solar energy is efficient during afternoon peak periods as a resource to be used for peak-shaving purposes [70], and that under low penetration of solar PV, the costs of intermittency are negligible.

However, the study [69] also refers to a barrier described as the *Operational Blend Wall*, after which the costs of operating solar PV outweigh its benefits. The operational blend wall in Saudi Arabia was established by the authors at 11 GW for the 2015 power system, assuming a crude oil price of $4.24/bbl. According to the authors, this

limit is not final, as there is a strong correlation between the fuel price and the operational blend wall. As fuel prices rise, so will the maximum capacity of solar PV that can be installed to achieve a lower cost of operation in the power grid. Indeed, the study found that the maximum capacity of solar PV that could be integrated into the grid could reach up to 52 GW if the crude oil price reaches $7/bbl.

2.6.3 Solar and Battery Storage Technologies and their Performance

An important consideration in PV integration, besides power system economics, is related to the behaviour of new, large-scale, storage technologies combined with PV and their impact on power generation from the grid to compensate for PV variations. Moreover, given the large number of electronics components involved in PV power stations, it is important to measure the Total Harmonic Distortion (THD) [71] that can occur when making interconnection to the power grid, as this reduces energy efficiency and can lead to equipment failure. This is possible in Saudi Arabia thanks to a power quality case study developed by [72] which examined an isolated grid in the northwest of the country. Tabuk, the site of the study, in the Western Operating Region, had solar resources of 9000 Wh/m^2 at the time, making it worthy of study. The authors considered a 40MW PV penetration with battery storage connected to the Tabuk grid, an isolated grid consisting of 12 buses with 132kV voltage levels, during 2013-2014. The load profile evaluated in the study varied between 720MW during the summer season (peak loading conditions) and slightly below 450MW during the winter season.

The study [72] developed a complete PV and battery storage system model. As shown in Figure 2.21, Bus 5 was selected as the slack bus, to manage the active power (P) and reactive power (Q) in a system, as this had the largest capacity, and two 20MW PV plants were established close to Bus 6, and this had sufficient available land. With battery interconnected storage, initial output of 1.4kV AC was increased to 132kV through two step-up transformers. Under the simulation, the DC battery storage was assumed to have 50% capacity of total PV power and the initial State of Charge (SOC) was set at 70% under $1000W/m^2$ irradiation. As simulation was performed, it was possible to verify the PV plus battery power output decrease as the battery was charged within the first 16 seconds of the simulation until 80% SOC was achieved. Then, as the battery discharged, with the injection of additional PV power output, it was

possible to deliver up to 60MW to Bus 6. Variations according to radiation were also evaluated in power fluctuations. When evaluating the impact of this generation pattern on the grid, the study showed minimal fluctuations in power stations to compensate for PV power input variations. More importantly, the research also shows no reactive power output from the PV plus battery configuration, and an electric current THD close to 2%, which is within permissible limits.

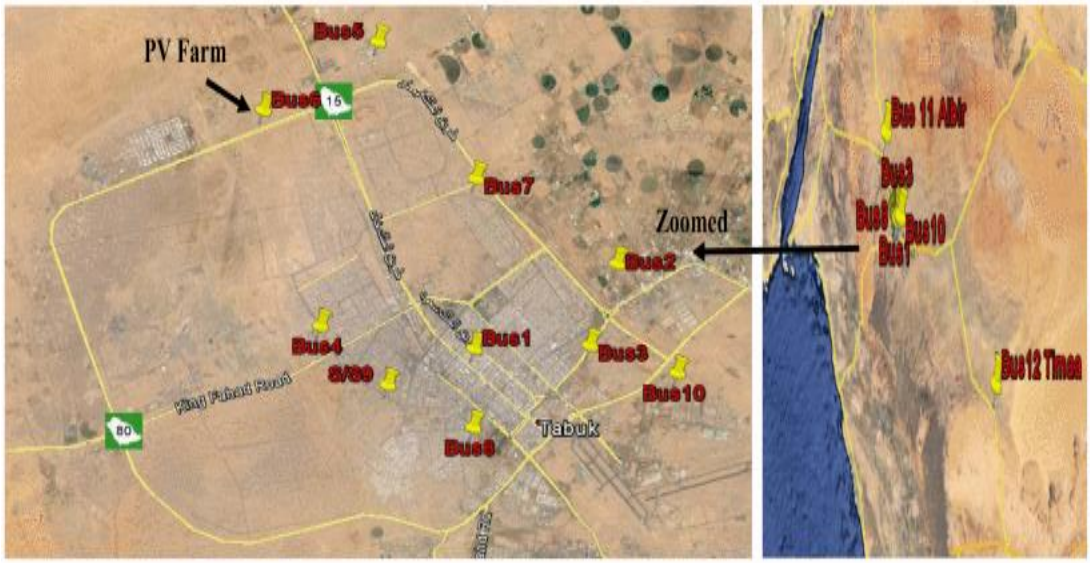


Figure 2.21 A typical setup for the PV-grid EVs charging system [65].

2.6.4 Voltage Rise due to PV Penetration in the Distribution Network – A Case Study Analysis and Solution

Finally, the integration of solar PV at a large scale also presents technical challenges in the overall operation of the power grid, notably those related to voltage fluctuations. Shalwala & Blejis [73] addressed the effects of grid-connected PV systems on voltage regulation in a residential electricity network in Saudi Arabia. The authors developed a steady-state analysis in a distribution system under different load and PV generation conditions to calculate bus voltage, voltage drops, power flows, and losses using Electrical Transient Analyzer Program (ETAP) simulation software [74]. The residential network under study had a radial configuration comprising of three feeders, each with a 110/11kV step-down power transformer, and a set of secondary substations that were connected to a customer feeder through another step-down transformer. Each branch was also equipped with an on-line tap changing transformer that changed the voltage level of the branch at the main substation bus in small steps

(0.5% of nominal voltage) that were adjusted by the Automatic Voltage Controller (AVC). From each secondary substation, six loads were tapped off. The study [73] focused on addressing calculations under different levels of concentrated PV penetration (at 40% cell-efficiency) under peak load (summer) and 40% peak load conditions (winter), with focus on the longest radial branch, as it was estimated to be the most sensitive section of the network. Results of steady-state analysis showed that the integration of PV increased the voltage at each substation across the branch and increased voltage for each consumer as well. Voltage variations found (0.99 - 1.01 up.) were always between permissible values across the branch (0.95 - 1.05 pu.), as established by the Saudi Electricity Company [75], with the highest voltage value occurring at higher PV penetration during winter conditions and the lowest voltage value in summer, without PV generation. Meanwhile, the feeder in the last substation of the radial branch just reached the higher limit for voltage regulation (1.05 pu.) on the last two customer nodes under winter conditions. To solve the voltage rise due to PV generation, the authors presented four alternative solutions. Of these, the most suitable methods for both the distribution network operator and the customer were using an on-line tap changer at the HV/MV prime substation or increasing the reactive power consumption of the PV generator by adjusting it at 0.9 lagging power factor (instead of a unity power factor).

In another study, [76] focused on providing a new control scheme based on the fuzzy logic concept as a solution to the voltage rise problem. Taking the same branch and node as a reference, the study shows how the tap changer transformer at the HV/MV prime substation of the branch could maintain voltage levels within permissible values across the entire branch under each case scenario. However, the scenario that used an off-line tap changer required the distribution network operator to dispatch an engineer to manually change the substation transformer’s tap changers each time voltage limits were exceeded, making this an impractical approach.

As a result, the authors [76] offered an alternative approach related to Fuzzy Logic Control (FLC), using MATLAB as a simulation tool for the performance evaluation of this control system. This controller consists of a single input (average customer voltage) and a single output (preferred tap changer setting in steps of 2.5%). Both variables are inversely proportional to one another. In other words, a high voltage (1.02 pu.) input variable results in a low setting (-2.5%) for the tap changer, while a

low voltage (0.98 pu.) input results in a high setting (+2.5%) output. The research found that there was a strong positive correlation between the load and the reactive power (Q) flow in the branch (more load demand, more Q). It also found a negative correlation between PV generation and active power (P) flow (more PV, less P). Based on these facts and using active and reactive power measurements, it was possible for the FLC scheme to automatically set the required tap position to keep voltage levels within permissible parameters. Under a linguistic algorithm proper of FLC, it was possible to establish control rules for the system assuming No PV, Min PV, and Max PV scenarios (calculated depending on P measurements) as well as High Load, Medium Load, and Low Load scenarios (determined based on Q measurements). Multiple advantages were identified from this approach, since all measurements were taken locally and there was no need for remote communication. In addition, this control method is independent of the branch and line parameters, and it can be applied to different types of networks, making it a simple and economic control technique.

More recently, Alshahrani and Omer [59] have shown that having a short and a long-term energy storage arrangement can help reduce the impact of large-scale renewable energy integration into grid system.

2.6.5 Outlook for Solar PV and the Saudi Power Grid

The renewable energy targets set in Saudi Arabia establish solar PV as the most important source of power for the future of the country's electricity grid, with up to 40 GW planned to be installed by 2030. The literature indicates that the integration of this large and intermittent source of energy into the power grid presents both challenges and advantages. Large-scale deployment solar PV could reduce the overall cost of the power grid operation through a combination of traditional fossil power plants and a renewable energy mix, as research [68] indicates that large solar PV capacity addition is more economically attractive than a conventional power source solution alone. However, studies [68,69] have shown that the Saudi power grid has a limit on the capacity of solar PV power that can be added before the costs outweigh the benefits for the grid. Such limit values are dependent on fuel prices and for the Saudi Arabian power grid, limits can vary from 11 GW (assuming $4.24/bbl.) to 52 GW ($7/bbl.). Voltage regulation solutions for distribution networks with PV generation have also been proposed in the literature [73] along with control techniques

such as FLC to improve the efficiency and performance of voltage regulation [76]. However, further research is needed to evaluate the impact of integrating large-scale solar PV generation into the Saudi power grid, especially with reference to reliability, stability, remote communication, availability, fault condition, and power quality.

2.7 Electric Vehicles (EVs) – Technologies and Trends

In order to evaluate the potential of renewable energy to meet the requirement for increasing need of EV into the grid and to find the best approach to introduce EVs into the Saudi grid, it is important to understand the different types of EVs, their features, and the current and future trends related to EVs. Therefore, in this section, first, an overview of EVs is presented. Then, the main types of EVs are discussed followed by purchase prices of EVs. Recent trends in EVs and EV charging infrastructures are discussed towards the end of this section.

2.7.1 An Overview of Electric Vehicles

Given the significant increases in air pollution through CO2 and NO_2 emissions, many countries are now promoting the use of EVs and sales have increased significantly since 2020 (See Figure 2.22).

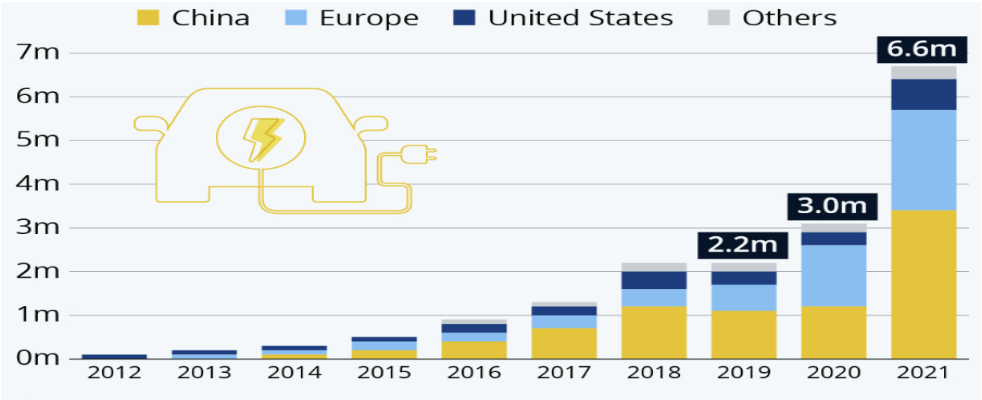


Figure 2.22 Number of electric vehicles sold in different regions between 2012 – 2021 [77].

As a result, production rates have risen rapidly and are forecast to reach 35 million by 2030. Figure 2.23 shows forecast EV production capacity up to 2030 and the key manufacturers in the market.

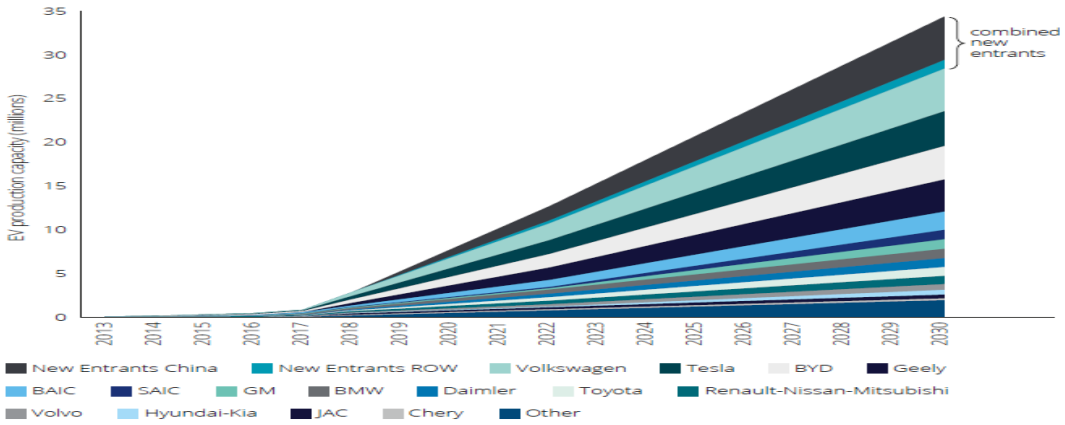


Figure 2.23 Electric vehicle production forecast of the big car manufacturers and new entrants [78].

EVs offer a number of advantages over ICEVs:

- ***Emissions**:* unlike ICEVs, EVs have zero emissions. Moreover, EV manufacturing processes also tend to be more environmentally friendly.
- ***Simplicity***: EV engines are simpler and more compact.
- ***Reliability***: having fewer and simpler components make EVs less likely to break down. Engine explosions, vibrations, and fuel corrosions related wear and tear are not suffered by EVs.
- ***Comfort***: the absence of engine-related vibrations and noise makes EVs more comfortable to travel in [79].
- ***Cost***: maintenance and electricity cost for EVs are much lower than maintenance and fuel cost for ICEVs (See Figure 2.24).

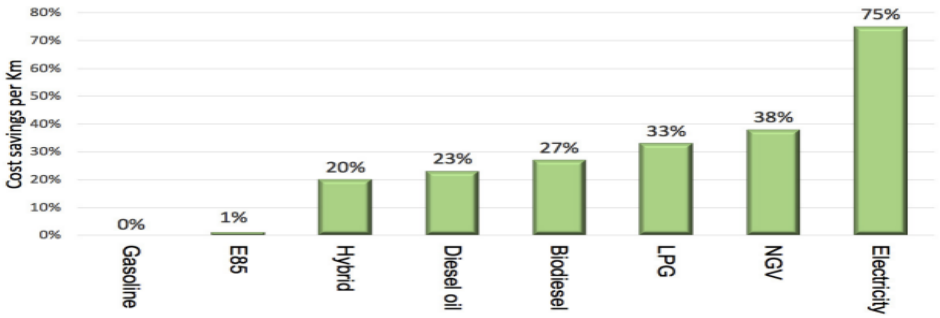


Figure 2.24 Comparison of savings per kilometre offered by different types of vehicles [12].

However, EVs also present a number of challenges, which include:

- ***Driving Range:*** EVs typically have a limited range of around 200 – 350 km on a full charge. However, this range is continually improving due to advances in battery technology; for example, the latest Tesla Model S has a range of over 600 km [80].

- ***Charging Time:*** charging the battery of an EV can be time consuming. For example, it can take around 4 – 8 hours for a full charge. However, again, charging times are continuously reducing due to advances in fast charging technologies. For example, the Tesla Model S can reach 50% charge in approx. 20 minutes and up to 80% in around 30 mins [80].
- ***Battery Cost:*** battery packs for EVs are expensive.
- ***Bulk and Weight:*** batteries can be heavy and can take a lot of vehicle space. Typically, an EV battery weighs around 200 kg, but this varies according to the battery capacity [81].

2.7.2 Main Types of Electrical Vehicles

EVs are generally classified according to the way they are powered, and there are three main types: Battery EVs (BEVs), Hybrid/Plug-in Hybrid EVs (HEVs, PHEVs), and Fuel Cell EVs (FCEVs). Although demand for EVs has increased exponentially since 2013 [58], a period which saw an estimated global increase in BEVs of 3.3 million and 1.8 million more PHEVs, FCEVs are not yet mainstream, with only 12,900 vehicles worldwide at the end of 2018, mostly in the US, Japan, and China. However, hydrogen FCEVs are expected to see a significant increase in numbers in the next decade, with forecasts indicating that 10-15 million cars and 500,000 trucks will be hydrogen-powered by 2030 [82].

The key features of each type of EV are shown in Table 2.5, and the advantages and challenges associated with them are discussed in more detail below.

Table 2.5 Main characteristics of different types of EVs [83].

Types of EV	BEV	HEV/PHEV	FCEV
Energy source(s)	Battery	Battery/ultra-capacitors, ICEs	Fuel cells, Supplementary battery
Propulsion technique	Electric motor drives	Electric motor drives, ICEs	Electric motor drives
Characteristics and feature	Zero emission, Short driving range, Higher initial costs	Low emission, longer range, more complex	Zero emission, Highest initial costs, Medium driving range

Major techniques	Electric motor control, Battery management, Charging device	Electric motor control, Battery management, managing multiple energy sources and optimal system efficiency, Components sizing	Fuel processor, Fuelling system, Fuel cell cost
Regenerative braking	Yes	Yes	Yes
Typical Battery Capacity	20-100 kWh	5-20 kWh	2-20 kWh
Number Worldwide	3.3 million	1.8 million	12,900

2.7.2.1 Battery Electric Vehicles (BEVs)

As the name suggests, BEVs use electric motors and batteries instead of traditional ICEs, and typically need to be plugged into an external electricity source to recharge (See Figure 2.25.) An alternative method, known as 'regenerative braking', can also be used, in which the vehicle's electric motor is used to help slow it down, allowing some of the energy which is usually lost as heat through the brakes to be recovered [84].

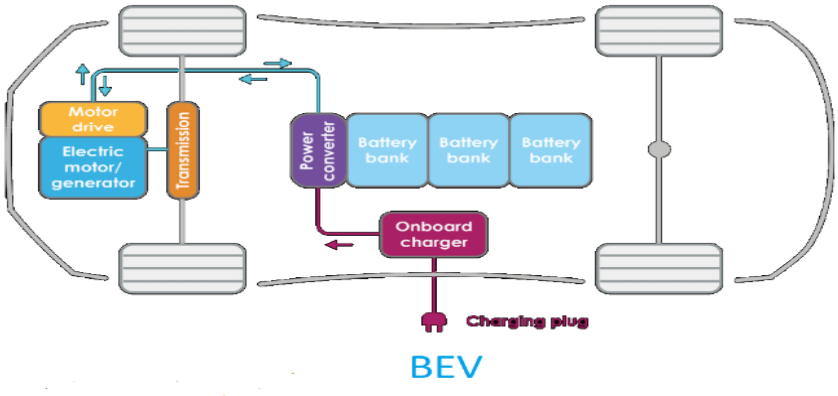


Figure 2.25 Schematic of a battery electric vehicle [84].

The main advantages associated with BEVs are a) zero emissions, b) easy to charge at home, c) smooth acceleration due to lack of gears, d) no need to change oil, and e) low overall operating costs. Some of the disadvantages are a) a shorter range and b) higher initial costs than ICEVs, although these are typically recouped in 2-3 years due to lower charging costs, and c) lack of charging infrastructure.

The number of BEVs on the roads has increased significantly in recent years, and estimates indicate there will be more than 125 million globally by 2030 [85]. However, several technical and infrastructure issues still need to be addressed. Figure 2.26 shows the concerns of consumers in key markets, notably driving range, cost, and lack of charging infrastructure. The factors associated with these are discussed below.

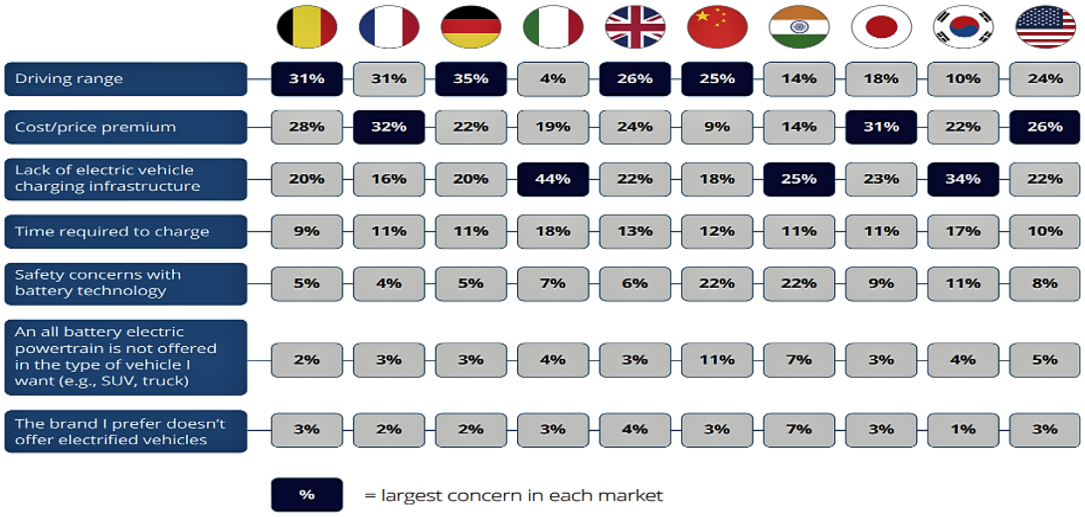


Figure 2.26 The percentage of concerns of customers regarding buying BEVs in different countries [78].

The electric motors in BEVs are highly efficient, using between 90 – 95% of the input power, and producing zero emissions [86], and the technical challenges associated with them, namely cost and the limited driving range, are directly related to the batteries they use. The growth in BEVs is largely driven by developments in the lithium-ion (Li-ion) batteries [87], which are used to store the electric energy which powers the vehicle. Although new forms of batteries, such as the Al-air and Li-air are still in development, Li-ion batteries currently outperform others, making them the most suitable candidate for EVs [86] (see Table 2.6). However, NaNiCl2 batteries are also used in some lower-capacity vehicles. Lead Acid (Pb/A) batteries are mainly used to power the electrical circuits of specific components (e.g., the starter) rather than being used as the main source of traction in a vehicle. Nickel-metal hydride (NiMH) batteries, although cheaper than Li-ion batteries, but are mostly found in hybrid electric vehicles rather than pure electric vehicles. Other battery types are rarely used in EVs these days.

Table 2.6 Current and projected battery specifications for EVs [86].

	Now			Projected		
	Specific power (W/kg)	**Specific Energy (Wh/kg)**	**Cycle life (deep cycles)**	**Specific power (W/kg)**	**Specific Energy (Wh/kg)**	**Cycle life (deep cycles)**
Pb/A (VRLA)	200	35	600	300	45	1500
NiMH	200	65	1000	300	75	1200
NaNiCl2	150	100	1000	400	120	1500
Li-ion	300	100	NA	500	150	1500
Zn-air	90	100-200	NA	110	300	600
Al-air	10	200-300	NA	16	1300	NA
Li-air	NA	NA	NA	Low	600-1000	NA
Fe-air	90	80	600	100	120	1000

Note: NA means the parameter is not applicable

The cost of Li-ion batteries forms a significant proportion of the purchase price of a BEV. For example, in 2022, a typical battery cost US $125/kWh, making a 40 kWh capacity battery around US$ 5,000 [88] and adding an extra US$ 12,000 to the cost of a BEV by comparison with similar ICEVs [89] ; however, it is estimated that these will decrease to around $112/kWh by the end of 2025 [90]. As higher capacity batteries attract higher costs, most BEV models have low capacity batteries with a driving range of less than 160 miles (250 km). However, more advanced models can now reach around 1000 km, and future models are expected to surpass this, notably the Tesla next generation ‘Roadster’, which was expected to achieve a range of 1000 km in 2024 [78][91].

Further improvements in range are expected to come through developments in battery technology. For example, the energy density of lithium-ion batteries can be enhanced by optimizing existing Li-ion cells or introducing new materials with superior performance. More effective battery management systems can extend battery life and improve driving ranges. Reductions in battery pack mass, improved pack design and optimized cooling, will also increase range, and future developments in lithium-air, solid state technologies, and high energy capacitors will further improve BEV’s range [78]. However, while BEV manufacturers such as Tesla have their own battery development plants, others rely on battery manufacturers, such as Samsung and

Panasonic. Therefore, if cutting-edge technologies are patented by individual companies (notably Tesla), it may become more difficult for others to compete [78].

The energy consumption of BEVs varies according to the speed of the vehicle, the driving conditions, and whether heating or air conditioning is used, and this can vary significantly between models, reaching as high as 200 Wh/km in some cases (See Table 2.7) As the driving range reduces as velocity increases, BEVs achieve the longest range where the speed does not exceed 50 km/hr, making them well-suited for city driving conditions [86]. However, in a large country such as Saudi Arabia, other EV types must also be considered.

Table 2.7 BEVs of different global manufacturers and the specification of the components and design [86].

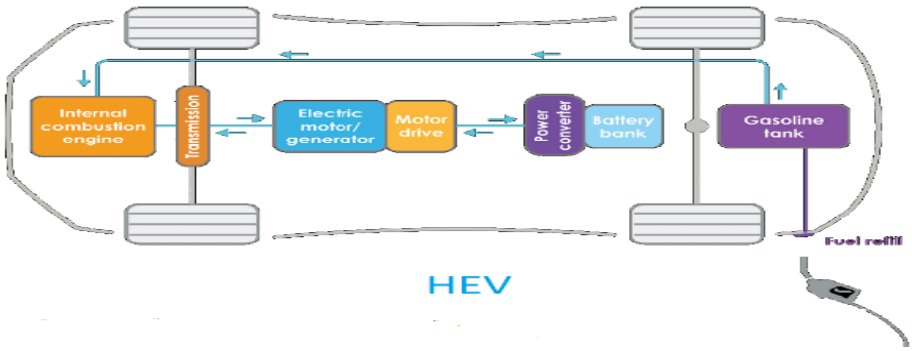
	Max. Power (kW)	Weight (kg)	Frontal Area (m2)	Cd	Battery		Motor	Fuel Consumption (Wh/km)
					Type	Capacity (kWh)		
Smart Fortwo Electric	30	854	1.95	0.38	NaNiCl2 (Zebra)	14	BLDC	120
Mitsubishi iMiev	47	1080	2	0.3	Lithium-ion	16	BLDC	125
Think city	30	1038	-	-	Sodium-nickel chloride (zebra)	28.3	AC-Induction	157
Ford Focus	100	1550	2.26	0.32	Lithium-ion	23	BLDC	190
Nissan Leaf	80	1585	2	0.28	Lithium-ion	24	BLDC	150
Fe-air	90	80	600	-	-	100	120	1000

Note: *Fuel consumptions are based on new European driving cycle and the specifications are by the car manufacturers. Cd- is the drag coefficient, aerodynamic friction term, depends on velocity, BLDC = Brushless Direct Current motor.*

2.7.2.2 Hybrid Electric Vehicles (HEVs)

In HEVs, the power is generated from both batteries and petrol through electric machines and ICEs (See Figure 2.27). While the ICE uses petrol to drive the wheel, the electric motor either supports the ICE in power transmission or drives the car independently, in line with the charge state of the battery and electric power train conditions. In contrast to BEVs, HEVs cannot be recharged from the grid, so their

energy comes from petrol and regenerative braking. When the battery charge is too low, the engine uses the motor to generate electric power to recharge the battery pack, and, when high speeds are required, the electric system switches to the ICE. A motor control unit and a power converter unit help to switch between these requirements. The ICE and the electric power train can be configured in several ways, including series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid configurations [93], each with its own advantages and disadvantages. However, as the engine stops when the vehicle is idling, notably in traffic jams, HEVs are generally considered advantageous in low-speed urban conditions, due to reduced fuel consumption and lower GHG emissions [93]. Two drive trains can work together to



enhance the performance of the configuration technologies used in HEVs.

Figure 2.27 Schematic of a Hybrid Electric Vehicle [84].

The dual system in HEVs offers several key advantages, the battery reduces idling, cutting gas consumption and emissions and enhances the 'stop-go' process, which is important in city driving. Although the battery can only power the vehicle up to about 40 mph, the combustion engine then takes over, offering higher speeds and greater ranges than BEVs, especially as the battery recharges internally. However, HEVs do not have zero emissions, and the complex mechanics required to manage both elements can lead to higher risk of failure and higher repair costs. In addition, research indicates that the operating costs of HEVs are 8-10 times higher than BEVs as they use petrol and require oil changes [93].

2.7.2.3 Plug-in Hybrid Electric Vehicles (PHEVs)

Like HEVs, plug-in hybrid electric vehicles (PHEVs) use both ICE and an electric power train; however, in PHEVs, electricity provides the main driving force, so a larger capacity battery is required (See Figure 2.28).

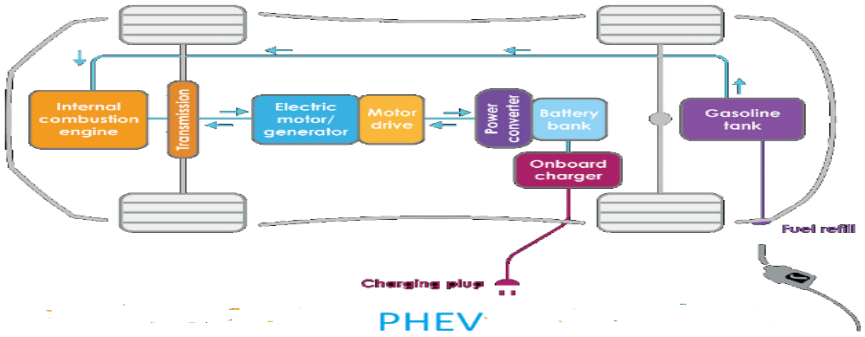


Figure 2.28 Schematic of a plug-in hybrid electric vehicle [84]

PHEVs are started and run in electric mode, with the ICE boosting the propulsion system or charging the batteries when they run low, thereby extending the driving range. PHEVs can be charged from the grid or through regenerative braking, so they consume less fuel and emit fewer emissions by comparison with HEVs [83].

2.7.2.4 Fuel Cell Electric Vehicles (FCEVs)

FCEVs, also known as fuel cell vehicles (FCVs), depend on chemical reactions in their fuel cells to produce electricity. As hydrogen is the fuel used, these vehicles are also known as the hydrogen fuel cell vehicles (HFCVs). The hydrogen is stored in a special high-pressure tank and combined with oxygen, drawn into the cell system from the atmosphere, to produce power. The electricity generated drives an electric motor, and batteries or supercapacitors are used to store the excess energy [94] (See Figure 2.29). A small range of FCVs with batteries are available commercially, including the Toyota Mirai and Hyundai Nexo.

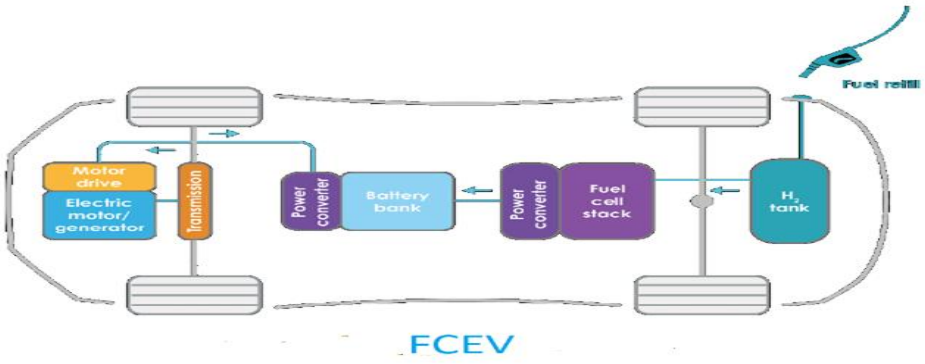


Figure 2.29 Schematic of a Fuel Cell Electric Vehicle [84].

The mixture of hydrogen and oxygen which powers FCVs produces water as a by-product; this is ejected from the car through the tailpipes, but there are no other emissions. There is no lengthy charging period, and FCV refilling times are similar to

those for ICEVs. However, fuel cell costs are high, hydrogen fuelling stations are still scarce, and there are safety concerns about potential hydrogen leaks [93].

The main characteristics of BEVs, HEVs and FCEVs and their advantages and challenges are shown in Table 2.8.

Table 2.8 Main characteristics of BEVS, HEVS, and FCEVS [95].

	BEV	HEV	FCEV
Propulsion	Electric motor drives	Electric motor drives	-
Internal combustion engines	Electric motor drives	-	-
Energy Storage subsystem	Battery and Supercapacitors	Battery, supercapacitors and Fossil fuels	Hydrogen tank, battery and supercapacitors to enhance power density
Energy source and infrastructure	Electrical grid charging facilities	Petrol stations, electrical grid facilities (PHEV)	Hydrogen, hydrogen production and transportation infrastructure
Advantages	High energy density, free of fossil fuel, zero emissions,	Low emissions, high fuel economy, long drive range, commercially available	Zero or low emissions, high efficiency, free of fossil fuels (if not using petrol to produce H2),
Disadvantages	Relatively short driving range, high initial cost, commercially available, safer.	Dependence on fossil fuels, higher cost than ICEs, less safe than BEVs	High cost, still under development, elevated risk

In summary, BEVs, HEVs, and FCEVs are the main types of EVs. Among these, in the current market, BEVs and HEVs are readily available while FCEVs have a much less noticeable presence in the market as the technology is still under development and therefore, they are 8–10 times more expensive to operate [93]. Among BEVs and HEVs, BEVs have the advantage of having ‘zero-emissions’ while HEVs have low levels of emissions as they still depend on fossil fuels. BEVs are also considered safer than HEVs. On the other hand, HEVs enjoy longer driving range compared to BEVs. Overall, in the context of Saudi Arabia, while HEVs can offer some help in reducing emissions, especially while undertaking long journeys, to achieve the target of net zero emissions, currently, BEVs are the most promising.

2.7.3 Purchase Prices of EVs

As discussed above, the high cost of the battery plays a significant role in determining the purchase price of BEVs and PHEVs. Table 2.9 compares current costs of battery packs with forecasts for 2025 and 2030, and indicates that costs are expected to reduce by more than 50% over that period [96]. This reduction will be driven by further research and development, advances in manufacturing and much greater production, making EVs much more affordable than they are today.

Table 2.9 Expected cost (in USD/KWh) of EV different types of EV battery packs in 2025 and 2030 [96].

Battery type	Current cost (2022)	2025	2030
Pouch NMC 622- Graphite anode	165	120	80
Pouch NMC 622 – Silicon alloy anode	131	85	50

Note: NMC = Nickel Manganese Cobalt

EV prices are also affected by the potential driving range, the ICE capacity, and the brand name, with cost increasing as capacity and mileage (mpg) increase [97]. Table 2.10 shows the brand, model, engine size, estimated mpg and manufacturer's suggested retail price (MSRP) for several popular HEVs. Most have an average mileage of 50 - 55 mpg, apart from Hyundai Ioniq PHEV which is estimated to achieve 125 mpg due to PHEVs enhanced fuel economy. Costs range from $22,000 - $34,395, with the Ioniq PHEV only slightly above average at $26,500, despite its superior mpg.

Table 2.10 The models, driving range, and cost of the HEVs [97].

Make	Model/Variant	Engine size (All 4 cylinder Automatic)	Estimated mpg	MSRP ($)
Hyundai	Ioniq Blue	1.6L	58	$22,200
Toyota	Prius Eco	1.8L	56	$25,165
Hyundai	Ioniq	1.6L	55	$22,000
Hyundai	Ioniq PHEV	1.6L	125	$26,500
Toyota	Camry Hybrid LE	2.5L	52	$27,950
Toyota	Prius	1.8L	52	$23,475
Kia	Niro FE	1.6L	50	$23,340
Kia	Niro	1.6L	49	$23,340
Honda	Accord Hybrid	2.0L	47	$25,100
Chevrolet	Malibu Hybrid	1.8L	46	$27,920
Chevrolet	Volt	1.5L	42	$34,395
Toyota	Camry Hybrid LXE	2.5L	46	$32,400

Toyota	Prius C	1.5L	46	$20,630
Kia	Niro Crossover	1.6L	52	$30,000
Ford	C-Max	2.0L	47-56	$24,995
Ford	C-Max PHEV	2.0L	85	$27,995

2.7.4 Recent Trends in Electric Vehicle Technologies

In this section, recent trends related to the different types of EVs are discussed.

2.7.4.1 Battery Electric Vehicles

Current BEV variants, notably the Tesla Model S and Model X, can achieve ranges of 600 km and 525 km respectively, on a single charge of a 100 kWh battery pack through the use of 18,650 cylindrical high capacity batteries. They have enhanced charging rates by up to 50% using V2 and V3 superchargers [98]. A typical battery arrangement in Tesla BEVs is shown in Figure 2.30.

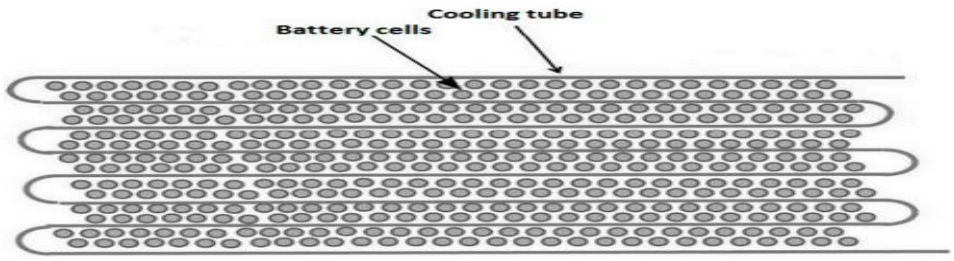


Figure 2.30 Battery arrangements in Tesla BEVs. The cooling tubes are used to remove the heat [93].

Tesla, the largest BEV manufacturer, claims that their future batteries will last for up to a million miles due to the incorporation of new electrolyte solutions to enhance cell performance [99]. Tesla has already submitted a patent for lithium-ion batteries with dioxozolones and nitrile sulfites as electrolyte additives, and it has previously patented a cooling system which has improved performance and lifespan without noticeable cost increases. Both innovations are expected to be deployed in future Tesla models [100].

In contrast to Tesla, Honda mainly produces HEVs (See below). However, they unveiled their complete electric Honda Clarity in 2016, with a range of approximately 89 miles, making it ideal for short and predictable trips. It runs on high voltage Lithium-ion batteries, with the capacity to recover lost energy through regenerative breaking, and can be charged at home, through charging stations or DC fast charging [101]. Toyota are also developing BEVs, partly to reduce pollution in urban areas;

their compact, zero emission vehicles are designed for city transportation and powered with batteries which are quick to recharge.

2.7.4.2 Hybrid Electric Vehicles

The global HEV manufacturers are Ford, Nissan, Honda, Toyota, Lexus, Mercedes, Hyundai, BMW, Kia, Volkswagen, Infiniti, Lincoln, Cadillac, Porsche, GMC, and Chevrolet. However, Honda and Toyota have the greatest range of hybrid cars in comparison with other global HEV manufacturers.

The latest Toyota hybrid, the Camry, has a 4th generation petrol - hybrid electric engine, which can deliver about 160 kW of power. It uses a nickel-metal hydride battery and a permanent magnet synchronous motor generator [102]. Nickel metal hydride batteries are made up of nickel hydroxide as positive electrodes and alloys of nickel, titanium, vanadium as negative electrodes. Their use brings a number of advantages, including a high operating temperature range, recyclable, eco-friendly, resistance to over-charge and discharge, and a longer cycle life [93]. As a result, most Toyota hybrid models now have a range of 100 km per gallon of fuel [102]. Honda hybrid vehicles now also offer longer miles per gallon (mpg) ratings, and are suitable for a range of trips. Their high voltage Lithium-ion batteries are designed to last longer (at least eight years), and they cause less impact on the environment, as Honda harvest their metals and other components and recycle them into other products [101].

2.7.4.3 Plug-in Hybrid Electric Vehicles

Chevrolet Volt and Toyota Prius are examples of PHEVs [93]. While most Honda and Toyota PHEV models provide a good range, the US recently claimed a patent on a four-wheel drive powertrain configuration which can be applied for PHEVs and HEVs, which would boost the PHEV range [103]. This two motor and two clutch hybrid system is shown in Figure 2.31).

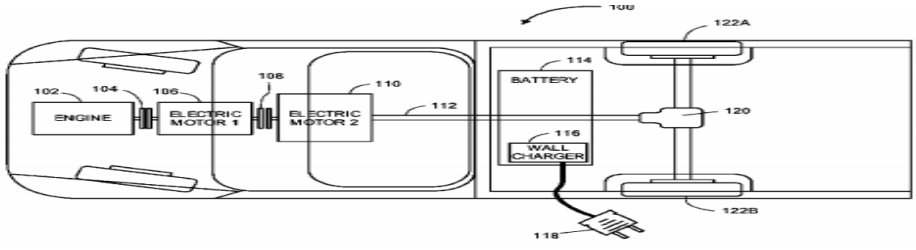


Figure 2.31 Two motor two clutch 4WD Hybrid configuration [103].

The Toyota Prius has a range of 100 km per litre of fuel [104], providing both reduced fuel consumption and lower carbon emissions. Honda PHEVs run-on stored electricity first, switching to fuel when needed, and can also recover energy through regenerative braking. Electric-only driving with a reduced range (typically 25-40 km) is also possible.

2.7.5 Electric Vehicle Charging Infrastructure

As mentioned above, the lack of appropriate charging infrastructure is a key obstacle to the adoption of EVs, and significant development will be required to bring them in line with petrol filling stations. The quality of the charging infrastructure for BEVs and PHEVs depends on many parameters, including the type of charging equipment, the cost of charging, the charging level, the charging time, the distance between charging stations, and their impact on the power grid, so standardized distribution strategies and controlling measures are essential if charging infrastructure is to be positioned most effectively [105].

Charging infrastructure for BEVs and PHEVs is composed of electric vehicle supply equipment (EVSE) which includes the charging points and their connections to the distribution grid. In some cases, this also includes transformers, generators and storage devices [106]. An illustration of an electric vehicle charging station infrastructure is shown in Figure 2.32. As can be seen, the charging station may include two-level charging points, connected through the electric vehicle meter (EVM) directly to the final customer meter (FCM) or through converter storage generation. The FCM is used to monitor the energy consumption (kWh) and peak consumption during the usage interval and is also known as the utility meter. The energy consumption (kWh) and the peak consumption (kW) is metered, and an EV Meter (EVM) generates the bill by utilizing the energy consumption, peak consumption, and duration of the EV's connection to its charging point.

As Figure 2.32 demonstrates, the FCM is located at the interface with the distribution line and EVMs are located next to each charging point; however, the EVM may also be embedded in the car. The green coloured shapes in the diagram represent the assets owned and operated by the Distribution System Operator (DSO). The red colour indicates the intermediary agents in facilitating the charging of EVs. Finally, the blue colour indicates the physical equipment associated with the end users [107].

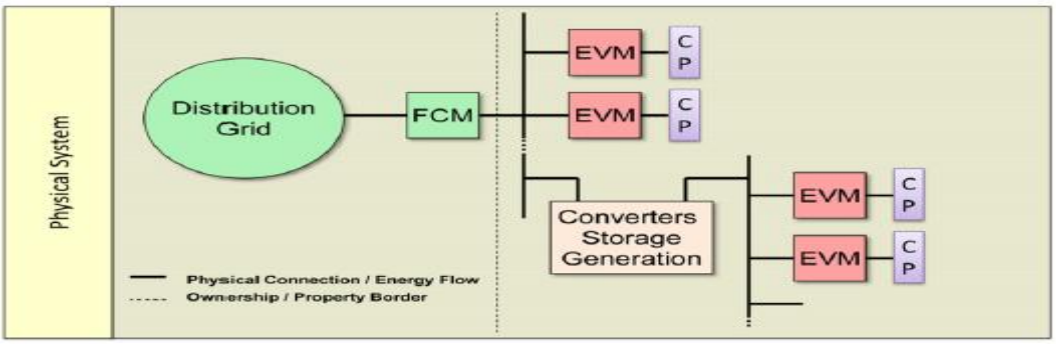


Figure 2.32 A schematic diagram of the charging station infrastructure [107].

From a policy perspective, standardization of charging points, including EVMs and EV connectors, is important to ensure interoperability and provide equal access for manufacturers [107]. To discourage the creation of market barriers and to promote the internal EV market, in 2016, the European Commission issued a standardization mandate to ensure interoperability, and standard plugs and sockets are now available in European charging station. These comply with IEC 61851 standard, which describes four different charging methods, as shown in Table 2.11.

Table 2.11 Charge methods available in Europe and their electrical rating [108].

Charge method	Connection	Power (kW)	Max. Current (A)	Location
Normal power	1-phase AC connection (110V)	3.7	10-16	Domestic
Medium power	1-or 3-phase AC connection (110-480V)	3.7-22	16-32	Semi-public
High power	3-phase AC connection	>22	>32	Public
High power	DC connection	>22	>3225	Public

The deployment of charging infrastructure is shown in Figure 2.33, and operates at three distinct levels, Level 1, 2 and 3. These are described briefly below.

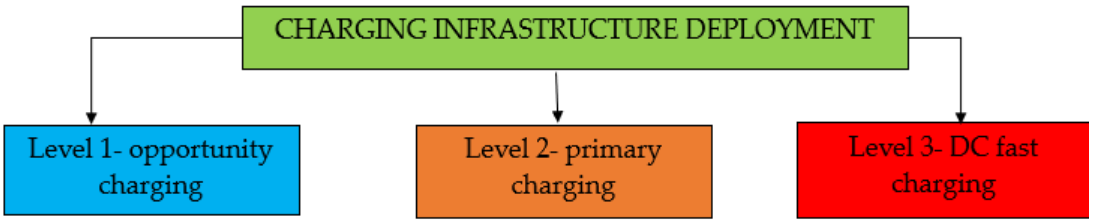


Figure 2.33 Charging infrastructure deployment [108].

2.7.5.1 Level-1 charging: Opportunity charging

Level 1, known as ‘opportunity charging’, is the cheapest and most convenient mode of charging system, and is typically used in residential and commercial buildings. However, it is also the slowest and lowest mode, so it is often deployed overnight [109]. In the USA, opportunity charging uses a standard 120V/15A single-phase outlet which is grounded with NEMA 5-15R connectors. The EV AC port has a standard J1772 connector and the overall cost for a housing Level 1 is in the range of USD 500 – USD 880 [105,106]. This can provide a 100 mile range in around 24 hours [107]. Depending upon the ampere rating, Level 1 draws power in the range of 1.4 - 1.9 kW, so EVs usually take 8-16 hours to fully charge the battery pack. This difference in the time duration is due to the battery type and size in the EV.

The infrastructure for EV charging stations varies from household electrical plugs to high power appliances which could potentially replace the conventional petrol pumps. The charger on an EV is sized based on the input voltage from the grid [110]. For example, if the grid supply specification is 120V, 15A or 240V, 32A then the charger specification on the EVs would be 1.4 kW or 6.6 kW respectively. Moreover, if the capacity of the battery pack on an EV is 40 kWh then the EV might have a 6.6 kW charger, which would take 6-8 hours for complete recharging of the battery pack [110].

2.7.5.2 Level-2 charging: Primary charging

Level 2 is the principal charging method in public and private utilities and it charges at either 208V or 240V (at up to 80A, 19.2kW). This can provide EVs with 100 miles of range within 4 - 12 hours [107]; however, as at Level 1, Level 2 chargers rely on single-phase systems and are classed as slow charging [110]. The level 2 charging is either assigned with 240 V or 400 V AC, with a current handling capacity of 40A and 80 A respectively for public installations. The Level 2 EVSE is installed with 40A circuits with a maximum of 32 A [110].

The Level 2 EVSE is easy to operate, with standardized vehicle-to-charger connections, and relatively fast charging time [107]. However, installing Level 2 EVSE at home must be done in accordance with strict procedures to ensure charging is safe and efficient, with ‘occasional-use cables’ deployed to protect against current and temperature when charging outside the home [107]. Commercial Level 2 public

charging station costs around $150,000 which is around 500% higher than the residential installation cost [107].

2.7.5.3 Level-3 charging: DC fast charging

Level 3 is DC fast charging, which is built for both private and public applications and operates in the same way as a petrol station does for ICEVs. Fast charging stations are usually located in shopping centres, hotels, car parks, theatres, and supermarkets [105]. Level 3 functions with 480V or higher three-phase circuits, requiring an off-board charger to supply regulated AC-DC adapter, and is more effective in public applications. The standardization of DC plugs and hardware is in progress and the setting up cost is of vigorous concern.

The characteristics of Level 1, Level 2 and DC fast charging are shown in Table 2.12.

Table 2.12. Characteristics of Level 1, Level 2 and DC fast charging [111].

Charging level	Voltage (V)	Typical power (kW)	Setting	Advantages	Disadvantages
Level 1	120 V AC, 12-16A (single phase)	1.2 -1.8 kW	Primarily residential in North America	Can charge the EV at home when the electricity price is low, usable for a long stay, cheap	Long charging time more than level 2
Level 2	200-240 V AC, 15-80A (split/single phase)	3.6-2.2 kW	Home, workplace and public	Usable for a short stay at a place (E.g., Consulting doctors),	Moderate charging time more than level 3, more expensive than level 1
Level 3	400 V DC, Max 400A (Polyphase)	50 kW or more	Public, primarily intercity	80% Charging in 10 minutes, off-board charger reduces the weight of EVs as onboard cabling minimizes.	Highly expensive and required an off-board power converter (AC/DC)

Note; V – Volt, AC – Alternating Current, DC – Direct Current, kW

Charging duration varies depending on battery size and type, but fast charging typically provides 80% of a full charge in 10 - 15 minutes. Charging an EV in 10 minutes would require Level 3 fast charging and a Level 3 connector (See Figure 2.34). High power DC fast chargers supply the power directly to the battery pack via this connector. IEC 61851 in Europe facilitates the charging of EVs at standard

supplies of current and voltage (as per IEC 60038) up to 690V AC and 1000V for DC [110].

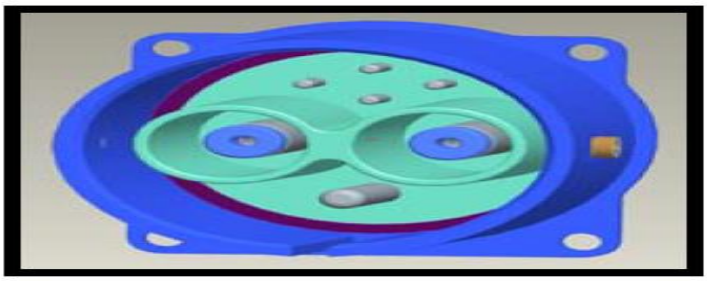


Figure 2.34 A typical level 3 charging connector fitted to the EVs [110].

An off-board charger is used to convert the AC power from the grid to DC power, with 208-600 V AC in a three-phase circuit that can support current up to 200 A to facilitate DC fast charging. Off-boarding the charger reduces the weight of the EV, as the complex onboard cabling is minimized [110] (See Figure 2.35).

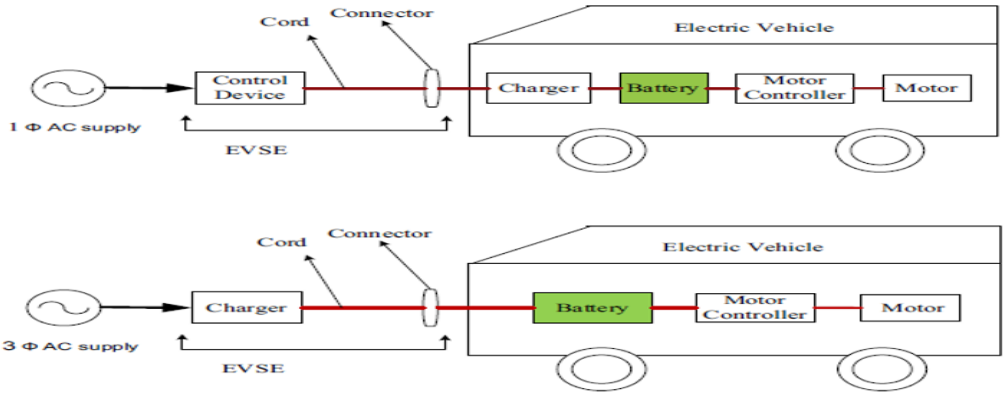


Figure 2.35 Schematic diagrams of charging levels in EVs (top) for level 1 and 2 slow charging (bottom) level 3 for dc fast charging [110].

2.7.5.4 Connection between the EV and the charging infrastructure

The charging infrastructure is also categorized as either Mode 1, Mode 2, Mode 3, or Mode 4. This relates to the connection between the EV and the charging infrastructure. On a shared circuit, Mode 1 consists of 120-240V and charging up to 16A without safety protocols, and Mode 2 with same voltage range but charging current up to 32A. Mode 2 has a standard outlet, with all the safety protocols including overcurrent protection, grounding detection, temperature limit and pilot data line. Mode 3 includes the same safety protocols, but involves 240 V charging (at any amperage) on a dedicated circuit in a wired-in charging station. Finally, Mode 4 is the DC fast

charging mode with 400V DC; it is a completely wired-in connection and demands advanced safety and communication protocols [111].

2.7.5.5 Charging plug-in type and size

The plugs and sockets used at Level 1 and 2 vary depending upon the region and speed of charging, and this can generate confusion while charging and hesitancy about buying EVs. In North America and Japan, almost all EVs use SAE J1772 connectors. This type of connector has five pins and a mechanical lock (See Figure 2.36 (left)). For Level 2 charging in Europe, Type 2 or Mennekes connectors are used, which have seven built-in pins, offering the flexibility to use both single phase and three phase alternating grid charging (See Figure 2.36 (centre)). Tesla uses a proprietary connector in North America (See Figure 2.36 (right)) and Type 2 plugins in Europe and Asia.



Figure 2.36 Images of AC charging connectors used in electric vehicles. (*left*) SAE J1772 connector used in North America and Japan (*centre*) Mennekes (Type 2) connector used in Europe (*right*) Tesla, the proprietary connector used in North America [108][111].

DC fast charging connectors also vary depending on the vehicle manufacturer and the country. Nissan and Mitsubishi introduced the CHAdeMO (Charge de Move) in 2011, and this type of connectors is also used by Kia, Citroen, and Peugeot (See Figure 2.37 (left)). The Combined Charging System (CCS) which uses SAE J1772 or Mennekes AC plug, with two additional DC pins for fast charging, is used by some automakers in the US and Europe, notably BMW, Daimler, Ford, Fiat Chrysler, General Motors, Honda, Hyundai, and Volkswagen (See Figure 2.37 (centre, right)). The CCS uses the same port on the EV as a Level 2 charger, but CHAdeMO requires a separate port. In the USA, Tesla uses its own plug for Level 3 DC fast charging; however, it has also a made Tesla-to-CHAdeMO adapter, and, as China recently introduced a new charging standard for all new EVs on Chinese roads, Tesla vehicles in China will use that standard [111].



Figure 2.37 Images of the most popular DC fast charging connectors. (*left*) CHAdeMO connector used in Nissan, Mitsubishi, Kia, Citron and Peugeot (*centre*) combined charging socket system used in North America (*right*) combined charging socket system used in Europe [108].

One of the main problems that EV owners face at the charging station or charging point is the charging time [112]. Improving charging performance to the stage where EVs could charge as quickly as ICEVs fill up at petrol stations would significantly reduce the large queues that form, especially in the cities. Both DC off-board charging and 3-phase AC onboard charging enable users to charge their EVs within a limited timeframe. DC off-board charging is more common today due to the high penetration of Japanese vehicles in the market, and the CHAdeMO socket, with a maximum power level of 50kW, is the only product currently available for DC connections [108] (See Figure 2.38 (left)). However, as mentioned above, the European Commission now mandates that all EVs must have Type 2 connectors installed to reduce interoperability and avoid problems at EV charging stations (See Figure 2.38 (right)).



Figure 2.38 The CHAdeMo (left) and Type 2 connector (right) [111].

The charging levels, the type of charger used, the charging time, and the distance that an EV can cover with an hour of charging are shown in Table **2.13.**

Table 2.13. The miles per charging hour, charging time, and charger used for Level 1, 2 and 3 charging [113,114].

Charging levels	Miles per charging hours	Charging time for a 24-kWh battery pack	Charger
Level 1	2-5	~ 17 Hours	SAE J1772
Level 2	10-20	~ 8 hours	SAE J1772
Level 3	50-70	~ 30 minutes	CHAdeMO, SAE Combo, Tesla Supercharger

2.7.5.6 Charging Stations and Charging Points

There is a significant difference between a charging station and a charging point. A charging point serves only one EV at a time, while a charging station has many charging points and can serve multiple vehicles [114] (See Figure 2.39).



Figure 2.39 A typical charging station (*left*) and a typical charging point (*right*) [114].

As technologies to facilitate fast charging are now being developed, charging multiple EVs simultaneously can create substantial power demand in the gridline. This affects the charging time and increases the cost of energy, distribution, and the charging infrastructure. The introduction of energy storage systems (ESS) can help to meet power demand during peak times, thereby reducing charging times and stress on the grid line [111]. Commonly used ESS's include the electrochemical storage system (batteries), electromechanical storage system (flywheel), and electrostatic storage systems (supercapacitors), which can store the excess energy and then release it when there is a demand [115].

A smart grid becomes essential as the number of charging stations increases, which linearly increases the power demand at the charging stations. The smart grid could balance the power demand between the charging stations and should minimize the time EV users spend waiting to get their cars charged. So, the smart grid is considered as the future electricity grid [114]. The main difference between the existing grid system and future smart grid system is shown in

Table 2.14. The difference between the existing grid technology and smart grid technology [114].

Existing grid	Future smart grid
Electromechanical	Digital
One-way communication	Two-way communication
Generation is central	Decentralized generation
Monitoring manually	Self or Smart monitoring
Non-adaptive	Adaptive
Fewer customer choices	More customer choices

Ensuring the optimal provision of public charging locations depends on factors such as access to home charging, travel patterns, the number of EVs in a specific location and the number of workplace chargers available. Consideration also needs to be given to the way users access them. In some countries, consumers typically need membership from individual service providers to access their public charging stations, meaning multiple memberships may be required [116]. However, in the Netherlands and Portugal, the situation is different, and EV consumers there have access to many charging stations from different companies.

Figure 2.40 and Figure 2.41 show the increased number of slow and fast chargers in major markets in the world between 2015 and 2021 [117]. There were around 1200 slow public chargers in 2021, an increase of over 670%, and while for the fast public chargers significantly increased by 2,270%. China had the most of steadily increasing in both slow and fast chargers [117].

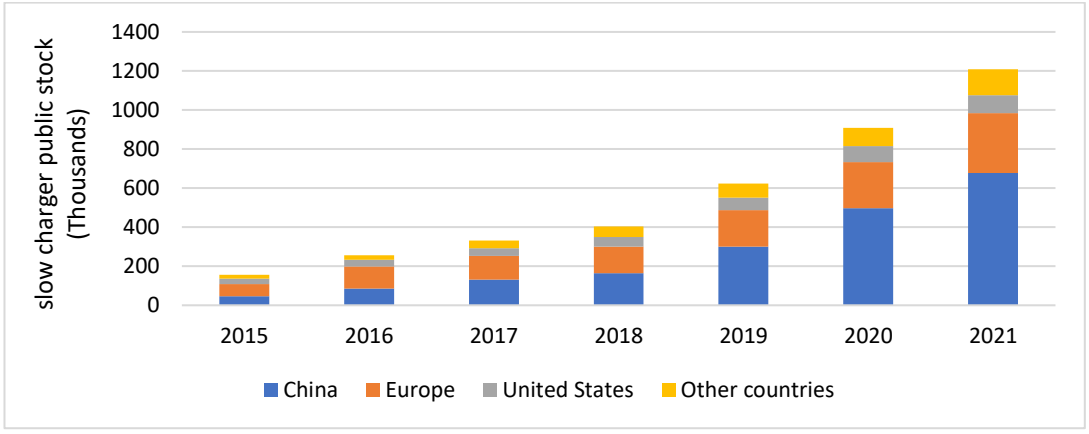


Figure 2.40 The increased number of slow public chargers from 2015 to 2021 in China, Europe, USA and other countries [117].

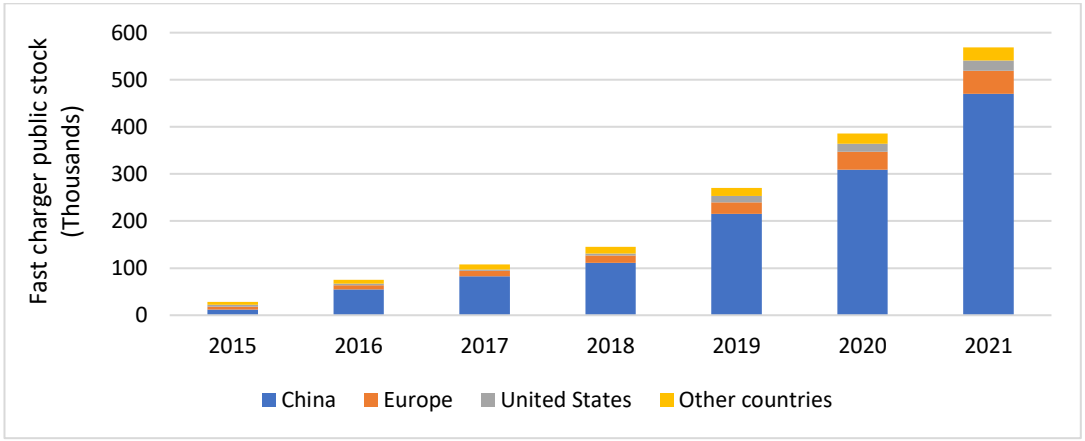


Figure 2.41 The increased number of fast public chargers from 2015 to 2021 in China, Europe, USA and other countries [117].

The situation regarding EVs in the United Arab Emirates (UAE) is particularly interesting in the context of this study. Market penetration of pure electric, plug-in and hybrid electric vehicles in the UAE is significantly lower than in Norway (22.4%), the USA (5.2%) and even Japan (0.5%) [118]. Lack of infrastructure, public awareness, and government incentives are cited as the primary reasons behind this low market share, but the Emirates' economic dependency on the oil trade also acts as a barrier [118]. However, there is increasing interest in the use of EVs in the UAE due to concerns about climate change and GHG emissions and the market is expected to expand significantly. A case study of Abu Dhabi, Al Ain, and western region of the UAE [118] estimated that the total number of EVs in Abu Dhabi would double from 34,320 in 2013 to 61633 by 2025; however, this would simply retain the same market share (5%) due to a comparable increase in the number of households over the same period [118] (See Table 2.15).

Table 2.15. The market share of EVs in Abu Dhabi, Al Ain and western region [118].

Year	Number of households	Total number of vehicles	Number of EVs	Percentage market share of EVs (%)
2013	200,000	686,400	34,320	5
2014	210,000	720,720	36,036	5
2015	220,500	756,756	37,838	5
2016	235,525	794,594	39,730	5
2017	243,101	834,324	41,716	5
2018	255,256	876,040	43,802	5
2019	268,019	919,842	45,992	5
2020	281,420	965,834	48,292	5
2021	295,491	1,014,125	50,706	5
2022	310,265	1,064,832	53,242	5
2023	325,779	1,118,073	55,904	5
2024	342,068	1,173,977	58,699	5
2025	359,171	1,232,676	61,633	5

The UAE has several agencies which generate power collectively and manage the transmission and distribution through all the seven emirates. The Dubai Electricity and Water Authority (DEWA) has taken a lead on EV promotion and installed more than 240 charging stations across the Emirates, which are now running successfully [118]. This is part of Dubai's wider plan to become a smart city, and linking these green

charging stations with developing digital platforms is part of the strategy to inspire residents to use sustainable energy systems and protect the environment [119].

A good example of a charging infrastructure utilizing solar energy is the roof-top solar car park in Mall of Emirates (MoE), United Arab Emirates [120]. A solar plant is being built at the rooftop parking that is designed to generate 3 GWh of electricity. This is achieved by the installation of 7291 solar panels over an area of 11,996 m², which is equivalent to the size of nearly two football fields and can accommodate 1000 cars. The MoE is already achieving reductions of 2,500 tonnes of carbon dioxide (CO^2) emissions every year, equivalent to the emissions produced by 500 petrol/diesel cars. These solar panels also shelter the cars below from extreme heat and dust, which are common in Dubai, and offer protection from harmful UV rays.

A case study based on this solar car park was envisaged for this study, and the author visited MoE and met its administration; however, due to COVID-19 restrictions at the time, the case study could not be completed. Some pictures of the solar car park (taken by the author) are shown in Figure 2.42.



Figure 2.42 Various photographs of solar car park at mall of emirates designed to accommodate 1000 cars at the roof top (Taken by the author).

As one location of Green Charger initiative over Dubai, DEWA has installed three charging stations at the MoE (See Figure 2.43). Despite this, Tesla has installed nine charging stations at the MoE (See Figure 2.44), this means that shopping mall is more attractive for such investment. In the first and second floors of MoE, Tesla charging ports are provided specifically for Tesla car owners to charge their cars up to 100 km of range to the battery per hour of charge. As a leading solar car park concept in the

Middle East, the solar carpark at MoE provides an opportunity for neighbouring countries to learn about the challenges and benefits of a solar car park and its charging facilities. A study was planned to be conducted as part of this thesis, however, due to the travel restrictions introduced as a result of the COVID-19 pandemic, it could not be completed.



Figure 2.43 Dubai Electric and Water Authority (DEWA) charging station at MoE to charge electric vehicles (Taken by the author).

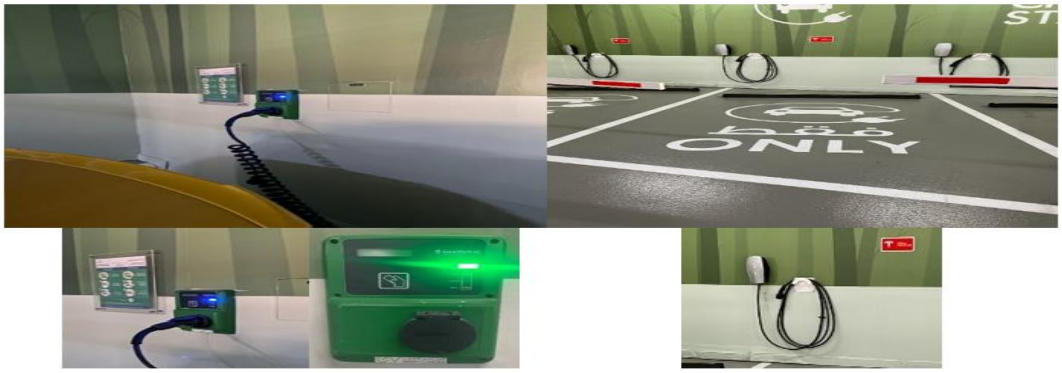


Figure 2.44 Different charging plugs and ports at MoE available for electric cars to charge. DEWA charging plug/port (left) and Tesla charging plug/port dedicated only for charging Tesla electric cars (Right) (Taken by the author).

2.7.6 Vehicle to Grid Technology

The increasing global uptake of EVs has initiated new business models to exploit the potential of EVs for electric storage, notably V2G technology. This enables EVs both to be charged and to discharge excess energy to the grid through domestic, commercial, or public charging stations [27]. Vehicles are charged when demand is low (at a low tariff), with excess energy discharged when the grid is short of supply (at a higher tariff), enabling owners to make a profit [121]. V2G offers flexible and responsive storage [122] and incentivizes EV owners to participate in charge/discharge systems; as such, it may offer a solution to some of the energy storage issues associated with EVs [123].

V2G has the potential to provide both short-term and longer-term benefits [124], and Tesla is already promoting its EVs as central to the 'self-powered home', in which they are integrated with solar panels and a so-called 'Powerwall' [125]. The longer-term benefits include potential reductions in GHG emissions and lower per-unit electricity prices, with research suggesting V2G could save around 13,429 kg CO_2 per year (with self-sufficiency of 99.1% and net metering) and reduce process by up to 12% [126]. In the context of this study, it is significant that Tesla recognises that the deployment of V2G systems will be enhanced by integration with solar photovoltaics [127].

The development of V2G is currently constrained by inadequate infrastructure, battery degradation, and low consumer awareness, and EV adoption rates do not yet justify new control architectures being implemented. As a result, just a few V2G compatible models are commercially available, including the Nissan e-NV200, Nissan Leaf, Mitsubishi Outlander PHEV, and Mitsubishi Eclipse Cross PHEV [128]. Nonetheless, studies of consumer acceptance of V2G suggest that key institutional and policy factors, such as direct subsidies, emission-based taxes, provision of charging infrastructure, and free parking, would incentivise current and future EV owners to utilise this technology.

In summary, the decision to adopt EVs on a large scale should not only consider the type and price of EV itself, but the overall necessary EV infrastructure associated with an EV technology. For example, for BEVs, appropriate charging stations, their locations, charger types etc. need to be considered. Similarly, for using V2G, the availability of compliant chargers should be ensured. The next section examines the factors which influence EV adoption, picking up some of the ideas introduced above and examining them in more detail.

2.8 Factors Affecting Electric Vehicle Adoption

There have been many studies of the factors influencing potential EV users and the importance of taking their views into consideration. Coffman et al. [129] found that high purchase price and high battery costs were the most important factors affecting EV adoption in China, while, in Germany, [130] concluded that EVs were most attractive to consumers with high annual mileage. Meanwhile, [131] identified policymaking as the key factor in influencing the rate of EV adoption, while [132]

suggested that knowing customers' needs and segmenting buyers by range requirements is critical. In regions such as Japan and California, US, for example, long-term government subsidies encourage drivers to switch to EVs [133], and the development of EV infrastructure also enhances acceptance, something which also requires policy support [131,134]. Such factors are expected to influence the perceptions of potential EV users in Saudi Arabia, and these are discussed in more detail below.

2.8.1 Lack of Infrastructure (Charging and Servicing)

The lack of infrastructure has a direct impact on consumers' intentions to purchase an EV [131,135,136]. Research indicates that an increase in public charging infrastructure development leads to an increase in EV sales; however, in the early stages of the EV market, private charging options, such as home or workplace charging, have also proven to be significant [110]. Indeed, the lower total costs associated with household charging unit installation and vehicle operation has been shown to significantly enhance consumer attitudes towards EVs [137]. Indeed, [138] recommends the development of comprehensive nationwide charging infrastructure prior to the introduction of EVs.

Lack of charging infrastructure is an issue in KSA, given its large size (over 2,000,000 km^2) and its desert climate. The long distances between cities and the need for air conditioning drains batteries more quickly, and Saudi drivers report feeling 'range anxiety' [139]. As a result, widespread access to charging stations is required. One possible solution would be the creation of isolated microgrids supplied by renewable energy, with diesel backup [139].

In addition, EVs consume a high amount of real power in a short period of time due to the non-linear nature of their loads, and this can cause instability in the power networks [109]. Overloading of charging may also affect aspects of the grid and distribution network, depending on driving and charging behaviour, so EVs can have a significant impact on the power network's load curve [140]. Thus, the widespread adoption of EVs will place additional burdens on an already overstretched grid unless further steps are taken to boost electricity production.

According to [141] the limited access to specialist EV repair centres and workshops has disappointed current EV owners. For example, a study in Denmark [142] found that relatively few workers were qualified and trained to fix EVs, so even simple repairs were costly and more complex repairs could take months.

2.8.2 EV Batteries and Costs

Lithium-ion batteries (LIBs) are used for EVs and grid storage applications because of their superiority to conventional lead-acid or nickel-cadmium batteries. An LIB stores chemical energy during charging and converts it to electrical energy while discharging; these are carried in groups connected as modules and joined to form complete battery packs [143]. The power density, cycle life, cost per kWh of energy, and calendar life correspond to the energy requirement of the battery system. However, the battery capacity and range of an EV are not linear: the larger the capacity of the battery pack, the greater the weight, and this reduces the efficiency of the vehicle on the road. It is therefore important to compare batteries and battery systems based on energy and power densities, rather than on range requirements. Different battery technologies and their energy and power ratings are shown in Figure 2.45.

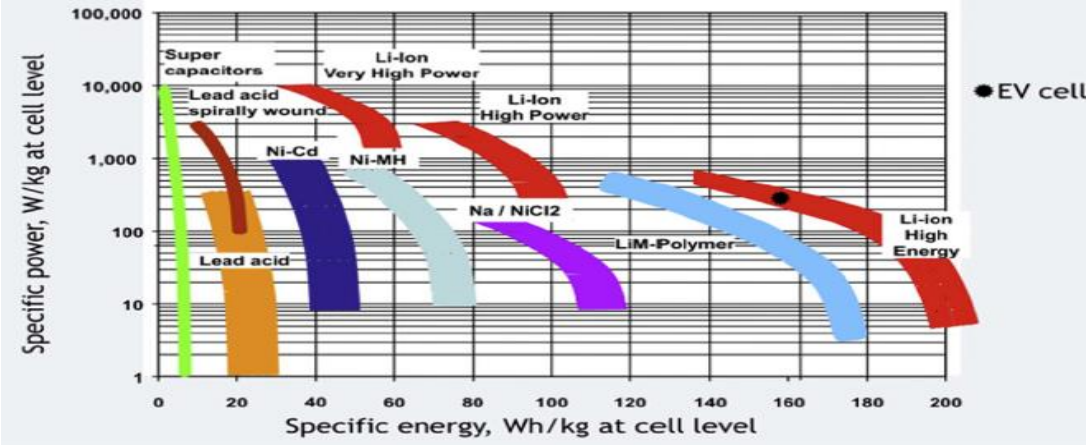


Figure 2.45 Various battery technologies used in EVs and their energy and power ratings [144].

Car manufacturers rarely make the batteries they use, although Tesla is an obvious exception, and battery cell production is largely concentrated in the USA, China, Japan and South Korea. Table 2.16 shows a list of major EV manufacturers, models, driving ranges, battery sizes, battery manufacturer, and battery assembly and production locations.

Table 2.16 Major electric car manufacturers and models, showing range, battery size, battery manufacturers, location of battery pack assembly and location of battery cell production [145-147]

Car Manufacturer	Model	Range (km)	Battery size (kWh)	Battery manufacturer	Battery pack assembly location	Battery cell production location
Lucid	Air Dream	640	118	LG Chem/ Panasonic	USA	USA/Japan
Tesla	Model S & X	600 &525	75 or 100	Panasonic/Tesla	USA	Japan/USA
BYD	Tang	528	86.4	BYD	China	China
BYTON	M-Byte	430-550	72-95	CALT	China	China
Tesla	Model 3	354-498	50-74	Panasonic/Tesla	USA	Japan/USA
Chevrolet	Bolt EV	383	60	LG Chem	USA	S Korea
NIO	ES8	425	84	CALT	China	China
Nissan	Leaf	243	30	Automotive energy supply corp.	USA	USA
Fiat	500e	135	24	SB LiMotive	USA	USA
VW	e-Golf	202	35.8	Samsung SDI	Hungary	S Korea
Ford	Focus Electric	190	33.5	LG Chem	USA	USA
BMW	I3	183	22-33	Samsung SDI	Hungary	S Korea
Kia	Soul EV	178	27	SK innovations	S Korea	S Korea

2.8.3 Battery Lifespan

Competition with conventional ICEVs requires EVs and their batteries to run reliably for 10–15 years under various climatic conditions and duty cycles. The main factors limiting battery lifetime are high temperature, state of charge (SoC), cycling at high depth of discharge (DoD), and C-rate [149]. While high temperature may not be a significant factor in some contexts, it is a pressing issue in KSA, where summer temperatures average 45°C [150]. The life cycles of some commonly used energy storage batteries and their characteristics are listed in Table 2.17 [151]. Among these, Lithium ion-based batteries, with a life cycle of around 2000 cycles and efficiency of over 95%, are commonly used in most new EV models, such as Nissan Leaf.

Table 2.17 Lifespans, characteristics, and applications of commonly used energy storage batteries [151].

Battery Type	Energy storage type	Specific energy (Wh/kg)	Specific power (W/kg)	Life cycle (cycles)	Efficiency (%)	Applications
Lead-acid	Lead-acid	35	180	1000	>80	Grid energy storage, UPS, electric vehicle lighting and ignition
	Advanced lead-acid	45	250	1500	_	
	Metal foil lead-acid	30	900	500+	_	
Nickel	Nickel-iron	50-60	100-150	2000	75	Digital cameras, electric vehicles, portable electronics, and toys
	Nickel-zinc	75	170-260	300	76	
	Nickel-cadmium (Ni-Cd)	50-80	200	2000	75	
	Nickel metal hydride (Ni-MH)	70-95	200-300	<3000	70	
Lithium	Lithium-ion	118-250	200-430	2000	>95	Electric vehicles, smart phones, laptops, electric toys, digital cameras
	Lithium-ion polymer (LiPo)	130-225	260-450	>1200	_	
	Lithium iron phosphate (LiFePO4)	120	2000-4500	42000	_	
	Lithium-ion sulphide (FeS)	150	300	1000+	80	
	Lithium-titanate	80-100	4000	18000	_	
ZEBRA	Sodium sulfur	150-240	150-230	800+	80	Automobile applications
	Sodium nickel chloride	90-120	155	1200+	80	
Metal air	Aluminium air	220	60	_	_	Grid storage and electric vehicles
	Zinc air	460	80-140	200	60	
	Zinc	460	_	_	_	
	Lithium air	1800	_	_	_	

Charging is most efficient when the battery has low charge or SoC, while charge acceptance slows towards saturation. Charging efficiency also depends on temperature and SoC. As the battery ages, internal resistance increases, and the charge rate slows. A SoC above 80% promotes capacity fade, while keeping the lithium-ion at high SoC affects lifetime more than cycling at mid-range SoC [152].

The performance of an EV battery can be affected by various climate conditions, including high or low temperature, humidity and altitude. For example, high temperature enables a relatively high charging rate, but it increases the solid electrolyte interface growth rate, thereby shortening the battery's lifespan. On the other hand, low temperature retards solid electrolyte interface growth, but it stimulates lithium deposition [153]. Consequently, batteries can be optimised for either high or low temperature, but it is challenging to maintain the same efficacy across a range of temperatures [117]. The battery technology utilised by EV manufacturers varied, ranging from cell chemistry to battery cooling method. For example, Nissan Leaf utilises an air-based battery cooling system [154]. Therefore, Nissan Leaf may be one of the brands appropriate for countries with a hot climate, such as Saudi Arabia.

2.8.4 Driving Ranges and Charging Times

The battery capacity of many current BEVs limits their driving range to 250 km, although some models now offer ranges of up to 400 km, and future models are expected to exceed this [89]. However, factors such as driving conditions and drivers' skills affect the vehicle's efficiency and, therefore, its real-world range (as opposed to the manufacturer's range). The time required for charging is also a key consideration. Table 2.19 lists some of the most modern EVs, their rated and actual driving ranges, and their battery charging times.

Table 2.18 The most modern EVs available in the market: predicted and real-world range, home and rapid charging times [145,146,148,155,156].

Model	Manufacturers' range (km)	Real-world range (km)	Charging time	
			Home charging (hours)	Rapid charging (minutes)
Tesla Roadster	998	965	32	44
Lucid Air Grand Touring	783	685	18	41
Tesla Model S	603	523	15	38
Volkswagen ID. 3	547	475	12.25	34
Tesla Model 3	547	475	11.75	22
BYD Tango	528	400	10.75	30
BYTON M-Byte	520	389	12	30
Polestar 2	498	450	12	28
Skoda vision IV	498	442	13.25	33
Jaguar I pace	470	407	13.50	44

Kia e-Niro	453	378	10.5	44
Mercedes-Benz EQC	450	362	12.75	35
Hyundai Kona Electric	449	394	10.5	44
NIO ES8	425	355	12	90

From Table 2.19, the shortest attainable rapid charging time is 22 minutes for the Tesla Model 3, while most other modern EVs can be rapidly charged fully within 45 minutes. Among these, the Tesla Roadster has the longest range, at 965 km, with a real-world range closer to the rated range than other EVs. Then, followed by Lucid by range of 783 km. The amount of time it takes to recharge an EV depends on the type of charger used, with the fastest chargers costing the most. There are currently three main types of chargers, AC Level 1, Level 2 and DC fast chargers, and their key performance details are shown in Table 2.19. AC Level 1 delivers charging through a 120-volt AC plug; AC level 2 delivers between 208-240 volt electrical supply and can be installed at home or as a public charging point; (DC) fast charging equipment provides 480-volt direct current, but this is only available at public stations for public safety reasons [157]. Of the three main types of DC charging systems, only the Japanese CHAdeMO standard chargers (used by Nissan, Mitsubishi, and Kia), are currently fitted with V2G technology [158].

Table 2.19 Chargers, miles per charging hour and charging times for each level of charging [113,157,158].

Charging levels	Miles per charging hour	Charging time for a 24-kWh battery pack	Charger standard
AC Level 1	2-5	~ 17 Hours	SAE J1772
AC Level 2	10-20	~ 8 hours	SAE J1772
DC fast Charging	50-70	~ 30 minutes	CHAdeMO, CCS, Combo, Tesla Supercharger

2.8.5 EV Cost

EV cost depends on several factors, including driving range, battery capacity, and km/kWh energy consumption. Table 2.20 lists the manufacturer's suggested retail price (MSRP) for selected US BEVs, showing their range, battery capacity, and km/kWh consumption. The fact that even the cheapest models come in at over $29,900 demonstrates that purchase price is a significant factor in relation to EVs, especially by comparison with ICEVs.

Table 2.20 EV manufacturers and models with range, battery capacity, per kWh energy consumption, and manufacturer's suggested retail price [97,159].

Manufacturer	Model	Range (km)	Battery capacity (kWh)	km/kWh	MSRP (US$)
Tesla	Model S 100D	564	100	5.65	94,000
Tesla	Model S P100D	542	100	5.42	135,000
Tesla	Model 3	498	78	6.39	35,000
Tesla	Model X 100D	474	100	4.75	96,000
Tesla	Model X P100D	465	100	4.65	140,000
Tesla	Model S 75D	442	75	5.90	74,500
Nissan	Leaf	400	40	5.74	37,500
Chevrolet	Bolt EV	383	60	6.39	36,620
Tesla	Model X75	381	75	5.08	70,532
VW	e-Golf	201	35.8	5.62	30,495
Hyundai	Ioniq Electric	200	28	7.13	29,900
Ford	Focus Electric	185	33	5.60	29,120
BMW	I3	183	33	5.55	44,450
Kia	Soul EV	178	30	5.95	32,250
Nissan	Leaf	172	30	5.74	29,900
Honda	Clarity Electric	150	25.5	5.61	33,400
Fiat	500e	140	24	5.84	32,995

As Table 2.20 demonstrates, almost all models exhibit similar range per kWh energy consumption, at 5-6 km/kWh, except the Tesla Model X variants, at less than 5 km/kWh. While Tesla models are broadly comparable with competitors' models in km travelled per kWh, they have superior ranges because of their larger battery capacity, compact packing, and efficient thermal management systems. The Hyundai Ioniq Electric has an impressive range per kWh of approximately seven kilometres, this high efficiency may be due to Hyundai's battery technology. If Hyundai could scale its battery capacity to the 100-kWh capacity of Tesla, then it would have a driving range of 710 km, far longer than any other model, including those of Tesla. However, the pricing shown here suggests that any such innovation would lead to a significant increase in price, as Tesla models are among the most expensive listed, with the highest suggested retail price of the Tesla Model X P100 D being the most expensive at $140,000.

2.8.6 EV Charging Costs

While the average purchase costs of EVs far exceeds those of ICEVs, the running costs are typically much lower. For example, EDF Energy's GoElectric 35 tariff [160], currently available to UK users, has an off-peak rate of £0.045/kWh ($0.06/kWh), enabling users to fully charge a standard 40 kW Nissan Leaf overnight for only £1.80 using a 7kW home charger. This is much lower than the equivalent fuel cost for a conventional petrol or diesel car. In any driving scenario, the recharge consumption of an EV can be determined by multiplying its drive efficiency (in kWh/mile) by miles travelled. In the case of level 2 charging, the A/C charge rate is equal to the EV's hourly recharge consumption and dividing the required daily recharge consumption by the vehicle charging rate gives the number of charge hours per day [161]. The optimal daily charging amount can be estimated using eq. (2.1) and eq. (2.2).

$$DHC = LMP_T * (CHR - (T-1) * VCR) + \sum_{n=1}^{T-1} VCR * LMP_n \quad (2.1)$$

$$T = \left(\frac{CHR}{VCR}\right) \quad (2.2)$$

DHC represents the daily hourly charges ($), VCR is the vehicle charge rate (kW), T is charging time (hours), CHR is the charge required (kWh) and LMPn is the Locational Marginal Price (LMP) during the n^{th} lowest-ranked hour of the day ($/kWh). When estimating DHC, the LMP values can, if necessary, be taken as starting from the lowest LMP hour and moving to the next rank ordered LMP hour. The savings achieved in the Tesla 3 Long-range and Chevrolet Bolt for a range of driver profiles (light, average, heavy, and Lyft/Uber) are shown in Table 2.21.

Table 2.21 Hourly and flat charging rates for Tesla and Bolt and corresponding savings over conventional petrol cars [161].

Driver profile [1]	Vehicle	Hourly ($)	Flat rate ($)	% Saving hourly	$ Saving hourly
Light driver	Tesla	37	91	59	54
	Bolt	40	98	59	58
Average driver	Tesla	74	182	59	108
	Bolt	81	196	59	115
Heavy driver	Tesla	132	303	57	172
	Bolt	143	327	56	184
Lyft/Uber	Tesla	289	607	52	318
	Bolt	315	654	52	339

[1] Light driver – 24 miles/day; average driver – 48 miles/day; heavy driver – 80 miles/day; Lyft/Uber driver – 161 miles/day.

2.8.7 Weather Conditions and Terrains

Research suggests that the performance of an EV varies considerably according to the climate and terrain in which it is driven [162]. In particular, the thermal behaviour of lithium-ion batteries is adversely affected by extreme heat, with both charging efficiency and life cycle significantly reduced when battery temperature exceeds 50 °C. For example, the Nissan Leaf's battery capacity was found to deteriorate when tested in the Arizona desert [163]. Given KSA's desert climate, this could raise doubts about the suitability of EVs in the country.

2.8.8 Safety of EVs

The risk of fire and other hazards associated with Li-ion batteries are particular issues for EVs for a variety of reasons, including high demands in terms of driving performance and charging speed and the resulting increase in the scale and energy density of battery packs [164]. There is an additional risk that Li-ion batteries may release toxic gases if they overheat [164]. Concerns around the risks associated with fires due to batteries overheating are likely to be exacerbated when external air temperatures are already high, as is the case in KSA.

2.8.9 Environmental Benefits

Although EVs are often promoted as a green transport option, users are frequently unsure whether driving an EV will actually reduce GHG emissions [165]. Evaluating the environmental aspects of EVs is a complex task that includes assessing the sources of the electricity used for charging and manufacture, the challenges associated with recycling EV batteries, and their overall contributions to environmental degradation. However, the use of renewable resources to power EVs could significantly enhance their green credentials.

Having explored the main factors associated with EV usage globally, the next section examines the factors which are likely to influence their adoption in KSA, notably recent rises in domestic fuel prices and the government's ambitious carbon reduction plans set out in Vision 2030.

2.9 Electric Vehicles Adoption in Saudi Arabia

KSA presents an interesting context within which to examine end-users' perceptions of EVs and the barriers to their widespread adoption. The country is a major producer of oil, but it now has ambitious plans to reduce its GHG emissions and achieve net-zero by 2060 [8]. This will require much greater use of public transport and the widespread adoption of EVs [9,166]. However, EVs are currently unavailable for purchase within Saudi Arabia, and potential users are obliged to import their vehicles, a costly and bureaucratic process. That is set to change with the signing of the deal with Lucid Motors, a US EV manufacturer, in May 2022, an early step in realising the country's aim to become a regional hub for EV manufacturing [167]. However, initiatives such as this are still at an early stages and considerable research and additional investment will be required if KSA's EV ambitions are to be realised. This is reflective of the approach to EVs within the petroleum-producing states of the Gulf Cooperation Council (GCC), with the notable exception of the UAE, where about 50% of Dubai's taxi fleet is now hybrid or electric, and over 300 charging stations are available across the city [168]. Indeed, many of the EVs currently in KSA were originally imported from Dubai [169].

2.9.1 Factors Affecting the Saudi Context

In 2018, the transportation sector consumed around 21% of total energy in KSA, at around one million barrels of oil equivalent per day, and 52% of this demand came from light duty vehicles. By 2019, there were over 18 million vehicles on Saudi roads [170], and numbers are expected to reach 25 million by 2030 [171]. As urban public transport is limited and fuel is subsidized, cars are affordable, even for low-income residents [172], and private vehicles constitute four fifths of those on the road. Given the expected rise in vehicle numbers by 2030, the widespread adoption of EVs could provide a significant reduction in CO_2 emissions.

Various studies have been conducted to assess the future of EVs in KSA and to estimate the GHG reductions they could achieve [173]. Despite the country's status as a leading oil producer, a key challenge which has emerged is the massive additional demand EVs will place on the grid, especially during the summer. Steps are now being taken to design systems to evaluate the impact of EVs on the grid [174], and one proposed solution is a techno-economic hybrid power system for EVs using a mixture

of green energy [175]. This would be a significant step forward, both in terms of developing sustainable EV infrastructure and meeting the country's GHG reduction targets.

Cost is another significant issue, both in terms of EV charging and purchase and maintenance costs. Between 2007 and 2015, petrol prices in KSA were fixed, with premium 95-octane petrol cost 0.60 Saudi riyals (SAR) per litre, while 91-octane petrol was at SAR 0.45 per litre. However, domestic fuel prices are now being reformed in order to reduce the cost of state subsidies, improve energy efficiency, and reduce consumption. In July 2021, the government capped petrol prices at SAR 2.33 and 2.18 per litre respectively [42], and residential and commercial electricity tariffs were set at SAR 0.18 and 0.20 per kWh respectively in January 2018 [47]. However, with consumers now feeling the effects of the petrol price increases, there is likely to be greater willingness to consider an EV. Removing the need to import vehicles will reduce initial costs significantly; however, harnessing the revenue generating potential of V2G may act as a greater incentive.

2.9.2 Saudi Standards, Metrology and Quality Organization (SASO)

Another area which will affect EV adoption in KSA is that of regulation. A survey conducted by [176] indicated that appropriate government regulation and policies are an important factor for potential EV users in the Kingdom, and ensuring high safety standards and compatibility with existing infrastructure are essential for widespread adoption [177]. In Saudi Arabia, some of this responsibility falls to the Saudi Standards, Metrology, and Quality Organization (SASO), a technical government body which works closely with the private sector, other government entities, consumer representatives, and other stakeholders to develop quality infrastructure in KSA. In the context of EVs, its primary responsibilities include ensuring compliance with SASO regulations, monitoring compliance throughout the life of an EV, and issuing conformity certifications required for EV deployment in KSA. In 2019, SASO established regulations setting out the minimum health and safety standards for EV consumers [169], marking another significant step towards the adoption of EVs in the country.

2.10 RETScreen Clean Energy Project Analysis Software

The RETScreen software performs a clean-energy project analysis and can be used for pre-feasibility and feasibility analyses of energy-efficient and renewable energy technologies [178]. The software has been developed by Natural Resource Canada with contributions from government, industry, and academia, to evaluate clean energy technology implementation at the preliminary feasibility stage. RETScreen model applies a computerised system with integrated mathematical algorithms to assess energy production, financial viability, life-cycle costs, and GHG emission reduction potential for various categories of renewable energy technologies (RETs) using a top-down approach [179]. The software tools are applicable to any energy system or combination of systems. Furthermore, it employs a comparison model that includes a base case, which is typically the conventional technology, and a proposed case, which is the renewable energy technology [180].

2.10.1 RETScreen Algorithms and Calculation Process

RETScreen uses a variety of algorithms to evaluate the technical and financial viability of renewable energy as following [180]:

a) Energy Analysis: It uses algorithms to calculate the energy output of different renewable energy technologies, such as solar, wind, and biomass. These algorithms take into account factors such as location, weather patterns, shading, and equipment performance to accurately estimate the amount of energy that can be generated by a particular project.
b) Financial Analysis: It includes financial algorithms that allow users to calculate the financial viability of their projects. The software considers factors such as capital costs, operating costs, revenue streams, and financing options to determine the financial feasibility of a project. The financial algorithms also account for inflation, discount rates, and other financial factors that can impact the financial viability of a project over time.
c) Environmental Analysis: It includes algorithms that can estimate the potential environmental benefits and greenhouse gas emissions reductions of different renewable energy and energy efficiency projects. These algorithms take into account factors such as fuel consumption, energy savings, and avoided emissions to determine the environmental impact of a project.

d) Performance Analysis: It includes tools that can be used to analyze the performance of renewable energy and energy efficiency projects over time. These tools allow users to track the performance of their projects and identify areas for improvement.

The calculation process in RETScreen typically involves entering project data, such as location, energy consumption, and equipment specifications, into the software. The software then uses its algorithms to analyze the data and provide output, such as energy production estimates, financial viability assessments, and environmental impact assessments. Users can then review and analyze the output to make informed decisions about their projects.

2.10.2 Limitations of RETScreen

RETScreen, like many other professional software, cannot consider certain factors that can have a significant impact on the performance and financial viability of a project, such as project-specific engineering and design considerations or local regulatory requirements. The software is designed to handle renewable energy including solar, wind, hydro, biomass and efficient buildings as these are the main tools used. However, the software's substitute renewable energy sources and loads enable the application of EV chargers as loads and V2G as an additional source alongside with solar PV energy as the primary source. RETScreen allows users to adjust various parameters and customized based on specific project requirements or user preferences. Flexibility and customization features, allowing users to modify the software parameters to their specific project requirements and preferences. This can help to provide more accurate and useful results when evaluating the technical and financial feasibility of renewable energy projects.

2.10.3 RETScreen Utility Grid Types

RETScreen provides information on the available grid types and their definition. Using this information helps assess the required functionality of the proposed use case in terms of the desired project implementation. Within the software, PV power systems are generally classified according to their functional and operational requirements, the configurations of their components, how the equipment is connected to power sources

and their electrical loads [181]. Figure 2.46 shows the different methods of PV array integration into the grid supported by RETScreen.

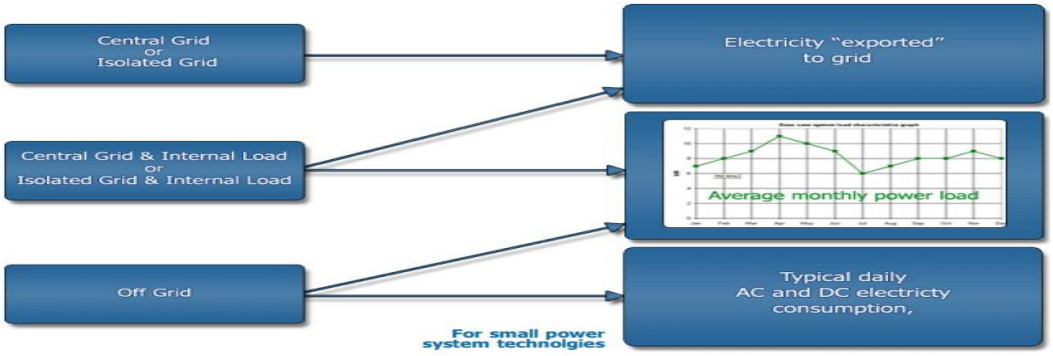


Figure 2.46 Types of grid systems supported by RETScreen [182].

The central grid (centralized PV integration system) is shown in Figure 2.47. It is often referred to as grid-connected or utility-interactive PV systems. These systems are designed in parallel and interconnect with the electric utility grid, transferring electricity generated by solar panels (the PV array) directly into the energy grid. This electricity is paid for by the grid operator at a certain tariff.

The primary component is the inverter, which is responsible for conditioning the DC power generated by the PV array into AC power, taking into consideration the voltage and power quality requirements of the utility grid. The inverter automatically stops supplying to the utility grid when it is not energized. Additionally, switching systems are available, thus allowing the AC power generated by the PV array to supply either AC loads on-site or to supply the grid when the PV output is sustainably greater than on-site needs. This switching feature, known as the on-site distribution panel/service entrance, is often required in all grid-connected PV systems [181].



Figure 2.47 Block Diagram of a Central Grid System [182].

In addition, there are also stand-alone (isolated) systems, designed to operate independently of the electric utility grid, which are generally designed and sized to supply certain AC and/or DC electric loads. The simplest set-up for a stand-alone system is a direct-coupled system which is only available during sunlight hours; here the DC output of a PV module or array is directly connected to a DC load. Standalone systems typically have batteries that are used for electricity energy storage and re-utilization [181].

In addition to centralized PV integration, there is also distributed PV integration. In contrast to centralised generation, where electricity is generated by a large central plant and then distributed to consumers through the power grid, distributed PV arrays are deployed in proximity to the end users of the power. This often involves PV arrays installed on the rooftops of commercial or residential buildings that require this energy, with any surplus transferred to the utility grid [183]. To depict clearly these differences, Figure 2.48 shows how these systems can be combined. In this study, only centralised PV integration was used for the techno-economic analysis.

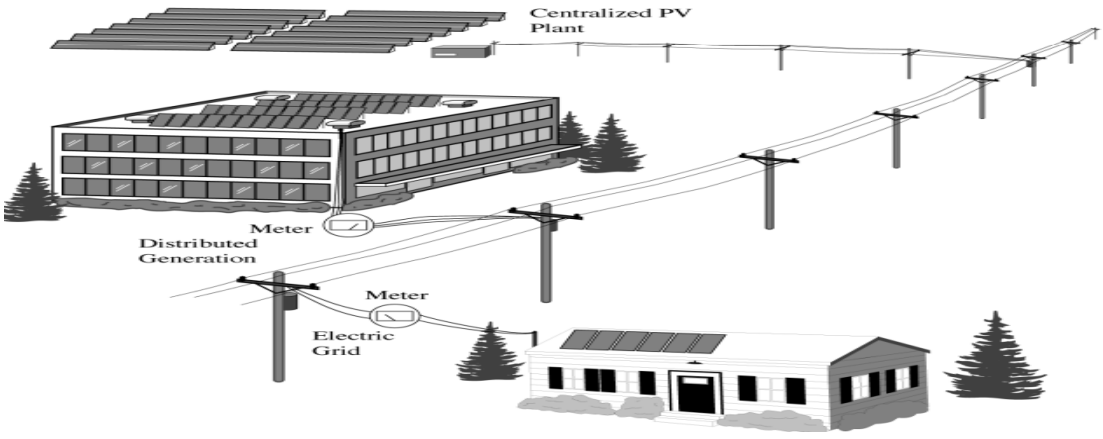


Figure 2.48 Combination of Centralized and Distributed Systems [182].

2.11 Techno-economic Analysis Using RETScreen

Techno-economic analysis is a method for evaluating the economic effectiveness of a process, product or service. Typically, software modelling is used to estimate initial costs, operating costs, and income based on technical and financial input parameters. This type of analysis is essential for understanding the competitiveness of emerging technologies in an uncertain future [184].

Many researchers used RETScreen to conduct an economic and environmental feasibility study on solar PV. Aniegbunem et al. [185] conducted a study on the

economic benefit analysis on the campus fleet with around 100 ICEVs of the University of Saskatchewan, Canada, in order to determine whether or not it is economically or financially feasible. The findings stated that the GHG emissions from the campus fleet can be reduced by 100%. In addition, the university will save approximately 90% on fuel expenses, and simple payback is 5 years. Moreover, on account of GHG emissions reduction, around $15,000 per year can be earned additionally. Similarly, a study [186] was conducted in Iran, to analyse the environmental, technical, and financial viability of solar power facilities. Based on three RETScreen scenarios, the study developed new electricity tariffs.

Many of the RETScreen-based studies in Saudi Arabia addressed the economic and feasibility analysis of solar PV or wind energy in certain regions of the country. Hussein et al. [187] use the software to conduct an economic and environmental feasibility analysis of implementing a photovoltaic system to fulfil proposed electric vehicle load demand in Dhahran, Saudi Arabia. The load in the case of a PV system without storage units offers an availability of 38.45%, which represents the proportion of the load for which the PV system provides service. The average number of interruptions per year is 581, with an average duration of 5391.6 hours. Another study [188] was conducted by developing 10 MW to assess the techno-economic viability in various locations in KSA. The feasibility study was performed using weather data, such as global solar radiation, sunshine length, dry bulb temperature, and relative humidity, to determine potential energy production, GHG emissions, and financial variables. Again, the study found that due to the most significant solar radiation intensity and longest sunshine duration, Bisha has been identified as the optimal location for a 10 MW installed capacity grid-connected PV power plant. After the study conducting sensitivity analysis, it is recommended that to begin construction of a large grid-connected PV facility in Bisha site with a 70% government grant because the electricity export rate in Saudi Arabia is 72.57% less expensive than the global price.

The purpose of the feasibility study [189] is to demonstrate the viability of installing a 144 MW PV facility in six locations across the KSA is assessed for different type PV plant systems such as tilted-fixed and one-axis tracking systems. The results indicate that the average cost of electricity production (CEP) is 2.22¢/kWh and that the average annual reduction in greenhouse gas emissions is 462 tCO_2/GWh when a

diesel power plant of comparable capacity is replaced with a natural gas power plant. Also, the study found that Bisha is the optimal location for a PV plant facility with the highest predicted IRR and the shortest equity payback period of 10.1% and 11.4 years, respectively, at an EEER of 6%. In terms of sensitivity analysis, the study concludes that with the government subsidy some of PV plant locations become very attractive such as Sakaka, while Dhahran is the least favourable location, with the project only being financially viable if the government provides a subsidy of at least 25%.

Some studies investigated in greater depth in sensitivity analysis and risk analysis such as [190] when analysing a PV plant in Chile, ±30% variation for five parameters revealed that the initial cost and electricity export rate have a significant impact on the project's result. Also, a study [191] conducted in Bangladesh evaluating the economic viability of a solar system for EVs. It found this technology to be economically viable and useful for the government. According to IRR, NPV, and BCR values, the project is economically attractive, and would assist in maintaining the annual GHG reduction cost of $42,950.

2.12 Conclusions

In this chapter, different types of EVs were reviewed and compared. These included Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). It was found that, currently, BEVs were the most popular type of EV while FCEV were the least common type of EVs in terms of acceptance and publicity. The batteries included in a BEV has larger capacity compared to other types of EVs. In terms of emissions BEVs and FCEVs have almost zero emission, while HEVs and PHEVs have relatively low emissions compared to ICEVs. But this depends on the source of electricity used to drive the vehicle in the first place. In terms of charging infrastructures, it was found that Level 1, Level 2, and Level 3 (DC fast charging) options were available. While Level 1 was primarily used in residential settings in North America, Level 2 charging was used in homes, workplaces, and in public. On the other hand, Level 3 charging was mainly available for public on intercity roads. Level 1 charging was found to be useful for long stay car parks (e.g., homes), Level 2 for short stays (e.g., in hospitals, and doctors' clinics etc.), and while Level 3 charging was found to be useful for quick charging (e.g., 80% of charge in 10 minutes). It was found that the cost of batteries

has a direct impact on the cost of EVs. However, as the battery costs are likely to decrease, it is expected that in future, more and more people will be able to afford EVs. It was found that the cost of batteries has a direct impact on the cost of EVs. However, as the battery costs are likely to decrease, it is expected that in future, more and more people will be able to afford EVs.

While plenty of research is available on the types of EVs, batteries, chargers etc., to the best of the author's knowledge, important features in an EV from a consumer's perspective and barriers to EVs adoption in a major oil exporting country like the KSA have not been investigated before. These will be investigated next (in Chapter 4 and Chapter 5) in this thesis. The literature review identified Nissan Leaf as a potential car model which can be used in simulations to estimate the viability of different strategies for unlocking the potential of EVs to enhance large scale PV solar energy integration into grid system. This is mainly due to its compatibility with the V2G technology. Therefore, while estimating the energy requirements for powering EVs (in Chapter 6) and performing techno-economic analysis of EVs application (in Chapter 7), simulations will consider input values corresponding to those of Nissan Leaf (e.g., a battery capacity of 40 kWh, a driving range of 400 km, and a price of $37,500).

In the next chapter, the methodology of this research is presented.

Chapter 3
Methodology

3.1 Introduction

This chapter describes the methodology used to complete this study. The study uses a mixed methods approach, including both quantitative and qualitative methods. Both primary and secondary sources were used for data collection. Primary data was obtained from a number of sources, including “Electric Vehicles Future in Saudi Arabia” survey (hereafter known as the “Saudi Survey”) distributed to EV users, experts, and the general public. In addition, primary data collected from an existing PV plant "Sakaka Solar PV Plant" was used to evaluate six possible sites around the Kingdom to determine the optimal location for the case study. Secondary data was collected with the help of a literature review which examined energy production and distribution in Saudi Arabia, EV technologies, grid integration strategies, and the current situation of EVs in the Kingdom. Secondary sources also included official Saudi government documents and other information collected from different ministries and organizations in KSA. Secondary data was also gathered from a focus group of current Saudi EV consumers at a workshop hosted by the Saudi Standards, Metrology, and Quality Organization (SASO). A techno economic modelling of EVs application is developed, using the software RETScreen to conduct simulations for evaluating the various locations for energy production, requirement of PV sizing, and for performing sensitivity analysis.

The research methodology summarized in Figure 3.1. To meet the first objective of reviewing the state-of-the-art of EV technologies and the impact of integration of large-scale solar PV into the grid system, a literature review was conducted in which reputed journals, conference proceedings, government documents, global standards etc. were consulted to understand the state-of-the art in EV and solar PV technologies and potential issues with large-scale solar PV integration into the grid system. Then, to meet the second objective of identifying the barriers to the widespread adoption of EVs in Saudi Arabia, primary data was collected using the “Saudi Survey” which was distributed among the general public, experts, and EV users. Similarly, to meet the third objective of identifying the current trends in EV usage and the features required

by end users in Saudi Arabia, data was collected with the help of a focus group conducted as part of an e-workshop on EVs organised by SASO. A questionnaire was also circulated during the focus group. This stage also provided validation of the findings of the Saudi Survey. The fourth objective was to identify and evaluate potential locations for utility-scale PV systems in Saudi Arabia. For this purpose, production data for the existing Sakaka PV plant in Saudi Arabia was obtained and simulations were performed (using the RETScreen software) to assess the suitability of six cities in Saudi Arabia for the installation of solar PV plants with the aim of using the power generated by these plants to support the application of EVs in these cities. Finally, the last two objectives of proposing different strategies for EV usage in a typical Saudi city and performing a techno-economic analysis of each strategy for EV application, were met by first considering the findings of the focus group, questionnaire, literature review, and the Sakaka solar PV plant to first devise strategies and then using the RETScreen simulation software to evaluate technical, economical, financial, and environmental viability of these strategies. The best strategy was identified based on a combination of these factors.

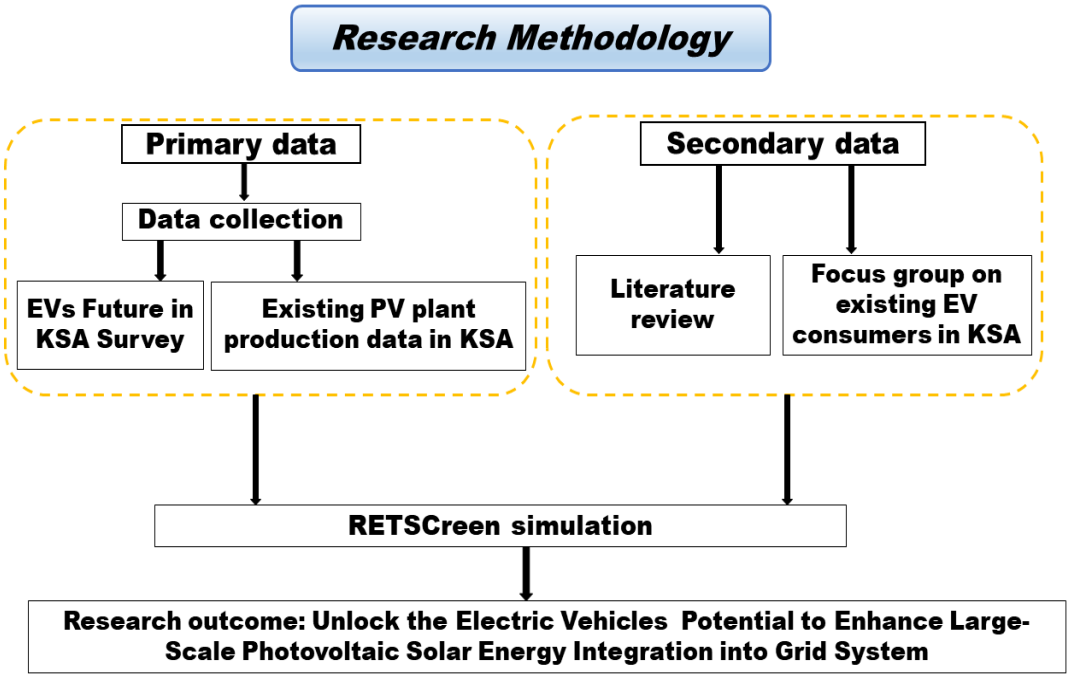


Figure 3.1 An overview of the research methodology.

The methods and procedures adopted at the main stages of the study are described in separate sections below.

3.2 Identification of Potential Barriers to Electric Vehicle Adoption and Current Trends in EV Usage in Saudi Arabia

A key objective of this study is to identify the potential barriers to EV adoption in Saudi Arabia from the perspectives of current EV users, experts and members of the general public. After a detailed review of the literature, the first step involved gathering data from potential EV drivers to assess their perceptions of the vehicles. As costs were identified as a significant concern, a calculation of the long-term cost of EV ownership was then made. Finally, a focus group discussion provided evidence of the actual challenges experienced by current EV owners in KSA. Each of these stages is described below.

3.2.1 Analysis of Perceptions of EV Users in the KSA

The aim of this analysis was to identify the barriers to the widespread adoption of EV in the Kingdom. A mixed methods approach was adopted, including quantitative data collected via an e-survey, the instrument being an e-questionnaire, the "Saudi Survey", self-administered by individuals identified via local vehicle suppliers [192]. This was selected as it is considered suitable for large data samples [193]. Sampling was non-random [194], Most of the 78 items were in the form of closed questions, which were scored on a 5-point Likert-scale from "not important" (1) to "very important" (5). Some additional open questions were used to elicit more subtle perceptions.

Three aspects of instrument validity were assessed: face, content, and construct validity [195]. For face validity, ten participants were asked to examine questionnaire items for logical links with the objectives [196]. For content validity, six EV experts assessed each item for purpose, i.e., whether it measures what it should measure [195]. Content validity was evaluated further via subjective feedback in a pilot study of 30 participants, since the pilot study is limited size of participants which also explored construct validity objectively to confirm the instrument's reliability and internal consistency [197]. This was achieved by means of Cronbach's alpha and exploratory factor analysis (EFA), which is used to develop theory, reduce complexity, and identify latent factors [197]. The experts in the field who reviewed the survey questions include an expert working on an EV chargers project at Saudi Electricity Company (SEC), two EV policy and regulatory experts working at the Saudi

Standards, Metrology and Quality Organization (SASO), and three other researchers working in the field of EVs in the Saudi context.

Both Arabic and English versions of the questionnaire were used to elicit responses from a wider population of drivers, comprising Saudi national, expatriates and others. Four bilingual experts examined the Arabic-to-English translations of the survey items and the responses to open questions. To ensure clarity and to reduce the risk of misunderstanding, the second page of the survey offers definitions of terms such as ‘hybrid vehicle’, ‘electric vehicle’, ‘conventional vehicle’ and ‘V2G’.

3.2.1.1 Qualitative Analysis

NVivo was used for qualitative analysis, following Braun and Clark [199] six steps of thematic analysis: 1) data familiarity, by iteratively reading responses to ensure understanding; 2) creating initial codes; 3) exploring textual data for themes by mapping initial codes to text; 4) reviewing themes; 5) defining and naming themes; and 6) preparing the report. The combined qualitative-quantitative analysis followed the approach of [201].

The response rate was enhanced by a combination of convenience, snowball, and volunteer sampling, thus compensating for any weaknesses among these strategies [201]. A sample size of 601 was calculated to be sufficient at a confidence level of 95% and a 4% margin of error [202], given Saudi Arabia’s population of 34.2 million [203]. When data were collected, 1012 questionnaires were returned, 698 of which were complete, giving a completion rate of 70%; the number of incomplete returns may be explained by the novelty of EVs in KSA. The instrument was developed on the SurveyMonkey platform, and in line with the increasing use of social networking sites by researchers seeking to strengthen engagement with surveys [194], Twitter, WhatsApp, and Telegram were used to recruit participants, as were emails.

The R software environment was used to perform data analysis, comprising descriptive statistics and factor analysis, including means and frequencies, an independent samples t-test, Cronbach’s alpha and Pearson correlation coefficients, one-factor repeated measures Analysis of Variance (ANOVA), EFA using the lavaan package [204], and ggplot2 for graphics [205]. Normal distribution and data homogeneity assumptions were confirmed by skewness and kurtosis tests, making the above procedures appropriate [206].

3.2.2 Calculation of the Cost of Long-term EV Ownership

The potential costs of ownership over a period of 10 years were calculated for both EVs and ICEVs based on their long-term costs, to compare the viability of owning an EV for Saudi users. The cost of ownership was deemed to include the initial cost and ongoing operation and maintenance (O&M) costs. Estimations of O&M costs were based on the cost of resources available in KSA. Maintenance and repair costs were calculated over a vehicle's entire expected lifetime and thus assumed to be constant across the 10-year analysis period. The fact that EVs are far cheaper to operate and maintain than ICEVs (as combustion engines require oil, filters, belts, and so on, and EVs do not) was also considered. A 10-year period was chosen to account for variation in daily driving ranges and because research indicates that the payback period for an EV might be up to 10 years due to the higher initial costs compared to ICEVs [207].

This calculation assessed annual running cost as follows:

- *Engine O&M:* This was calculated for ICEVs only, as EVs require little engine maintenance, so this is not considered when estimating the cost of their long-term ownership.
- *Other O&M:* These include costs associated with tires, brake pads, gearbox oils, etc. [208,209], which are generally similar for EVs and equivalent ICEVs.
- *Battery replacement:* Battery replacement is a major cost associated with long-term EV ownership [205]; however, it is estimated that these will decrease rapidly [80]. The US Department of Energy set cost targets of $300/kWh by 2015 and $125/kWh by 2022 [88], so this study took $125/kWh as the cost of the battery. Battery replacement was assumed to be required eight years after purchase, but only in EVs with a high usage rate. This was taken into consideration when estimating the battery replacement costs for vehicles in all mileage ranges. The fact that EVs with larger batteries will incur greater replacement costs was also recognized; thus, for the Tesla Model 3, a 75-kWh battery capacity was assumed, making the estimated battery replacement cost around $9,375 (SAR 35,000).
- *Administration fees:* These include fees paid to the government, for vehicle registration, annual renewal, periodic inspection, and plate registry [210]. KSA currently imposes no road tax, congestion charges, or emission charges.

- *Car insurance:* Some Saudi motor insurance companies offer fixed annual insurance prices, and the annual average cost is reported to be SAR 1050 ($280) [211]. This cost is used for all car brands and all mileage ranges.

Due to the absence of EV dealerships in KSA, the initial price for the Tesla is obtained by examining Tesla prices in the UAE, which is similar to the KSA market in terms of prices, standards, and other factors, and set at Dirham (AED) 200,000 ($54,450) (SAR 204,400) [212]. The initial cost for the three Toyota ICEVs was based on new vehicle prices at Saudi Toyota, as follows: the Camry was priced at SAR 99,000 ($26,400), the Prado at SAR 213,000 ($56,800) and the Value Extreme Rally (VXR) Land Cruiser at SAR 404,500 ($108,000) [213].

Depreciation was not included in the analysis as it was assumed that all EVs and ICEVs were purchased outright, rather than via loans or instalment plans, and that ownership persists for the full ten years, making depreciation inapplicable. In addition, as currently the Saudi government offers no grants for ownership of EVs, whereas the UK government, for example, provides up to £1,500 under its net-zero strategy [214] and the Irish government provides €5000 grants [215], no costs were set for government incentives.

Finally, the cost of ownership of a vehicle over 10 years was calculated as follows per eq. (3.1) [216].

$$COO_{10} = (\mathrm{PP} - \mathrm{GI}) + \mathrm{BR} + \sum_{y=1}^{10} \left(FC_y(\mathrm{D}) + \mathrm{T} + OMC_y\right) \qquad (3.1)$$

where COO_{10} is the 10-year cost of ownership, PP is the initial cost of the vehicle, GI represents government incentives to purchase it (currently zero in KSA), BR is battery replacement cost, FC_y is forecasted cost of fuel per year, D is the annual distance travelled by the vehicle, T is the motor tax on the vehicle (again, zero in the KSA), and OMC_y is O&M cost per year (excluding fuel consumption).

3.2.3 Analysis of Electric Vehicle Consumer Confidence in Saudi Arabia

This part of the research was exploratory in nature and explores the actual challenges Saudi EV users experience based on a workshop held by the Saudi Standards, Metrology, and Quality Organization (SASO). Focus group discussion is beneficial since it can capture a wide range of response interviews and shows how participants

communicate within a certain topic, which helps to moderate extreme or underrepresented viewpoints [217]. In addition, this part of the research is considered ground-breaking since it is the first study of EVs to draw on SASO's expertise in this way.

SASO organized the workshop with four experts from their department of Electrical and Electronic Products and five members from other departments, including the Media and General Standards departments, and current EV users within KSA were invited to attend. 65 invitations were sent to users via SMS text messages and emails, with a link to the workshop schedule and a registration link for those who wished to participate. Users were identified based on certification issued by SASO to approve the import of EVs into the Kingdom. There were 28 participants in total.

Data were collected via an e-focus group at a two-hour online workshop and an e-questionnaire that was disseminated within the e-focus group session. The researcher is an employee of SASO and a former member of its technical committee, so he was able to participate in the focus group within the wider workshop. The focus group concentrated on the challenges users experienced with their EV in KSA and was conducted virtually using the Cisco Webex software, the Webex poll as an e-survey, and a link for the panel to respond to the closed and open questions.

A qualitative method was adopted to analyse the e-focus group data using content analysis, which involves "*immersion in the details and specifics of the data to discover important patterns, themes, and interrelationships*" [218]. The proceedings of the e-focus group were audio recorded, transcribed, and coded using thematic analysis method [219]. NVivo software was used to analyse the qualitative data derived from e-focus group whereas SPSS software was used for quantitative data. Face validity by experts and Cronbach's alpha internal consistency were applied to ensure reliability and internal consistency. The alpha value was above the cut-off 0.7, which is considered high since anything below this is considered unsatisfactory [220].

This phase of the study formed part of SASO's standard procedure for investigating such issues (See Figure 3.2). This involves three phases. When SASO receives inquiries concerning the EV industry, a literature review which focuses on mapping the EV industry in KSA is conducted. Based on the outcomes, an investigation of the specific challenges is carried out, in this case via a workshop involving a focus group

and a questionnaire. In the third phase, SASO's technical committee for EV promotion, consisting of stakeholders from the government and private sectors, assesses the outcomes of the second phase and takes appropriate action, such as amending standards and regulations, if required.

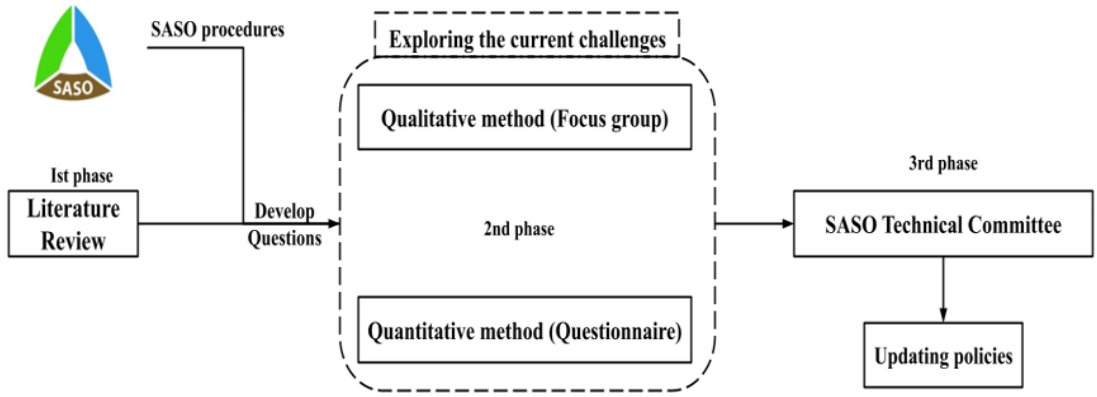


Figure 3.2 The approach adopted for addressing EV related consumers issues in Saudi Arabia.

3.3 Techno Economic Analysis

In order to understand the best approach to introduce EVs into the Saudi grid, a techno economic analysis of EVs application is conducted. The methodology used for conducting the techno-economic analysis of EVs application is presented in this section. The study was conducted based on varying estimates of expected numbers of EVs in Saudi Arabia in 2030.

3.3.1 Determining the Case Study Location

Six different locations which are representative of the different regions of Saudi Arabia were evaluated to determine the most suitable site for the case study. These included either major population centres or locations with good potential for electricity generation using solar PV. The method used to validate the selection of the chosen case study location is shown in Figure 3.3.

Initially, the projected number of EVs by 2030 was estimated for each six cities, Jeddah, Riyadh, Dammam, Sakaka, Bisha and Madinah, which based on the most recent official government statistics available at the time [170]. Subsequently, the expected number of EVs which would require parking (27%) in each city was calculated, along with the load required to charge the EVs.

Using data from the Sakaka solar PV plant, the energy requirements, and the size of PV panels sufficient to meet EV energy demand in 2030 were modelled using RETSCreen software. As a result of the analysis, the city of Riyadh, the Saudi capital was selected as the case study location.

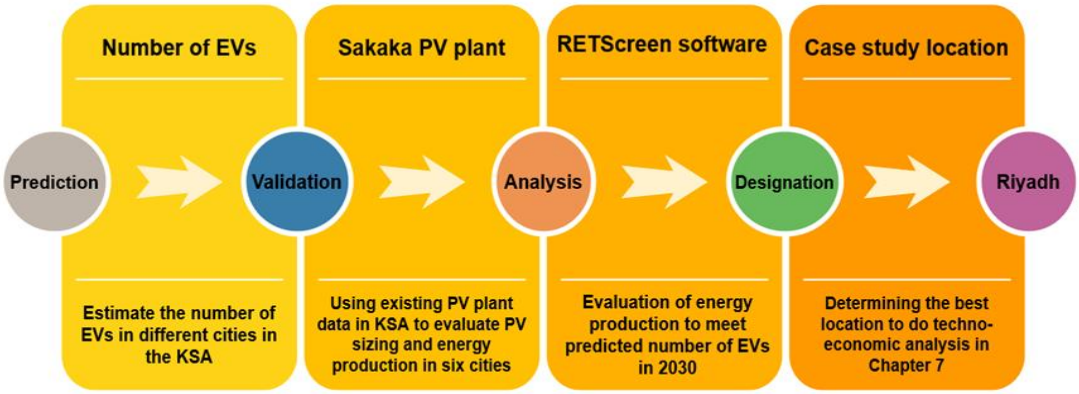


Figure 3.3 Approach used to select the case study location.

3.3.2 Estimated Peak Load Requirements

The peak load requirement in the year 2030 is estimated as follows per eq. (3.2):

$$Estimated\ Peak\ Load\ Requirement\ =\ Maximum\ charging\ need\ of\ a\ single\ EV\ \times\ No\ of\ vehicles\ in\ 2030\ \times\ Proportion\ of\ vehicles\ parked\ between\ 8{:}00am\ and\ 6{:}00pm\ \times\ Proportion\ of\ EVs\ among\ all\ vehicles\ in\ 2030. \quad (3.2)$$

3.3.3 Projected PV Plant Size Implementation Modelling

Based on RETSCreen software the three models were considered to evaluate the viability of EVs and related infrastructure in the city of Riyadh. In the first model (Model 1), installation of a PV plant was considered. In the second model (Model 2), the impact of introducing EV charging stations was also considered. Finally, in the third model (Model 3), the Vehicle-to-Grid (V2G) concept was considered.

3.4 Projected Model 1

As part of the Saudi survey conducted by the author, parking habits and durations of parked vehicles were gathered to create a parking profile for Saudi drivers. Then the expected number of EVs in 2030 is used to predict the PV solar plants size for three uptake scenarios: low, medium, and high.

3.4.1 Expected Number of EVs Scenarios

The actual number of electric vehicles in a country can be difficult to predict. Therefore, three different estimates were used for the number of electric vehicles in Saudi Arabia. These estimates are presented as realistic scenarios and have already been used in the literature by Elshurafa & Peerbocus [173]. The three scenarios are:

Scenario 1: Low Uptake Scenario (LUS) – 3.5% of cars sold annually are EVs.

Scenario 2: Medium Uptake Scenario (MUS) – 7% of cars sold annually are EVs.

Scenario 3: High Uptake Scenario (HUS) – 14% of cars sold annually are EVs.

3.4.2 Prediction of the PV Plant Export Rate to the Saudi Grid

As per Saudi government policy, the price of selling a megawatt-hour of electricity is $23.4 which is approximately Saudi Riyal (SAR) 87.75/MWh. This is the tariff used when transferring electricity to the grid at the Sakaka Solar Power Plant, which is the first large-scale PV facility tendered by Saudi Arabia and successfully connected to the grid in 2019 [221]. The Sakaka Solar Power Plant set a new world record for low costs in the solar PV sector when it was introduced in 2019 [221].This tariff was therefore used as a benchmark value during simulations, and the revenue from the PV plant can be calculated using eq. (3.3)

$$Revenue\ from\ PV\ plant\ =\ Energy\ generated\ X\ Export\ rate \qquad (3.3)$$

3.4.3 PV Components Specifications

As discussed in the literature review, Saudi Arabia has a successful solar PV power project in Sakaka, which uses solar panels manufactured by Chint Solar, an inverter maded by Huawei, and tracker system manufactured by Nexttracker. Since Riyadh has a similar climate, similar functional components to those in the Sakaka solar project could be used. However, Chint Solar PV panels are not available in the RETScreen software. Therefore, for simulation purposes, Canadian Solar PV panels (mono-silicon, mono-Si-CS6U-345M), which share similar characteristics to those of Chint Solar, were used. The characteristics of the panels, inverters and tracker systems are shown in Appendix B.

3.4.4 Cost Estimation of the PV plant

The costs associated with different PV installation, their running costs, and the maintenance costs of the PV power plant itself are described in Table 3.1.

Table 3.1 Breakdown of the costs involved in the development and running of the power plant

Initial Costs	
Feasibility study	Site investigation, preliminary design, environmental assessment, detailed cost estimate and report preparation.
Development	Contract negotiations, permits and approvals, project management, travel, and accommodation.
Engineering	PV system design, electrical design, tenders, and construction supervision.
Power system	PV modules, inverters, substations, and transmission lines
Balance of system	Module support structure (controllers, tracking system), electrical equipment, system installation, construction of transportation and spare parts
Miscellaneous	Training and contingencies.
Annual costs	
Operation and maintenance	Property taxes/insurances, labour, and contingencies.
Periodic costs	
Inverter's replacement	Costs of inverter replacements when its life end up
End of project life	Costs of remediation or decommissioning that must be incurred at the end of the project life

The total cost of the PV power plant could then be estimated using eq. (3.4) below.

$$PV\ Powerplant_{cost} = Initial_{cost} + Annual_{cost} + Periodic_{cost} \quad (3.4)$$

Here, $Initial_{cost}$, $Annual_{cost}$, and $Periodic_{cost}$ are the initial, annual, and periodic costs associated with the PV power plant.

The initial cost, $Initial_{cost}$, was estimated as in eq. (3.5).

$$Initial_{cost} = FS_{cost} + Dev_{cost} + ENG_{cost} + PS_{cost} + BOS_{cost} + MISC_{cost} \quad (3.5)$$

where, FS_{cost}, Dev_{cost}, ENG_{cost}, PS_{cost}, BOS_{cost}, and $MISC_{cost}$ are the costs associated with feasibility study, engineering, development, power system, balance of system, and miscellaneous respectively.

For the cost analysis, certain assumptions had to be made due to the absence of data in relation to these components. Assumptions were made in relation to the capacities of each plant related to each scenario, while keeping the associated costs for feasibility studies constant. The remaining costs were initially assumed for the LUS and then extrapolated for the MUS and HUS scenarios based on the associated percentage increase in the capacity of the associated plants. This constraint could have been avoided by the presence of a valid run-down of the costs of an already implemented PV plant; however, such data is usually not made public. Therefore, if any of the desired scenarios presented in this study were to be implemented, a market survey would need to be done in relation to actual present worth values of all related costs.

3.4.5 Financial Viability Parameters

The financial viability parameters considered in this study included simple payback, equity payback, internal rate of return (IRR), net present value (NPV), annual life cycle savings, net yearly cash flow, benefit-cost ratio (BCR), GHG reduction cost, and energy production cost (EPC).

The simple payback period is the time required for the project's revenues or savings to cover the initial expenditure represented by eq. (3.6) [222].

$$\text{Simple payback period} = \frac{C}{\mathrm{C_{income}} - \mathrm{C_{cost}}} \qquad (3.6)$$

The equity payback period $\mathrm{N_{PCF}}$ is the first year in which the project's cumulative cash flows are positive calculated by eq. (3.7) [222]

$$\text{Equity payback} = \sum_{n=0}^{\mathrm{N_{PCF}}} C_n \qquad (3.7)$$

The Net Present Value (NPV) is a ratio that expresses the future net cash flow of a project in terms of its current currency value as given in eq. (3.8) [222]. When the NPV value is zero, the plant's total income equals the plant's total cost of production. Positive cash flow shows that a business is receiving more money than its outgoings. Negative cash flow indicates that the expenditure is greater than the income [223].

$$\text{NPV} = \sum_{t=1}^{\text{T}} \frac{C_t}{(1 + i)^t} - C_0 \qquad (3.8)$$

Ct is the period's net cash flow, C_0 is the initial capital investment, i is the discount rate, and t is the number of periods. Typically, a project is considered economically viable if the IRR is more than the rate of return at which it would be unviable [188]. IRR is the discount rate at which the project's NPV of the equal zero, calculated using eq. (3.9)

$$\text{NPV} = \sum_{t=1}^{\text{T}} \frac{C_t}{(1 + \text{IRR})^t} - C_0 = 0 \qquad (3.9)$$

BCR is used by investors to determine the relationship between the benefits of a proposed project and its cost, and can be obtained using eq. (3.10) [224].

$$\text{BCR} = \frac{\text{NPV} + \text{Total cost of project}}{\text{Total cost of project}} \qquad (3.10)$$

3.4.6 GHG Emission Reduction

The RETScreen software was used to generate GHG emissions reduction data. The software uses baseline transmission and distribution losses, PV emissions, and proposed system transmission and distribution losses to generate GHG emissions reduction data. Transmission and distribution (T&D) losses are losses in energy delivery between sources of supply and consumption, including technical losses, energy pilferage, and/or energy consumed but not paid for as a result of issues such as non-registered consumers, un-metered electricity, and erroneous metering and invoicing [225].

The input parameters are shown in Table 3.2. T&D losses of 10% and 9.3% were adopted for the base and proposed case electricity system respectively, based on data from the Saudi Water and Electricity Regulatory Authority [43]. To calculate GHG emissions reduction, it was assumed that the plant's predicted yearly energy production will be similar to that produced by conventional electricity generation. A comparison was made between the baseline GHG emissions case and the case in which a portion

of the energy produced by a traditional plant was replaced with electricity generated by a PV plant, which emits no GHG.

Table 3.2 Input for GHG emissions reduction analysis

Input	Description	Value
Baseline T & D Losses	Losses of electricity from transmission and distribution	10%
PV Emissions	The PV project is 100% solar, and does not emit GHG	0%
Proposed system T&D Losses	Transmission and distribution losses in the proposed electricity system into which the PV plant is integrated	9.3%

The software was then used to calculate the reduction in total GHG emissions when the base case power plant was replaced with the proposed PV electricity generation system in the LUS, MUS and HUS scenarios.

3.5 Projected Model 2

Number of EVs is estimated in different cities by 2030 as electricity load requirement under the LUS, MUS and HUS scenarios which powered by a PV plant (Model 1) as shown in Chapter 6. The charging power for a single electric vehicle was established by using 22 kW, and each EV can take up to three hours to feed its battery from 0% to 100% capacity.

The total cost of the Model 2 could then be calculated using the eq. (3.11) provided below.

$$Model\ 2_{cost} = Model\ 1_{cost} + (Charging\ station\ cost(Initial_{cost} + Annual_{cost} + Periodic_{cost}) \quad (3.11)$$

3.5.1 Revenue from EV Charging Stations

As discussed in Chapter 2, RETScreen allows users to provide input parameters which can be used in the several mathematical equations which are used by the software to compute different output parameters. For example, after adding the number of required EV charging stations which need to be powered by a solar PV plant, the revenue from surplus electricity which is exported to grid and the charging stations

can be computed. The cost of charging an EV is determined by the size of the battery and the rate at which power is supplied. According to the most recent figures available, it costs around $0.18 per kilowatt-hour (kWh) to power a Nissan Leaf EV [226].

The total revenue parameter is added to the software by the manual calculations using eq. (3.12)

$$Total\ revenue\ =\ (electricity\ exported\ to\ grid\ \times\ rate\ of\ export)\ +\ (electricity\ consumed\ by\ EVs\ \times\ charging\ rate) \quad (3.12)$$

The charging rate of EVs can be adjusted mathematically and inserted into software using eq. (3.13), at the same rate of exported energy to the grid at $23.4/MWh.

$$Charging\ rate\ =\ \frac{Revenue\ from\ charging\ stations}{Electricity\ consumed\ by\ charging\ stations} \quad (3.13)$$

The revenue from charging stations can be calculated by finding the difference between the total revenue and the revenue from PV electricity production using eq. (3.14).

$$Revenue\ from\ charging\ stations = total\ revenue\ -\ revenue\ from\ PV\ electricity\ production \quad (3.14)$$

3.6 Projected Model 3

To implement V2G in Model 3, it is estimated that 10% of the total charging stations would be required to be capable of supporting V2G chargers in each scenario. Since V2G technology relies primarily on public charging infrastructure, five weekdays have been considered, with the assumption that each charger provides V2G services for 30 minutes per day.

The total cost of the Model 3 can be calculated using the eq. (3.15).

$$Model\ 3_{cost}\ =\ Model\ 1_{cost}\ +\ Model\ 2_{cost} + (V2G\ Charging\ station\ cost\ (Initial_{cost}\ +\ Annual_{cost} + Periodic_{cost}) \quad (3.15)$$

3.6.1 Export Rate of Revenue from V2G

The export rate of revenue from V2G can be computed using eq. (3.16).

$$Export\ Rate\ = \frac{Overall\ Revenue}{PV\ electricity\ production} \quad (3.16)$$

3.6.2 Vehicle to Grid Revenue Potential

With V2G technology, EV users can generate revenue by exporting surplus electricity to the grid. The total revenue that a user can generate in this way can be computed as in eq. (3.17).

$$Revenue\ potential\ =\ Revenue\ from\ export\ to\ grid\ -\ Cost\ of\ charging \quad (3.17)$$

In order to estimate the cost of charging, some assumptions are necessary, as not all electric vehicles support V2G. Here, it is assumed that the EV has a 40-kWh battery. This is based on the fact that an EV must be compatible with a CHAdeMO connector to support V2G [227]. The Nissan Leaf (with a battery capacity of 40 kWh) is a popular car in this category. Therefore, the cost of charging computations in this study assumes a Nissan Leaf vehicle with 40 kWh of battery capacity.

$$Cost\ of\ charging\ =\ Battery\ capacity\ \times Carging\ rate \quad (3.18)$$

In eq. (3.18), battery capacity is assumed to be 40 kWh (based on the above discussion) while the rate is estimated as \$0.048/kWh. This rate is equivalent to the rate of SAR 0.18/kWh which the Saudi Electric Company uses to charge residential customers. Based on these estimates, the cost of charging a 40-kWh battery is \$1.92.

An alternative way to calculate the revenue from exporting surplus electricity to the grid can be found using eq. (3.19).

$$Total\ revenue\ from\ export\ V2G\ to\ grid\ for\ 30\ min\ =\ Eport\ rate\ \times Charger\ capacity\ \times Time\ (hours) \quad (3.19)$$

In eq. (3.19), the export rate is estimated as \$0.44/kWh. This is equivalent to the export rate offered by OVO Energy in the UK (£0.0336/kWh). The time is assumed to be 30 mins. this is because the half-hourly tariff model offered by OVO Energy was found to be more effective in terms of savings from V2G compared to other tariff models [228]. Finally, the charger capacity is assumed to be 22 kWh. Based on these estimated values and eq. (3.17), exporting surplus electricity to the grid for 30 mins can generate

using eq. (3.19). The revenue potential from a 30 min V2G export from one vehicle can be calculated using eq. (3.20)

$$Revenue\ from\ a\ 30\ min\ V2G\ export\ from\ single\ vehicle\ = Total\ revenue\ from\ export\ V2G\ -\ revenue\ from\ PV\ electricity\ production \quad (3.20)$$

3.6.3 GHG Emissions Reduction

The GHG emissions for Model 2 include the emissions for Model 1 and the emissions associated with the changing stations. The GHG emission reduction of charging stations was calculated manually as in eq. (3.13)

$$GHG\ emissions\ reduction = \left[\left(\frac{fuel\ efficiency\ of\ ICEV}{fuel\ efficiency\ of\ EV} \times CO2\ tailpipe\ emissions\ for\ gasoline\ vehicles\right) - \frac{Co2eq\ emissions}{kWh}\right] \quad (3.21)$$

3.7 Conclusions

This chapter has described the methods adopted to achieve the study objectives, the types of primary and secondary data collected, and the analysis and calculations conducted. The findings of the "Saudi Survey" targeting potential EV users, named "Results_1", were used to assess the barriers to EV adoption in KSA (See Chapter 4) and used to create the parking time profile for the RETSCreen simulations described in Chapters 6 and 7. The results from the focus group, Results_2, were used to inform the selection of the case study site and to evaluate the probability of EV adoption in the Kingdom.

Figure 3.4 shows the overall research methodology of this study, showing how the primary and secondary data informed the final research outcomes.



Figure 3.4 The overall research methodology.

Chapter 4
Identification of Potential Barriers to Electric Vehicle Adoption in Saudi Arabia

4.1 Introduction

Although the widespread adoption of EVs will depend on the extent to which they meet consumers' economic, social, and environmental needs, end-users' perceptions of EVs remain largely unexplored [229]. Although KSA has ambitious plans to promote EV usage (Vision 2030), EVs are not yet available for purchase in the country, and research exploring Saudi consumers' attitudes towards them and the challenges to their adoption is scant. This chapter reports the findings of an e-survey, the "Saudi Survey", which targeted potential EV end-users' in Saudi Arabia, with the aim of identifying the key barriers to their widespread adoption in KSA. It begins by describing the demographic data of the participants, then presents both quantitative and qualitative analysis of the research data. A framework to classify the barriers identified as either technical, social, financial, infrastructure or policy-related is then proposed, and an assessment of the long-term cost of EV ownership is made. The barriers identified in each category are then discussed in relation to the literature and possible solutions within the Saudi context are suggested.

4.2 Analysis of the Questionnaire Data

This section begins by proving the demographic data of the participants, then presents quantitative and qualitative analysis of their responses. A framework of barriers, which ranks them in order of importance, is then created by combining the quantitative and qualitative data. As costs was identified as a major concern for consumers in the literature, the section concludes by calculating the long-term cost of EV ownership in KSA over 10 years. A copy of the Saudi survey is available in Appendix A.

4.2.1 Demographic Data of the Participants

There were 698 valid responses to the questionnaire. Most respondents were Saudi citizens (around 96%) and around 85% of them were men. This gender difference was anticipated, since women have only recently been permitted to drive in KSA [230]. A

majority (around 60%) were from the Central Region of KSA (including the capital, Riyadh), with around 20% from the Western Region (which includes the major cities of Jeddah, Makkah, and Medina). Most were aged 30–50 (more than two-thirds), followed by 18 to 29 years old (around 18%). Just over half (around 51%) had an undergraduate degree, while 22% had higher degrees (e.g., master's or doctorate). Only 1% of participants did not have a high school diploma. The major demographic data are provided in Table 4.1.

Table 4.1 Demographic data on survey participants.

Variable	Classification	No.
Nationality	Saudi	669
	Non-Saudi	28
Gender	Female	105
	Male	593
Marital status	Single	169
	Married	520
	Others	9
Region	Northern	18
	Southern	52
	Eastern	68
	Central	419
	Western	140
Age	18-29	123
	30-39	260
	40-49	222
	Above 50	93
Education level	Below high school	7
	High school	103
	Diploma	68
	Bachelor's degree	359
	Higher degree	159
	Other	1

4.2.2 Quantitative Findings of Potential EV User's Perceptions

This section reports participants' responses relating to current vehicle usage (vehicle ownership and daily distance travelled), and the calculations made to assess the cost effectiveness of EVs for them, based on distance travelled. As the desire to reduce CO2 emissions is a key driver of EV adoption for the Saudi government, the tailgate CO2 emissions are also calculated. It goes on to report participants' preferences in

terms of EV price and battery range and their willingness to use V2G if it was financially beneficial for them, and whether this is more popular with respondents who own more than one vehicle. The section concludes by providing quantitative analysis of participants' perspectives on the most significant barriers to EV adoption in KSA.

4.2.2.1 Current Vehicle Usage

Almost half of respondents reported owing vehicles with six-cylinder engines, followed by a third with four cylinders, and a fifth with eight. This may reflect the long distances and rough terrain, including vast expanses of desert, in the country. In order to assess daily distance travelled, participants were asked to choose between several mileage segments, with average mileage as the mid-point of the range (See Figure 4.1). 37% of participants selected 26-50km, while 21% travelled less than this. Just over 30% selected 51-100km, with around 3% reporting that they travelled more than 150 km per day.

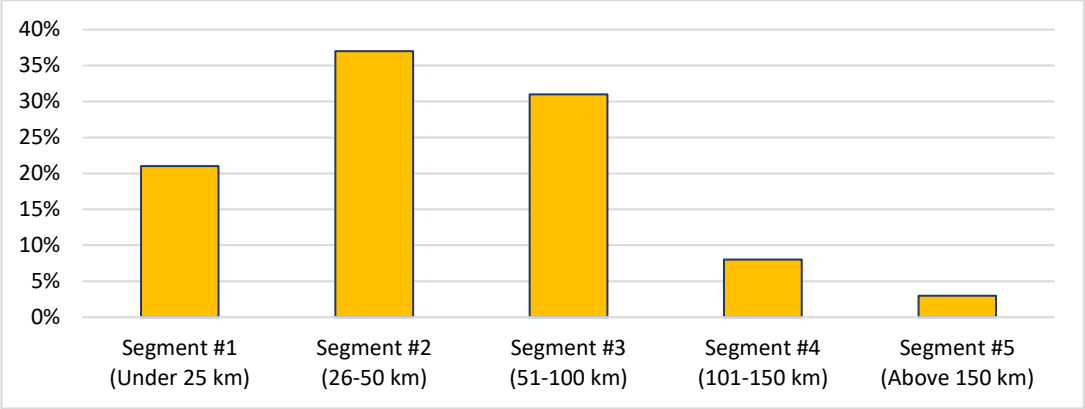


Figure 4.1 Daily mileage of participants.

4.2.2.2 Fuel Consumption Costs (Based on Distance Travelled)

To test whether EVs would be cost effective of in terms fuel consumption for these participants, a calculation of the comparative fuel consumption costs between ICEVs and EVs was made using the mileage ranges shown in Figure 4.1. Three popular Toyota ICEV models (Camry, Land Cruiser Prado, and Land Cruiser VXR) were used to represent ICEVs, because Toyota came top of the 2019 Brand Index for car makers in Saudi Arabia [231], with the Tesla Model 3 used to represent EVs, as it was the best-selling EV around the world in 2020 [232].

Fuel cost per day for ICEVs in eq. (4.1) was measured according to the current petrol price (SAR 2.18/L) and fuel efficiency for the above three Toyota brands as 18.3, 10.1 and 8.2 km/L respectively [213]. The fuel cost per day of EVs in eq. (4.2) was calculated according to the Saudi electricity tariff (0.18 SAR/kWh). The estimated battery capacity of the Tesla Model 3 is 75 kWh, and its consumption is 0.151 kWh/km [233].

$$\text{Fuel cost per day of ICEV} = Average\ km\ per\ day\ (km/day) \times Fuel\ cost\ (SAR/L) \times Fuel\ efficincy\ (km/L) \quad (4.1)$$

$$\text{Fuel cost per day of EV} = EV\ consumption\ (kWh/km) \times Electricity\ tarrif\ (SAR/kWh) \times Average\ km\ per\ day\ (km/day) \quad (4.2)$$

Figure 4.2 compares daily cost of consumption for the four models across all the segments based on the manufacturers' specifications. Among ICEVs, the Camry has the lowest cost in each segment, and this increases with engine size. Thus, in Segment 5, the VXR costs SAR 50 per day to run and the Prado SAR 38.20. However, the Tesla Model 3 is a much cheaper in terms of fuel costs in all segments, at about six, ten, and thirteen times lower than the Camry, Prado, and VXR models respectively.

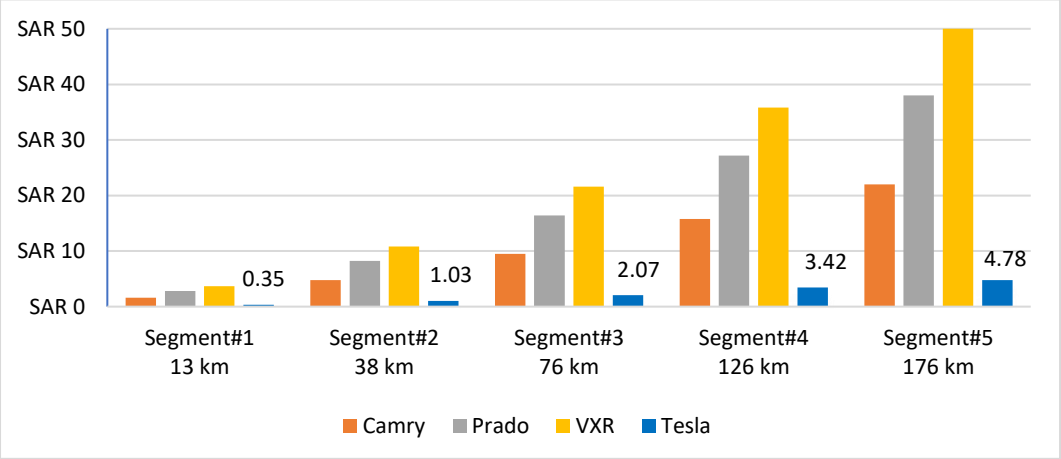


Figure 4.2 Fuel consumption per day of various ICEVs and EV.

4.2.2.3 CO2 Emissions (Based on Distance Travelled)

Eq. (4.3) was used to estimate and compare emissions from EVs and ICEVs. The figure of 2.29 kg/L was based on data from National Resource Canada [234], who estimate the CO_2 tailpipe emissions for petrol vehicles at 2.29 kg/L. As before, the Camry, Prado, and VXR were used as examples.

$$CO_2\ (kg/L) = 2.29 * \left(\frac{\text{Average km per day}}{\text{Fuel efficiency (km/L)}} \right) \quad (4.3)$$

Figure 4.3 indicates that CO_2 tailpipe emissions increase rapidly as driving range and engine size increase, with the highest emissions, at 22.02, 39.90 and 49.15 kg/L for the Camry, Prado, and VXR respectively (Segment 5).

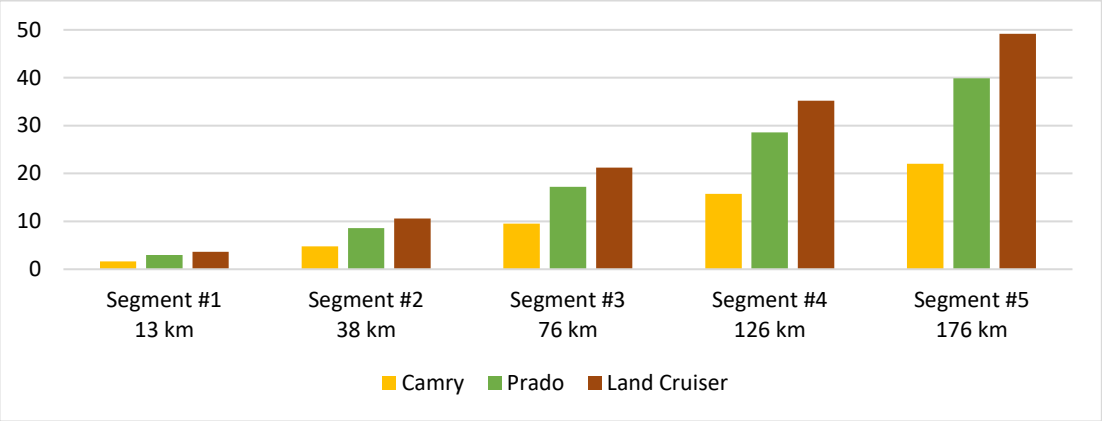


Figure 4.3 CO2 emissions (kg/L).

4.2.2.4 Impact of EV Prices

As purchase price was identified as a key barrier to EV adoption in the literature, respondents were asked about the maximum price they would be willing to pay. Figure 4.4 shows their preferences in terms of EV price and battery range, with the majority (62%) choosing the lowest price band of (SAR 70,000 to 100,000) and just 3% opting for the most advanced battery specifications (SAR 250,000 to 500,000). According to this, the majority of participants choose the lowest price, so boosting EVs sales could be achieved by subsidising the initial price that encourage EV adoption.

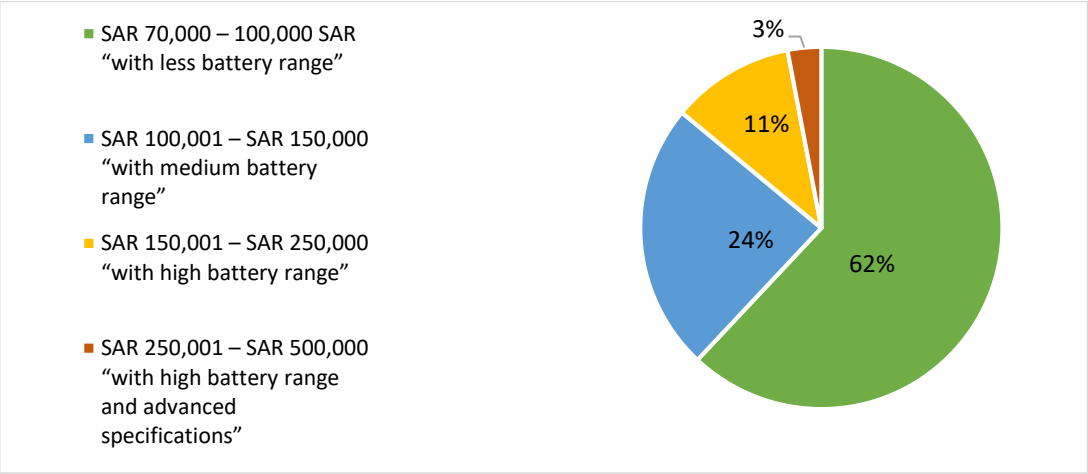


Figure 4.4 Respondents' EV price preferences in terms of battery range.

4.2.2.5 Acceptance of V2G Technology

In order to assess the acceptability of introducing V2G technology to Saudi Arabia, participants were asked if they would be willing to supply their excess electricity to the grid if they gained some economic benefit. The concept of V2G was explained in simple terms in the questionnaire to ensure respondents understood the question.

As Figure 4.5 shows, around 75% of respondents said they would be willing to use V2G technology, while just under a quarter were not. 2.5% of respondents selected the 'Other' option, with some expressing doubts about costs versus financial benefits, technical issues, including reliability and safety in the hot Saudi climate, or the risk that frequent charging and discharging would reduce battery life more quickly, meaning the cost of battery replacement would outweigh the benefit gained. Consequently, this obviously indicates the extent to which users accept this technology's ability to generate revenue and contribute to grid support during peak demand.

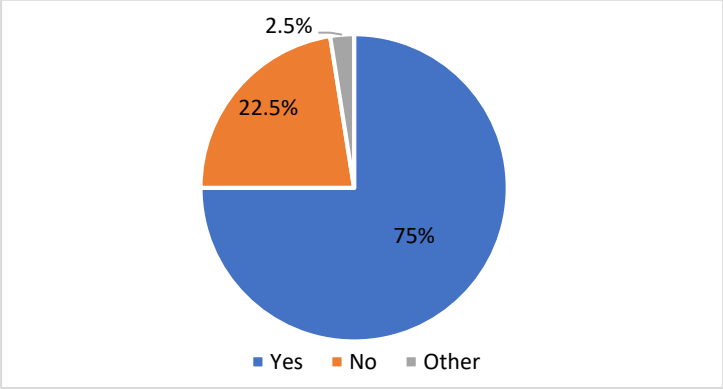


Figure 4.5 Respondent's willingness to use V2G if they derived economic benefit from doing so.

Analysis of responses to this question via ANOVA indicated that respondents who showed greater interest in financial incentives and environmental matters elsewhere in the survey were significantly more positive in their replies regarding V2G.

In order to calculate the potential number of EV's available to feed the grid, respondents were asked about their current level of car ownership. 58% reported owning a single car, 27% owned two, and 15% had three or more. Of those who owned more than one vehicle, many reported choosing to drive 4x4 vehicles in desert areas and small cars in towns, something which is common given KSA's desert terrain.

4.2.2.6 Ranking the Barriers to EV Adoption

Respondents were then asked to rate 10 potential barriers to EV adoption which had identified from the literature in terms of their impact on their purchasing decisions. The resulting EV barriers scale was subjected to descriptive analysis. Table 4.2 ranks the ten barriers in descending order of importance, with verbal interpretations following [235]. The most important barriers according to mean weight was availability of charging stations, with the fact that KSA does not need EVs as it is one of the biggest petroleum-producing countries ranked as least important. Duration of charging, lack of trust in EVs as a new technology, and high maintenance costs all ranked highly, but respondents were less concerned about potential safety issues with rechargeable batteries, and the costs associated with purchasing and charging an EV. An interesting concern in the Saudi context is that there is no need for EVs as KSA is one of the world's largest petroleum producers; this concern could result from a lack of knowledge about EVs in general, their environmental benefits, and KSA's GHG emission reduction goals [8].

Table 4.2 Mean ranking of barriers.

Item	Barrier	Mean ranking
Q10	Availability of charging stations	3.85
Q18	Duration of charging	3.74
Q14	Lack of trust in EVs as new technology	3.36
Q15	High maintenance costs	3.22
Q16	Limited driving range,	3.16
Q20	Terrain and weather conditions in KSA are not suitable for EVs	3.04
Q12	Costs involved in charging	2.84
Q13	Purchase an EV is more expensive than an ICEV	2.79
Q17	Safety concerns about rechargeable battery	2.71
Q11	No need to use EVs as KSA is one of the biggest petroleum-producing countries	2.32

The independent-samples t-test comparing all barriers by gender found a statistically significant gender difference for terrain and weather conditions only ($p=0.003$), with males ($M=2.98$, $SD=1.094$) being more concerned about these barriers than females ($M=2.90$, $SD=1.000$). This may indicate that men are more likely to spend time in desert areas, for example, in off-road driving; however, it is also possible that they

have more experience in terms of a vehicle performance in desert terrain, and also in the summer heat, since women have only recently been permitted to drive in KSA [200]. In addition, the independent-samples t-test revealed a statistically significant difference in willingness to use V2G (Q9) in relation to the limited driving range barrier (Q16) (p=0.000), with respondents who said they were not willing to use V2G (M=3.42, SD=1.195) more concerned about these barriers than those who were (M=3.08, SD=1.120). This suggests that these respondents are less interested in the financial benefits of V2G than in ensuring that the EV has sufficient range to cover their everyday journeys.

ANOVA applied to the means among age groups revealed a statistically significant difference (p=.004) regarding the availability of charging stations (Q10), with younger participants seeing them as more significant: 18–29 (M=4.07, SD=1.129), 30–39 (M=3.93, SD=1.204), 40–49 (M=3.79, SD=1.251), over 50 (M=3.49, SD= 1.230). This suggests that younger people have a larger driving range or may be more likely to make unexpected trips than older ones. ANOVA applied to the means among the five daily distance travelled segments also revealed a statistically significant difference (p=.000) between the segment groups in relation to EVs limited driving ranges, with the largest segment (over 150 km), considering this to be most significant: Segment#1 (under 25 km) (M=3.10, SD=1.121), Segment#2 (26-50 km) (M=3.22, SD=1.167), Segment#3 (51-100 km) (M=3.59, SD=1.186), Segment#4 (101-150 km) (M=4.04, SD=1.188), and Segment#5 (over 150 km) (M=4.22, SD=1.121). Thus, as anticipated, the issue of limited range is of more concern to those who travel the greatest distances.

ANOVA was also applied to investigate the relationship between respondents' demographic data and their attitudes towards two local barriers: weather and terrain and KSA's position as a major oil-producer meaning that there was no need for EVs. As was anticipated, participants in the Eastern and Western regions, which have very hot summers, rated weather and terrain most highly (M=3.26, SD=1.205), (M=3.11, SD=1.367) respectively, followed by those in Northern and Central regions (M=3.06, SD=1.145), (M=3.00, SD=1.096) respectively. Those in the Southern region, which is mountainous and relatively cool, were least concerned (M=2.98, SD=1.291). With regards to KSA's position as a leading oil-producer, those with the highest annual incomes were most concerned about this (M=2.85, SD=1.307), with concerns

decreasing as annual income decreased. This suggests that lower-income families did not regard this as a barrier and would support the use of EVs, regardless of the country's ability to continue fuelling ICEVs.

ANOVA also revealed a positive relationship between concerns about duration of charging and the number of cars owned. Participants with one car (M=3.82, SD=1.086), two cars (M=3.66, SD=1.071), and three or more cars (M=3.62, SD=1.058) differed significantly (p=.003) in their answers. As was expected, there is less concern about charging times among participants who have more than one car, as they can switch to another vehicle while charging is in progress.

4.2.3 Qualitative Findings of EV User's Perceptions

Thematic analysis was applied to the qualitative data generated by the questionnaire.

4.2.3.1 Ranking the Barriers to EV Adoption (Thematic Analysis)

Thematic analysis was applied to the comments provided by participants in response to the barrier ranking question, with respondents identified by an alphanumeric code. The barriers were ranked in terms of the frequency with which they were mentioned, with 'reliability' mentioned most and 'insurance price' least (See Table 4.3).

Table 4.3 Thematic analysis of the barriers to EV adoption.

Themes	Freq.	%	Example of comments
Reliability	21	12.3	"EV problems are more than its benefits" - P311
Lack of repair and maintenance workshops	19	10.3	"Difficulty of maintenance and unqualified labour" – P85
Lack of knowledge of EVs	18	9.6	"Society needs to change its perceptions about EVs" – P646
Weather conditions and terrains	18	9.6	"EVs are not suitable with KSA weather, which is too hot in the summer season- P311
Safety	16	8.2	"How to deal with EVs accidents and its battery fire?" – P486
Absence of awareness raising about EVs	15	7.8	"Education in the schools and universities about EVs and covering all the progress, including the positive and negative aspects" – P203
Lack of charging stations, (public and private)	14	7.1	"EVs charging stations must be completed before launch it" – P554
Higher purchase price	13	6.4	"The prices of EVs are so expensive and exaggerated" – P148
Lack of trust that EVs can be used in the desert	10	5.5	"Trust of EVs for use it in desert and endurance like conventional cars" – P622
Put more load on the electricity grid	9	4.7	"Using EVs will cause electricity shortage especially in the summer when the electricity is highly demand because air conditioning" – P293
Battery replacement cost	9	4.7	"Replacement batteries are costly and will increase the running costs" – P714

Limited range	8	3.2	"Driving range is still too short in EVs for a big country like KSA" – P966
Limited battery life	7	2.5	"High temperature will affect the batteries' life and quality" – P986
Lack of environmental sustainability	7	2.5	"EVs are not environmentally friendly, especially batteries part" – P210
Higher electricity price for charging	6	2	"EVs are high consumers of electricity and electricity is already expensive" – P94
Duration of charging	4	1.7	"It is charging very slowly, so what can I do when I have an emergency trip?" – P972
Deploying EVs will badly affect the country's economy	3	1	"The spread of EVs will cause decreasing export of crude oil and that will strongly affect the Saudi economy" – P285
Lower resale price	2	0.7	"The resale price of EVs does not encourage consumers" - P132
Insurance price	1	0.2	"Because of the high prices of batteries, EV insurance will be very expensive" – P750

Concerns about the reliability of EVs are significant, especially in the context of KSA's hot climate and desert terrain. Issues relating to safety and access to qualified and affordable maintenance care are also prominent. The lack of concern about insurance costs may reflect the fact that ICEVs insurance costs in KSA are relatively low at around $280 per year [211]. Concerns about the adoption of EVs affecting the economy shows a novel concern among Saudi drivers, which may also be reflected in other oil-producing states.

4.2.4 Creating a Combined Barriers Framework

The approach adopted by Adhikari and Ghimire [236] used a hierarchical tree that was formulated after considering a total of 19 barriers to integrate quantitative and qualitative results into a single framework. This comprises five linked categories: infrastructure, performance, financial, social, and policy, with the barriers in each category ranked in order of importance according to the frequency with which they were mentioned across both sets of results. The green-coloured barriers include those originally identified by Adhikari and Ghimire [236], while those in yellow have emerged from this study and relate to the Saudi context (See Figure 4.6).

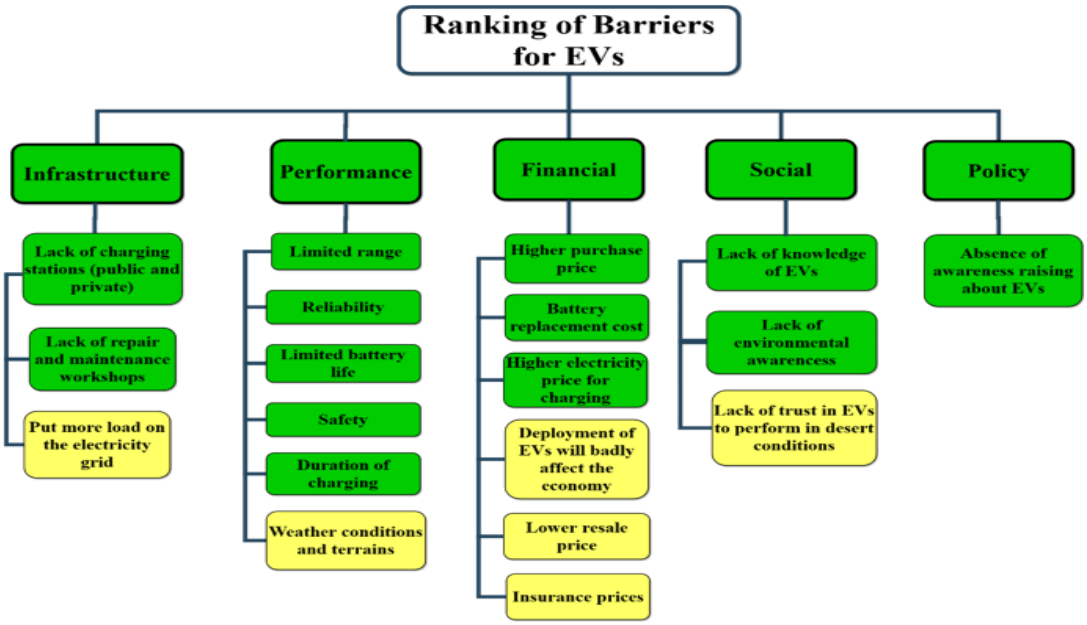


Figure 4.6 Thematic framework

4.2.5 Assessing the Cost of Long-Term EV Ownership

As a number of financial barriers were identified in Figure 4.6, an estimate of the relative costs of EV and ICEV ownership over a 10-year period was made following [237] methodology. As before, the Tesla Model 3 EVs was used to represent EVs and the Toyota Camry, Prado, and VXR for ICEVs. The calculations are based on eq. (3.1), and the results are presented in Figure 4.7.

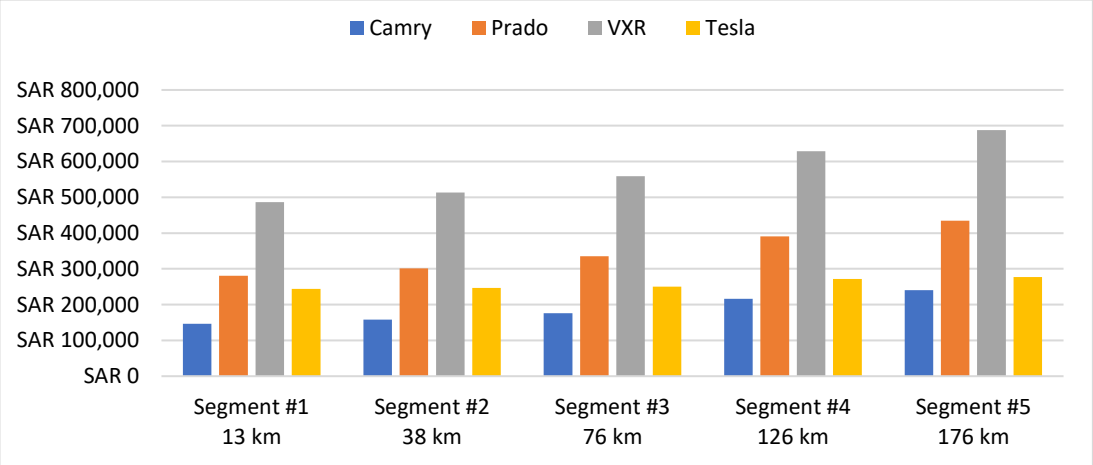


Figure 4.7 Cost of ownership of EVs and ICEVs over a 10-year period.

As the table shows, the Tesla costs less than the VXR and the Prado, indicating that, in the long run, owning an EV is cheaper than a high-end ICEV. However, across all segments, the long-term costs of the Camry is much lower than the Tesla Model 3. Thus, in Segment 1, the Camry is up to 40% cheaper than the Tesla and it is 13%

cheaper in Segment 5. This supports the findings of Weldon and Morrissey [216] who found that EVs were more affordable for those with higher than average annual driving distances. However, the introduction of subsidies, such as those in the Netherlands, France, and the UK, could make the total cost of EV ownership comparable to that of ICEVs [238], so policymakers should explore the viability of grants and incentives to promote EV adoption in KSA.

4.3 Discussion of the Findings

The major barriers to EV adoption among potential users in KSA identified in Figure 4.6 are discussed below in relation to the Saudi context and the literature review.

4.3.1 EVs Infrastructure Indicator

Infrastructure is an essential prerequisite for the adoption of EVs, and the significant demand among respondents for both urban and rural charging stations is consistent with the existing literature. However, concerns about the additional load on the grid are particularly pertinent in Saudi Arabia, where demand for air conditioning places significant strains on the existing energy supply. The top ranking of charging stations also reflects local concerns that EVs may not be viable in a large country with vast desert areas, and anxieties over limited range, long charging times, and the need to replace petrol stations with a charging network [239]. Palomino & Parvania [240] identify the development of an extensive charging network as a significant early step in accelerating EV adoption, and, in the case of KSA, this should also include rapid chargers for drivers who travel more than 100 km per day. However, clear policy is also required to identify where the responsibility for developing infrastructure rests, since EV manufacturers typically expect government agencies to develop infrastructure, while governments believe the industry should also play a part [142]. Thus, collaboration across both the private and public sector is required, with encouragement for the private sector in the form of competitive investments and grants.

Concerns regarding maintenance are unsurprising given that EV adoption is still at an early stage in KSA, and these are likely to reduce over time. However, the demand EVs place on the grid is likely to pose a significant barrier in the longer term, and stakeholders must find alternative ways to mitigate the risk of grid overloading, such

as managing charging times, and implementing effective policies and strategies. As connecting EVs to the power grid may result in higher short-circuit currents, voltage fluctuation, demand surges, and reduced equipment lifespan [241], the national grid infrastructure must also be upgraded in order to meet this new demand [242]. In addition, in order to avoid increasing GHG emissions, policy makers must consider energy generation and renewable energy usage when developing infrastructure to support EVs. In this regard, it is significant to note that potential EV users in KSA identified the need to deploy renewable sources of electricity as a significant positive influence on their willingness to adopt EVs [123]. Resource diversification in this way would be sensible for both load profile and for EV users in the country.

4.3.2 EVs Performance Indicator

Participants rated performance factors (range, reliability, battery lifespan, charging duration, safety, and weather conditions and terrains) as particularly important, with significant concerns expressed about the reliability of EVs in the country's extreme conditions. EV manufacturers and lawmakers must take these concerns into account if EVs are to be widely adopted and ensure that they are durable, cost-effective and easy to maintenance and repair [137]. Concerns over limited ranges and long charging times are recognised as the greatest barriers to consumer acceptance of EVs in the passenger vehicle market [243], and anxiety about the safety and reliability of EV components is also a significant barrier [244,245]. However, the climate in KSA raises concerns about the exposure of Li-ion batteries to high temperatures and the potential risk of fire. Although effective insulation means the risk of an electrical shock from a vehicle is very low [246], concerns about the effectiveness of EVs across the various terrains and hot weather conditions in KSA persist. As US tests in the Arizona desert found that driving ranges could fall by 29% when temperatures reached 41 °C [247], extensive testing in desert conditions should be conducted by battery and EV manufacturers, notably Lucid Motors and Ceer Motors, to reassure consumers that EVs are a viable option in the Kingdom.

4.3.3 Financial Indicator

The most significant barrier in the financial category is the high purchase price of EVs; however, lower running costs (e.g., fuel and maintenance) make the total cost of EV

ownership more competitive, especially by comparison with high-end ICEVs over longer distances (See Figure 4.7). The cost of the battery forms a major part of the purchase price, and these are expected to decline significantly as batteries become cheaper [83]. Concerns about the higher cost of electricity in KSA may reflect the fact that electricity subsidies have recently been cut (increasing bills by +260%) rather than actual costs, as it is still much cheaper to charge an EV than to fill an ICEV with petrol [42]. Concerns about maintenance costs are more firmly grounded though, reflecting the fact that leading brands, such as Mercedes and BMW, are particularly expensive to maintain in KSA.

Both the qualitative and quantitative data reflects consumer concerns about the possible impact of EV adoption on the Saudi economy, which is built on oil production. This is a novel concern in the context of EVs; however, evidence from the suggests these fears may be misplaced. Energy demand for transportation is anticipated to treble by 2030 [35]; therefore, EVs are unlikely to decrease oil production but rather help to meet rising energy demand. EVs also require oil as raw materials and for their manufacture, and it is difficult to predict when this might change. Finally, deploying EVs at a rate that is manageable in terms of energy consumption would mean more Saudi oil could be sold on the international market, thereby helping the country's economy rather than damaging it.

The last two financial barriers are the lower resale and insurance prices. Multiple factors, including mileage, modification, brand and model, condition, and cost of maintenance can impact the resale value of a vehicle, but the cost of battery replacement means EVs tend to lose value more quickly than ICEVs [248]. In addition, in the early stages of EV adoption, resale values are unclear, making users more uncertain about this [137,249]. By contrast, although participants may believe that the high cost of EV batteries will affect the insurance prices, research suggests that, on average, EV insurance is about $200 less per year than for a similar ICEV [250].

4.3.4 Social Indicator

The social dimension is often ignored when sociotechnical systems, such as EVs, are designed [251], yet these findings suggest this is a significant barrier in the Saudi context. The qualitative data indicates that the lack of consumer awareness about the benefits of EVs may impact purchasing decisions, and this is supported in the literature

[252]. The limited number of EVs in KSA may explain why users have limited practical knowledge about them, but this is compounded by a lack of awareness of their environmental benefits too. The fact that participants recognise environmental sustainability as a factor in relation to EVs indicates that consumers in KSA are becoming more environmentally aware; however, despite this, they placed relatively little importance on environmental issues in relation to EVs. This suggests that Saudi consumers may also be poorly informed about the advantages of EVs, including their potential to reduce GHG emissions, and EV manufacturers in the Saudi market need to enhance their marketing and educational efforts in order to achieve market penetration. Given the finding that older respondents in this study were more environmentally aware, efforts regarding the environmental advantages of green transport should be directed at younger drivers in particular.

4.3.5 Policy

Policy on tax and infrastructure are seen as key factors in the promotion of EV adoption, alongside financial support for EV purchases and R&D projects [253]. However, the findings of this chapter suggest that a broader range of policy instruments, based on specific public policy goals, will be required. For example, awareness-raising on environmental challenges should be introduced from an early age through the government's education policy, and greater investment in public transportation, both within and between cities, would reduce the number of car journeys taken. In addition, while EVs are generally regarded as environmentally friendly, with a lower carbon footprint than other vehicle types, thought must be given to the source of the energy which powers them before they can be considered truly green [255].

The latter issue is of particular interest in the context of this study. The qualitative data show that consumers are aware of the need for alternative energy resources to be utilized to avoid overloading the grid, and, if renewable sources, notably solar energy, were utilized, V2G technology could help to ease fluctuations and peak load shaving. However, concerns about V2G technology, including fears about potential reductions in battery life, should also be examined and addressed. In addition, financial incentives, infrastructure availability, and possible fuel-related savings are anticipated

to be crucial factors in influencing consumer behaviour towards EVs [142], all areas in which the government can play a significant role.

4.4 Conclusions

With the recent deal with Lucid Motors and the first Saudi EV manufacturer "Ceer", the Saudi government is taking a major steps to promote EV use in the country; however, significant barriers to their widespread adoption still need to be overcome. This chapter has examined public perceptions of EVs in the Kingdom, identified the barriers to their adoption, and created a framework which ranks them in order of their importance to potential users. While many of these barriers are applicable internationally, others are particularly significant within Saudi Arabia. Indeed, the extreme climate in KSA and the varied terrain, give rise to a number of barriers, including concerns about the safety and effectiveness of batteries at high temperatures, and doubts about the overall ability of EVs to perform effectively in desert conditions. Manufacturers would be advised to take steps to address these concerns if they wish to achieve market penetration in Saudi Arabia and in other countries in the region.

Greater awareness raising campaigns by both manufacturers and governments are also required as the study suggests that the public do not yet fully appreciate the economic and environmental benefits of EVs, with misplaced concerns about charging costs and possible damage to the Saudi economy continuing to persist. By contrast, evidence suggests that the widespread adoption of EVs could benefit the economy, especially if they are powered by renewable sources of electricity, making MUS and HUS more probable scenarios compared to LUS. Such a switch would also enhance EVs environmental credentials and reduce some of the pressures on the grid. The use of V2G technology would help with this, but it would require both advances in charging technology and the provision of enough charging points to allow consumers to exchange energy freely with the grid.

Removing the barriers to EV adoption in Saudi Arabia would boost EV sales and have a significant impact on the cost-effectiveness of the model to power EVs using solar PV. Since the correct identification of these barriers is so important, the findings from this chapter were validated by conducting a focus group discussion with actual EV users in Saudi Arabia. The findings of this focus group are presented and discussed in the next chapter.

Chapter 5
Challenges and Concerns in Developing Confidence among Electric Vehicle (EV) Users in Saudi Arabia

5.1 Introduction

This chapter investigates the technical and regulatory challenges experienced by current EV users in Saudi Arabia to identify which of the potential barriers identified in the previous chapter are most significant in practice. It draws on data from a focus group discussion conducted as part of an e-workshop on EVs organised by SASO and a questionnaire which was circulated during the focus group. In particular, it explores the suitability of available EVs for the Saudi market, in terms of brand, battery capacity, and users' daily mileage, and examines other issues reported by current Saudi users in order to determine the actual barriers to EV adoption in the Kingdom.

5.2 Findings from the SASO Workshop

The findings from the focus group and the questionnaire are presented in two separate sections below. Demographic data for the focus group participants are presented, followed by qualitative data relating to their EV usage and daily mileage and their experience of battery power and driving range. Three key themes emerged from qualitative analysis of the questionnaire results (Infrastructure, Battery, and Policy), so the findings from the questionnaire are presented thematically.

5.2.1 Focus Group Results

5.2.1.1 Demographic Information

Questions were asked to obtain demographic data on the participants and to identify differences among them. Table 5.1 includes the most important demographic data. 96% of respondents were male, but this was to be expected as women have only been allowed to drive legally in KSA since June 2018 [230]. 70% of respondents lived in the Central region (which includes the capital, Riyadh), and there were no EV drivers from the Southern or the Northern regions. Almost half of the sample (45%) held post

graduate degrees (masters or doctorate), showing the technical maturity of the participants.

Table 5.1 Demographic data of the workshop participants

Variable	Classification	%	Variable	Classification	%
Gender	Female	4%	***Age***	18-29	7%
				30-39	56%
	Male	96%		40-49	26%
				Above 50	11%
Education level	High School	7%	***Residency***	Central Region	70%
	BSc	48%		Western Region	19%
				Southern Region	0
	Postgraduate	45%		Eastern Region	11%
				Northern Region	0

5.2.1.2 EV Usage and Daily Mileage

Participants were asked about their pattern of usage of their EVs. The fact that 93% of respondents used their EVs daily suggests that they trust their EVs; however, concerns about the availability of charging stations on long trips deterred the remaining 7% from using their EVs as frequently. Participants were also asked if they were ready to switch to EVs completely, discarding their current ICEVs. 15% of respondents reported that they already drove EVs exclusively, 30% were ready switch, and 22% thought this would be possible at some stage (See Figure 5.1). Overall, this indicates an acceptable level of confidence among actual EV users in KSA, despite the barriers identified in Chapter 4.

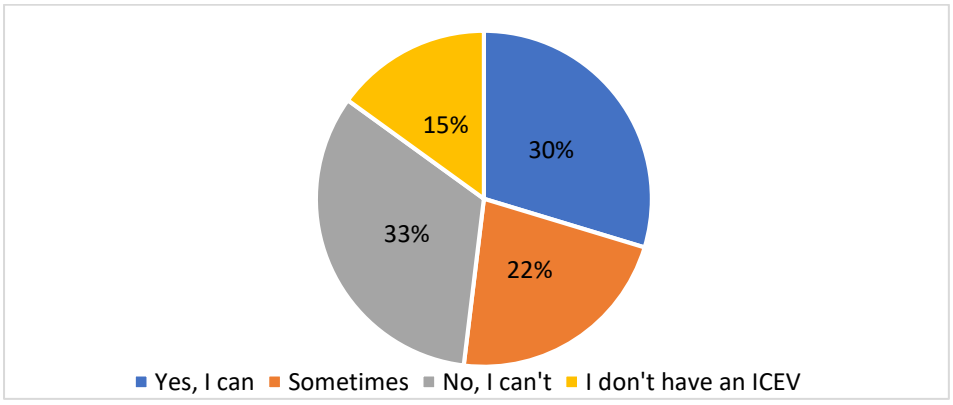


Figure 5.1 Participants' willingness to abandon their ICEVs and own only EVs.

In terms of daily mileage, 59% of participants use their EVs to travel 51 km – 100 km per day, with 30% travelling between 5 km – 50 km. Just over 10% use their EVs to travel more than 100 km per day (See Figure 5.2). Lack of EV infrastructure, notably charging stations on the major roads, might be a contributing factor here.

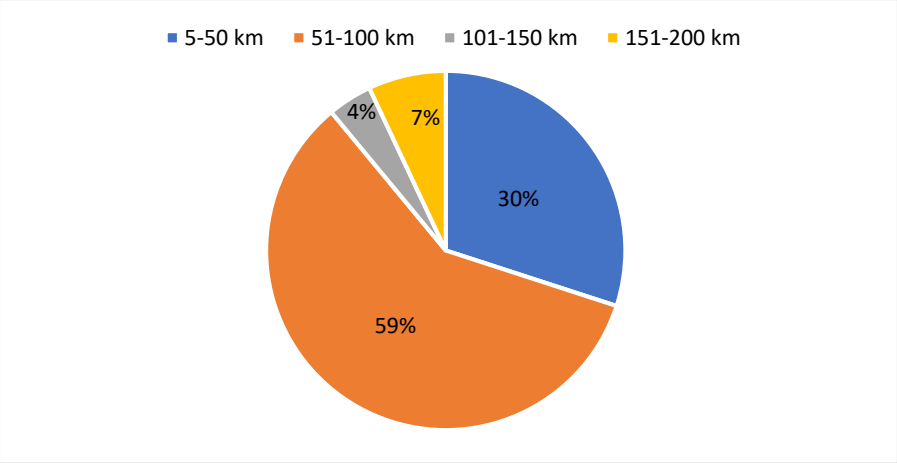


Figure 5.2 Daily mileage of participants.

Analysis revealed that women typically drive shorter distances than men, with 98% of women travelling from 5 km to 50 km per day, and just 2% travel 51 km – 100 km. The independent-samples t-test comparing whether participants were willing to give up their ICEVs revealed a statistically significant gender difference (p=0.001), with females (M=3.12, SD=1.072) being more willing than men (M=2.94, SD=1.006). This suggests that women are more likely to be able to cover their daily mileage despite the lack of infrastructure. In addition, younger participants were more reluctant to give up their ICEVs completely: 18–29 (M=4.02, SD=1.113), 30–39 (M=3.97, SD=1.201), 40–49 (M=3.84, SD=1.266), and 50+ (M=3.57, SD= 1.270). This may reflect a lack of environmental concerns, but it may also indicate that younger people have a greater driving range or are more likely to make last minute trips, this require public charging.

5.2.1.3 Battery and Driving Range

Participants were asked if they noticed a reduction in driving range when using the A/C in their EVs. As shown in Figure 5.3, 81% said they had noticed a decrease. This is a significant challenge as A/C is a necessity in a hot country like KSA. Participants also noticed an impact of A/C on battery efficiency, with 59% reporting losing 20% – 25% of their battery charge, and 34% reporting losses of 30% – 35%. Around 7% of participants reported losing 40% – 45% of the battery while using A/C.

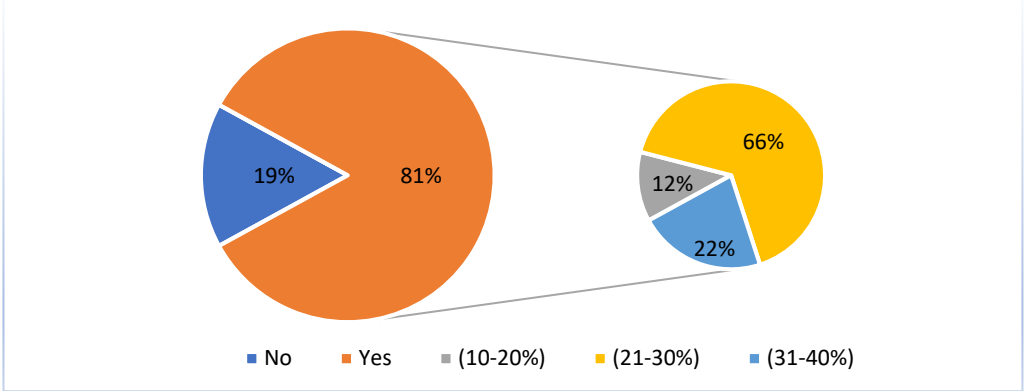


Figure 5.3 Percentage of participants who noticed a decrease in battery levels while using A/C and the approximate percentage levels lost.

ANOVA indicated a correlation between respondents who were not prepared to give up their ICEVs (i.e. selected "I cannot") and the decrease in battery levels while using A/C. The responses of participants with battery loss ranging from 31-40% (M=4.19, SD=1.203), 21-30% (M=3.89, SD=1.110), and 10-20% (M=3.73, SD=1.074) differed significantly (p=0.002), with those least willing to replace their ICEVs having the greatest concern over this barrier. This suggests that the impact of A/C on battery performance is a major barrier to the widespread adoption of EVs in KSA.

Although most participants (88%) did not report any other battery-related issues in their EVs, 12% said that their batteries heated up during hot weather, posing a further challenge to their safety and efficacy. In addition, 70% indicated that their EV battery did not provide the mileage advertised by the manufacturer, with just 12% reporting receiving the mileages on their batteries (See Figure 5.4).

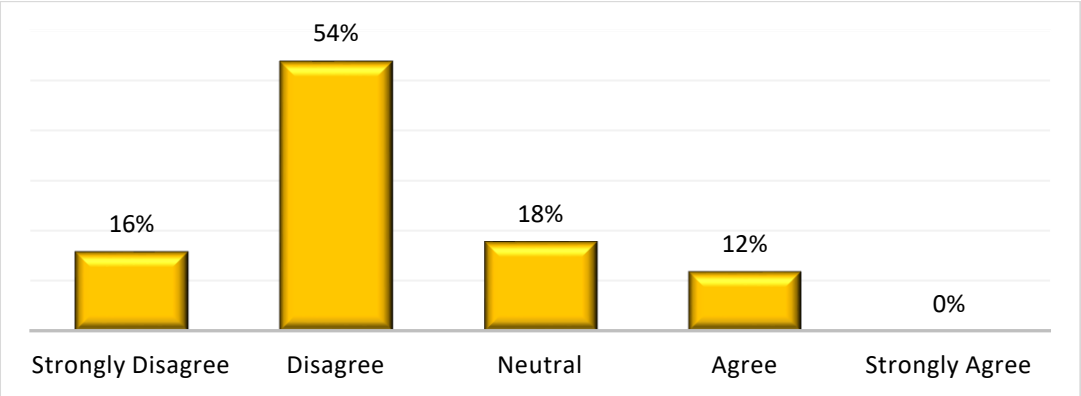


Figure 5.4 Do you get the manufacturer advertised mileage from your EV batteries?

It is interesting to note that when ANOVA was applied to the responses to this question, participants with postgraduate degrees were more likely to "Strongly disagree" than those with lesser qualifications. This may indicate a heightened

awareness or interest in the specifications and mileage range advertised by EV manufacturers.

Overall, the results obtained from the focus group suggest that, approximately, one in three participants is willing to abandon ICEVs and own only EVs. Another important finding is that a vast majority of the participants (nine in ten) use their EVs to travel up to 100 km per day using their EVs. Air conditioning has a negative impact on the EV battery as four in five participants noticed a decrease in EV battery levels when air-conditioning was switched on. Finally, the results suggest that manufacturers' advertised battery mileage is generally not achievable as seven in ten participants either disagreed or strongly disagreed when asked if they experienced manufacturer-advertised mileage from their EV batteries.

5.2.2 Questionnaires Results

Content analyses of the focus group discussion revealed three main themes, each with two subthemes, as follows:

Theme 1: Infrastructure

Subtheme 1.1: Lack of charging

Subtheme 1.2: Lack of maintenance centres

Theme 2: Battery

Subtheme 2.1: Efficiency of Battery

Subtheme 2.2: Battery Life cycle

Theme 3: Policy

Subtheme 3.1: Importing regulations

Subtheme 3.2: Differences in KSA Voltage

These themes were then used to examine the responses to the questionnaire which was circulated electronically during the focus group. The participants were invited to discuss their responses, and these were recorded verbatim and then translated into English. The following section reports their views on the main themes and sub-themes identified above.

5.2.2.1 Theme 1 - Infrastructure

As was expected, EV users suffer from a lack of EV infrastructure, as the Kingdom has not yet completed the infrastructure network, which includes charging stations within and outside cities, maintenance centres, and EV dealerships.

Subtheme 2.1- Lack of charging

The group expressed concern about the way the lack of charging infrastructure restricts their EV usage because they are obliged to return home to recharge their vehicles. For example, participant P21 said: *"I cannot travel far from my house because there is no infrastructure."* Similarly, participant P08 said: *"I must ensure that my vehicle's battery is fully charged before leaving home in order to meet my daily obligations".* Some participants also reported changing their driving behaviour in order to ensure one charge would cover their trip. For example, participant P11 said: "*My car's driving range is 500-550 km, but when I travel from Riyadh to Dammam, which is around 450 km, I cannot exceed 90 km/h to ensure the battery covers the distance."*

Subtheme 2.2 - Lack of maintenance centres

The absence of maintenance facilities in KSA is also an issue, obliging users to turn to other countries and incur additional costs. For example, participant P18 said: "*If my car requires maintenance, I should ship it to Dubai, as it is the closest location with service centres, which costs me a lot of money."* Software repairs can also be costly. For instance, participant P6 stated: *"I had a configuration issue that required configuration at Tesla. However, because there is no Tesla agent in KSA, unfortunately, I shipped it [my EV] to Dubai to be fixed, which cost me around SAR 6500 (~ £1300) for shipping from Jeddah to Dubai".*

5.2.2.2 Theme 2 - Battery

Subtheme 2.1 - Efficiency of battery

The negative impact of A/C on the driving range of many users EVs means some avoid using them in the summer. For example, participant P22 said: *"I rarely use my EV in summer because using air conditioning will take most of the battery capacity, which means it needs to be recharged [more often] if I use it a bit far from home."*

Subtheme 2.2 - Battery life cycle

EV users also mentioned that the life cycle of the battery reduced with time. For example, participant P24 said: *"The life cycle of my EV decreased when my car completed around 30,000 Km - the battery efficiency decreased."*

5.2.2.3 Theme 3 - Policy

In addition to the technical challenges, users also reported facing regulatory challenges, particularly in respect of importing EVs into the country, both in terms of the import process and the need for adaptors to manage differences in voltage.

Subtheme 3.1 - Importing regulations

The import process is administered by government agencies such as SASO and the Customs Authority, and some users felt that the process should be simplified and made more user-friendly. For example, participant P6 said: *"Cooperation with other government sectors to facilitate importing of EVs and make it easier for drivers".* Also, participant P19 mentioned: "*Adopting the best practice of advanced countries regarding EVs regulations, including the requirements for importing EVs, [these] need to be easier than now."*

Subtheme 3.2 - Differences in voltage

Saudi Arabia is among 9% of countries that use dual-distribution voltage (127/220 volts) in homes, where standard voltage 127 volts is used for some appliances (lighting fixtures, refrigerators, and televisions) and 220 volts for higher-load appliances (air conditioners, elevators, pumps) [256]. Imported vehicles do not usually use the same voltage, so a voltage converter is required, especially as most EV users charge at home. Participant P15 stated: "*I've a problem with the dual-distribution voltage 127/220 volts in my home, so when you export EV you should make sure that it will not be charging with the old system, otherwise you will have to pay for an adaptor."*

5.3 Discussion of the Findings

The data obtained from the focus group of Saudi EV drivers identified the following issues:

Infrastructure: The participants ranked the absence of charging stations inside cities and on highways as the most significant challenge, possibly because over 70% travel more than 50 km per day. Lack of related infrastructure, such as repair centres and sales agents, also presents challenges. This supports the findings of Chapter 4, which found that potential Saudi EV drivers considered the lack of charging stations and maintenance centres to be the most important barriers.

Performance: The data revealed evidence of performance issue, with over 80% of participants reporting a decline in battery efficiency, especially due to air-conditioning use in the summer season. About 60% of the EVs are losing up to a quarter of the battery energy, while 7% are losing up to 50% of the battery capacity. These reported percentages exceed those in other studies which have explored EV driving range and life cycle in hot locations, for example, the 29% drop [274] experienced in the Arizona desert. As 70% of participants considered that the mileage advertised by manufacturers was not practically achievable in KSA, intensive testing of EV batteries under desert conditions should be undertaken to ensure batteries can function effectively in such extreme weather conditions.

Policy: The results also highlighted consumer concerns about policies, including complex processes to import EVs and the differences in voltage requirements. The former has cost implications while the later raises safety issues alongside the cost of adapters. Policies are required to address these issues and also to improve awareness by providing accurate information on related matters, including safety standards, guides for using and charging EVs, how to import them from abroad, how to perform maintenance in the absence of local repair centres, how to avoid the dangers of accidents, as well as guidance for firefighting personnel and others who may have to deal with incidents involving EVs.

The previous chapter found that barriers to EV adoption in KSA were mainly related to infrastructure, performance, financial, social, or policy issues. The thematic results obtained in this chapter point at similar issues. However, despite these challenges, the findings suggest that the adoption of EVs in KSA would be welcomed, as about 30% of the participants in this study had already given up ICEVs in favour of EVs.

5.4 Conclusions

This chapter has examined the challenges reported by current EV users and identified concerns about battery efficiency due to air conditioning load as a key issue. This requires further consideration in a hot country such as KSA. Consumer concern about the lack of infrastructure is also very high. While lack of adequate infrastructure is an issue in many countries, the policy issues raised by participants, notably complex import regulations, are specific to Saudi Arabia and should be addressed as a matter of urgency to facilitate greater use of EVs. Addressing these issues and those identified in Chapter 4, would enhance consumer confidence in EVs and support their adoption in KSA. It is hoped that these findings will assist policymakers, EV manufacturers, and other related stakeholders in taking the measures required to ensure EVs are viable choices for Saudi consumers. Doing so would boost future EV sales in the Kingdom, but that would have significant consequences for the energy grid. As a result, the next chapter evaluates the solar PV requirements for powering EVs in different locations across Saudi Arabia.

Chapter 6
Solar PV Energy Requirements for Powering EVs in Different Locations in Saudi Arabia

6.1 Introduction

Saudi Arabia currently generates almost all its electricity using fossil fuels (61% from natural gas and 39% from crude oil), with renewable energy generation accounting for less than 0.5% of power generation [44]. However, the Saudi government plans to replace some of the oil used for power generation with solar photovoltaics (PV) in order to reduce GHG emissions and to make more oil available for export [257]. Given its hot climate and long hours of sunshine, KSA has excellent potential for solar power projects; however, due to variations in climate and terrain in different parts of the country, such projects may be more economically viable in some regions than in others.

This chapter assesses different locations in Saudi Arabia to determine the solar PV sizing requirements to support the adoption of EVs in the locality. As infrastructure to support these vehicles is also required, including charging stations and maintenance centres, locations with well-established infrastructure and the potential to secure capital for further infrastructure investment were prioritised. As the major cities in KSA currently attract more investment, have larger numbers of potential EV users due to their larger populations, and have better-developed infrastructure, these were targeted for investigation. The evaluation of each city's potential for electricity generation through solar PV was based on assessments of climatic conditions, solar irradiation levels, and the types of solar PV systems available (including fixed-tilt, one-axis- and two-axis-tracked systems). However, as powering EVs is one of the main target applications of solar PVs in these cities, it is also important to consider the expected growth in the number of EVs in these cities. For this purpose, the expected number of EVs in these cities is also considered while considering the suitability of each city.

6.1.1 Climate data for different locations in KSA

Geographically, Saudi Arabia can be divided into different regions: the central, eastern, western, southern, and northern regions (See Figure 6.1). Due to their different climates, these locations have different levels of potential for electricity generation through solar PV. In order to investigate the solar PV energy requirements for EV application in these regions, major cities in each area were targeted for analysis as follows: Riyadh (central region), Dammam (eastern region), Jeddah and Medina (western region), Bisha (southern region), and Sakaka (northern region). These cities were assumed to be representative of the climates in the different regions of KSA.



Figure 6.1 Map of the Kingdom of Saudi Arabia [47].

6.1.1.1 Levels of solar irradiation in each location

The geographic location of KSA is well-placed for capitalizing solar energy with the average daily solar radiation levels between 5.69 - 6.62 kWh/m^2 and 80% - 90% of clear sky days over the year as shown in Figure 6.2 . According to Vision 2030, Saudi Arabia aims to boost its renewable energy resources in its total energy share by producing nearly 9.5 GW of energy from sustainable energy sources by 2023, of which solar photovoltaic (PV) generation comprises a considerable portion [259].

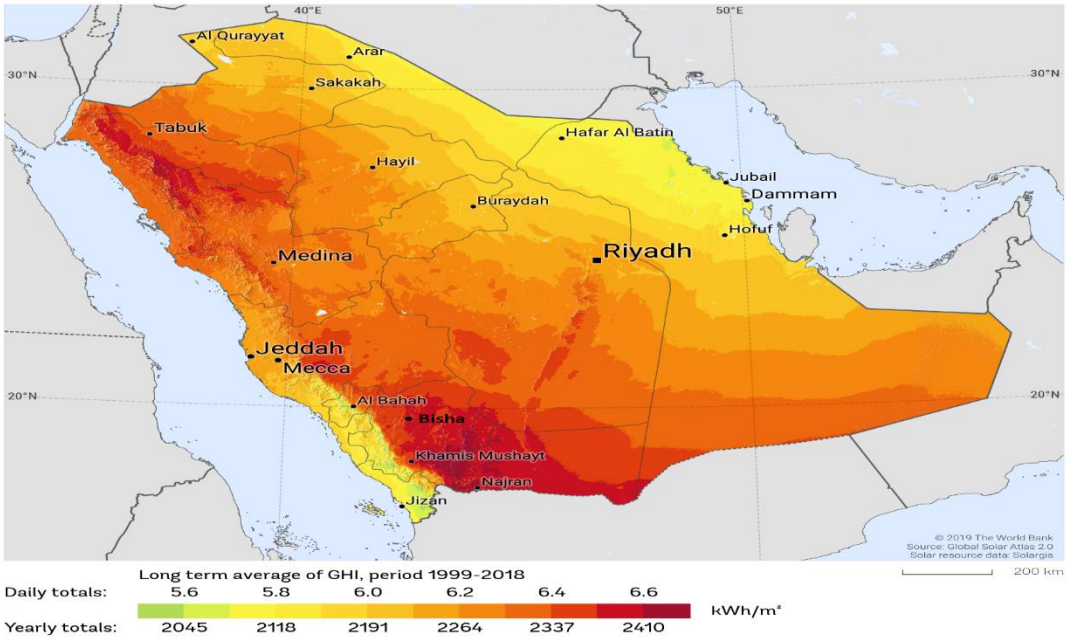


Figure 6.2 Horizontal solar irradiation [56].

Data relating to the average monthly solar radiation on a horizontal surface for the six cities was taken from the RETScreen climate database, which collects its data from NASA satellites [260]. Details of the average monthly solar radiation levels and the air temperature for the cities is provided in Figure 6.3 - Figure 6.10 below. The data showed that the city of Bisha has the highest average annual solar radiation of 7 kWh/m^2 followed by Madinah and Jeddah with 6.36 kWh/m^2 and 5.94 kWh/m^2 respectively. Riyadh and Sakaka receive similar amounts of radiations (5.78 kWh/m^2 and 5.77 kWh/m^2 respectively), while Dammam with 5.6 kWh/m^2 receives the least.

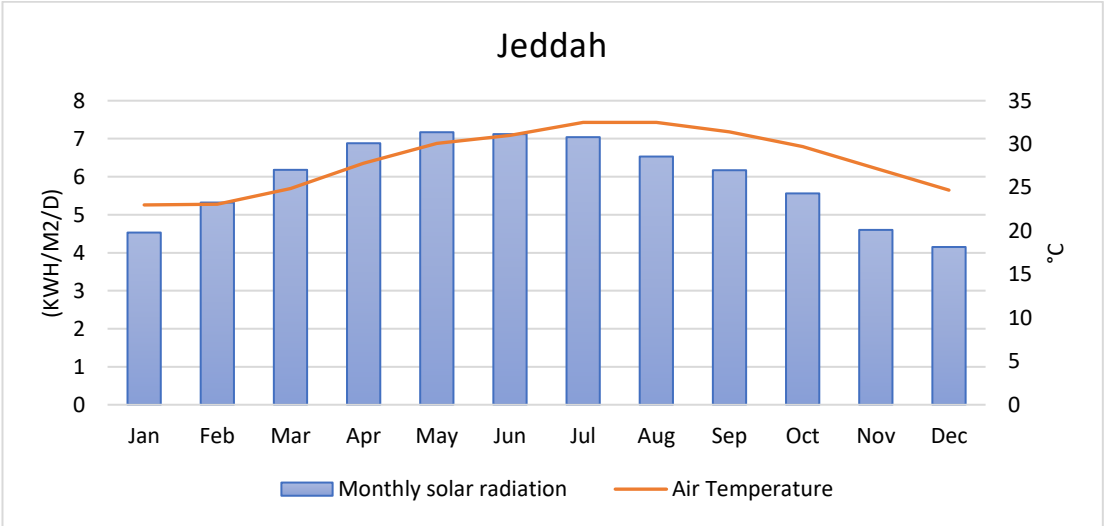


Figure 6.3 Monthly average horizontal solar radiation with air temperature for Jeddah city.

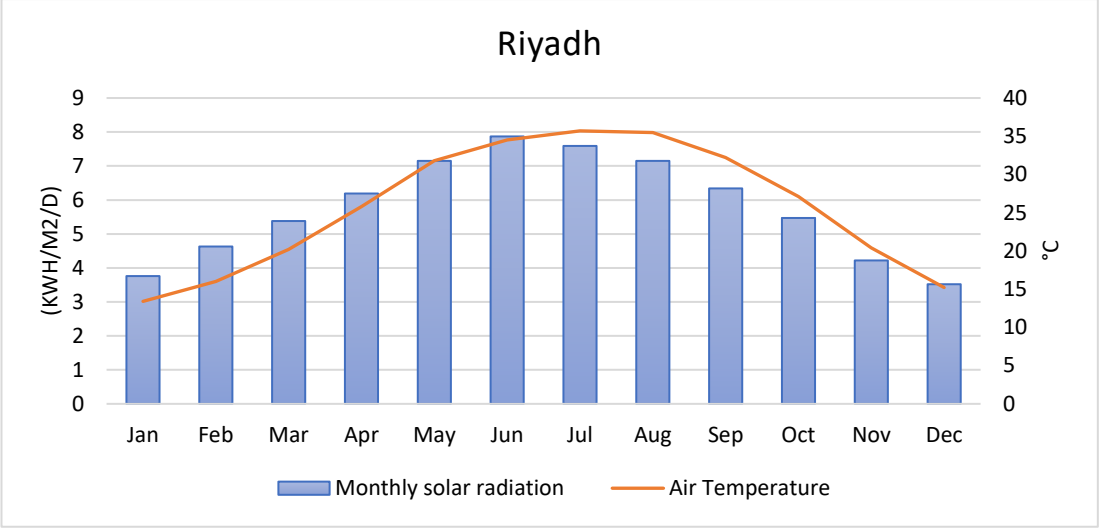


Figure 6.4 Monthly average horizontal solar radiation with air temperature for Riyadh city.

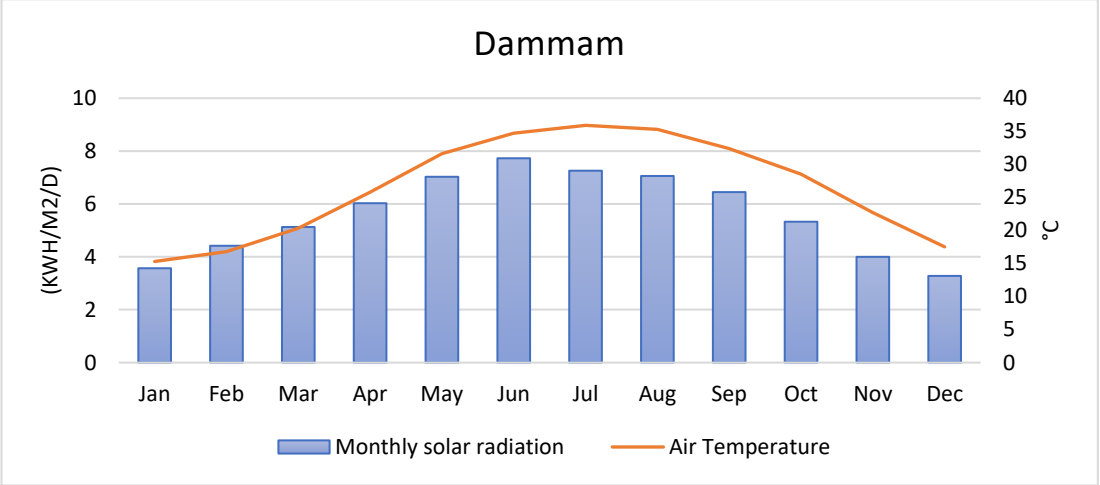


Figure 6.5 Monthly average horizontal solar radiation with air temperature for Dammam city.

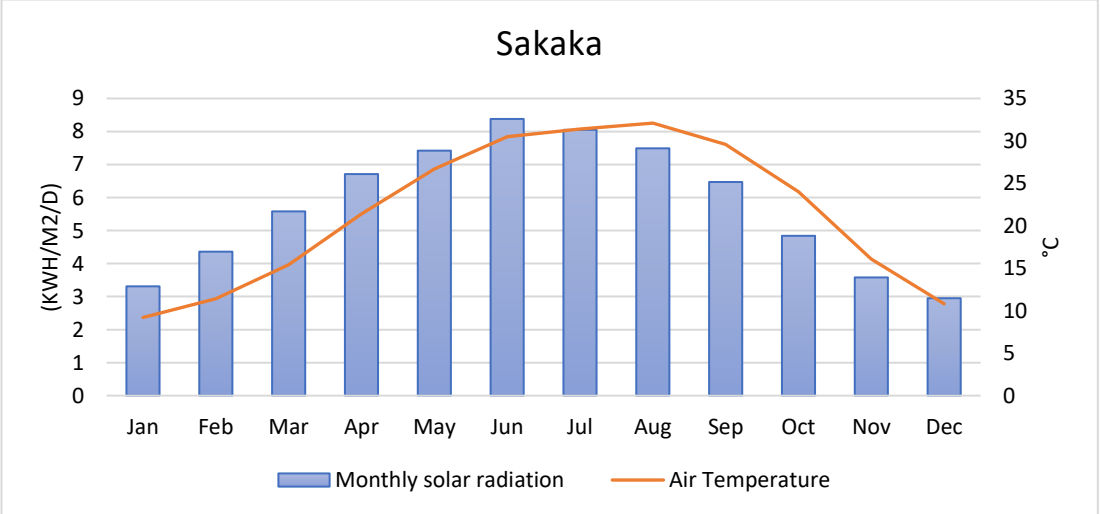


Figure 6.6 Monthly average horizontal solar radiation with air temperature for Sakaka city.

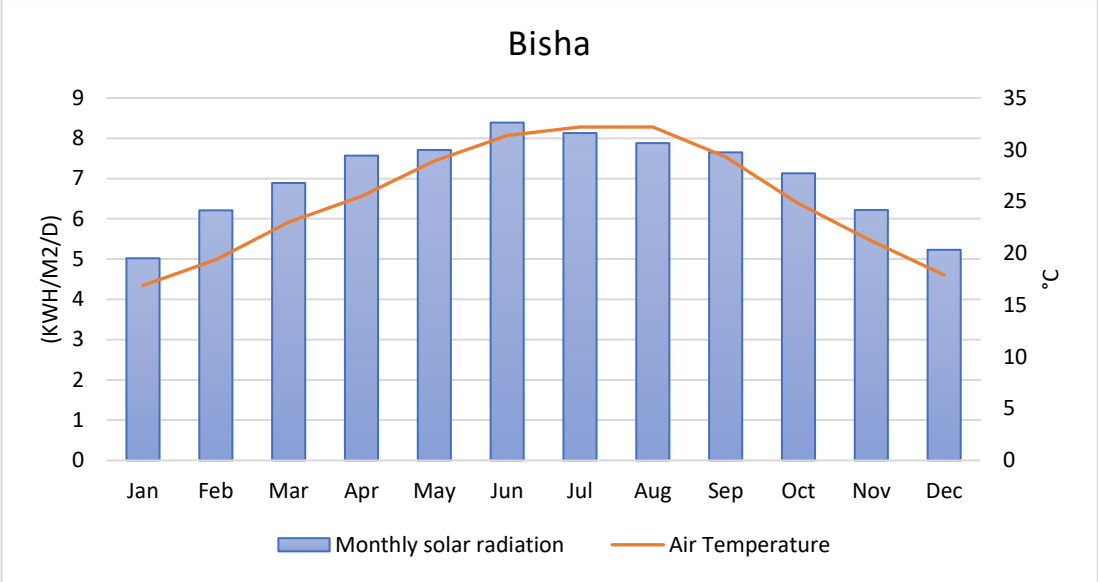


Figure 6.7 Monthly average horizontal solar radiation with air temperature for Bisha city.

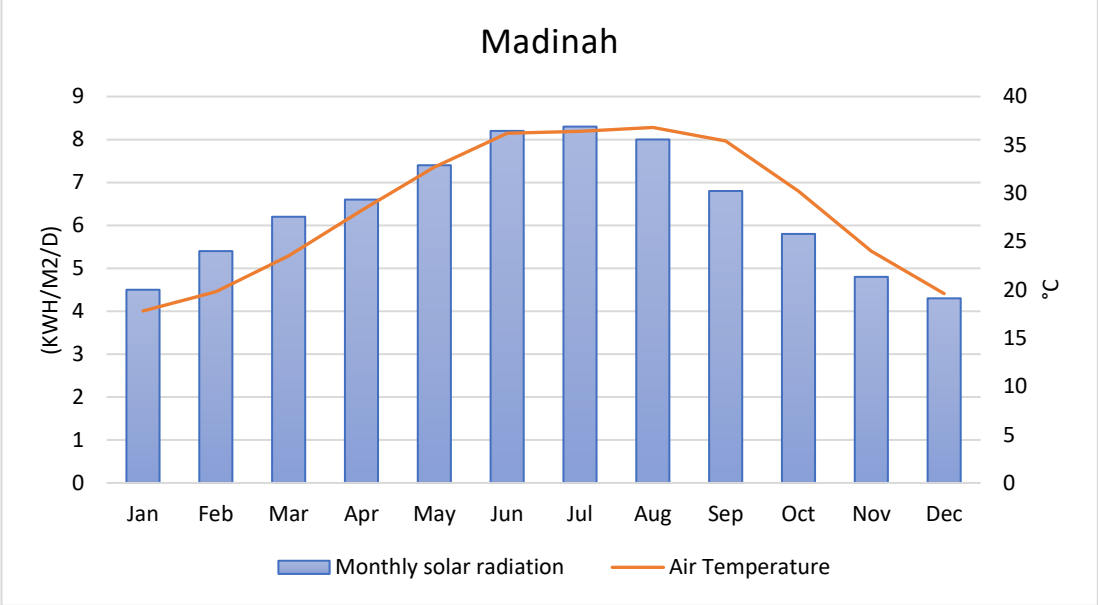


Figure 6.8 Monthly average horizontal solar radiation with air temperature for Madinah city.

Due to its proximity to the equator (at around 20° latitude) (See Figure 6.2), Bisha receives the highest daily average solar radiation almost every month when compared to the other cities, especially in the winter months. It also has a uniform distribution of average monthly solar radiation on a horizontal surface (See Figure 6.9).

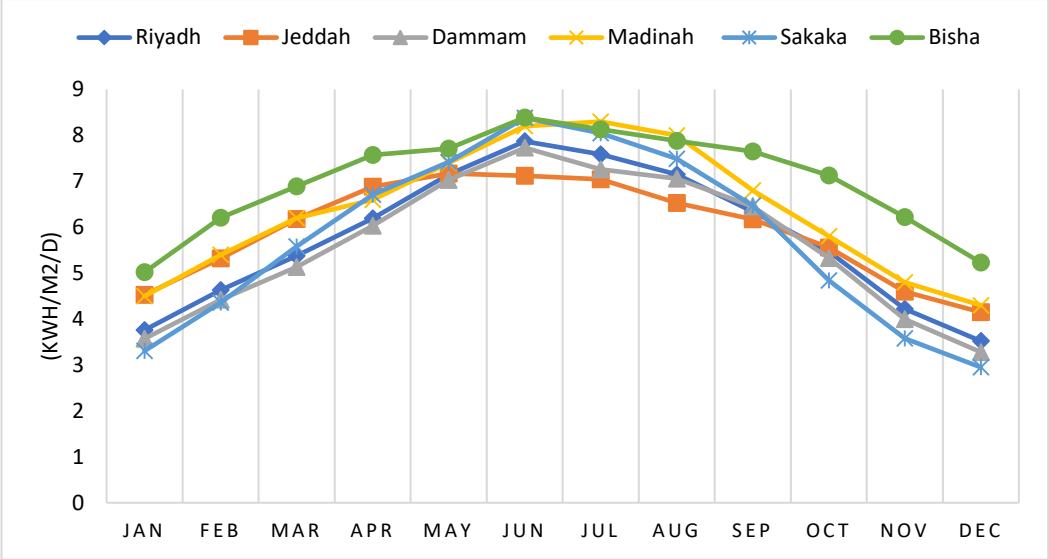


Figure 6.9 Monthly average horizontal solar radiation for the six cities.

It is interesting to note that, in terms of annual average temperature, Madinah and Jeddah are the hottest cities, with temperatures of 28.4 ºC and 28.2 ºC respectively. They are followed by Dammam, Riyadh, Bisha, and Sakaka with average temperatures of 26.5 ºC, 25.7 ºC, 25.3 ºC, and 21.6 ºC respectively (See Figure 6.10).

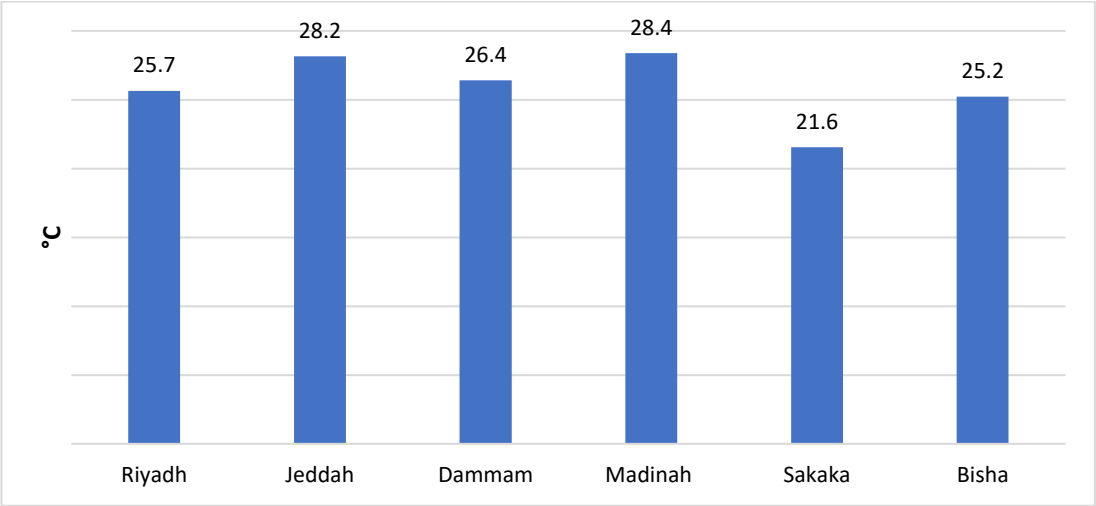


Figure 6.10 Annual average air temperature for the six cities.

6.1.2 Vehicles Number Prediction in 2030.

Having explored the levels of solar radiation in each location, the next stage was to identify the potential demand for solar energy from EVs. The first step in this process involved estimating the number of vehicles in each city by 2030. According to the Saudi Ministry of Transportation [170], more than 18 million vehicle activities were recorded in various Saudi cities and towns in August 2019. Recent official statistics

also estimate that light vehicles, such as cars, accounted for about 80 percent of the total number, which is expected to reach 25 million vehicles by 2030 [171]. Figures from the Ministry of Transportation [170] also showed the total number of vehicles in the six cities – Jeddah, Riyadh, Dammam, Madinah, Sakaka, and Bisha – and the proportion of the total number this represented (See Table 6.1).

Table 6.1: Number of vehicles in the six cities in 2019.

City	Vehicles in 2019	
	Total number	Share of vehicles (%)
Jeddah	5,200,000	27.7
Riyadh	2,700,000	15
Dammam	1,500,000	8
Madinah	1,300,000	7
Sakaka	444,000	2
Bisha	160,000	0.8

Estimates of the distribution of vehicles in regions and major cities like Jeddah, Riyadh, Dammam, and Medina by 2030 were also provided by the Ministry (See Figure 6.11). Based on these, and the expectation that there would be 25 million vehicles in total, it was possible to estimate the expected number of vehicles in each city (See Table 6.2).

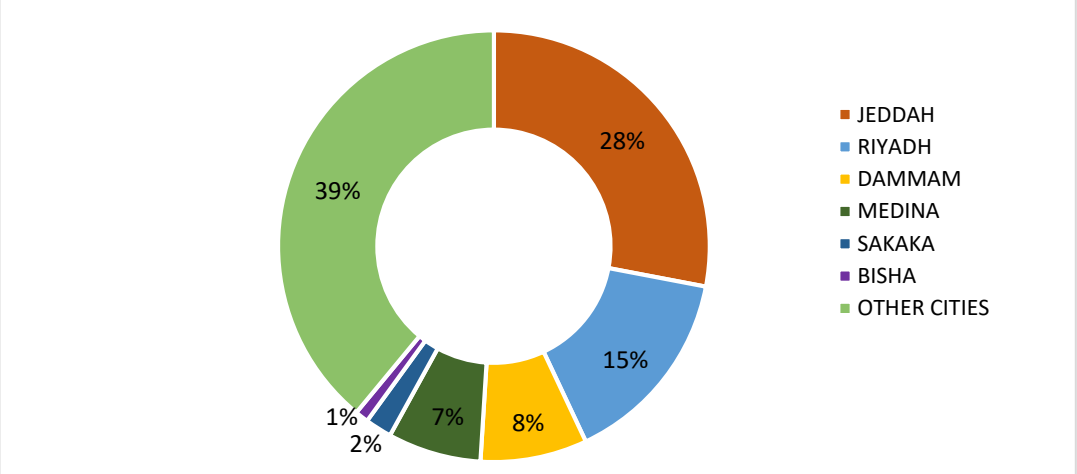


Figure 6.11 Distribution of vehicles in major cities in Saudi Arabia in the year 2019 [170].

Table 6.2 provides a simple statistical comparison of the six cities, showing the number of vehicles in 2019 and the estimated numbers by 2030, and ranking the cities accordingly. The percentage increase over 2019 figures by 2030 is also shown.

Table 6.2 Rankings of different cities in Saudi Arabia by expected number of vehicles in 2030.

Rank	City	Vehicles in 2019		Predicted numbers of Vehicles in 2030	
		Total number	Share of vehicles (%)	Total number of vehicles	Increase over 2019 (%)
1	Jeddah	5,200,000	27.7	6,925,000	33
2	Riyadh	2,700,000	15	3,700,000	37
3	Dammam	1,500,000	8	2,000,000	33
4	Madinah	1,300,000	7	1,750,000	34
5	Sakaka	444,000	2	500,000	13
6	Bisha	160,000	0.8	200,000	25
Other Cities		6,696,000	39.5	9,825,000	
Total		***18,000,000***		***25,000,000***	

It is interesting to note that, while Jeddah has the most vehicles, Riyadh is expected to see the fastest growth in the number of vehicles by 2030 at 37%. Based on these statistics and assuming a steady relation in terms of the development of the different cities and growth trends in the number of vehicles, there will be approximately 3.7 million vehicles in Riyadh by 2030. This constitutes a significant increase on the figures for 2019 (2,700,000), the growth in the number of EVs is expected to follow a similar trend. Therefore, the capacity of any future PV plant would need to take this forecast number of vehicles into account.

6.1.3 Expected Number of Electric Vehicles in the KSA

Having established the estimated numbers of vehicles in the six cities, it was then possible to estimate the expected number of EVs by 2030 based on the Low Uptake Scenario (LUS), Medium Uptake Scenario (MUS), and High Uptake Scenario (HUS) (See Section 3.3.5). The results are presented in Table 6.3. As can be seen, Bisha and Sakaka are expected to have fewest EVs, even in the most liberal HUS scenario. On the other hand, Jeddah will have the highest number of EVs in 2030.

Table 6.3 Expected number of EVs in the six cities in 2030 (Based on LUS, MUS, and HUS scenarios).

City	Predicted Number of EVs in 2030		
	LUS	MUS	HUS
Jeddah	65,440	130,883	261,765
Riyadh	34,965	69,930	139,860
Dammam	18,900	37,800	75,600
Madinah	16,538	33,075	66,150
Sakaka	4,725	9,450	18,900
Bisha	1,890	3,780	7,560

6.1.4 Vehicles Parking Habits and Durations

As EVs are typically charged while they are parked, it was also important to consider the parking habits of drivers in KSA, especially time spent parking at home, when home charging could be applied. The parking patterns of Saudi drivers in both summer and winter are shown in Figure 6.12. This data was obtained as part of the survey conducted by the author to identify potential barriers to EV adoption in Saudi Arabia [123] (See Chapter 4). As the figure shows, while an average of around 27% of vehicle users are expected to park their cars for more than one hour between 8:00am and 6:00pm, over 60% are parked between midnight (12:00am) and the early morning (7:00am). This reflects typical working patterns, when most car owners are out in the day and at home at night. However, although this period would provide the longest time for charging, vehicles could not utilise electricity generated from a PV plant to charge overnight unless energy storage was also provided.

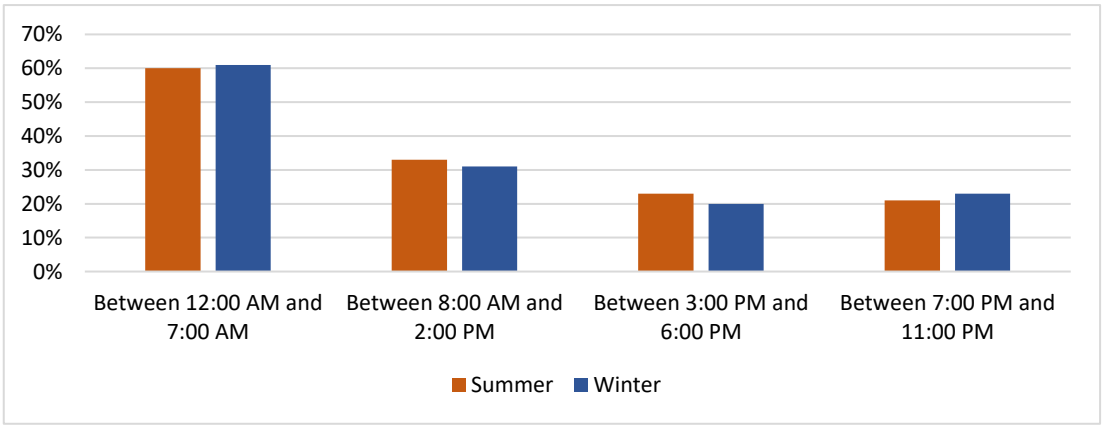


Figure 6.12 Parking Survey Summary [123].

6.1.5 Estimated Peak Electricity Load Requirements

Having estimated the likely number of EVs in each city by 2030 and identified typical parking patterns, it was possible to estimate the electricity load requirement in 2030 under the LUS, MUS and HUS scenarios. However, it was first necessary to consider the charging power required for a single EV. According to Mobility House [261], the charging needs of an EV range from 3.7 kW to 22 kW depending on the onboard charger. Therefore, the upper limit of 22 kW was established as the charging power required for a single EV.

The electricity load requirements in 2030 under each scenario were then estimated based on the following assumptions:

- 27% of the vehicles in each location are parked for up to 10 hours between 8am and 6pm (See Table 6.4).
- Of the vehicles parked between 8:00am and 6:00pm, 3.5% (LUS), 7% (MUS) and 14% (HUS) are EVs, according to the adopted scenarios.
- The charging needs of a single EV = 22 kW.

Table 6.4 Number of vehicles expected to be parked for up to 10 hours in different cities of Saudi Arabia by 2030.

	Jeddah	Riyadh	Dammam	Madinah	Sakaka	Bisha
Total number of vehicles expected in 2030	6,925,000	3,700,000	2,000,000	1,750,000	500,000	200,000
27% of vehicles	1,869,750	999,000	540,000	472,500	135,000	54,000

Based on these figures, Table 6.5 presents the load specification for each city based on the three adopted scenarios (LUS, MUS and HUS). This was calculated using eq. (3.2). In each scenario, Jeddah has the highest requirement for solar PV generation, since it is expected to have the highest number of EVs in 2030.

Table 6.5 Load (GW) requirement (computed using eq. (3.2)) for EVs in different cities of Saudi Arabia under LUS, MUS, and HUS scenarios.

City	Load (GW)		
	LUS	MUS	HUS
Jeddah	1.44	2.88	5.76
Riyadh	0.77	1.54	3.08
Dammam	0.42	0.83	1.66
Madinah	0.36	0.73	1.46
Sakaka	0.10	0.20	0.41
Bisha	0.042	0.083	0.166

6.2 Solar PV Sizing Assessment (Sakaka solar PV plant data)

The assessment of the size of PV plant required to meet the demand in each location was based on the existing PV system model at the Sakaka power plant. The data for production (for the year 2020), PV panels, and inverters used in the plant were obtained from ACWA Power Company which is the site owner of the Sakaka power plant. It is a 300 MW PV solar farm developed on a 6 km² site close to the city of Sakaka, in Al Jouf province in the northern region of KSA, and consists of 1.2 million solar panels (See Figure 6.13). It is the first utility-scale solar power project in the country and was connected to the national grid in November 2019. The Sakaka project will supply renewable electricity to 45,000 Al Jouf households, reducing CO_2 emissions by around 500 tonnes each year [221].

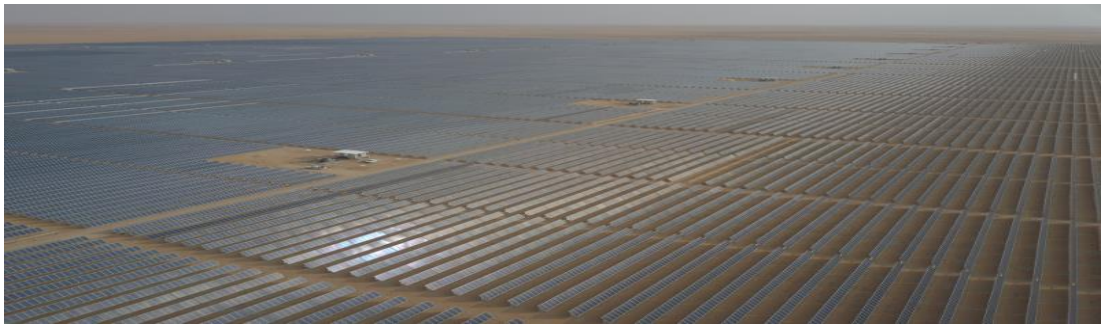


Figure 6.13 An aerial view of Sakaka solar plant [221].

The PV panels used at Sakaka are manufactured by “Chint Solar” using mono-crystalline silicon PV panels. The DC/AC inverters are based on a 100kW (DC/AC) inverter, manufactured by Huawei. The datasheets for each of these components are provided in Appendix B. The PV panels have efficiency in the range of 17.6% to 17.8% for 340Wp and 345Wp panels respectively.

The monthly production data for the Sakaka power plant in 2020 are shown in Table 6.6 Sakaka PV plant production data for 2020 (created by the author based on data provided by ACWA Power Company).based on figures obtained from the site operating company. These include the total running hours (in decimal form) for each month during 2020, the average hourly solar irradiance (in Wh/m^2), the irradiance on a panel or plane of array (POA) (in kWh/m^2 per day), and the total daily Global Horizontal Irradiance (GHI), and the average temperature. The highest recorded air temperature (55.8 °C) was in July and the lowest temperature (23.4 °C) was in January.

Table 6.6 Sakaka PV plant production data for 2020 (created by the author based on data provided by ACWA Power Company).

Month	Plant running	Average Hourly Solar Irradiance	Solar Irradiation Plane of Array (POA)	Total Daily Global Horizontal Irradiance (GHI)	Temperature
	Decimal	(Wh/m^2)	(kWh/m^2 per day)	(kWh/m^2)	(°C)
January	10.55	462.4	4.88	3.92	23.4
February	11.11	567.4	6.31	4.94	27.9
March	12.20	603.8	7.37	5.86	34.7
April	12.99	692.7	8.98	7.11	41.2
May	13.51	712.5	9.63	7.65	47.5
June	14.05	782.3	***10.99***	8.31	50
July	13.65	763.3	10.42	7.88	***55.8***
August	13.03	***784.8***	10.21	7.41	51.5
September	12.16	681.7	8.29	6.26	51.4
October	11.48	651.3	7.48	5.68	45.2
November	10.68	483.6	5.17	4.06	31.9
December	10.25	428.8	4.40	3.44	25.5

The solar irradiation profile of the Sakaka plant for 2020 and the average temperature on the plane of the array are shown in Figure 6.14. As can be seen, although the average temperature was highest in July (55.8 ^oC) the solar irradiation level reached its peak in June (at nearly 11 kWh/m^2/day for the tilted surface).

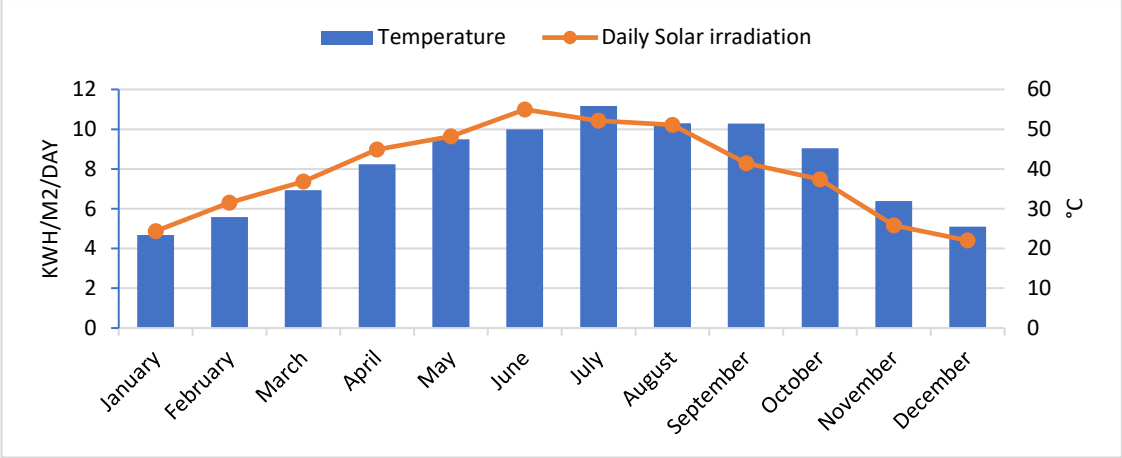


Figure 6.14 Sakaka PV plant daily solar irradiation and average temperature on the plane of the array for 2020. Based on data obtained by e-mail from ACWA Power Company.

Similarly, the average hourly solar irradiance profile of the Sakaka plant for 2020 (shown in Figure 6.15) shows that June, July, and August received the highest average hourly solar irradiance.

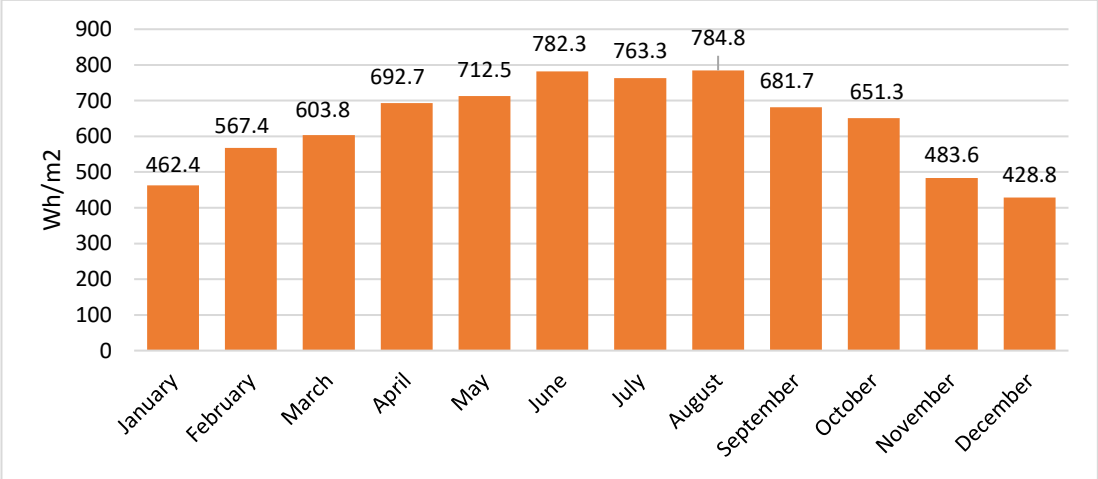


Figure 6.15 Sakaka PV plant average hourly solar irradiance for the year 2020.

6.2.1 Modelling Setup

The date gathered from the Sakaka plant was then used to evaluate the viability of installing a similar 300 MW grid-connected solar photovoltaic system in the six cities – Jeddah, Riyadh, Dammam, Madinah, Sakaka, and Bisha – through modelling and simulation using the software RETScreen.

6.2.1.1 Simulation Parameters and Characteristics

As detailed in the Methodology chapter (See Section 3.3.3), the software RETScreen was used to determine the parameter characteristics of the Canadian Solar mono-Si -

CS6U-345M solar modules, as shown in Table 6.7. Canadian Solar panels were used as Chint Solar PV panels are not available in the RETScreen software and they share similar characteristics.

Table 6.7 Parameter characteristics of the system solar module for all locations.

Property	Value
Power capacity	300 MW
PV technology type	mono-Si
Manufacturer of PV panels	Canadian Solar
Model of PV	mono-Si - CS6U-345M - MaxPower
Efficiency of PV	17.74%
Nominal operating temperature	45 °C
Temperature coefficient	0.4% /°C
Manufacturer of inverter	HUAWEI
Efficiency of inverter	100%

6.2.2 Electricity Generation Potential using Solar PV

Simulations were then run to assess the potential of each city to generate solar electricity using a number of different solar PV systems: fixed-tilt, one-axis tracked, and two-axis tracked. Solar panels that can follow the sun can considerably boost a power plant's generation capacity, however, the installation and tracking system needs additional funding. Due to the increased initial cost of the tracking system, most previous studies have examined fixed-mounted solar panels. Nevertheless, the significant decline in the price of tracking systems has made their implementation possible [262].

Figure 6.16 - Figure 6.18 show the estimated average monthly electricity generation potential in the six locations using fixed-tilt, one-axis tracked, and two-axis tracked solar PV systems (based on electricity exported to the national grid). These were generated using the RETScreen simulation software. As can be seen, for all cities, exports to the grid peak between May and August, then fall sharply, except in Bisha. Indeed, Bisha exports more electricity to the grid than the other cities for all types of PV systems, notably in September and October, when exports elsewhere decline sharply. Bisha also has a more equal distribution of average monthly electricity production in the fixed-tilt system. This may be due in part to the fact that Bisha has the second lowest air temperature, which positively affects the efficiency of the panels.

In winters (Nov – Feb), Madinah and Jeddah seem to be generating more electricity compared to Sakaka; however, in the summers, the reverse is true.

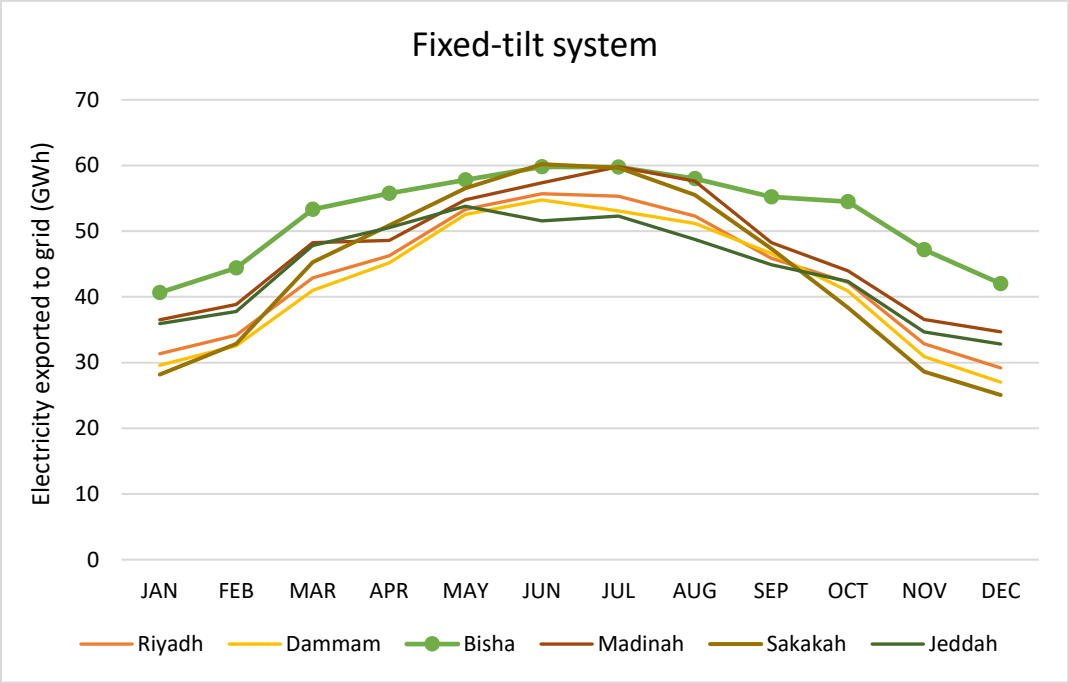


Figure 6.16 Monthly average electricity production for fixed-tilt system in different locations.

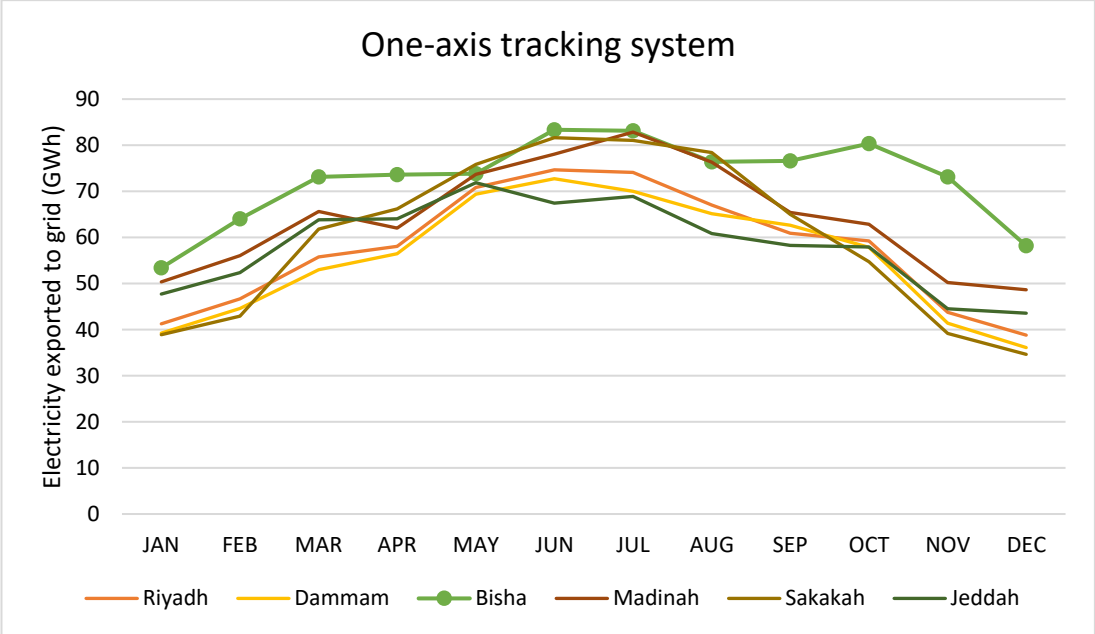


Figure 6.17 Monthly average electricity production for one-axis system in different locations.

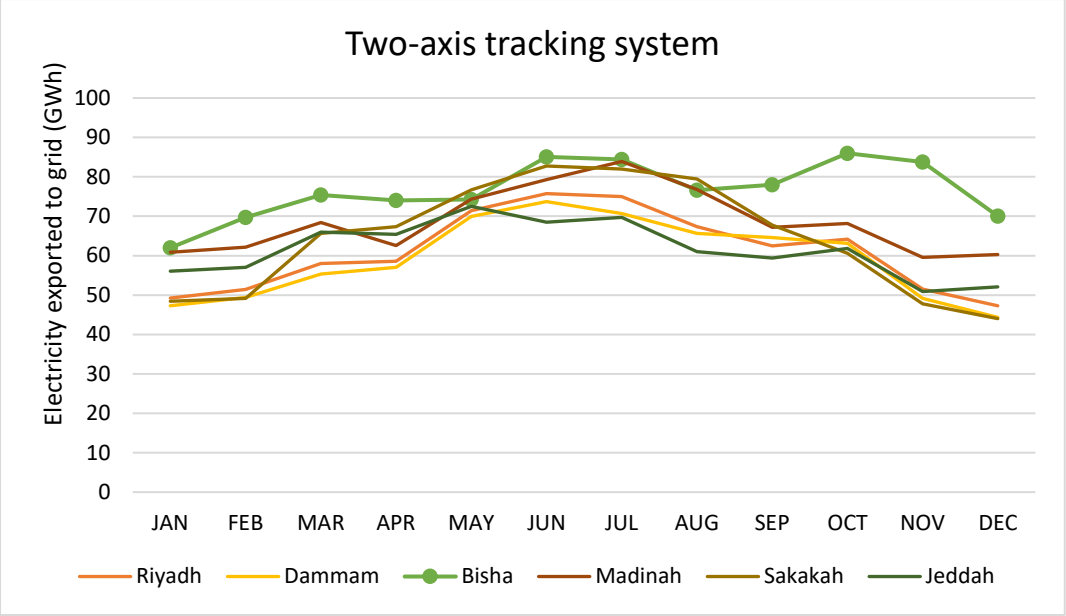


Figure 6.18 Monthly average electricity production for two-axis system in different locations.

6.2.3 Results of the Simulations

The simulation results in this section show the PV sizing and energy production required to meet the load requirements for each city under the LUS, MUS, and HUS scenarios (based on the expected number of EVs presented in Table 6.3). These were obtained by considering an efficiency of 100% for the system and are shown in Table 6.8 - Table 6.10.

Table 6.8 PV sizing and energy production requirement for different cities under Low Uptake Scenario (LUS).

City	Power capacity (MW)	Number of panels	Solar collector area (m^2)	Annual energy production (GWh)	Number of charging points
Jeddah	1,440	4,173,913	8,117,249	3,554	21,813
Riyadh	770	2,231,887	4,340,479	2,420	11,654
Dammam	420	1,217,392	2,367,532	994	6,300
Madinah	360	1,043,480	2,029,314	988	5,513
Sakaka	100	289,855	563,698	257	1,575
Bisha	42	121,739	236,753	129	630

Table 6.9 PV sizing and energy production requirement for different cities under Medium Uptake Scenario (MUS).

City	Power capacity (MW)	Number of panels	Solar collector area (m^2)	Annual energy production (GWh)	Number of charging points
Jeddah	2,880	8,347,826	16,234,498	7,108	43,628
Riyadh	1,540	4,463,768	8,680,947	4,840	23,310
Dammam	830	2,434,783	4,735,063	1,989	12,600
Madinah	730	2,115,942	4,114,994	2,004	11,025
Sakaka	200	579,710	1,127,395	514	3,150
Bisha	83	240,739	467,870	254	1,260

Table 6.10 PV sizing and energy production requirement for different cities under High Uptake Scenario (HUS).

City	Power capacity (MW)	Number of panels	Solar collector area (m^2)	Annual energy production (GWh)	Number of charging points
Jeddah	5,760	16,695,653	32,468,998	14,217	87,255
Riyadh	3,080	8,927,537	17,361,896	9,679	46,620
Dammam	1,660	4,811,595	9,357,386	3,930	25,200
Madinah	1,460	4,231,884	8,229,989	4,008	22,050
Sakaka	410	1,188,406	2,311,162	1,055	6,300
Bisha	166	481,160	935,740	509	2,520

As the tables show, under all scenarios Jeddah requires the greatest number of solar panels (~4 million to ~16 million), the largest solar collector area (~8 km^2 to ~32 km^2), and the highest number of charging points (~22 thousand to ~87 thousand). This is followed by Riyadh, with nearly half the number of solar panels (~2.2 million to ~ 9 million), a 50% smaller solar collector area (~4 km^2 to ~17 km^2), and around half the number of charging points (~12 thousand to ~47 thousand) required compared to Jeddah. Sakaka, and Bisha require the least number of solar panels, the smallest size of solar collector area, and the least number of charging points, reflecting the much lower numbers of expected EVs by 2030. Similar trends can be observed in the annual energy production data.

6.3 Identifying the Best Location for Techno-Economic Analysis

This data was then used to identify the most suitable city for the case study i.e. the city which had had both a sufficiently high estimated numbers of EVs and good potential for generating electricity using solar PV. Although the data suggest that Bisha and Sakaka have excellent potential for solar PV generation, both are small cities, and they have the lowest expected numbers of EVs by 2030. While Jeddah expects to have the highest number of EVs, its solar PV potential is relatively low, especially during the hot summer months. Riyadh, on the other hand, has good potential for electricity generation using solar PV and is expected to have the second highest number of EVs after Jeddah. In addition, the Saudi government is aiming to make Riyadh one of the ten largest city economies in the world and is planning for an increase in the population from 7.5 million today to around 15-20 million in 2030 [263]. This will require significant investment and further infrastructure development, although this is already well-established, as Riyadh is the capital city. Therefore, Riyadh was targeted for further investigation in terms of the techno-economic feasibility of applying a system in which EVs are powered by solar PVs (See Chapter 7).

6.4 Conclusions

This chapter has explained the process which was used to identify the most suitable location for a case study to assess the techno-economic viability of developing an integrated solar energy system to support the adoption of EVs in a major Saudi city. The identification was made based on analysis of each location's potential for electricity generation using solar PV and the forecast number of EVs in each city in 2030. Consideration was also given to the potential to attract capital investment to support the necessary infrastructure development. Riyadh, the capital city, emerged as the preferred candidate for further investigation, as it has significant potential for solar PV generation, is expected to have the second highest number of EVs in 2030, and has been earmarked for significant investment and development by the Saudi government. The next chapter builds on these findings to provide an in-depth techno-economic analysis of the potential application of solar-powered EVs in the city of Riyadh.

Chapter 7
Techno-Economic Analysis of Electric Vehicles Application

7.1 Introduction

This chapter presents a techno-economic analysis of the feasibility of introducing EVs supported by solar energy into the Saudi Arabia, using the capital Riyadh as a case study. Riyadh was identified as the most suitable location for this case study based on its potential for solar PV, the expected growth in the number of vehicles in the city by 2030, and its potential to attract investment to support successful EV infrastructure development. The analysis here considers the three scenarios of EVs uptake identified previously (LUS, MUS, and HUS), with LUS reflecting the most conservative estimates for the number of EVs in Riyadh and HUS the most liberal. The analysis described here involves three potential models (Model 1, Model 2 and Model 3) was completed in three stages: Stage 1 considers the installation of a PV based solar power plant in Riyadh to meet the demand for electricity created by EVs (Model 1); Stage 2 additionally includes EV charging stations/points (Model 2); and Stage 3 introduces the facility for Vehicle-to-Grid (V2G) transmission in addition to Stage 2 (Model 3). The financial and environmental impacts of the models in each scenario are examined in detail, and the models are compared to identify the most effective option for implementation in Riyadh. The chapter begins by providing the background information necessary for this analysis, including an overview of the city of Riyadh and details of the parameters used, before assessing the viability of the three models, selecting the most effective one, and providing a justification for the choice.

7.2 Case Study Background

This section provides an overview of the city of Riyadh, with a focus on its geography and climate and the economic opportunities in the city, as these inform the techno-economic analysis of the adoption of EVs in Riyadh. The financial parameters used in the analysis are also presented, including the installation (and decommissioning) costs for the potential PV plant.

7.2.1 Case Study Location (The City of Riyadh)

Riyadh is both the capital of Saudi Arabia and the capital of the Riyadh region. It is the seat of the Saudi government and houses ministries, embassies, diplomatic missions and major, financial, technical, agricultural, and commercial organizations, and Riyadh International Airport is one of the largest in the world. The city is rapidly developing its educational and social and tourism provision as part of Vision 2030, and it is now home to many international hotels, as well as five privately owned universities, six government owned/public universities, specialised institutes, middle-level colleges, sport facilities and stadiums, and public libraries and cultural information centres [264]. According to the Saudi General Authority for Statistics, in mid-2021, the population of KSA was 34.2 million, of which around a quarter (8.6 million) lived in the city of Riyadh [203].

7.2.1.1 Geography and Climate of Riyadh

Geographically, Riyadh is located in the centre of the country (See Figure 7.1) and approximately 600 meters above sea level. It has an area of 404,240 km². Based on Köppen-Geiger climate classification [265], Riyadh has a hot desert climate, with above 45°C ambient temperature in the summer and below 5°C in the winter. Relative humidity is low and average annual rainfall is around 84.4 mm. The area is exposed to recurrent sandstorms being surrounded by desert sand dunes [264]; however, it experiences over 60% clear skies in an average year, with 40% of days overcast or mostly cloudy. Duration of daylight varies from 10.6 to 13.6 hours, and the monthly maximum global horizontal radiation varies from 236 kWh/m^2 in summer to 131 kWh/m^2 in winter, resulting in intense solar radiation over the course of the year (See Figure 7.2).



Figure 7.1 Map of Riyadh region [278].

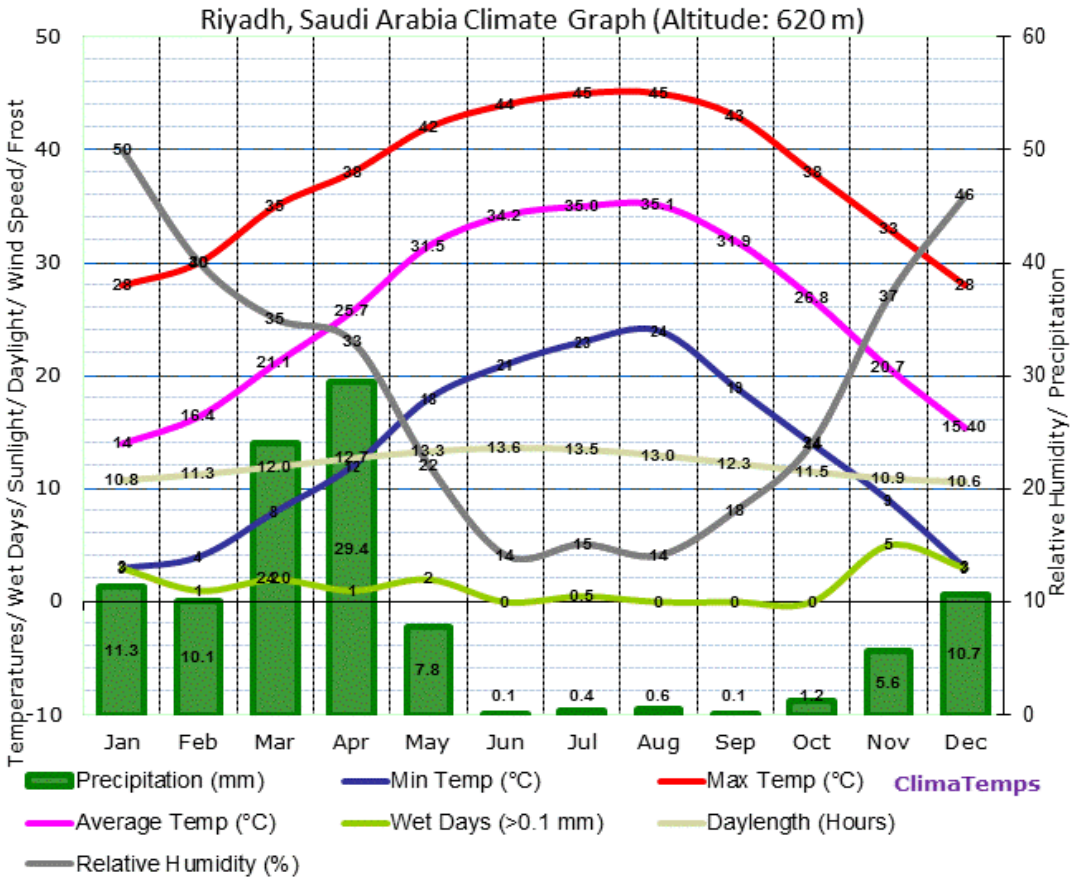


Figure 7.2 Climate data for Riyadh [267].

7.2.1.2 Economy Opportunities in Riyadh

Riyadh is currently placed 86th in Global Financial Centres Index's 2022 rankings [268]; however, under Vision 2030, the Saudi Finance Minister aims to transform Riyadh into a top-ten global financial marketplace by 2030 [269]. Growth in the city has traditionally been driven by revenues from oil and gas; however, environmental concerns and the need to reduce GHG emissions mean KSA is now looking to play a leading role in Renewable Energy (RE) investment for a sustainable future, and much of this is centred in Riyadh. Riyadh is also attracting investment through innovations such as the Green Riyadh project, which aims to increase the green space per capita in the city from 1.7 m^2 to 28 m^2 by planting 7.5 million trees and creating new parks and gardens [269]. The Gross Domestic Product (GDP) of Riyadh in 2021 amounted to about SAR 734 billion ($196 billion), and 29 % of the GDP of KSA [270,271].

7.2.2 Financial input Parameters

According to the Saudi Central Bank [270], the inflation rate in KSA is 1.2%. The discount rate for the economic study has been set at 5% and escalation rate of fuel is 4% based on previous studies from the same region [271,272]. Electricity escalation is set at 3% [188].

The amounts reported in this study are in U.S. dollars (USD). The Saudi Arabian Riyal (SAR) is tied to the U.S. dollar at a rate of 3.75 [270]. Currently, the sale price of utility-scale PV power is determined by the price at the Sakaka 300 MW PV plant at rate of $23.4 MWh [232]. A summary of the financial input parameters is provided in Table 7.1.

Table 7.1 Financial Parameters Assumption

Parameter description	Input value
Escalation rate of fuel	4%
Rate of Inflation	1.2%
Discount rate	5%
Project Lifetime	25 Years
Electricity export rate	$23.4/MWh
Escalation rate of electricity	3%

7.2.3 Installation cost

Table 7.2 shows the cost details for fixed-tilt, one-axis, and two-axis tracking systems. The estimated costs of fixed tilt, one-axis, and two-axis tracking utility-scale PV plant are $0.84/W, $0.95/W, and $1/W respectively [273,274]. The operation and maintenance (O&M) costs account for 1% of total capital costs per year for fixed-tilt PV and 1.28% and 1.5% for one-axis and two-axis tracking systems, respectively [274]. The life cycle of an inverter is assumed to be 10 years, and the periodic cost of inverter replacement is estimated to be $0.19/W [275]. According to the International Energy Agency (IEA), the cost of closing the plant at the end of the project lifetime (25 years) is 10% of the initial cost of the plant [276].

Table 7.2 Cost (in $) breakdown for different PV power systems for the city of Riyadh.

Type of cost ($)	Fixed tilt	One-axis tracking	Two-axis tracking
Initial	$723,800,000	$770,000,000	$847,000,000
Inverter's replacement (every 10 years	$146,300,000	$146,300,000	$146,300,000
Operation & Maintenance Cost (annual)	$7,238,000	$9,856,000	$12,705,000
End of project	$72,380,000	$77,000,000	$84,700,000
Total	***$949,718,000***	***$1,003,156,000***	***$1,090,705,000***

As the table shows, the fixed-tilt PV panel is the cheapest option costing nearly $950 million, while the two-axis tracking system is the most expensive at nearly $1.1 billion. The one-axis tracking solar panel system is expected to cost just over $1 billion. There is a difference of around $141 million between the cheapest and the most expensive options.

7.3 Assessing the Viability of the Three Models

In this section, the models developed at each stage of the analysis are presented: Model 1 (PV Plant), Model 2 (PV Plant + EV Charging Stations), and Model 3 (PV Plant + EV Charging Stations + Vehicle-to-Grid). For each model, cost, finances, emissions, and sensitivities are analysed and discussed. Finally, a comparative analysis of the three models is presented.

7.3.1 Stage 1 – PV Plant Only (Model 1)

In stage 1, Model 1 – PV Plant Only was used as a base model. The model is based on a PV plant which is capable of generating sufficient electricity to fulfil the EV energy requirements in each scenario (LUS, MUS and HUS). As these scenarios are all proposed at the same location and with the same climate data, there are no differences in their characteristics except for the power plant. For the techno-economic feasibility of Model 1, the installation of moderate and large-scale, grid-connected PV power plants of 770, 1540 and 3080 MW (to cover the expected EV loads in 2030 in each scenario) are considered, each with two-axis tracking systems. Although this is the most expensive option, it is also the most efficient, and recent declines in the price of tracking systems has made it more economically viable [262].

In this model, it is assumed that all the electricity generated by the solar PV plant is exported to the national grid. The total amount of electricity (in TWh) exported to the grid in a year for each scenario is given in Table 7.3. HUS has the highest electricity production capacity of 9.68 TWh per annum, followed by MUS and then LUS with annual productions of 4.84 TWh and 2.42 TWh, respectively.

Table 7.3 Annual electricity available for export to the national grid for the different uptake Scenarios.

Scenario	PV size (m^2)	Number of panels	Amount of electricity generated and exported to grid (TWh)
LUS	4,340,479	2,231,887	2.42
MUS	8,680,947	4,463,768	4.84
HUS	17,361,896	8,927,537	9.68

The values given in Table 7.3 are totals over one year. However, due to variations in climatic conditions over the year (different levels of solar radiations for horizontal and tilted panels during different days/months), the amount of electricity available each month may be different (See Figure 7.3 and Figure 7.4). It should be noted that daily solar radiation on horizontal surface is the quantity of solar radiation received on a horizontal surface on an average day at the location, in kWh/m^2/day while daily solar radiation on the plane of the panels is the average daily solar radiation received on a tilted surface at the location, in kWh/m^2/day.

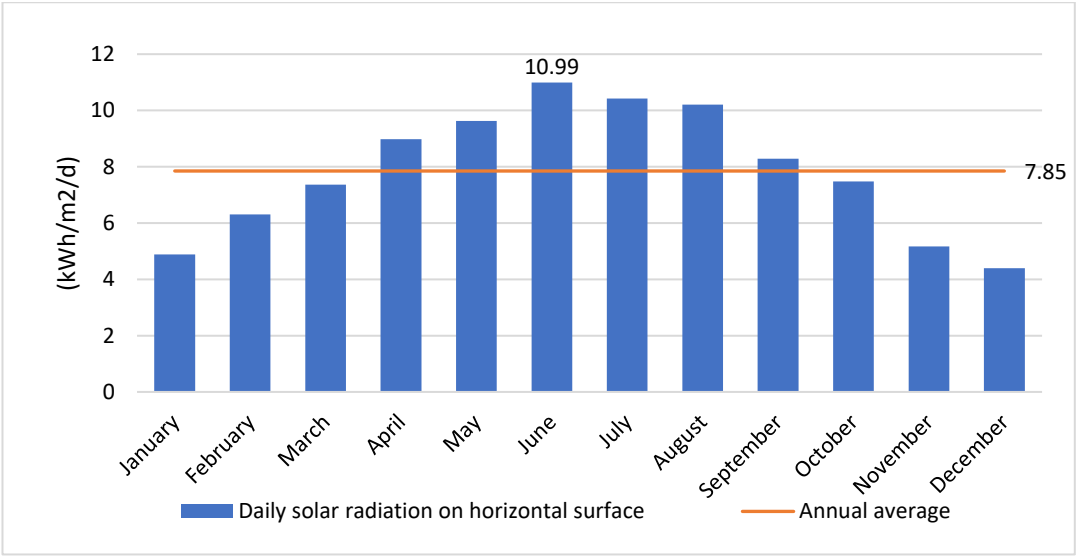


Figure 7.3 Daily solar radiation on horizontal surface and annual average.

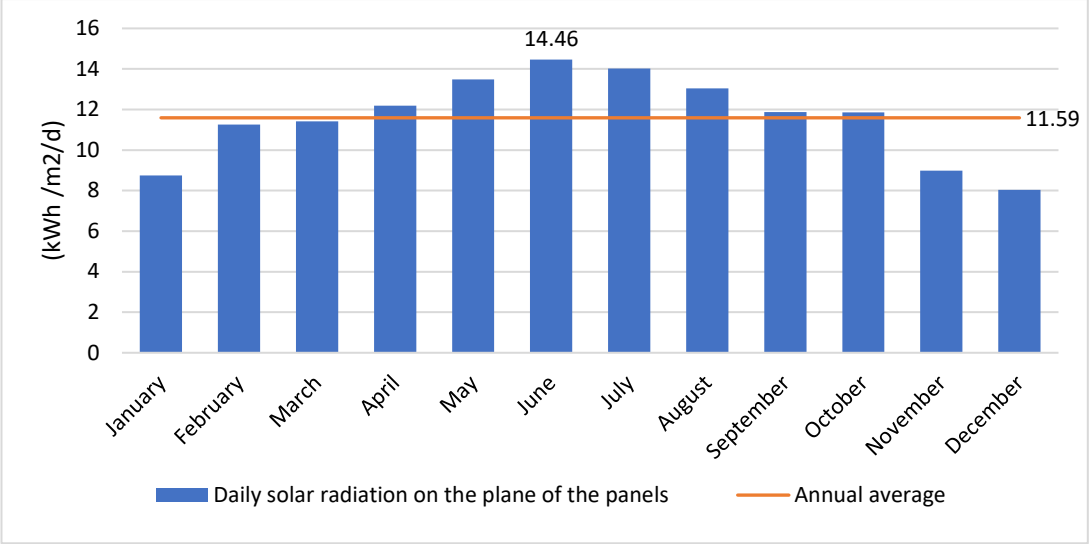


Figure 7.4 Daily solar radiation on the plane of the panels and annual average.

Figure 7.5 provides a breakdown of the available electricity each month in the three scenarios. In each scenario, the month of June provides the maximum amount of electricity for export to the national grid, an increase of almost 50% compared to December. For example, in LUS, 156 GWh of electricity in December rises to 235 GWh in June. Similarly, in HUS, 625 GWh of electricity in December reaches 939 GWh in June. This is because the daily solar radiations for both horizontal and tilted solar panel layouts is at its peak (10.99 and 14.46 kWh/m^2/day, respectively) in June.

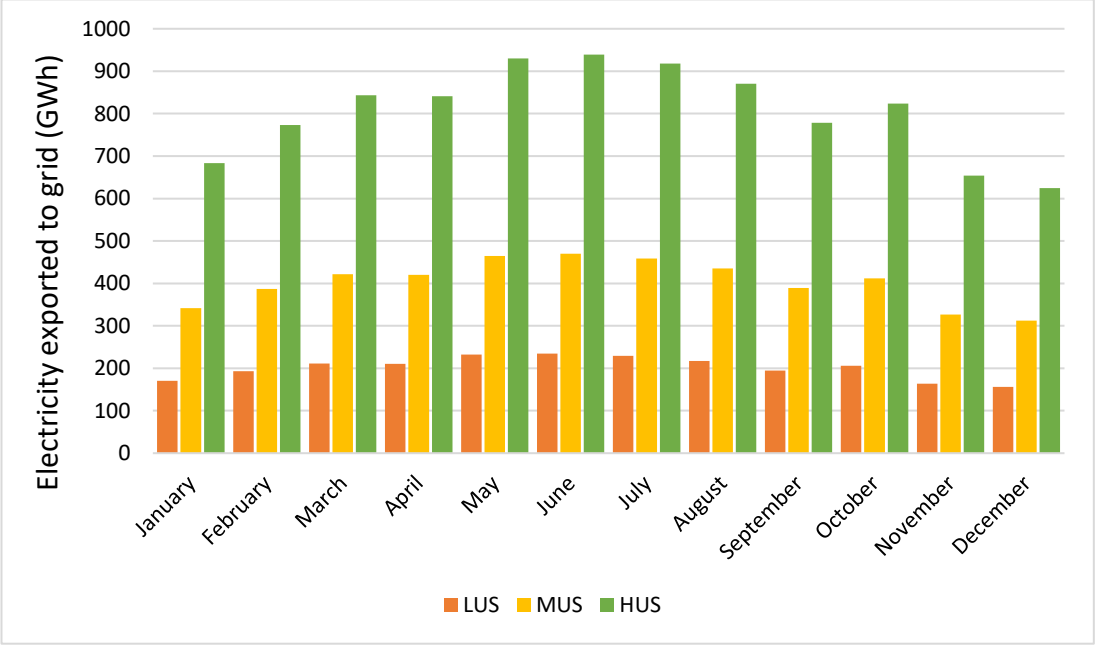


Figure 7.5 Monthly amount of exported production to grid (GWh) for LUS, MUS and HUS.

7.3.1.1 Cost Estimation for the Solar PV Plant

As solar PV has matured as a technology, total costs associated with solar plants have decreased, with some components showing significant reductions. For example, between 2010 and 2020, cost reductions in modules and inverters accounted for 61% of the fall in global weighted-average total installed cost [274]. However, regional cost differences still exist, and the total installed cost of solar PV plants varies by country. The Russian Federation has the highest total installed cost of $1889/kW, India has the lowest at $596/kW, and the total installed cost in KSA is $1008/kW, slightly above the global average of $883/kW [274].

In Model 1, the overall cost of installing a PV based solar power plant depends on three types of costs: initial cost, periodic cost, and annual cost (See eq. (3.4)).

The initial cost for the base scenario of LUS was estimated at $1000/kW based on the total installed cost of $1008/kW for KSA [274]. However, it is anticipated that the per kilowatt cost of electricity generation will decrease as the plant's power capacity increases [273], and, according to the National Renewable Energy Lab (NREL), the decrease can be up to 10% [275]. Therefore, for MUS and HUS, the initial cost was estimated at $900/kW (10% less than in LUS) and $800/kW (10% less than in MUS). A major proportion (~70%) of the initial cost is attributed to the power system followed by the balance of system, which accounts for approx. 23% of the initial cost. These are the most expensive elements, as the feasibility study, engineering, and development comprise less than 1% of the total initial cost [188]. Inverter replacement was assumed to be the only periodic cost, as inverters are required to be replaced every ten years. The cost of inverter replacement was estimated as $190 per kW [275]. Similarly, operation & maintenance costs are expected to be incurred annually, and these were estimated at $10.4 per kW per year [262]. Finally, following guidance from IEA, the project decommissioning cost was estimated at 10% of the initial cost of the plant [276].

These estimates were fed as inputs to the RETScreen software to generate the total initial, periodic, annual, and end of life costs for the proposed plant in each scenario. These were then totalled to generate estimated overall costs for LUS, MUS and HUS. The total installation cost of the proposed Model 1 PV plant in each scenario is shown in Table 7.4; these indicate that the plant would cost approximately $1 billion (LUS), $1.8 billion (MUS), or $3.3 billion (HUS) to install, depending on the scenario.

Table 7.4 Initial and periodic cost breakdown of the PV solar plant in the different scenario (in USD).

Type of Cost	Cost Component	% of initial cost	Cost ($)		
			LUS	MUS	HUS
Initial	Feasibility Study	0.25%	1,925,000	3,465,000	6,160,000
	Development	0.19%	1,463,000	2,633,400	4,681,600
	Engineering	0.17%	1,309,000	2,356,200	4,188,800
	Power System	69.49%	535,073,000	963,131,400	1,712,233,600
	Balance of System	22.90%	176,330,000	317,394,000	564,256,000
	Miscellaneous	7%	53,900,000	97,020,000	172,480,000
	Total	**100%**	**770,000,000**	**1,386,000,000**	**2,464,000,000**
Periodic	Inverter Replacement (Every 10 years)		146,300,000	292,600,000	585,200,000
	End Project Life	10%	77,000,000	138,600,000	246,400,000
Annual	Operation and Maintenance (Annually)		8,008,000	16,016,000	32,032,000
Total			***1,001,308,000***	***1,833,216,000***	***3,327,632,000***

The cost of electricity production in each scenario was then calculated at 32.26 $/MWh (LUS), 29.91 $/MWh (MUS), and 27.57 $/MWh (HUS) (See Figure 7.6). As was anticipated, the LUS production cost was 8% higher than in MUS and 17% higher than in HUS. This supports the belief that an increase in power capacity leads to lower production costs because more electricity is available for export to the grid [273].

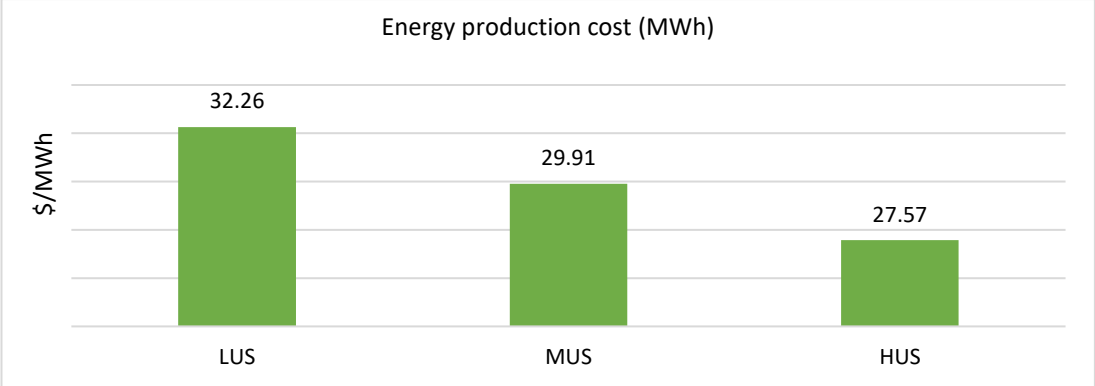


Figure 7.6 Cost of energy production ($/MWh) for the three scenarios (LUS, MUS and HUS)

7.3.1.2 Financial Obligation of the Solar Plant

7.3.1.2.1 Annual Revenue Estimation

There are two main potential revenue sources for Model 1. The first is the export of the generated electricity to the national grid (See eq. (3.3)), while the second is income arising from the reduction in GHG emissions. The latter mainly comprises the financial incentives offered to investors for reducing GHG emissions and carbon trading. Table 7.5 shows the projected revenue for Model 1 in each scenario. The electricity export rate has been estimated as $23.4/MWh, as this is the rate for the Sakaka plant [221]. In this base case, with the existing energy mix, no revenue from GHG reduction is expected.

Table 7.5 Annual revenue from electricity export to grid and GHG emissions reduction. The export rate of electricity is estimated at $23.4/MWh.

Revenue	LUS	MUS	HUS
Electricity export to grid (TWh)	2.42	4.84	9.68
Electricity export revenue in million ($)	**57.10**	**114.20**	**228.42**
Gross GHG reduction – 25 Years ($mtCO_2$)	28.67	55.88	114.53
Gross GHG reduction revenue ($)	0	0	0

7.3.1.2.2 Cash Flows

Table 7.6 illustrates the financial viability of Model 1 in each scenario. As can be seen, in the best-case scenario (HUS), the proposed model has a simple payback period of around 13 years, while in the worst-case scenario (LUS), the period is around 16 years.

Similarly, the model's Net Present Value (NPV) is at least $12.8 million in LUS and could potentially increase to around $692 million in HUS. In MUS, an NPV of around $186 million is estimated. (See eq. (3.8) for NPV estimation).

Table 7.6 Financial viability of the scenarios. The values in brackets represent % increase on LUS.

Financial viability parameters	LUS	MUS	HUS
Internal rate of return – IRR (%)	5.2	6.9	7.5
Simple payback (years)	15.8	13.3	12.7
Equity payback (years)	14.8	13.2	12.8
Net Present Value (NPV) in million ($)	12.85	185.83 *(+1345.67%)*	691.92 *(+5282.73%)*
Annual Life Cycle Savings in million ($/yr.)	0.912	13.19 *(+1345.67%)*	49.01 *(+5282.73%)*
Net yearly cash flow (Year 1) in million ($)	48.62	97.23	194.46
Benefit -cost ratio (BCR)	1	1.2	1.3
GHG reduction cost ($/tCO2)	-0.7	-5.4	-10.72
Energy production cost ($/MWh)	32.26	29.91	27.57

The cumulative cash flows in the three scenarios over the project lifetime (25 years) are shown in Figure 7.7 – Figure 7.9. The dips in cashflow at Year 10 and Year 20 represent the cost of inverter replacement every 10 years.

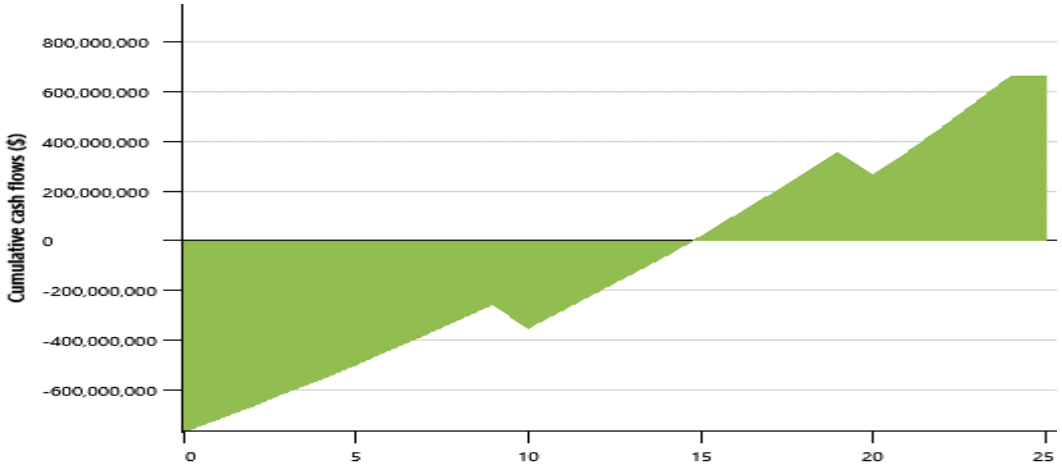


Figure 7.7 Cumulative cash flows of LUS over the project lifetime (25 years)

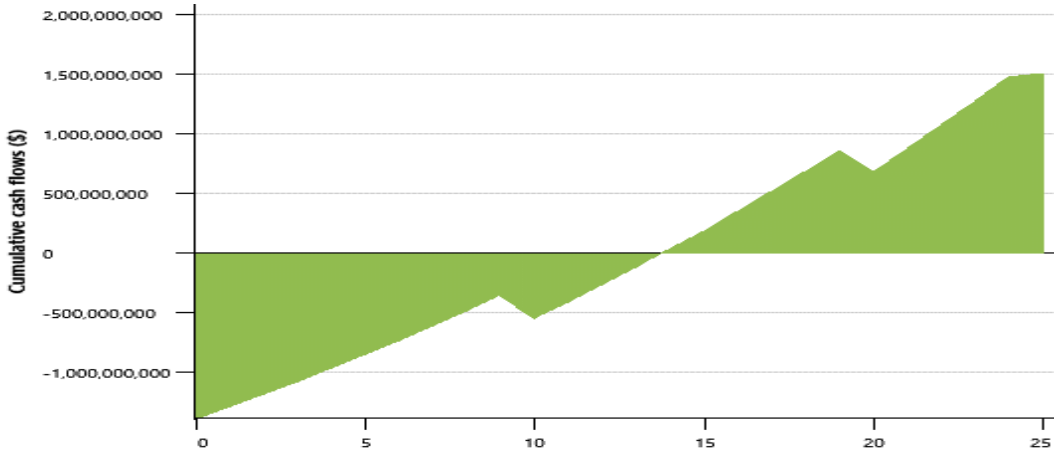


Figure 7.8 Cumulative cash flows of MUS over the project lifetime (25 years).

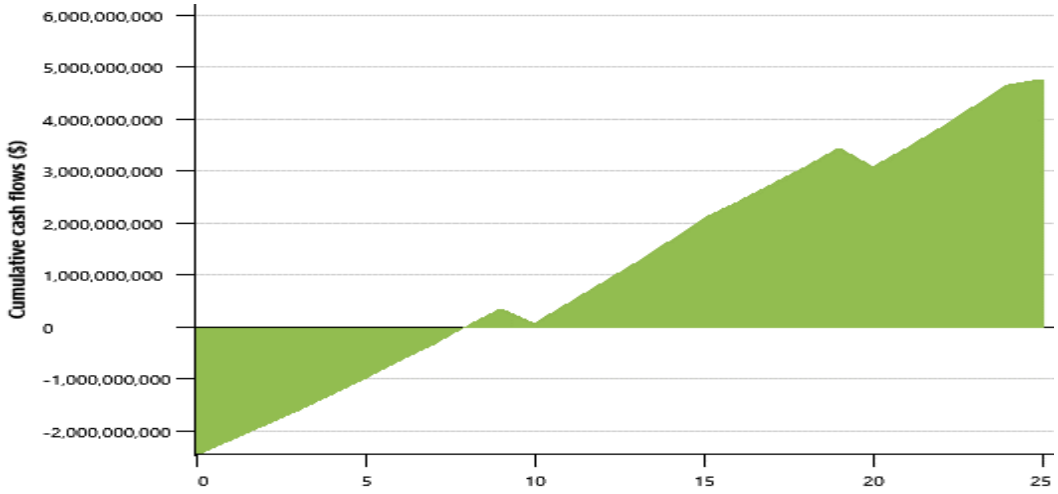


Figure 7.9 Cumulative cash flows of HUS over the project lifetime (25 years)

Figure 7.10 shows the total payback periods (simple payback and equity payback) for the proposed PV project in each scenario over the 25 year life cycle. LUS has the longest payback period (15.8 years) followed by the MUS (14.3 years), while HUS has the shortest period (12.8 years). It is only in HUS that the equity payback period is longer than the simple payback (at 12.8 and 12.7 years respectively), which can be both calculated using eq. (3.6) and (3.7). This is because the project's cumulative cash flows become positive earlier in HUS than in LUS and MUS. This is due to the massive increase in total annual revenue and life cycle savings (an increase of 272 % on MUS and 5,283% on LUS).

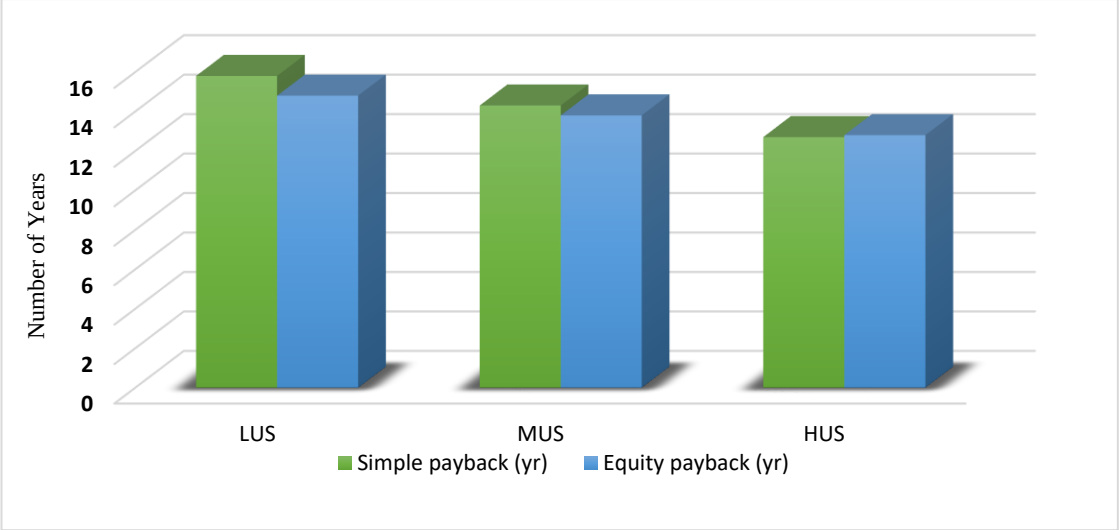


Figure 7.10 Payback period for the LUS, MUS and HUS.

Figure 7.11 shows the variation in IRR, energy production costs (EPC) and electricity exported to the grid (EEG) in the three scenarios. HUS has the highest IRR on equity at 7.5%, while the lowest is 5.2% in LUS. The IRR on equity for MUS is 6.2%, and it can be estimated by eq. (3.9). The energy production cost (EPC) is found to be $32.26 (LUS), $29.91 (MUS) and $27.57 $/MWh (HUS), suggesting that, as the project increases in size, the production costs reduce and become closer to the export rate of 23.24 $/MWh. The figures for electricity exported to the grid (EEG) are 2.4 TWh/year (LUS), 4.8 TWh/year (MUS), and 9.7 TWh/year (HUS).

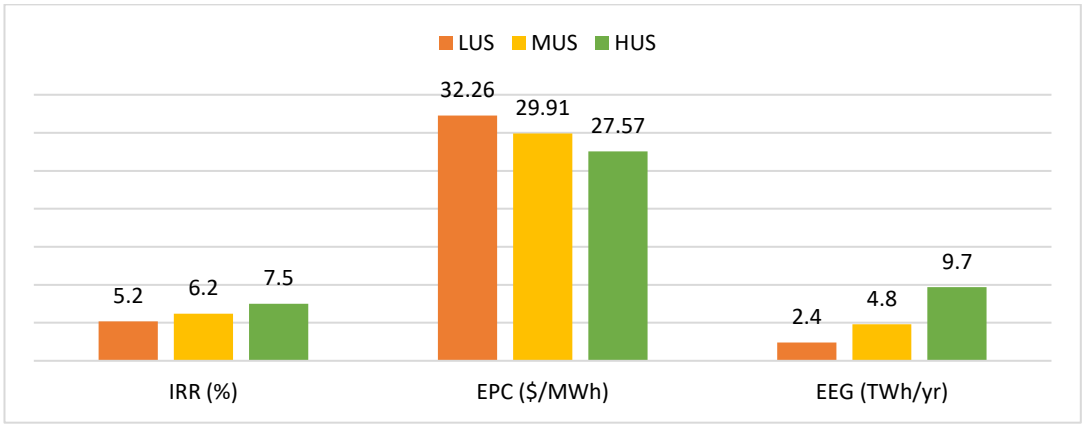


Figure 7.11 Variation of IRR, energy production cost (EPC) and electricity exported to the grid (EEG).

The equity payback period and benefit cost ratio (BCR) obtained are shown in Figure 7.12. The equity payback period for LUS is 14.8 years and decreases by one year for MUS (13.8 years) and two years for HUS (12.8 years). Conversely, the BCR increases, from 1 for LUS to 1.1 and 1.3 for MUS and HUS respectively. (See eq. (3.10) for BCR calculation).

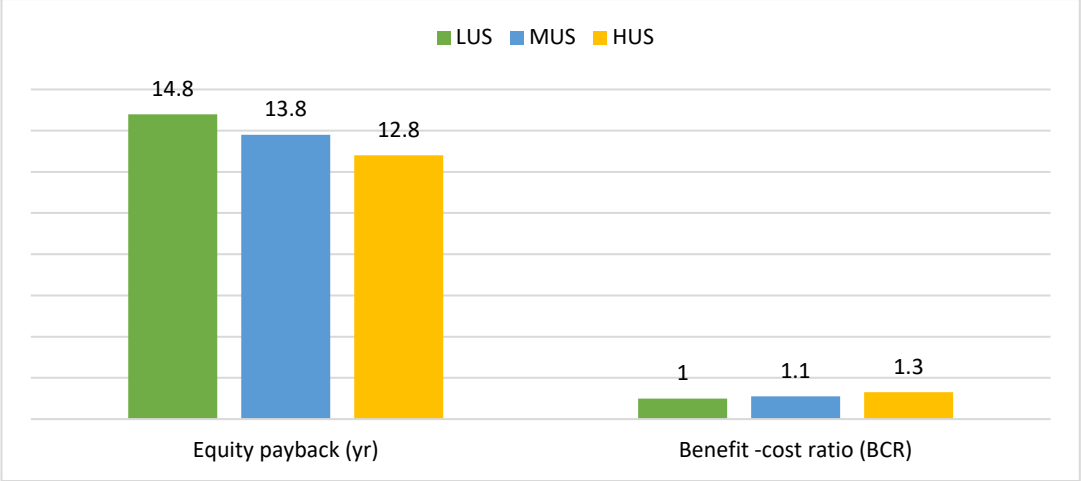


Figure 7.12 Variation of equity payback and benefit cost ratio (BCR)

Based on the analysis in this section, 'Model 1 – PV Plant Only', is expected to be best exploited under HUS, with the lowest IRR of 7.5% among the three scenarios. Similarly, HUS has the shortest simple and equity payback lengths of 12.7 years and 12.8 years respectively. It also has the highest NPV, annual life cycle savings, net yearly cashflows, and BCR, and the lowest GHG reduction costs and energy production costs. However, the model is also viable under LUS and MUS.

7.3.1.3 Emission Analysis of the Plant

Solar energy is one of the cleanest sources of energy (Figure 7.13). Saudi Arabia, currently, generates only 0.3% of its electricity using solar energy. Most of its electricity (60.7%) is generated using natural gas followed by oil (39%) both of which are high producers of greenhouse gas (GHG) emissions [44].

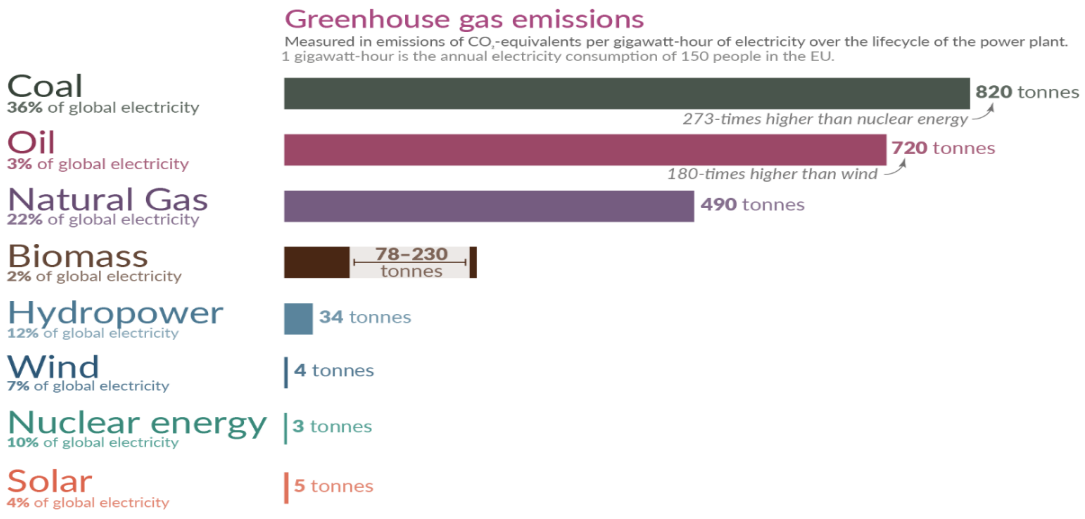


Figure 7.13 Cleanest sources of energy [277]

With the installation of the PV plant proposed in Model 1, the energy mix is expected to change in favour of solar energy, with a resulting decrease in the use of oil. Based on the electricity generated in each scenario, the resultant energy mix for LUS, MUS, and HUS are given in Table 7.7.

Table 7.7 The assumed mix electricity generation

Fuel type	LUS	MUS	HUS
Solar	1.3%	3%	7%
Oil	37.7%	36%	32%
Natural gas	61%	61%	61%

The PV plant is totally powered by solar radiation; therefore, it is assumed that it emits no GHGs. Table 7.8 shows the GHG emissions reductions in each scenario and compares the base case, in which electricity is produced using the existing energy mix, to the proposed Model 1. Gross annual GHG reductions of up to 90.7% can be achieved using Model 1 compared to the base case. This is equivalent to a saving of nearly 3 million barrels of crude oil in LUS and over 10 million barrels in HUS. This also equates to taking over two hundred thousand cars and light trucks off the road in LUS and over eight hundred thousand in HUS.

Table 7.8 GHG emission reduction summary

GHG emission	LUS	MUS	HUS
Base case (tCO_2)	1,371,204	2,677,708	5,050,958
Proposed case (tCO_2)	127,522	249,027	469,739
Gross annual GHG emission reduction (tCO_2)	1,243,682	2,428,681	4,581,219
Gross annual GHG emission reduction (%)	**90.6**	**90.6**	**90.7**
Barrels of crude oil saved	2,892,284	5,648,095	10,653,998
Cars & light trucks not used	227,781	444,813	839,051

7.3.1.4 Sensitivity Analysis of the Solar PV Plant

7.3.1.4.1 Sensitivity of Financial Parameters

To perform the sensitivity analysis on the financial parameters, each input variable in Table 7.1 was varied by ±5% from its base value, while the other input variables remained fixed. However, the project life was varied by ±2 years due to software limitations.

Of all the input parameters, the export rate of electricity is the most important parameter impacting the Net Present Value (NPV). Figure 7.14 provides a sensitivity diagram for NPV vs variation in electricity export rate, and shows that the most sensitive scenario is HUS, where a 5% rise in the electricity export rate results in a huge increase in the final NPV at +25%, compared to LUS and MUS, which have a lesser gap. A reduction of 5% in the export rate of power has a smaller effect on the three scenarios. In conclusion, the export rate of electricity is not only the most critical input parameter, but it also has a beneficial impact on NPV growth.

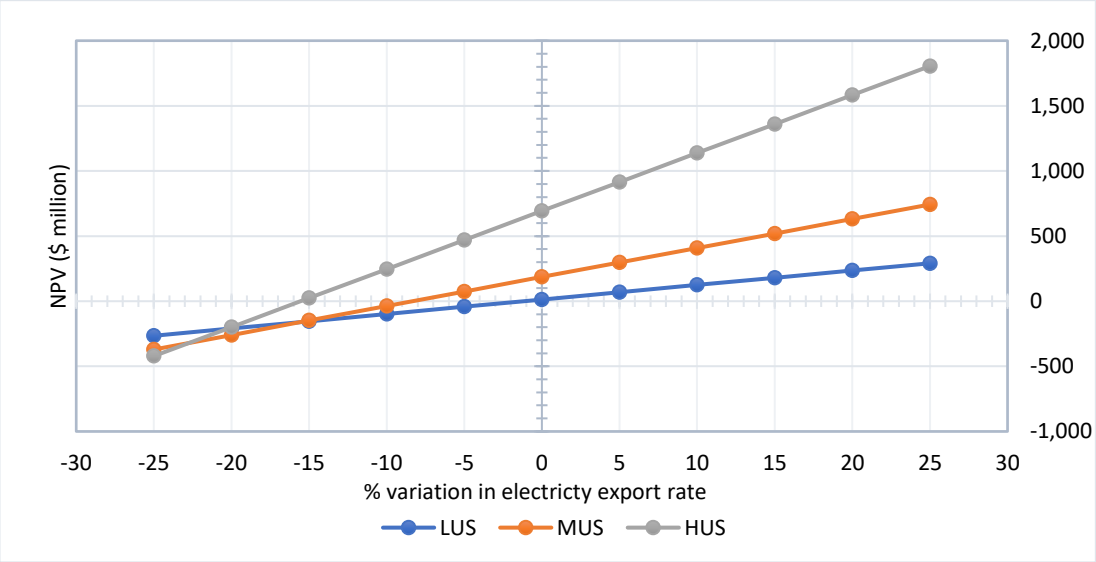


Figure 7.14 Sensitivity diagram for NPV vs variation in electricity export rate.

The next important factor is project life period followed by discount rate, while the inflation rate has the lowest effect on NPV. Figure 7.15 provides a sensitivity diagram for NPV vs variation in project life, and shows that the NPV is negatively affected when the project life is reduced by two years (to 23 years) in the LUS, by four years (to 21 years) in the MUS, and by eight years (to 17 years) in the HUS). In contrast, all three scenarios exhibit a significant positive response when the project lifespan is increased by 2 years from the base value (25 years), which indicates that the length of project life is an important parameter.

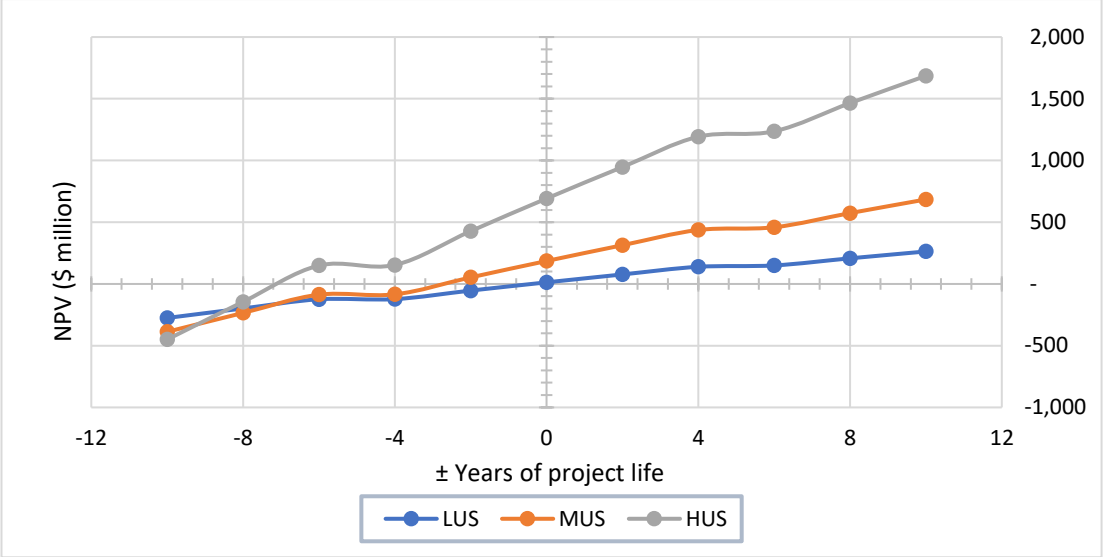


Figure 7.15 Sensitivity diagram for NPV vs variation in project life.

7.3.1.4.2 GHG reduction credit for the solar plant

GHG emissions reduction credits are currently valued at \$0/tonne CO_2. However, KSA is planning to establish a voluntary carbon offset and credit trading platform in the Middle East and North Africa region [278]. Table 7.9 shows the GHG reduction revenue assuming the PV plant would receive GHG emissions benefits of US \$16/ton CO_2, with a 3% escalation rate for 15 years. As the table shows, the GHG reduction revenue in HUS and MUS will be around 237% and 80% higher than in LUS.

Table 7.9 Annual GHG revenue with GHG reduction credit based on a GHG reduction credit rate of 16 \$/tCO2 and a duration of 15 years (in USD).

GHG reduction revenue	LUS	MUS	HUS
Net GHG reduction ($mtCO_2$/yr.)	1.24	2.24 (+79.73%)	4.19 (+237.26%)
Net GHG reduction for 15 yrs. ($mtCO_2$)	18.66	33.53 (+79.73%)	62.92 (+237.26%)
GHG reduction revenue in million (\$)	19.90	35.77 (+79.73%)	67.11 (+237.26%)

Table 7.10 shows a comparison of the GHG reduction revenues for Model 1 both with and without GHG reduction credits for each scenario.

Table 7.10 Financial results for Model 1 both with and without GHG emission reduction credits.

GHG reduction revenue changes	**LUS**		**MUS**		**HUS**	
GHG reduction credit	Without	**With**	Without	**With**	Without	**With**
NPV ($)	12,854,497	**269,658,736**	185,833,751	**687,324,798**	691,923,118	**1,637,885,273**
IRR (%)	5.2	**8.3**	6.2	**9.6**	7.5	**11**
Simple payback (yr.)	15.8	**11.2**	14.3	**10.2**	12.7	**9.2**
Equity payback (yr.)	14.8	**11.2**	13.8	**10.5**	12.8	**8**
Benefit to cost ratio	1	**1.4**	1.1	**1.5**	1.3	**1.7**
Annual lifetime saving ($/yr.)	912,058	**19,132,950**	13,185,361	**48,767,383**	49,093,646	**116,211,985**

Figure 7.16 shows the percentage increase in NPV with GHG emission reduction credits. This additional revenue would have a significant positive effect on the project, with the NPV rising by almost 2000% for LUS, 270% for MUS, and 137% for HUS. In addition, the effect of GHG emission reduction credits on simple payback is a reduction of around 40 % in the LUS (41%), MUS (40%), and HUS (38%) scenarios.

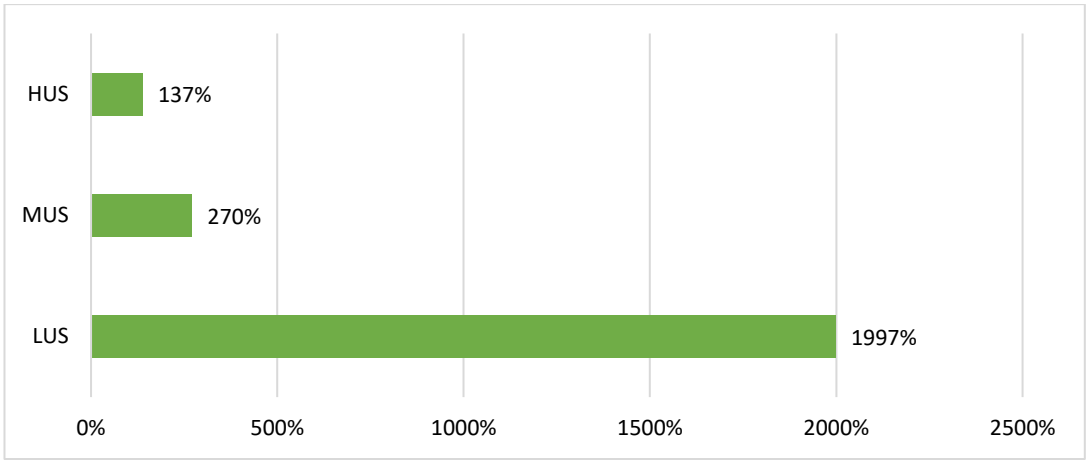


Figure 7.16 Percentage increase in NPV with GHG emission reduction credit.

7.3.1.4.3 Government Subsidy

The impact of government subsidy on IRR is illustrated in Figure 7.17. In this evaluation, the assumed EER, the Electricity Export Escalation Rate (EEER), and the credit for GHG emission reductions were set to \$23.4/MWh, 3%, and \$16/tCO_2, respectively. The impact is evaluated for the assumed subsidies of 0% to 25%. As the figure shows, HUS has the highest IRR (11% - 15.9%) for all assumed subsidy rates.

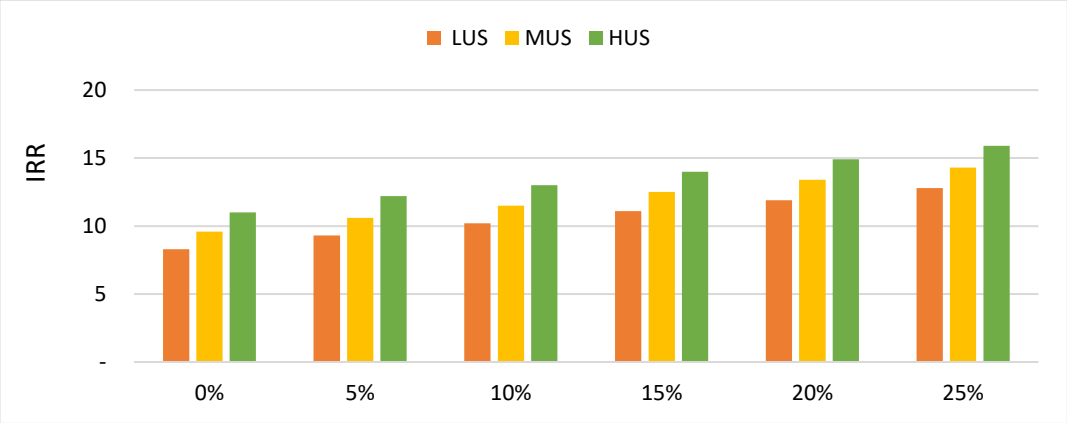


Figure 7.17 Variation of IRR with the assumed percentage subsidies on the total initial cost.

Figure 7.18 shows the variation of BCR with the assumed percentage subsidies on the total initial cost, and demonstrates that the increase for HUS is higher at higher rates of subsidy compared to LUS and MUS. This means that the impact of the subsidy is more prominent at higher rates of subsidy.

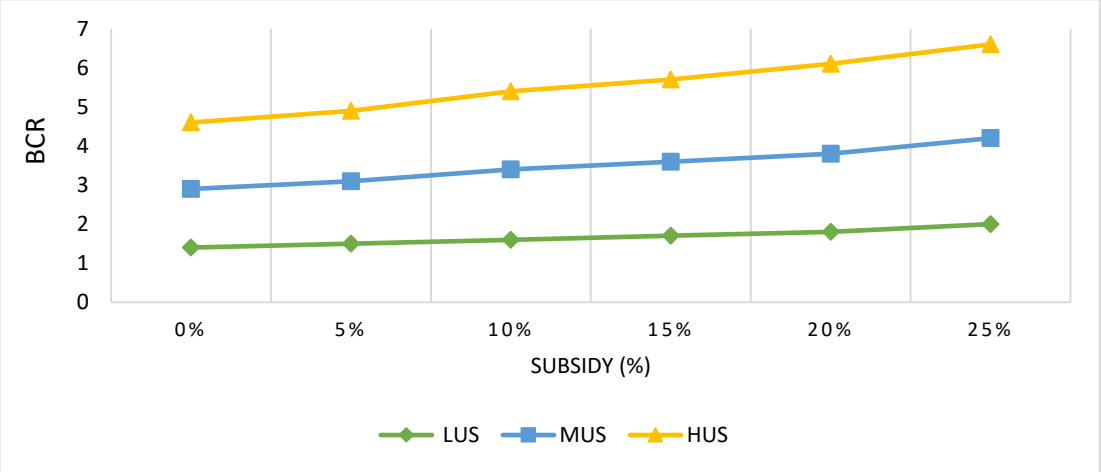


Figure 7.18 Variation of BCR with the assumed percentage subsidies on the total initial cost

The variation of GHG reduction cost with assumed percentage subsidies on the total initial cost is shown in Figure 7.19. The decrease in cost due to GHG emissions reduction is also higher at higher rates of subsidy.

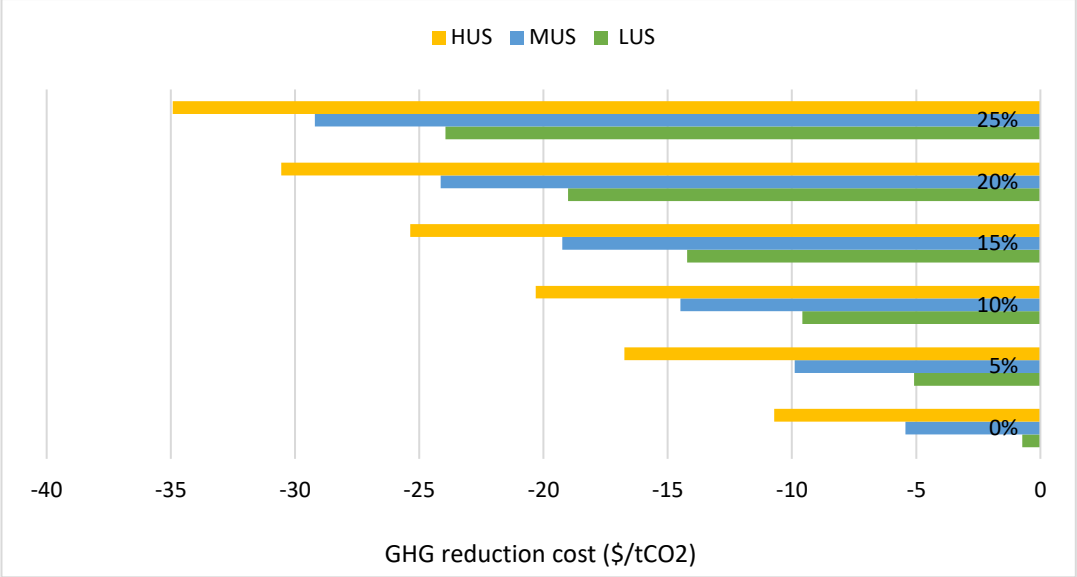


Figure 7.19 Variation of GHG reduction cost with the assumed percentage subsidies on the total initial cost

The EEER (here assumed to be 3%) is the expected average annual increase in the electricity export rate. As the Saudi economy is highly dependent on crude oil exports, recent fluctuations in oil prices are likely to have an impact on future budgets. Subsidies on oil products for residential use have already declined dramatically, and the trend is expected to continue, which will raise the cost of producing power.

7.3.1.5 Risk analysis

The risk analysis displays the relative impact of uncertainty on each parameter related to the financial indicator's variability. The RETScreen software recalculated the energy production cost (EPC) five thousand times using Monte Carlo simulation methods and displayed the results as an impact graph and a distribution graph [279].

Figure 7.20 - Figure 7.22 show the impact of energy production costs in each scenario, and indicate that the variation in the EPC is caused by variations in the different parameters. To evaluate the impact of the different variables on EPC, the initial cost, O&M costs, and electricity exported to the grid were each varied by ±25%. As was expected, an increase in the initial and O&M costs raises the cost of producing energy, while an increase in the amount of electricity exported to the grid lowers the cost.

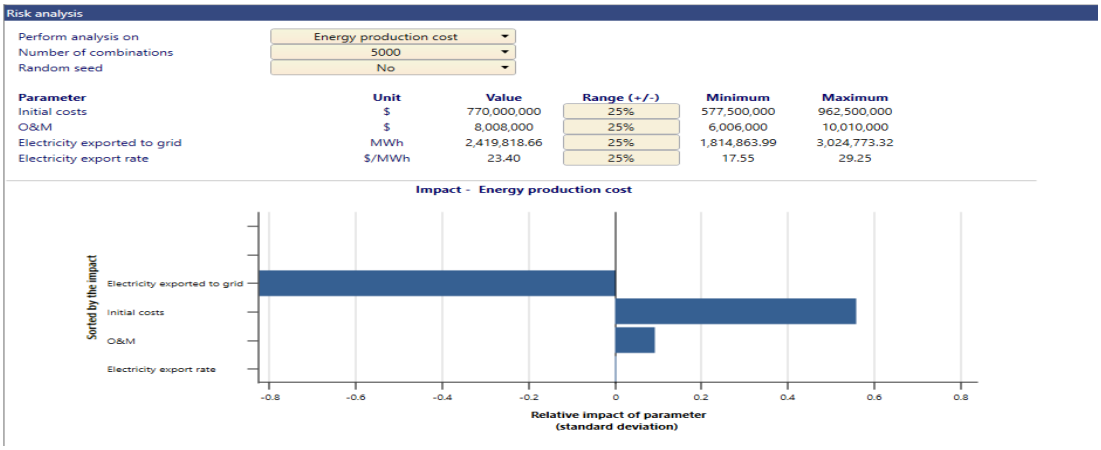


Figure 7.20 Impact of energy production cost for LUS

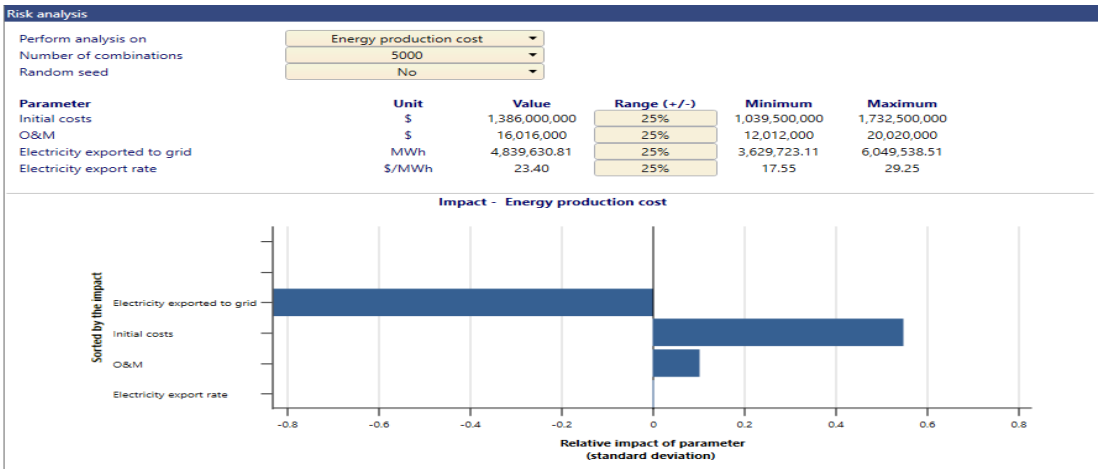


Figure 7.21 Impact of energy production cost for MUS

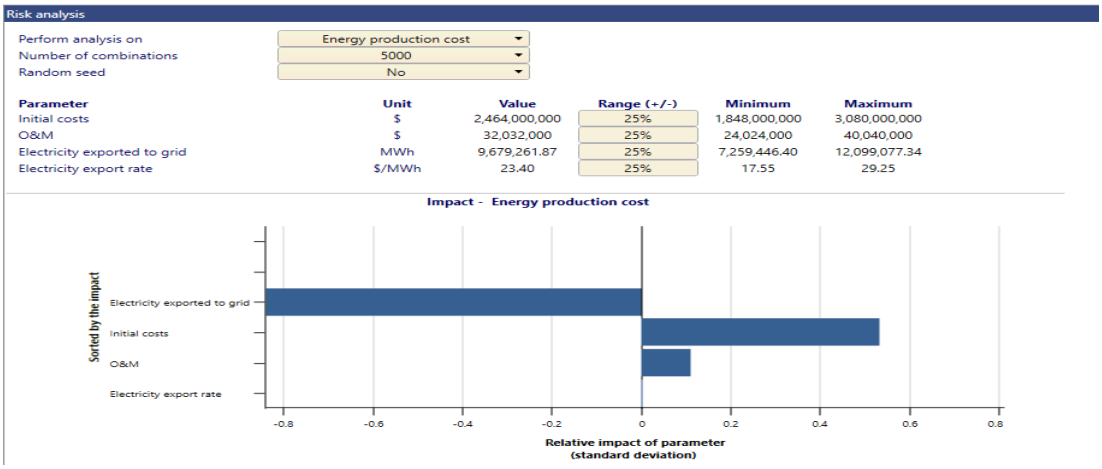


Figure 7.22 Impact of energy production cost for HUS.

Table 7.11 shows the EPC and NPV at different risk levels for all three scenarios. When size of the scenario increases, the median EPC decreases from US$32.2/MWh (LUS) to US$29.9/MWh (MUS) and US$27.5/MWh (HUS). When the risk level increases, the ranges of both EPC and NPV decrease in all scenarios. Considering the

risk analysis, the NPV for 0% risk varies between $-482 million and $608 million (LUS), $780 million and $1,346 million (MUS), and $1,189 million and $2,949 million (HUS). However, the NPV remains positive across all risk levels, meaning that all models (LUS, MUS and HUS) are financially feasible.

Table 7.11 Range of EPC and NPV at different risk of levels for LUS, MUS and HUS

		LUS				MUS				HUS			
		EPC ($/MWh)		NPV ($ million)		EPC ($/MWh)		NPV ($ million)		EPC ($/MWh)		NPV ($ million)	
		Median		Median		Median		Median		Median		Median	
		32.2		11		29.9		182		27.5		685	
Level of risk (%)	**Confidence level (%)**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
0	100	23.2	48	-482	608	21.6	44.3	-780	1,346	20.1	40.7	-1,189	2,949
10	95	27.4	38.15	-222	258	25.5	35.3	-275	669	23.5	32.5	-215	1,642
20	90	28.4	36.6	-168	199	26.3	34	-172	554	24.3	31.3	-9.8	1,411
30	85	29.1	35.8	-136	160	27	33.2	-107	478	24.9	30.6	113	1,265
40	80	29.7	35.10	-110	131	27.6	32.5	-56	420	25.3	30	213	1,149

7.3.2 Stage 2 – PV Plant with EV Charging Stations (Model 2)

In Model 2, the load of charging stations for EVs is considered in addition to the PV power plant. EVs can be charged using either AC or DC electricity, however, while AC is compatible with all charge points, DC is compatible only with rapid or ultra-rapid charge points [280]. In addition, Type 1 or Type 2 connectors are typically used for slow/fast AC charging, while either a Combined Charging Standard (CCS) or CHAdeMO connector type is used for ultra-rapid/rapid DC charging [280]. As discussed in Chapter 6, a 22 kW charger was used in this model and a total parking time of 10 hours (8 AM to 6 PM). The time required to charge an EV using different types of charger is shown in Table 7.12. Charging at 22 kW would take up to 3 hours.

Table 7.12 Charging type and time [280].

Type	Slow AC	Fast AC	Rapid AC	Rapid DC	Ultra-rapid DC
Power	3-6 kW	7-22 kW	23-50 kW	50+ kW	150+ kW
Charging time	8-12 hours	3-6 hours	20-40 minutes	15-30 minutes	~ 10 minutes

Given that it could take up to 3 hours to charge a single EVs batteries from 0 to 100% capacity using the fast-charging type, three periods of charging time were considered to fully charge the entire fleet of EVs within the 10 hour period. On this basis, it was assumed that the total number of chargers in each scenario would be a third of the total number of EVs (See Table 7.13).

Table 7.13 Proposed number of chargers to charge the fleet of EVs during 10 hours of parking time considering a ratio of 1:3 for the number of EVs and number of chargers and EVs.

Scenario	Number of EVs	No. of chargers	Total charging capacity (kW)
LUS	34,965	11,654	256,388
MUS	69,930	23,308	512,776
HUS	139,860	46,615	1,025,530

7.3.2.1 Cost Analysis of the PV Combined EVs Charging Stations Model

RETScreen Clean Energy Software was again used to assess the feasibility of Model 2 (i.e., PV Power Plant and EV Charging Stations). The hardware components of the charging infrastructure are shown in Figure 7.23.

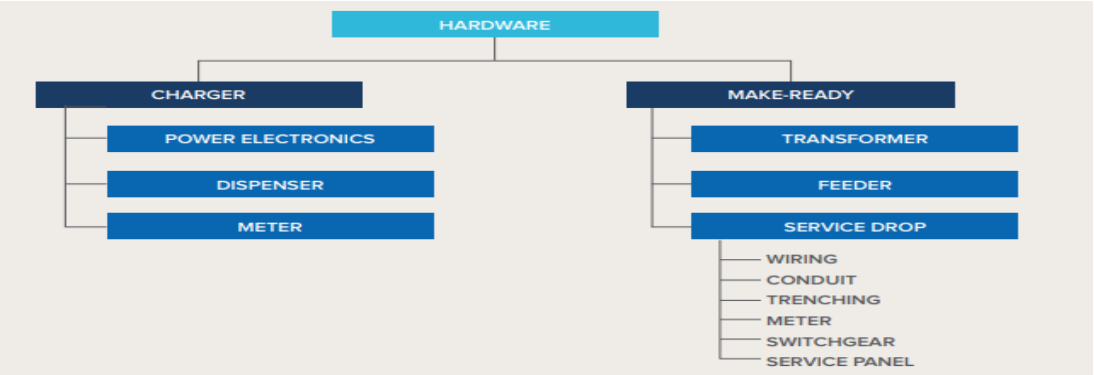


Figure 7.23 Hardware components of the charging stations [281].

As a share of total project expenses, the components of a charging site's hardware and software would account for up to 30% of total costs [281]. The rest of the project's expenditures are for utility grid hardware and different installation aspects, including soft charges. In one proposed budget for a project in California, USA, 11.6% was for conduit, 22.5% was for feeder wire, and 17.8% was for trenching [281]. The remaining 48% of the budget was allocated to various breakers, additional wire, electrical panels, nuts, and bolts, permits and drawings, and line items for installation. However, the average cost of a charger was $558 per kW, with O&M cost of $575 per charger [281].

Table 7.14 shows the cost breakdown for Model 2. The overall cost includes the initial cost of installing the EV charging stations, the periodic costs (mainly due to inverter replacement), the annual costs (mainly O&M), and the cost of installing the PV power plant (as in Model 1). As the table shows, the overall cost for Model 2 increases to $1.19 billion (from $1 billion) in LUS, $2.21 billion (from $1.8 billion) in MUS, and $4.09 billion (from $3.3 billion) in HUS.

Table 7.14 Cost breakdown of Model 2. The overall cost of Model 2 includes the cost of Model 1 and the initial, periodic, and annual costs of EVs charging points (computed using eq. (3.11)).

Type of Cost	Head	% of initial cost	Cost ($)		
			LUS	MUS	HUS
$Initial_{EV}$	Feasibility study	0.05%	71,532	143,065	286,123
	Development	0.05%	71,532	143,065	286,123
	Engineering and labour	51.9%	74,250,478	148,500,955	296,995,539
	Balance of system and miscellaneous	48%	68,670,962	137,341,924	274,677,955
	Total	**100%**	**143,064,504**	**286,129,008**	**572,245,740**
$Periodic_{EV}$	Charger Replacement Costs (Every 10 years)		42,919,351	85,838,702	171,673,722
$Annual_{EV}$	Operation and maintenance	Annually	6,701,050	13,403,250	26,806,500
Model 1 Cost			**1,001,308,000**	**1,833,216,000**	**3,327,632,000**
Model 2 Cost = Model 1 Cost + $Initial_{EV}$ *+* $Periodic_{EV}$ *+* $Annual_{EV}$			**1,193,992,905**	**2,218,586,960**	**4,098,357,962**

7.3.2.2 Financial Analysis of Model 2

The financial viability of Model 2 under LUS, MUS, and HUS is illustrated in Table 7.15. As income can be generated by the charging process (see Section 7.3.2.2.1), the installation of charging stations has a positive impact, and Model 2 is viable under LUS, MUS, and HUS. The IRR are 17.5% (LUS), 19.4% (MUS), and 21.6% (HUS) compared to the respective IRRs of 5.2%, 6.9%, and 7.5% in Model 1. AS the table shows, HUS has the shortest simple payback period (4.4 years) followed by MUS (4.8 years) and LUS (5.3 years). The NPV in LUS is around $1.25 billion, and this more than doubles (to around $2.67 billion) in MUS and more than quadruples (to around

$5.66 billion) in HUS. Similarly, while LUS has annual lifecycle savings of around $89.1 million, this more than doubles (to around $189.5 million) in MUS, increases over four-and-a-half times (to around $401.8 million) in HUS. The BCR for Model 2 is 2.4 (LUS), 2.6 MUS, and 2.9 (HUS). Finally, reducing GHG emissions are expected to result in a reduction of $90, $120, and $111 per tCO_2 in LUS, MUS, and HUS respectively. Hence, emissions reduction is expected to be more useful in the case of MUS.

Table 7.15 Financial Viability of the different scenarios (LUS, MUS, and HUS)

Financial viability parameters	LUS	MUS	HUS
Pre - Tax IRR – Assets (%)	17.5	19.4	21.6
Simple payback (yr)	5.3	4.8	4.4
Net Present Value (NPV) ($)	1,255,947,767	2,672,014,090	5,664,145,706
Annual Life Cycle Savings ($/yr)	89,112,580	189,585,966	401,885,056
Benefit cost ratio (PV plant & EVs charging stations)	2.4	2.6	2.9
GHG reduction cost ($/$tCO_2$)	-90	-120	-111

7.3.2.2.1 Revenue from EVs Charging Stations

Charging stations can generate revenue by charging customers for charging their EVs, using eq. (3.13) to be per kilowatt hour cost of charging EVs is $0.1564. Table 7.16 shows the projected total annual electricity production, the electricity consumed by EVs, the remaining amount exported to grid, and the annual revenue, (assuming an export rate of $23.4/MWh and an electricity export escalation rate of 3%) in each scenario.

Table 7.16 Annual revenue from PV electricity production in Model 2 in each scenario.

	LUS	MUS	HUS
PV electricity production (MWh)	2,419,695	4,839,390	9,678,778
EV consumed (MWh)	842,234	1,684,469	3,368,866
Electricity available for export to grid (MWh)	1,577,460	3,154,920	6,309,912
PV electricity production revenue ($)	**56,620,876**	**114,209,605**	**228,419,184**

The total revenues from Model 2 in each scenario, computed using eq. (3.14), are shown in Table 7.17.

Table 7.17 Total revenue for Model 2 including income from charging stations in each scenario.

	LUS	MUS	HUS
Revenue from charging EVs ($)	151,602,224	303,204,449	606,395,889
Revenue from exporting remaining energy to grid ($)	37,228,079	74,456,133	148,913,945
Total revenue ($)	**188,514,811**	**377,660,582**	**755,309,834**

7.3.2.3 Emission Analysis of Model 2

In order to calculate the total annual amount of GHG emissions reduction per EV in Model 2, values for CO_2 equivalent emissions, fuel efficiency (for EVs and ICEVs) and CO2 tailpipe emissions for gasoline vehicles were identified as follows: In KSA, CO_2 equivalent emissions per kWh is 0.7956 Co2 eq/kWh [282]. For fuel efficiency of EVs, Tesla Model 3 was used as a baseline with fuel efficiency of 14.9 kWh/100 km [212]. For ICEVs, Toyota Prado was used as a baseline with fuel efficiency of 10.6 L of gasoline/100 km [213]. CO_2 tailpipe emissions for gasoline vehicles are 2.29 kg/L [178].

Based on these values, a figure for GHG emissions reduction of 0.833kgCO2eq/kWh was obtained. GHG emissions reduction per charger were then calculated at 0.833 kg Co2eq/kWh * 22 kWh = 18.34 kg Co2. Table 7.18 shows the total annual amount of GHG emissions reduction per EV for Model 2 in each scenario.

Table 7.18 GHG emissions reduction due to charging stations for each scenarios.

Scenario	No. of EVs	GHG emissions reduction kg Co2	Annual GHG emissions reduction tCo2
LUS	34,965	641,258	234,059
MUS	69,930	1,282,516	468,118
HUS	139,860	2,565,032	936,237

Table 7.19 shows the total annual GHG emission reduction from the PV plant and the charging stations, and the barrels of crude oil equivalent not consumed. These figures indicate that a huge amount of oil would be saved by charging EVs via solar PV plants. According to the U.S. Environmental Protection Agency [283], reducing 0.43 metric tons of CO_2 is approximately equivalent to saving 1 barrel of oil.

Table 7.19 Annual GHG emissions reduction for Model 2 in each scenarios. The values in brackets represent percentage increase compared to Model 1.

GHG emission	LUS	MUS	HUS
Annual GHG emission reduction (tCO_2) due to charging stations	234,059	468,118	936,237
Annual GHG emissions reduction (tCO_2) of Model 1	1,243,682	2,428,681	4,581,219
Total Annual GHG emissions reduction (tCO_2) of Model 2	***1,477,741 (+18.81%)***	***2,896,799 (+19.27%)***	***5,517,456 (+20.43%)***
Barrels of crude oil not consumed	3,434,180 (+18.73%)	6,731,887 (+19.18%)	12,821,585 (+20.34%)

7.3.2.4 Sensitivity Analysis of Model 2

7.3.2.4.1 GHG reduction credit

Table 7.20 shows the financial viability in the presence of revenue ($16/tonCO2eq with a 3% escalation rate for 15 years) from GHG emissions reduction. The GHG reduction credit is expected to increase the IRR by at least 9.27% (in MUS) and up to 12.57% (in LUS). GHG reduction credit is also expected to reduce the simple payback period, in the case of LUS by up to half a year. Similarly, in the presence of the reduction credit, the NPV is expected to increase by at least 12.23% (in MUS) and up to 16.28% (in LUS). Similar trends can be seen for the increase in annual lifecycle savings, with LUS benefitting the most from the introduction of GHG reduction credit. Finally, GHG reduction credit will add 0.2 to the BCR in each scenario.

Table 7.20 Financial results for Model 2 after accounting for GHG emission reduction credits

	LUS		MUS		HUS	
GHG Reduction Credit	Without	**With**	Without	**With**	Without	**With**
Pre - Tax IRR – Assets (%)	17.5	**19.7 (+12.57%)**	19.4	**21.2 (+9.27%)**	21.6	**23.9 (+10.64%)**
Simple payback (years)	5.3	**4.8 (-0.5 years)**	4.8	**4.5 (-0.3 years)**	4.4	**4 (-0.4 years)**
Net Present Value (NPV) $	1,256	**1,460 (+16.28%)**	2,672	**2,998 (+12.23%)**	5,664	**6,411 (+13.20%)**
Annual Life Cycle Savings ($ million/yr.)	89,113	**103,627**	189,586	**212,782**	401,885	**454,943**
Benefit cost ratio (BCR) (PV plant & EVs charging stations)	2.4	**2.6**	2.6	**2.8**	2.9	**3.1**

7.3.3 Stage 3 – PV with Charging Stations & Vehicle-to-Grid Model (Model 3)

7.3.3.1 Cost Analysis of Model 3

Model 3 extends Model 2 to include Vehicle-to-Grid (V2G) facilities. V2G has been shown to be beneficial in terms of efficiency of the grid, and it can also generate income for EV owners, reducing the cost of ownership and, therefore, promoting EV adoption [284,285].

As previously stated, charging a single EV from 0% to 100% capacity can take up to three hours. In terms of introducing V2G technology, it is estimated that each scenario would require 10% of the total number of charging stations to be capable of supporting V2G. The proposed number of charging stations, both with and without V2G support, is shown in Table 7.21. These values are based on the Nissan Leaf with a 40-kWh battery capacity and assume that one charging station can support three vehicles.

Table 7.21 Proposed number of charging stations for LUS, MUS, and HUS. 10% of the charging stations are assumed to be capable of supporting V2G.

Scenario	Number of EVs	No. of charging stations	Charging stations with V2G support	Charging stations without V2G support
LUS	34,965	11,654	1,165	10,489
MUS	69,930	23,308	2,331	20,977
HUS	139,860	46,615	4,662	41,953

A cost breakdown for Model 3 based on the number of charging stations in each scenario is shown in Table 7.22. It is assumed that only 10% of charging stations would support V2G technology. Current EV infrastructures need to be upgraded to provide V2G services; therefore, the cost of each charging station with V2G support is estimated at $2,000, while its O&M is estimated to cost 5% of the initial cost [286]. As the table shows, the total cost of Model 3 is around $1.34 billion in LUS. The cost almost doubles to around $2.61 billion in MUS and increases to around $4.9 billion in HUS.

Table 7.22 Cost breakdown of Model 3 in LUS, MUS, and HUS. Model 3 is based on Model 2 with an addition of V2G enabled charging stations (10%)

Type of Cost	Head	% of initial cost	Cost ($)		
			LUS	MUS	HUS
$Initial_{EVV2G}$ [1]	Feasibility study	0.05%	72,697	145,396	290,785
	Development	0.05%	72,697	145,396	290,785
	Engineering and labour	51.9%	75,459,748	150,920,533	301,834,695
	Balance of system and miscellaneous	48%	69,789,362	139,579,684	279,153,475
	Total	**100%**	**145,394,504**	**290,791,008**	**581,569,740**
$Periodic_{EVV2G}$	Charger Replacement Costs	Every 10 years	699,000	87,237,302	174,470,922
$Annual_{EVV2G}$	Operation and maintenance	Annually	116,500	13,725,643	27,450,711
Model 2			1,193,992,905	2,218,586,960	4,098,357,962
Model 3			*1,340,202,909*	*2,610,340,913*	*4,881,849,335*

7.3.3.2 Financial Analysis of Model 3

Table 7.23 shows the financial viability of Model 3 in each scenario. As in Model 2, the installation of charging stations has a positive impact, mainly due to the income generated by charging stations.

Table 7.23 Financial viability of Model 3 in each scenario

Financial viability parameters	LUS	MUS	HUS
Pre - Tax IRR – Assets (%)	23.4	25.2	28.2
Simple payback (years)	4.1	3.8	3.5
Net Present Value (NPV) (million $)	1,947	4,020	8,846
Annual Life Cycle Savings (million $/year)	138	285	627
Benefit cost ratio (PV plant & EVs charging stations)	3.1	3.4	3.9
GHG reduction cost ($/tCO$_2$)	-183	-189	-207

[1] **Initial** EVV2G **:** Initial cost of electric vehicle chargers enabling vehicle to grid model.

As can be seen in Table 7.23, Model 3 is financially viable in all three scenarios. For example, it has minimum IRR of 23.4% (in LUS) and a maximum of 28.2% (in HUS). Similarly, it has a maximum simple payback period of just over four years (in LUS) while the earliest payback is within three-and-a-half years (in HUS). The NPV in LUS is around $1.94 billion which more than doubles to just over $4 billion in MUS and is the highest at around $8.84 billion in HUS. The annual lifecycle savings for LUS are over $138 million which almost doubles to $285 million in MUS and rises to over $627 million in HUS. Model 3 has a minimum BCR of 3.1 (in LUS) and a maximum of 3.9 in HUS. Finally, GHG emissions reduction is projected to decrease the cost by $183, $189 and $207 per tonne of CO_2 in LUS, MUS, and HUS respectively.

7.3.3.2.1 Export Rate for V2G

The revenue from EV charging stations in Model 3 is the same as in Model 2 (i.e. $188,514,811) since the energy mix is the same as in Model 2. Considering the overall revenues and PV electricity production values, the export rate of revenue from V2G is calculated to be $0.077/kWh computed using eq. (3.16).

7.3.3.2.1.1 Revenue Potential for Users

The revenue potential from all the vehicles using V2G technology in each scenario is shown in Table 7.24. As V2G technology is generally based on public charging infrastructure, weekdays have been considered and the assumption is that each charging point provides V2G services for 30 minutes per day can generate $4.84 using eq. (3.19). As a result the potential revenue for an EV user is $ 2.92 based on eq. (3.20).

Table 7.24 Annual revenue potential from V2G in each scenario (in USD).

Scenario	No. EVs	Revenue potential ($)	Revenue potential ($/annum)	Revenue potential ($/annum/EV)
LUS	1165	3,402	884,520	**759.2**
MUS	2331	6,807	1,769,820	
HUS	4662	13,613	**3,539,380**	

The figures in Table 7.24 indicate that overall, at least $884,520 could be earned per year (in LUS) with a potential to earn $3.5 million per year (in HUS). This suggests that a single EV owner could earn nearly $760 per year (SAR 2,850) from exporting surplus electricity to the grid.

7.3.3.2.2 Benefits for the Grid System

The potential for electricity export to grid in each scenario is illustrated in Table 7.25.

Table 7.25 Potential for electricity export to grid in each scenario.

Scenario	No. of EVs	Power capacity (kW)	Potential of electricity export to grid (MWh)
LUS	1165	12,815	112,259
MUS	2331	25,641	224,615
HUS	4662	51,282	**449,230**

The annual revenues from Model 3 are shown in Table 7.26. As can be seen, over $57 million in revenue can be generated from PV electricity production in LUS, and this e doubles (to $114 million) in MUS and quadruples (to $228 million) in HUS.

Table 7.26 The annual revenues from Model 3 (in USD)

	LUS	MUS	HUS
PV electricity production (kWh)	2,419,695,560	4,839,390,036	9,678,778,989
EV consumed (kWh)	-842,234,580	-1,684,469,160	-3,368,866,050
V2G electricity production (kWh)	112,259,400	224,615,160	449,230,320
Electricity exported to grid (kWh)	1,689,720,380	3,154,920,876	6,309,912,939
PV electricity revenue ($)	**57,104,796**	**114,209,605**	**228,419,184**

7.3.3.3 Emissions Analysis of Model 3

7.3.3.3.1 GHG emissions reduction from V2G

If users charge their EVs overnight, using a home charging facility that is fed by the national grid, which is often fuelled by diesel, gas, or coal, then GHG emissions would not be reduced. However, if those users decided to utilise V2G technology to export energy back to the grid, then emissions reductions could be achieved. The potential emissions reduction in each scenario are shown in Table 7.27.

Table 7.27 GHG emissions reduction for V2G (computed using eq. (3.21)).

GHG emissions	LUS	MUS	HUS
Base case (tCO_2)	2,659	5,320	10,641
Proposed case (tCO_2)	247	495	990
Gross annual GHG reduction (tCO_2)	2,412	4,825	9,651
Annual GHG emissions reduction of Model 2	1,477,741	2,896,799	5,517,456
Annual GHG emissions reduction of Model 3	1,480,153 (+0.16%)	2,901,624 (+0.16%)	5,527,107 (+0.17%)
Barrels of crude oil not consumed	3,426,867	6,717,873	12,796,421

As these figures show, utilising V2G to export electricity for only 30 minutes per day for just 1165 EVs in LUS would reduce GHG emissions by 2,412 tCO2 per year, which is equivalent to 5,609 barrels of crude oil. The reduction doubles in MUS (to 4,825), and quadruples in HUS (to 9,651), which suggests that GHG reduction increases as the V2G capacity is increased.

7.3.3.4 Sensitivity Analysis of Model 3

7.3.3.4.1 Increasing in the number of V2G chargers

In order to assess the impact of the number of charging stations with V2G support, sensitivity analysis was performed using three different percentage values (10%, 20%, and 30%) for charging stations with V2G support. The number of charging stations in each case is shown for each scenario in Table 7.28

Table 7.28 Financial viability parameters for each scenario. In the base case 10% of the charging stations are assumed to be capable of supporting V2G, rising to 20% (Case 2) and 30% (Case 3).

Scenario	Number of EVs	No. of charging stations	Base Case (10% of stations support V2G)	Case 2 (20% of stations support V2G)	Case 3 (30% of stations support V2G)
LUS	34,965	11,654	1,165	2,331	3,496
MUS	69,930	23,308	2,331	4,662	6,992
HUS	139,860	46,615	4,662	9,323	13,985

The financial viability of Model 3 based on different percentages of charging stations with V2G support is shown in Table 7.29.

Table 7.29 Financial viability parameters for each scenario. In the base case 10% of the charging stations are assumed to be capable of supporting V2G, rising to 20% (Case 2) and 30% (Case 3).

Financial viability parameters	LUS	MUS	HUS
Base case - V2G charging stations (10%)			
Simple payback (years)	4.1	3.8	3.5
Net Present Value (NPV) ($ million)	1,948	4,020	8,847
GHG reduction cost ($/tCO$_2$)	-183	-189	-207
Case 2: V2G charging stations (20%)			
Simple payback (years)	3.4	3.1	2.8
Net Present Value (NPV) ($ million)	2,645	5,413	11,632
GHG reduction cost ($/tCO$_2$)	-235	-240	-258
Case 3: V2G charging stations (30%)			
Simple payback (years)	2.8	2.6	2.4
Net Present Value (NPV) ($ million)	3,341	6,806	14,418
GHG reduction cost ($/tCO$_2$)	-282	-287	-304

The NPV for each case in each scenario is shown in Figure 7.24. LUS is the most beneficial scenario in terms of NPV, with an increase of 36% on the base case in Case 2 and an increase of 72% from Case 2 to Case 3. By contrast, HUS shows the lowest percentage increases, with 31% on the base case in Case 2 and 62% from Case 2 to Case 3. This suggests that V2G is more attractive in LUS in terms of overall expenses, such as PV plant set-up, charging stations and V2G chargers, and it should be prioritised for deployment in locations with lower EV adoption potential.

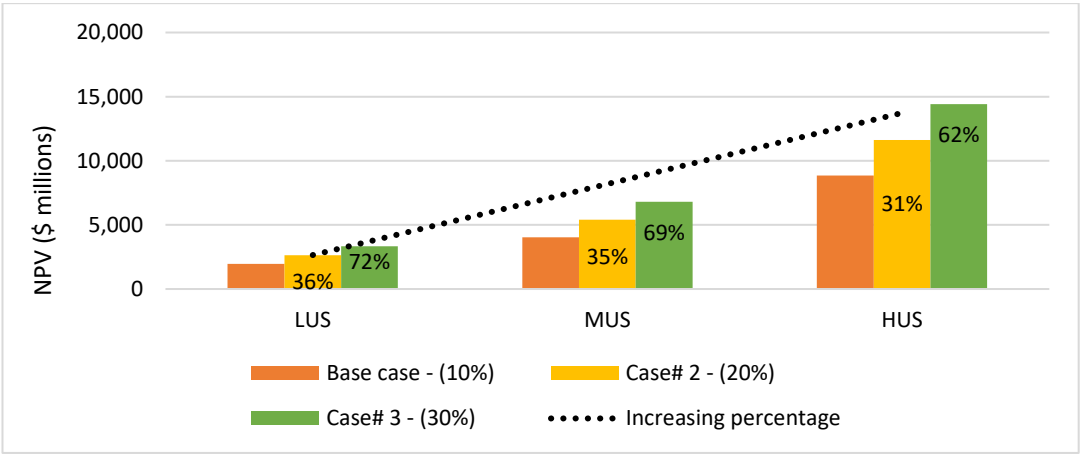


Figure 7.24 NPV in $ millions with the increasing percentage in each scenario in each case.

An increase in the number of V2G supported charging stations is also expected to result in an increase in PV electricity production and the export of electricity to the national grid in each scenario (See Table 7.30).

Table 7.30 Electricity generation in Model 3 with different number of V2G chargers. Base case (10%), Case 2 (20%) and Case 3 (30%).

	LUS	MUS	HUS
PV electricity production (MWh)	2,419,696	4,839,390	9,678,779
EV consumed (MWh)	842,235	1,684,469	3,368,866
Base case - V2G charging stations (10%)			
V2G electricity production (MWh)	112,259	224,615	449,230
Electricity exported to grid (MWh)	1,689,720	3,154,921	6,309,913
Case 2: V2G charging stations (20%)			
V2G electricity production (MWh)	224,615	449,230	898,364
Electricity exported to grid (MWh)	1,802,076	3,604,151	7,208,277
Case 3: V2G charging stations (30%)			
V2G electricity production (MWh)	336,875	673,749	1,347,595
Electricity exported to grid (MWh)	1,914,336	3,828,670	7,657,508

7.3.3.4.2 GHG Reduction Credit

Figure 7.25 shows the changes in IRR when GHG emission credit is added. If it is assumed that the PV plant will get emissions benefits of US $16/ton CO_2 equivalent with a 3% escalation rate for 15 years, the IRR will increase regularly based on the capacity of the power plant. Comparing IRR before and after adding the mission reduction credit reveals that it is most effective in MUS, resulting in an increase of 6.70%, whereas LUS and HUS experience slightly lower increases of 6.40%.

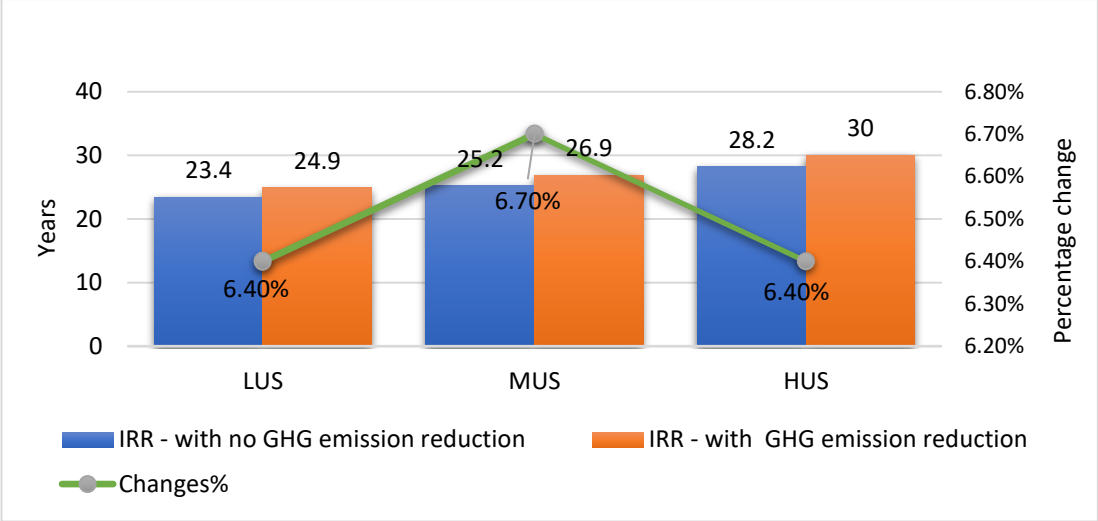


Figure 7.25 The changes in IRR when GHG emission credit is added to Model 3.

Figure 7.26 shows the changes in NPV when GHG emission credit is added. The strongest positive impact is in LUS, with growth of 8.1%; however, in MUS and HUS the response is less positive, indicating that as the power capacity increases, the impact of selling GHG emission credits decreases.

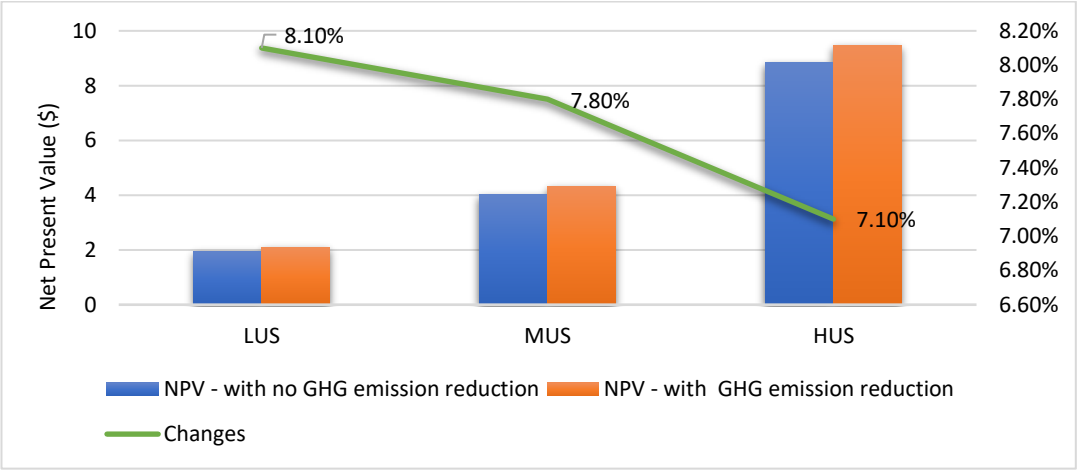


Figure 7.26 The changes in NPV when GHG emission credit is added to Model 3

7.3.3.4.3 Impact of V2G Duration

This section evaluates the impact of increasing the base case duration of V2G (30 minutes) to 60 mins, 90 mins, and 120 mins.

Impact on GHG emissions reduction: As shown in Figure 7.27, increasing the V2G duration from 30 mins to 60 mins increases the GHG emissions reduction by 99%. However, further increasing the V2G duration to 90 mins and 120 mins reduces the increase in GHG emissions reduction to 51% and 34% respectively.

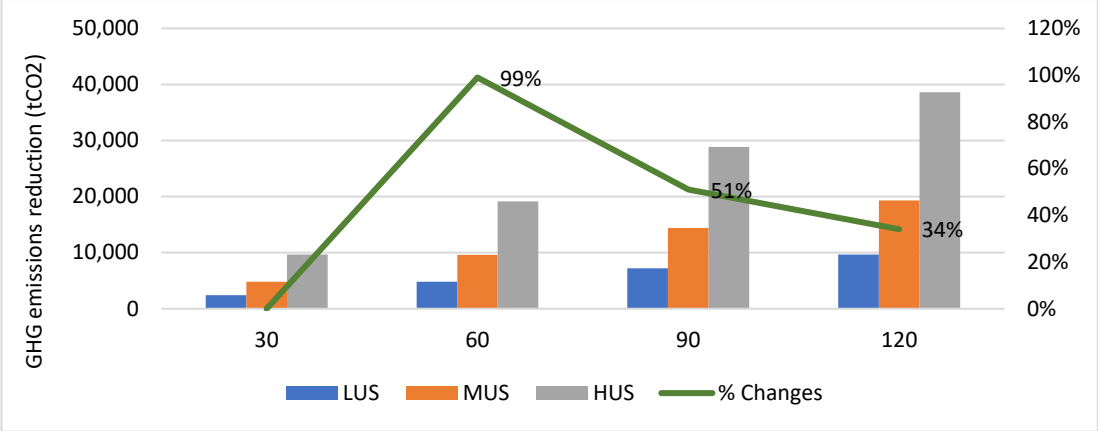


Figure 7.27 The changes in GHG emission reduction for various V2G durations.

Impact on electricity export to grid from V2G: Table 7.31 shows the amount of electricity available for export to the grid based on the different durations of V2G in each scenario. As can be seen, enabling V2G for only 30 mins can make around 112 GWh – 449 GWh of electricity available to the grid. Similarly, 120 minutes of V2G duration, can make around 449 GWh – 1796 GWh of electricity available to the grid.

Table 7.31 The amount of electricity available for export to the grid from V2G in MWh for different durations of V2G.

V2G duration (minutes)	Power capacity (kW)			Electricity export to grid from V2G (MWh/annum)		
	LUS	MUS	HUS	LUS	MUS	HUS
30	12,815	25,641	51,282	112,259	224,615	449,230
60	25,630	51,282	102,564	224,519	449,230	898,461
90	38,445	76,923	153,846	336,778	673845	1,435,291
120	51,260	102,564	205,128	449,038	898,461	**1,796,921**

7.3.3.4.4 Benefit-Cost Ratio for Model 3

As reported above, the overall parking time established in the baseline scenario is 10 hours and the V2G duration is 30 minutes. Figure 7.28 shows the BCR for Model 3 in each scenario and with different V2G durations. As the figure shows, increasing the duration of V2G provides significantly more value to the project, with BCR increasing by, on average, 20% in LUS, and 19.5% and 18.5% in MUS and HUS, respectively.

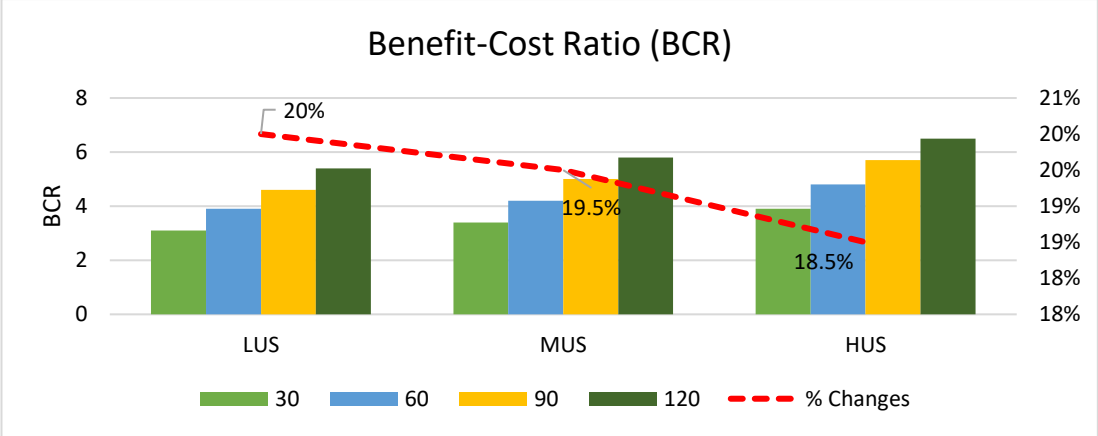


Figure 7.28 Benefit-Cost Ratio (BCR) under different V2G durations.

GHG Reduction Cost: Increasing the V2G duration will also have a favourable effect on the cost of reducing GHG emissions and the IRR (See Figure 7.29 and Figure 7.30). As the figures demonstrate, both the IRR and the cost of reducing GHG emissions drop as the duration of V2G increases.

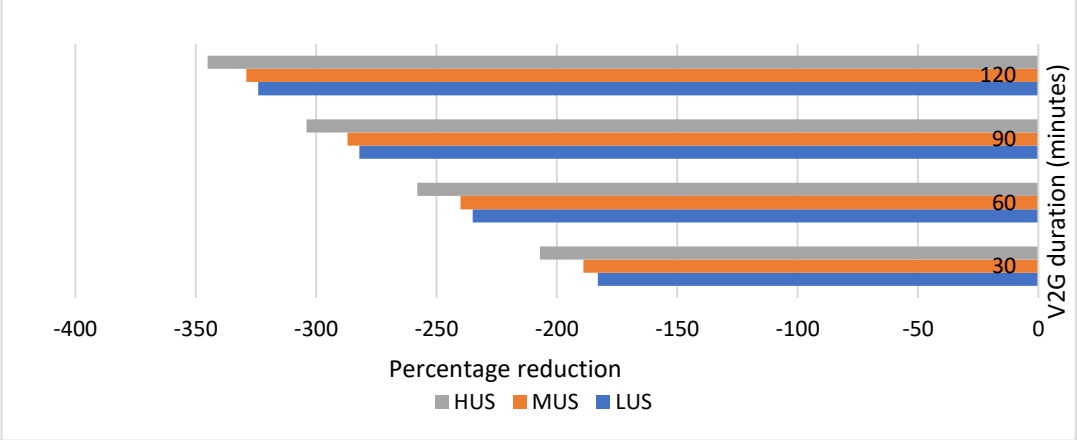


Figure 7.29 GHG reduction cost for different V2G durations.

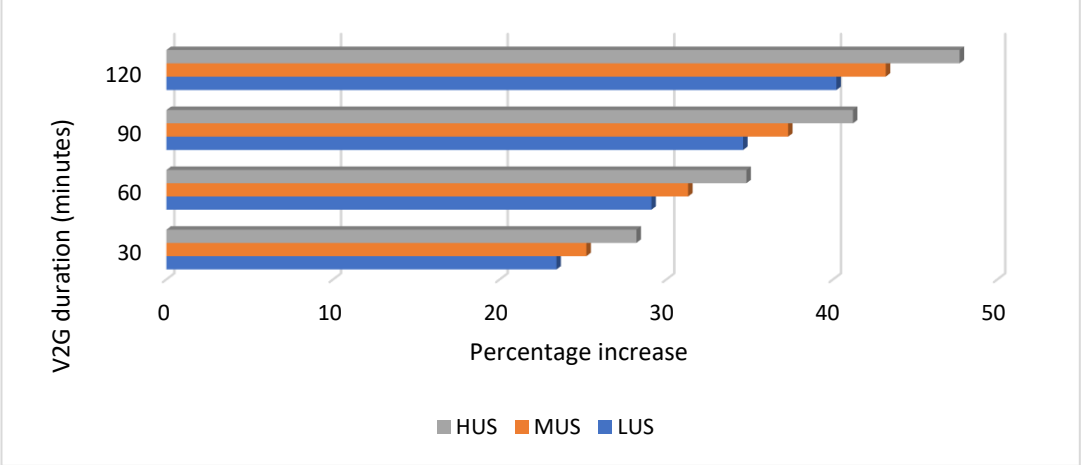


Figure 7.30 IRR for different V2G durations.

7.3.4 Comparison of the three Models

In this section, the cost, emissions, and financial aspects of Model 1, Model 2, and Model 3 are compared in order to decide which model would be most suitable for implementation in Riyadh, the case study city.

7.3.4.1 Cost Comparison of the Three Models

The costs associated with implementing Model 1, Model 2, and Model in each scenario are shown in Figure 7.31.

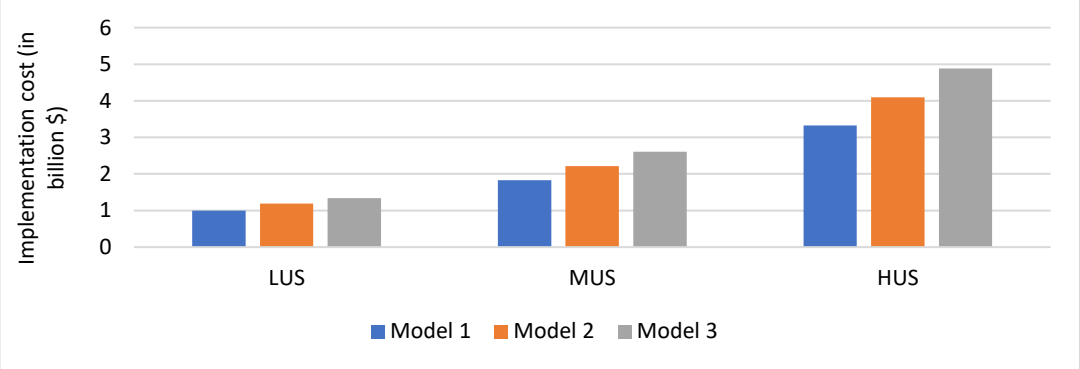


Figure 7.31 Implementation cost ($) of the three models in each scenario (in USD).

As the figure shows, the project can cost anywhere between around $1 billion to nearly $5 billion depending on the scenario and the model. In addition, under any given model, moving from LUS to MUS or from MUS to HUS almost doubles the cost of implementation. However, when moving from Model 1 to Model 2 or Model 2 to Model 3, the rise in cost is less substantial in relative terms. This increase is least prominent in LUS (a difference of nearly $340 million between Model 1 and Model 3) and most prominent in HUS (a difference of nearly $1.5 billion).

In summary, it can be said that, in the context of EV adoption in KSA, in the worst-case scenario of EV adoption (LUS), the project would cost between $1 billion to $1.3 billion, while in the best case scenario (HUS), the project would cost between $3.3 billion to $4.9 billion.

7.3.4.2 Finance Comparison of the Three Models

In this section, the financial viability parameters of Model 1, Model 2, and Model 3 are compared.

Figure 7.32 shows a comparison of the Internal Rate of Return (IRR) of the three models under different scenarios.

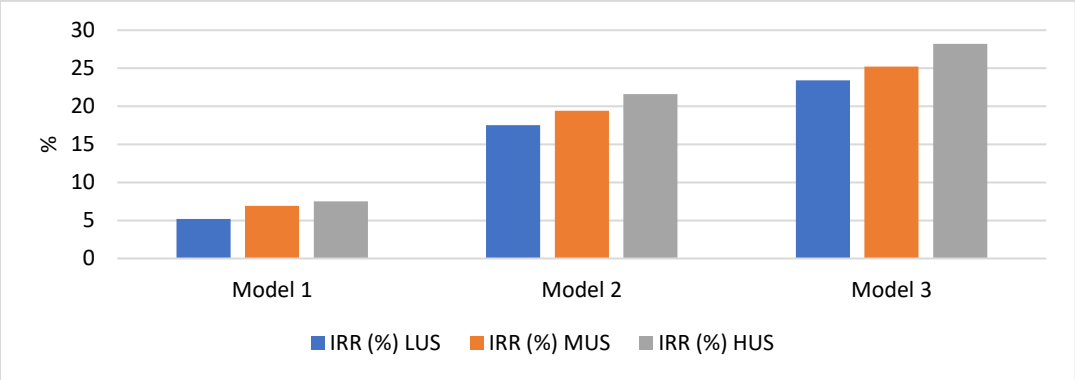


Figure 7.32 The variation in the Internal Rate of Return (IRR) of each model in each scenario.

Figure 7.33 shows a comparison of the simple payback period (in years) for the three models in each scenario.

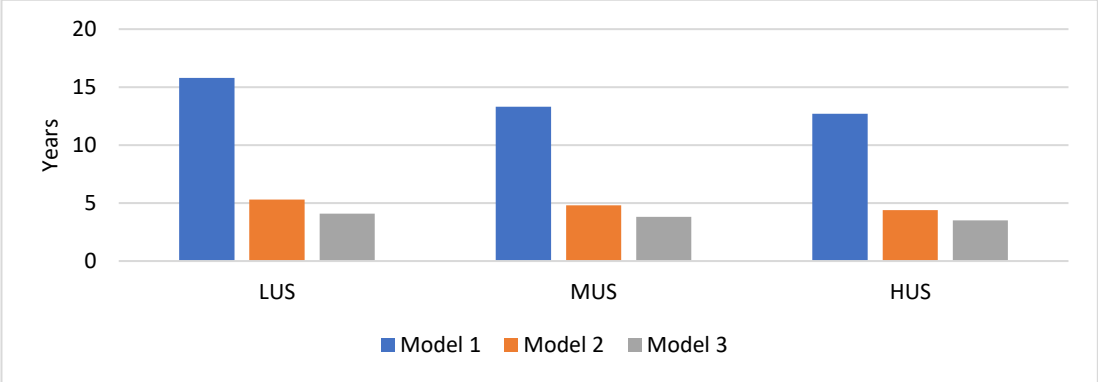


Figure 7.33 Simple payback period (in years) for various models and scenarios.

Figure 7.34 shows a comparison of the NPV ($) of the three models under different scenarios.

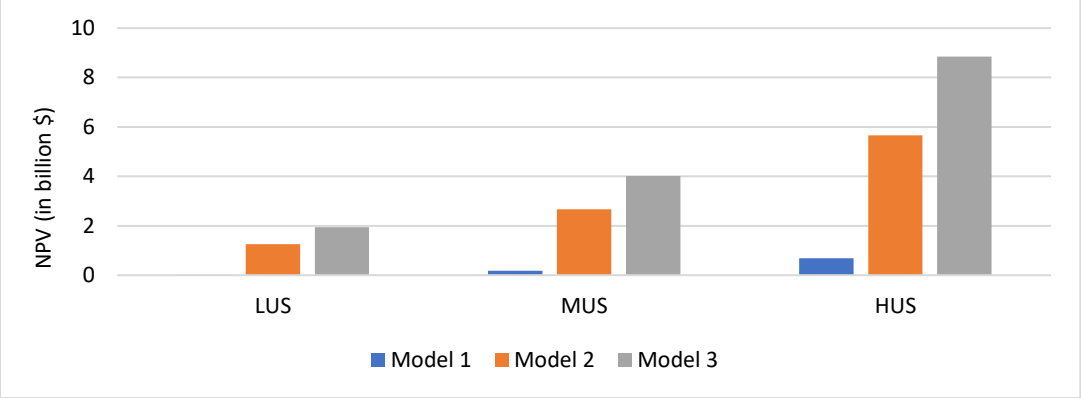


Figure 7.34 NPV of various models and scenarios.

Figure 7.35 shows a comparison of the BCR of the three models in each scenario.

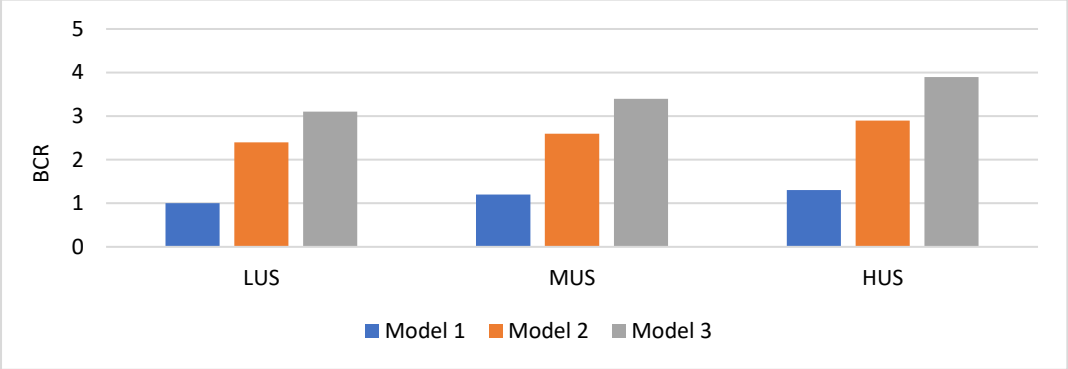


Figure 7.35 BCR of various model and scenarios.

7.3.4.3 Impact of the Emissions

The GHG emissions reductions for Model 1, Model 2, and Model 3, in each scenario are shown in Figure 7.36.

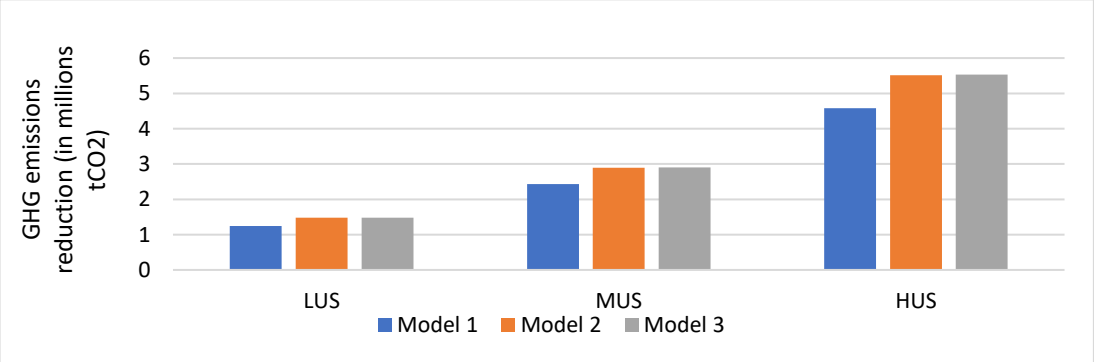


Figure 7.36 Annual GHG emissions reduction for the models in each scenario.

According to the results in Figure 7.36, HUS is the most environmentally-friendly scenario for a given model as it reduces the GHG emissions the most, followed by MUS and LUS respectively. In all scenarios, the emissions reduction seems to improve while moving from Model 1 to Model 2; however, the reduction seems to be negligible when moving from Model 2 to Model 3.

7.4 The Most Suitable Model for Riyadh

The preceding sections have assessed three different models for implementation in Riyadh: Model 1, was based on the PV plant only; Model 2 was based on PV plant combined with EV charging stations; and, Model 3 included the PV plant, EV charging stations, and Vehicle to Grid (V2G) facilities. Detailed cost, emission, financial, and sensitivity analyses were presented for each model under three scenarios: LUS, MUS,

and HUS. The findings indicate that Model 3 would be the most cost-efficient model for implementation in Riyadh in any given scenario, followed by Model 2. In terms of GHG emissions reduction, Model 3 offers a slightly higher reduction compared to Model 2, and a much greater reduction compared to Model 1.

7.5 Conclusions

This chapter has provided a techno-economic analysis of three models to support the adoption of EVs in Riyadh, based on three different scenarios for EV uptake (LUS, MUS and HUS). The results of the analysis indicate that Model 3, which combines a PV plant, with EV charging infrastructure and V2G technology, would provide the greatest financial and environmental benefits; however, these benefits are greatest when there is a higher penetration of EVs in the Saudi market (e.g., MUS and HUS). Therefore, in order to reap the full benefits of solar PV energy and EVs, the barriers and concerns identified in Chapter 4 and Chapter 5 need to be addressed so that a greater number of Saudi drivers opt for EVs over ICEVs. In addition, efforts should be made to promote the benefits of V2G technology, as the findings here indicate that a typical EV user in KSA could expect to earn around SAR 2850 (~$760) per annum from a single EV by exporting surplus electricity to the national grid.

The results obtained in this chapter have implications for EV users, the national grid, the government, and the potential investors who might be considering investing in solar PV power plants in Saudi Arabia. For example, while payments for V2G exports are likely to reach up to $3.5 million per annum, the national grid would benefit by receiving up to 449 GWh of additional electricity per annum. There are also clear potential benefits for the government. For instance, the proposed models have the capacity to reduce emissions by up to 5.5 million tonnes of CO_2, which would contribute to the national goal of achieving net-zero emissions by 2060 [8]. Similarly, implementation of the proposed models could save up to 12.8 million barrels of crude oil, which could instead be sold in the international market for a higher price. Finally, the findings could also be of interest to potential investors, as implementing the proposed model solar PV plant in KSA could help them generate between $57 million - $228 million per annum from the sale of electricity generated using solar PV energy.

The next chapter concludes this thesis by providing answers to the research questions, identifying the limitations of the study and suggesting potential directions for future research on the topic of EVs in Saudi Arabia.

Chapter 8
Conclusions, Limitations, and Future Work

8.1 Introduction

Saudi Arabia has initiated a tremendous shift in its energy policy in order to reduce its dependency on oil and capitalise on its natural resources by using more renewable energy. Due to its hot climate and high levels of solar irradiance, the country is ideally suited for solar PV power, and the government aims to generate around 40 GW of energy from this source by 2030. In addition, due to its international and domestic environmental commitments as well as a desire to reduce domestic oil consumption, Saudi Arabia is seeking to shift its transport sector from traditional ICEVs to more environmentally friendly EVs. In order to support these national aims, this thesis has investigated the use of EVs as a renewable energy carrier for the large-scale integration of solar energy into the Saudi grid system, with the aim of proposing an integrated, cost-effective, and environmentally friendly model to support the large-scale application of EVs in a major Saudi city.

8.2 Answering the Research Questions

The objectives established for this study were:

1. To review the state-of-the-art of EV technologies (e.g., fuel economies, GHG emissions, costs, charging technologies etc.) and the potential impact of the integration of large-scale solar PV into the grid system.
2. To identify recent trends in EV usage and the features which are most significant for end users in Saudi Arabia.
3. To identify the barriers to the widespread adoption of EVs in Saudi Arabia, among both potential and current EV users.

4. To identify and evaluate potential locations in Saudi Arabia for a utility-scale PV system to support EVs at the city level.

5. To propose different models to support EV usage in a major Saudi city, based on the case study location identified in Objective 4.

6. To perform a techno-economic analysis to identify the most effective model for implementation in the case study city, from a financial and environmental perspective.

In order to achieve these objectives, a number of research questions were established as follows:

1. What are the barriers to widespread EV adoption in Saudi Arabia, among both potential and current EV users?
2. What is the potential of solar PV to meet the increased need for electricity to power EVs, and what effect would this have on the national grid?

3. What is the most cost-effective and environmentally beneficial model to adopt when introducing solar PV into the Saudi grid to support EVs at the city level?

Each of these objectives and questions have been explored in this thesis. A summary of the main chapters is presented below along with discussion of the key findings in relation to the research questions.

Chapter 2, the literature review chapter, addressed Objective 1 and the first part of Objective 2 (identifying recent trends in EV usage). It began by exploring Saudi Arabia's energy outlook in terms of both consumption and distribution, with a particular focus on the Saudi national grid. It moved on to examine solar PV application in KSA, the challenges associated with large-scale solar PV integration into grid systems, and the potential benefits for the Saudi grid. The chapter then described the technologies and trends associated with EVs globally, including the main types of EVs, purchase price, charging infrastructure, and the benefits of V2G technology, before going on to consider the requirements for EV adoption in KSA.

Chapter 3 explained the methodology used to investigate the answers to the research questions.

Chapters 4 and 5 addressed the second part of Objective 2 and Objective 3 and answered the first research question i.e. *'What are the barriers to EV adoption in KSA, among both potential and current EV users?'* ***Chapter 4*** provided analysis of an online survey conducted to examine public perceptions of EVs in the KSA and identified the barriers to their adoption from the public perspective. A framework was then created which classified them as either infrastructure, performance, financial, social, or policy concerns and ranked them in order of importance. Respondents ranked the availability of charging stations and maintenance centres highest, but novel barriers in the Saudi context were identified, including concerns about battery safety and performance at high temperatures and the suitability of EVs in desert conditions. EV manufacturers should address these concerns directly if they wish to penetrate the market in KSA and other Gulf states. Concerns were also expressed about EVs posing a potential risk to KSA's oil-based economy; however, this study indicates that EVs would benefit the economy, especially if they were powered by solar PV, as more oil would be available for sale on the international market. The proposed general framework could also be used in other regions or countries, if the analysis was customized accordingly.

Chapter 5 analysed the findings which emerged from a workshop with current Saudi EV drivers hosted by SASO. During this workshop, a focus group was conducted in which drivers were invited to provide feedback on their experience of owning and driving an EV in KSA. They identified the lack of charging stations and maintenance facilities as a major infrastructure issue, while the impact of air conditioning on battery efficiency was the major technical issue. Finally, difficult import regulations and voltage incompatibilities were identified as issues that needed to be addressed through policy interventions.

According to the findings of the survey and the focus group, lack of infrastructure (including charging facilities, maintenance, and sales agencies) and the poor performance of EV batteries during the hot summer season are the most significant barriers to EV adoption in KSA. The lack of infrastructure should be addressed at the government level by speeding up the pace of infrastructure development, while EV manufacturers should take into consideration the poor performance of EV batteries in extremely hot temperatures and rugged terrains.

Chapter 6 addressed Objective 4 and the second research question: ***'****What is the potential of renewable energy to meet the increased need for electricity to power EVs, and what effect would this have on the national grid'?* By assessing the future potential of solar PV energy to provide the load requirements in low (LUS), medium (MUS), and high (HUS) EV uptake scenarios in different cities in Saudi Arabia. Six potential cities were identified as representative of the different regions of the country: Madinah, Sakaka, Riyadh, Bisha, Dammam, and Jeddah. The estimated number of EVs in each city was calculated based on official forecasts of the number of vehicles in 2030 and typical parking patterns were identified from analysis of the public survey in Chapter 4. The demand for charging points was also calculated based on the expected number of EVs. The potential for electricity generation through solar PV in each city was calculated based on solar irradiation levels and other climatic data, and the peak electricity load required to support the estimated number of EVs in each scenario was calculated. The required loads were found to be 770 MW (LUS); 1,540 MW (MUS); and 3,080 MW (HUS). Data from the existing 300 MW PV Sakaka solar power plant was then used to identify the PV sizing (no. of solar panels and size of collection area) and the energy production required to meet the load requirements in each city in the three scenarios.

Under all scenarios, Jeddah was estimated to have the highest number of EVs in 2030 and the greatest peak load requirements, followed by Riyadh. However, given Riyadh's status as a capital city and its potential to attract both government and private investment to support EV adoption, Riyadh was selected as the site for the techno-economic assessment of three models for solar PV-powered EV adoption in the city.

In ***Chapter 7***, Objectives 5 and 6 were addressed and the third research question was answered i.e.: '*What is the most cost-effective and environmentally-beneficial model to adopt when introducing solar PV into the Saudi grid to support EVs at the city level?*' This chapter provided techno-economic analysis of three different models to support the introduction of solar PV to power EVs in major Saudi cities. Model 1, the base case model, considered the installation of a solar PV power plant only; Model 2 combined the PV power plant with EV charging stations; and, Model 3 encompassed a PV power plant, EV charging stations and Vehicle-to-Grid (V2G) technology. For each model, financial and environmental indicators were evaluated, including the associated costs of implementation, IRR, payback period, NPV, BCR, and annual

GHG reductions. Sensitivity analysis was carried out to evaluate the impact of changes in several parameters, including a change in the GHG reduction credit and government subsidy. For Model 3, the impact of different V2G durations was also assessed.

Analysis of the financial and environmental indicators identified Model 3, which combines solar PV plants with EV charging stations and V2G technology, as the best approach for introducing EVs into Saudi grid. This could be implemented at a cost of around $1.3 billion - $4.8 billion depending on the uptake scenario in the year 2030. Although the implementation cost of Model 3 is higher than Model 2 (around $1.2 billion - $4.1 billion), it offers a higher IRR (up to 28.2%) than the other models and has a shorter payback period (ranging from 3.5 to 4.1 years). It also enjoys a significantly higher NPV (up to $8.8 billion) and a significantly higher BCR (up to 3.9). The inclusion of V2G was found to result in significant increases in the expected electricity production in each scenario (from 112 GWh to 449 GWh in HUS), with drivers able to earn nearly $760 per year (SAR 2,850) from exporting surplus electricity to the grid. This would generate total incomes of around $885,000 per year in LUS, and $3.5 million in HUS and help to offset the higher initial costs associated with EVs.

The environmental benefits of Model 3 are similar to Model 2 and include the capacity to reduce CO_2 emissions by around 5.5 million tonnes. This would save the equivalent of 12.8 million barrels of crude oil, providing the government with the opportunity to sell this oil on the open market instead, particularly with current high oil prices. Extending Model 3 to other locations in KSA would multiply the financial benefits while increasing the amount of renewable power generated, thereby contributing to Saudi Arabia's goal of achieving net-zero emission by 2060. If other steps were also taken to promote more sustainable production systems and cleaner electricity grid mixes, this could cut the cost of charging EVs and further reduce GHG emissions.

8.3 Contributions of the Thesis

The main contributions of the thesis are as follows:

1. It takes Saudi Arabia as a case study and analyses the barriers to the adoption of EVs in a major oil-producing nation. It identifies the lack of charging infrastructure and the additional load placed on the national grid as the most important barriers

in this context, with concerns about the impact of EVs on Saudi's oil-based economy, the high costs associated with purchase and maintenance, low resale value, and lack of awareness about EVs also emerging as significant local factors. To the best of the author's knowledge, this is the first study conducted to identify barriers to EV adoption in the context of major oil-producing nations like Saudi Arabia. This contribution is presented in **Chapter 4**.

2. It identifies the current trends in EV usage in Saudi Arabia and the features which are most important for end users in KSA. This is achieved by conducting a workshop with the help of the Saudi Standards, Metrology, and Quality Organization (SASO) where current EV users are invited to provide their inputs. This is the first workshop of its kind conducted in Saudi Arabia to assess the experience of Saudi EV users. Three main themes emerged from the workshop: infrastructure, batteries, and policy, with the lack of public charging infrastructure in KSA hindering long distance travel using EVs, the lack of EV dealerships making it difficult and expensive to maintain EVs, and the current import regulations making it costly to import them. The findings of this workshop can also be used beyond this research to devise policies for EV users in Saudi Arabia. Therefore, it can play an important part in promoting the use of EVs in Saudi Arabia. This contribution is presented in **Chapter 5**.
3. It assesses six different locations in Saudi Arabia for their suitability as potential sites for a utility-scale PV system. The assessment is based on factors such as installation and generation costs, emissions reduction potential, payback period etc. The study identifies the city of Bisha as a suitable candidate for utility-scale PV system in Saudi Arabia, with the potential to generate 2.36 TW of electricity using two-axis tracked systems at a relatively cheap cost of $37.76/kWh and a relatively short payback period of around 20 years. This is a unique study which provides the government and policymakers with useful information about the cost and environmental impact of different types of solar PV plants in different locations of Saudi Arabia, providing a cost-effective way to boost energy production while reducing CO_2 emissions significantly. This contribution is presented in **Chapter 6**.

4. Finally, the thesis provides a detailed techno-economic analysis of EV application in Riyadh. Financial, emissions, cost, and sensitivity analysis are performed

considering different levels of EV usage in the city and using different application strategies. It finds that installing solar PV plants, charging stations, and Vehicle to Grid (V2G) facility is the most cost-efficient and environmentally friendly strategy for EV usage in Riyadh. The major contribution of this chapter is in proposing novel models for the application of EVs in Riyadh and evaluating their financial and environmental impact. To the best of the author's knowledge, these models have never before been envisaged in the context of Saudi Arabia. This contribution is presented in **Chapter 7**.

8.4 Limitations of the Research

This research is subject to a number of limitations that must be considered when reviewing the findings. The following statements might be used to identify the areas concerned:

1. The adoption of EVs in KSA is in the early stages of implementation. There are very few users and almost no infrastructure, particularly chargers enabling V2G. Therefore, any estimates or forecasts relating to the future status of EVs in the country, although based on the best available data, should be understood in this context.

2. The case studies are constrained by the fact that they are predicated on estimates of the load in Riyadh in 2030 based on expected amounts of EVs. Moreover, the load also depends on the behaviour of drivers, such as time of parking or driving range. Although data specific to Saudi drivers was gathered as part of this study, behaviours change according to individual circumstances, and this makes it more difficult to draw firm conclusions about future driving patterns.

3. The novelty of EVs in KSA makes it difficult to account for the long-term effects of V2G on battery performance in a context in which EV owners are already suffering poor battery performance when using air conditioning in the summer season.

8.5 Future Directions for Research

As EVs become more widely established in KSA, this research could be extended in several directions. Some suggestions for future research projects are given below:

1. While solar PV has excellent potential in Saudi Arabia, and several solar PV projects are in different stages of completion in the country, it may be useful to identify and assess the potential of other renewable energy sources, including wind and biomass, to power EVs. This may enable a version of Model 3 to be adopted in other locations and would help KSA meet its ambitious renewable energy adoption targets.

2. The same study should also be performed in other locations in KSA with greater expected numbers of EVs in 2030, such as Jeddah, or with greater solar irradiation, such as Bisha. These results could be compared to those obtained for Riyadh in this study to determine how much of the country could be serviced by the proposed model, or a variation of it.

3. On a related topic, Makkah experiences extremely heavy traffic during the holy month of Ramadan and Hajj season, which results in inconvenience for both pilgrims and residents and increases CO_2 emissions. The feasibility of introducing solar-powered mass transportation systems using a similar model to that proposed here should be investigated as a potential solution.

4. In the current study, it is assumed that EV drivers have no effect on the power market price, thus the price is assumed to be fixed. However, in a future study, variables rates based on peak and off-peak hours can be considered.

5. It is important to establish a national economic evaluation of adopting EVs and integrating them into the grid as decentralised energy storage. This was beyond the scope of this study, but its findings could be discussed with various parties, such as the Ministry of Energy, Saudi Electricity Company, and SASO, in order to unify efforts to create policies and initiatives to support EVs while mitigating their impact on the grid.

6. NEOM city, in the northwest of KSA, is being planned based on futuristic concepts and ideals of 100% clean energy generation using solar and wind energy [287]. One of the highlights of the city is the ambitious The Line, which is a 200 m wide and 170 km long region which is expected to accommodate 9 million people. It is envisaged as a zero-emissions city, with no roads or cars, and all its energy needs are expected to be met by renewable energy sources [288]. The

implications of integrating renewable energy sources like solar PV and wind energy into the grid as set out in this research can be extended to ensure any potential problems arising from integrating renewable energy sources into the grid on a large-scale grid are mitigated early.

Saudi Arabia is implementing ambitious plans to increase renewable energy production, particularly from solar PV, and to promote the widespread adoption of EVs. This study has examined the adoption of EVs within the Saudi context and the effect this will have on the national grid in low, medium, and high uptake scenarios. In light of the challenges associated with large-scale solar integration, it has assessed the potential of EVs to enhance this process and provided a viable model to enable this potential to be realised, which offers both financial and environmental benefits.

References

[1] A. AlGhamdi, “Saudi Arabia Energy Report” King Abdullah Petroleum Studies and Research Center KAPSARC., Riyadh, Sau. Ara., Rep. no. ks-2020-dp25, 2020.

[2] Statista, “Electricity consumption per capita worldwide in 2021,” *Statista Data* [Online], Jul 2022. Available: https://www.statista.com/statistics/383633/worldwide-consumption-of-electricity-by-country/. [Accessed: 10-May-2023].

[3] J.-P. Favennec, “Economics of Oil Refining,” in *The Palgrave Handbook of International Energy Economics*, Hafner, M., Luciani, G., Ed.: Palgrave Macmillan, Cham, 2022, pp. 59-74.

[4] J. Lelieveld, K. Klingmüller, A. Pozzer, R. Burnett, A. Haines, and V. Ramanathan, “Effects of fossil fuel and total anthropogenic emission removal on public health and climate,” *Proc. Natl. Acad. Sci.,* vol. 116, no. 15, pp. 7192-7197, Mar 2019.

[5] H. M. Al-Torkistani, M. A. Salisu, and K. A. Maimany, “Modeling a sustainable Saudi Arabian economy: the real issues,” *Int. J. Sustain. Dev. World Ecol.,* vol. 23, no. 2, pp.186-193, Nov 2016.

[6] G. Al Zohbi and F. G. AlAmri, “Current situation of renewable energy in Saudi Arabia: Opportunities and challenges,” *J. Sustain. Dev,* vol. 13, p. 98, Mar 2020.

[7] C. Malek (2022, Apr. 16), *How solar power is aiding energy transition in Saudi Arabia and other Arab Gulf States, Arab News* [Online]. Available: https://www.arabnews.com/node/2064541/saudi-arabia. [Accessed: 18-Aug-2022]

[8] Saudi & Middle East Green Initiatives (2021, Oct. 23) *HRH the Crown Prince and prime minister announces the Kingdom of Saudi Arabia's aims to achieve net zero emissions by 2060* [Online]. Available: https://www.greeninitiatives.gov.sa/news-and-announcements/hrh-the-crown-prince-and-prime-minister-announces-the-kingdom-of-saudi-arabia-s-aims-to-achieve-net-zero-emissions-by-2060/ [Accessed: 14-Jan-2022].

[9] K. Ullah, G. Hafeez, I. Khan, S. Jan, and N. Javaid, “A multi-objective energy optimization in smart grid with high penetration of renewable energy sources,” *Appl. Energy,* vol. 299, p. 117104, Oct 2021.

[10] N. Odnoletkova and T. W. Patzek, “Data-driven analysis of climate change in Saudi Arabia: Trends in temperature extremes and human comfort indicators,” *J. Appl. Meteorol. Climatol.,* vol. 60, no. 8, pp. 1055-1070, 2021.

[11] R. G. Alajmi, “Factors that impact greenhouse gas emissions in Saudi Arabia: Decomposition analysis using LMDI,” *Energy Policy,* vol. 156, p. 112454, Sept 2021.

[12] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, “A review on electric vehicles: Technologies and challenges,” *J. Smart Cities,* vol. 4, no. 1, pp. 372-404, Mar 2021.

[13] B. Schwartz (2022, Oct.23), *Lucid Motors announces New Factory in Saudi Arabia, Lucid Insider Blog - Lucid Air & Lucid Motors News* [Online]. Available: https://www.lucidinsider.com/2022/05/18/lucid-motors-announces-new-factory-in-saudi-arabia [Accessed: 18-May-2022]

[14] Ceer Motors (n.d). *Driving the Future* [Online]. Available: https://ceermotors.com/about-us/. [Accessed: 18-Feb-2022].

[15] S. Shannak, J. Mikayilov, and R. Dua, “How to Mitigate Transportation Emissions in Saudi Arabia? The Role of Energy Price Governance,” King Abdullah Petroleum Studies and Research Center, Riyadh, Saudi Arabia, 2022.

[16] A. Allouhi, “A novel grid-connected solar PV-thermal/wind integrated system for simultaneous electricity and heat generation in single family buildings,” *J. Clean. Prod.,* vol. 320, p. 128518, Oct 2021.

[17] K. M. Tan, T. S. Babu, V. K. Ramachandaramurthy, P. Kasinathan, S. G. Solanki, and S. K. Raveendran, “Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration,” *J. Energy Storage,* vol. 39, p. 102591, Jul 2021.

[18] A. Farahat, H. D. Kambezidis, M. Almazroui, and E. Ramadan, “Solar potential in Saudi Arabia for southward-inclined flat-plate surfaces,” *Appl. Sci.,* vol. 11, no. 9, p. 4101, Apr 2021.

[19] J. Wang, L. Kang, X. Huang, and Y. Liu, “An analysis framework for quantitative evaluation of parametric uncertainty in a cooperated energy storage system with multiple energy carriers,” *Energy J.,* vol. 226, p. 120395, Jul 2021.

[20] R. Wingert, H. O'Hern, M. Orosz, P. Harikumar, K. Roberts, and T. Otanicar, “Spectral beam splitting retrofit for hybrid PV/T using existing parabolic trough power plants for enhanced power output,” *Solar Energy,* vol. 202, pp. 1-9, May 2020.

[21] M. K. H. Rabaia *et al.*, “Environmental impacts of solar energy systems: A review,” *Sci. Total Environ.,* vol. 754, p. 141989, Feb. 2021.

[22] J. Aghaei and M.-I. Alizadeh, “Demand response in smart electricity grids equipped with renewable energy sources: A review,” *Renew. Sust. Ener. Rev.,* vol. 18, pp. 64-72, Feb 2013.

[23] J. Leadbetter and L. G. Swan, “Selection of battery technology to support grid-integrated renewable electricity,” *J. Power Sources,* vol. 216, pp. 376-386, Oct 2012.

[24] Y. Chen *et al.*, “A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards,” *J. Energy Chem.,* vol. 59, pp. 83-99, Aug. 2021.

[25] Y. Fang *et al.,* "A fully sodiated NaVOPO4 with layered structure for high-voltage and long-lifespan sodium-ion batteries," *Chem,* vol. 4, no. 5, pp. 1167-1180, 2018.

[26] B. Lebrouhi, Y. Khattari, B. Lamrani, M. Maaroufi, Y. Zeraouli, and T. Kousksou, “Key challenges for a large-scale development of battery electric vehicles: A comprehensive review,” *J. Energy Storage,* vol. 44, p. 103273, Dec. 2021.

[27] L. Noel, G. Z. de Rubens, J. Kester, and B. K. Sovacool, *Vehicle-to-Grid*. Switzerland: Springer, 2019.

[28] Y. Zhou and X. Li, “Vehicle to grid technology: A review,” in *2015 34th Chinese Control Conference (CCC)*, Geneva, 2015, pp. 9031-9036.

[29] Lumivero, NVivo 14, Available: https://lumivero.com/products/nvivo/. [Accessed: 10-May-2023].

[30] SPSS statistics - overview, “IBM”, Available: https://www.ibm.com/products/spss-statistics [Accessed: 10-May-2023].

[31] RETScreen, “Natural Resources Canada”, Available: http://www.retscreen.net./ [Accessed: 10-May-2023].

[32] Bp Global. (2022, Jun.) *Downloads: Energy economics: Home* [Online]. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/primary-energy.html [Accessed: 25-Nov-2022].

[33] International Energy Agency. (2020 Aug.), *Saudi Arabia - countries & regions, IEA*. [Online]. Available: https://www.iea.org/countries/saudi-arabia [Accessed: 27-Sep-2022].

[34] EIA. (2022, Jun), *Data source: U.S. Energy Information Administration, International Energy Statistics* [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=709&t=6 [Accessed: 25-Nov-2022].

[35] Saudi Energy Efficiency Center, "Enhancing vehicles energy efficiency in Saudi Arabia," G20 Transport Task Group workshop [Online], Sept 2018. Available: https://theicct.org/sites/default/files/KSA_AlRoge_Enhancing%20Vehicles%20Energy%20Efficiency%20in%20Saudi%20Arabia.pdf. [Accessed: 25-Nov-2022].

[36] J. Blazquez, L. C. Hunt, B. Manzano Gonzalez, and A. Pierru, "The value of saving oil in Saudi Arabia," *Econ. Energy Environ. Policy*, vol.9, no. 1, pp. 207-222, Mar 2020.

[37] B. Fattouh, "Saudi oil policy: Continuity and change in the era of the energy transition," The Oxford Institute for Energy Studies, Oxford, OIES Paper: WPM no. 81, 2021.

[38] Saudi Central Bank. (2022, May 31) *Economic reports and statistics* [Online]. Available: https://sama.gov.sa/en-US/EconomicReports/Pages/YearlyStatistics.aspx [Accessed: 25-June-2022].

[39] E. Jr. (2013, Sep. 26) *German delegation to promote solar power, water desalination* [Online]. Available: http://www.arabnews.com/news/465863 [Accessed: 15-Nov-2022]

[40] J. S. Al-Sughai. (2014, Aug. 2014) *Energy waste costs local economy SR135BN annually* [Online]. Available: http://www.arabnews.com/economy/news/621821 [Accessed 19-jan-2019].

[41] General Authority for Statistics, "Electrical Energy Statistics," Electricity Energy Statistics 2021 datasheet, 2021 [Revised Nov. 2022].

[42] M. Aldubyan, A. Gasim, "Energy price reform in Saudi Arabia: Modelling the economic and environmental impacts and understanding the demand response," *Energy Policy*, vol.148, pp.111941, 2021.

[43] ECRA, "Annual Statistical Booklet for Electricity," Electricity and Cogeneration Authority Riyadh, Saudi Arabia, 2020.

[44] EIA. (2021, Feb.), *Independent Statistics and Analysis U.S. Energy Information Administration* [Online]. Available: https://www.eia.gov/international/overview/country/SAU.

[45] Saudi Press Agency. (2022, Nov. 30) *Minister of energy announces discovery of two new unconventional gas fields* [Online]. Available: https://www.spa.gov.sa/viewfullstory.php?lang=en&newsid=2405523#240523 [Accessed: 26-Jan-2023].

[46] Saudi Electric Company (2017, Dec. 12) *Tariffs & Connection Fees* [Online]. Available: https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx [Accessed 15-Nov-2022].

[47] Saudi Electricity Company, "Annual report 2016," [Online] Dec 31 2016. Available: https://www.se.com.sa/en-us/Pages/AnnualReports.aspx

[48] Xcel Energy, "Overhead vs. Underground, Information about burying high-voltage transmission lines," Information Sheet [Online], Apr 21 2021. Available:

https://www.greenwoodtodenverterminal.com/dist/pdf/Overhead_vs_Underground_High-Voltage_Transmission.pdf

[49] Power Saudi Arabia. *National renewable energy program eProcurement portal* [Online]. Available at: https://powersaudiarabia.com.sa/web/index.html [Accessed: 09-Nov-2022].

[50] O. S. Kalehsar (2019, Feb. 1) *Challenges and opportunities for Saudi Arabia's energy transition from oil* [Online]. Available: https://insidearabia.com/saudi-arabias-energy-transition-oil. [Accessed: 15-Dec-2022].

[51] S. Rehman, "Saudi Arabian geothermal energy resources—an update," in *Proceedings of the World Geothermal Congress*, Bali, Indonesia, 2010, pp.1-6.

[52] C. Frohlich, "Construction of a composite Total Solar Irradiance (TSI) time series from 1978 to present," Physikalisch-Meteorologisches Observatorium Davos, *Switzerland,* 2006.

[53] M. Asif, "Growth and sustainability trends in the buildings sector in the GCC region with particular reference to the KSA and UAE," *Renew. Sust. Energ. Rev.,* vol. 55, pp. 1267-1273, Mar 2016.

[54] S. Rehman and I. El-Amin, "Performance evaluation of an off-grid photovoltaic system in Saudi Arabia," *Energy J.,* vol. 46, no. 1, pp. 451-458, Oct 2012.

[55] A. Almasoud and H. M. Gandayh, "Future of solar energy in Saudi Arabia," *J. King Saud Uni. Eng. Sci.,* vol. 27, no. 2, pp. 153-157, Jul 2015.

[56] Global Solar Atlas (2019, Oct) *Solar Resource Map, Global horizontal irradiation* [Online]. Available: https://globalsolaratlas.info/download/saudi-arabia [Accessed: 26-Mar-2020].

[57] D. Wogan, S. Pradhan, and S. Albardi, "GCC energy system overview–2017," *King Abdullah Petroleum Studies and Research Center: Riyadh, Saudi Arabia,* 2017.

[58] L. El-Katiri, A. Khalid, R. Mills, M. Salman, and R. Ibrahim, "Renewable energy market analysis: GCC 2019," *The International Renewable Energy Agency (IRENA), Abu Dhabi,* pp. 1-154, 2019.

[59] A. Alshahrani, S. Omer, Y. Su, E. Mohamed, and S. Alotaibi, "The technical challenges facing the integration of small-scale and large-scale PV systems into the grid: A critical review," *Electronics,* vol. 8, no. 12, p. 1443, 2019.

[60] B. Hartono, Y. Budiyanto, and R. Setiabudy, "Review of microgrid technology," in *2013 international conference on QiR*, Yogyakarta, Indonesia, 2013, pp. 127-132.

[61] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renew. Sust. Energ. Rev.,* vol. 90, pp. 402-411, Jul 2018.

[62] A. F. Abdul Kadir, T. Khatib, and W. Elmenreich, "Integrating photovoltaic systems in power system: power quality impacts and optimal planning challenges," *Int. J. Photoenergy,* vol. 2014, 2014.

[63] P. K. Bhatt and N. P. Patidar, "Intelligent transformer tap controller for harmonic elimination in photovoltaic interfaced micro-grid network," *Eng. Optim.,* pp. 1-19, 2022.

[64] A. Alshahrani, S. Omer, and Y. Su, "An investigation into the potential of hosting capacity and the frequency stability of a regional grid with increasing penetration level of large-scale pv systems," *Electron.,* vol. 10, no. 11, p. 1254, 2021.

[65] A. R. Bhatti, Z. Salam, M. J. B. A. Aziz, and K. P. Yee, "A critical review of electric vehicle charging using solar photovoltaic," *Int. J. Energy Res.,* vol. 40, no. 4, pp. 439-461, 2016.

[66] Sullivan Solar Power (2023). *Solar powered electric vehicles - clean energy*, [Online]. Available: https://www.sullivansolarpower.com/solar-power/electric-vehicles. [Accessed: 26-Apr-2021].

[67] A. M. Elshurafa and A. R. Muhsen, "The upper limit of distributed solar PV capacity in Riyadh: a GIS-assisted study," *Sustainability*, vol. 11, no. 16, p. 4301, 2019.

[68] G. Markus and G. Alexandre, "Impact of high renewable penetration scenarios on system reliability: two case studies in the Kingdom of Saudi Arabia," *arXiv preprint arXiv:1709.03761*, 2017.

[69] A. M. Elshurafa and W. Matar, "Adding solar PV to the Saudi power system: what is the cost of intermittency?," *Ener. Transit.*, vol. 1, pp. 1-9, 2017.

[70] Z. Su and L. Yang, "Peak shaving strategy for renewable hybrid system driven by solar and radiative cooling integrating carbon capture and sewage treatment," J. *Renew. Energy*, vol. 197, pp. 1115-1132, 2022.

[71] D. Shmilovitz, "On the definition of total harmonic distortion and its effect on measurement interpretation," *IEEE Trans. Power Deliv*, vol. 20, no. 1, pp. 526-528, 2005.

[72] H. Albalawi, E. Makram, and T. Alogla, "PV penetration with battery storage for an isolated northwest Grid of Saudi Arabia," in *2015 North American Power Symposium (NAPS)*, North Carolina, 2015, pp. 1-6.

[73] R. Shalwala and J. Bleijs, "Impact of Grid-Connected PV systems on voltage regulation of a residential area network in Saudi Arabia," in *2010 1st International Nuclear & Renewable Energy Conference (INREC)*, Amman, Jordan, 2010, pp. 1-5.

[74] K. Brown, F. Shokooh, H. Abcede, and G. Donner, "Interactive simulation of power systems: ETAP applications and techniques," in *Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting*, Seattle, Washington, 1990, pp. 1930-1941.

[75] Saudi Electricity Company. (n.d.). *Standards for Connection of Generator Based REG systems* [Online]. Available: https://www.se.com.sa/en-us/Lists/REG_Guides_ConcentratedSolarPowerCSP/Attachments/4/Standards%20for%20Connection%20of%20Generator%20Based%20REG%20systems.pdf [Accessed: 12-Nov-2022].

[76] R. Shalwala and J. Bleijs, "Voltage control scheme using Fuzzy Logic for residential area networks with PV generators in Saudi Arabia," in *2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, New Delhi, 2010, pp. 1-6.

[77] F. Richter, "Infographic: Global Electric Car Sales doubled in 2021," *Statista Infographics* [Online], Feb 15 2022. Available: https://www.statista.com/chart/26845/global-electric-car-sales/. [Accessed: 12-Nov-2022].

[78] Deloitte, "New market. New entrants. New challenges. Battery Electric Vehicles," [Online], Feb. 2018. Available: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Technology-Media-Telecommunications/deloitte-digital-maturity-model.pdf. [Accessed: 26-May-2020].

[79] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 704-718, 2007.

[80] Tesla (n.d). *Model S* [Online]. Available: https://www.tesla.com/en_eu/models. [Accessed: 26-Jan-2022].

[81] D. Berjoza and I. Jurgena, “Effects of change in the weight of electric vehicles on their performance characteristics,” *Agron. Res,* vol. 15, no. 1, pp. 952-963, 2017.

[82] W. Gis, “Ecological and functional aspects of operation of electric vehicles with fuel cell,” *J. KONBiN,* vol. 50, no. 2, pp. 165-176, 2020.

[83] S. Alotaibi, S. Omer, and Y. Su, “A review on the potential of electric vehicles in reducing world CO2 footprints,” in *Open Science Index, Transport and Vehicle Engineering*, Paris, France, pp.570-578, 2020.

[84] TuDelf (2018, Nov. 30), *2.2.2 Lecture Notes: Types of ev, electric cars introduction* [Online]. Available: https://ocw.tudelft.nl/course-readings/2-2-2-lecture-notes-types-of-ev/ [Accessed: 26-May-2020].

[85] International Energy Agency, “Global EV Outlook 2018.” [Online]. Available: https://iea.blob.core.windows.net/assets/387e4191-acab-4665-9742-073499e3fa9d/Global_EV_Outlook_2018.pdf, 2018 [Accessed: 26-Jan-2020].

[86] D. Bakker, “Battery electric vehicles: performance, CO2 emissions, lifecycle costs and advanced battery technology development,” MSc Thesis, Copernicus Institute University of Utrecht, Utrecht, 2010.

[87] Y. Miao, P. Hynan, A. Von Jouanne, and A. Yokochi, “Current Li-ion battery technologies in electric vehicles and opportunities for advancements,” *Energies,* vol. 12, no. 6, p. 1074, 2019.

[88] S. Khan, A. Kushler, “Plug-in electric vehicles: Challenges and opportunities,” American Council for an Energy-Efficient Economy**,** Washington D.C., rep. no. T133, 2013.

[89] T. Hawkins, B. Singh, G. Majeau-Bettez, A. Stromman, “Comparative environmental life cycle assessment of conventional and electric vehicles,” *J. Ind. Ecol.* vol. 17, pp. 53-64, 2013.

[90] M. Lewis, S. Amr, B. Francisco, S. Alessandra, and S. Deger, “Electric Vehicles: Technology Brief,” *International Renewable Energy Agency,* Abu Dhabi, United Arab Emirates, 2017.

[91] NIO. (2023) *ES8 Model. New Horizons* [Online]. Available: https://www.nio.com/es8 [Accessed: 25-nov-2022].

[92] Tesla. (2023). *Roadster* [Online]. Available https://www.tesla.com/en_gb/roadster [Accessed: 10-May-2023].

[93] F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain, “A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development,” *Energies,* vol. 10, no. 8, p. 1217, 2017.

[94] P. Thounthong, S. Raël, and B. Davat, “Utilizing fuel cell and supercapacitors for automotive hybrid electrical system,” in *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005.*, Long Beach, California, 2005, vol. 1, pp. 90-96.

[95] C. C. Chan, A. Bouscayrol, and K. Chen, “Electric, hybrid, and fuel-cell vehicles: Architectures and modeling," *IEEE transactions on vehicular technology,* vol. 59, no. 2, pp. 589-598, 2009.

[96] N. Lutsey and M. Nicholas, “Update on electric vehicle costs in the United States through 2030,” *Int. Counc. Clean Transp,* vol. 12, 2019.

[97] L. Fulton, “Ownership cost comparison of battery electric and non-plugin hybrid vehicles: a consumer perspective,” *Appl. Sci.,* vol. 8, no. 9, p. 1487, 2018.

[98] Tesla. (2013, Nov. 11). *Introducing V3 Supercharging* [Online]. Available: https://www.tesla.com/en_gb/blog/introducing-v3-supercharging.

[99] C. W. Babbitt, "Sustainability perspectives on lithium-ion batteries," *Clean Technol. Environ. Policy,* vol. 22, no. 6, pp. 1213-1214, 2020.

[100] J. Klender. (2020, Jan 30). *Tesla 1 million-mile battery in sight with new electrolyte solvent patent, TESLARATI*, Jan. 30 2020. [Online]. Available: https://www.teslarati.com/tesla-electrolyte-patent-1-million-mile-battery/ [Accessed: 26-Jan-2021].

[101] Honda Motor Co. (n.d) *Clarity electric* [Online]. Available: https://global.honda/innovation/technology/automobile/Clarity-Electric.html [Accessed: 18-Jun-2021].

[102] Toyota UK Media Site. (2018, Oct. 18) *The new Toyota Camry Hybrid* [Online]. Available: https://media.toyota.co.uk/the-new-toyota-camry-hybrid/. [Accessed: 10-Sep-2022].

[103] A. Frank, "Four-wheel drive powertrain configurations for two-motor, two-clutch hybrid electric vehicles," USA Patent No. 10 384 527, 2019.

[104] Toyota Europe Newsroom. (2017. Feb. 06), *Toyota Prius Plug-in Hybrid* [Online]. Available: https://newsroom.toyota.eu/toyota-prius-plug-in-hybrid/ [Accessed: 15-Feb-2020].

[105] I. Rahman, P. M. Vasant, B. Singh M. Singh, M. Abdullah-Al-Wadud, and N. Adnan, "Review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures," *Renew. Sust. Energ. Rev.,* vol. 58, pp. 1039-1047, 2016.

[106] S. Hardman, A. Jenn, G. Tal, J. Axsen, G. Beard, N. Daina, et al., "A review of consumer preferences of and interactions with electric vehicle charging infrastructure," *Transp. Res. D. Transp. Environ.,* vol. 62, pp. 508-523, 2018.

[107] T. G. San Román, I. Momber, M. R. Abbad, and Á. Sánchez Miralles, "Regulatory framework and business models for charging plug-in electric vehicles: Infrastructure, agents, and commercial relationships," *Energy Policy,* vol. 39, no. 10, pp. 6360-6375, 2011.

[108] D. Hall and N. Lutsey, "Emerging best practices for electric vehicle charging infrastructure," The International Council on Clean Transportation (ICCT), Washington, DC, USA, White paper 54, 2017.

[109] H. Shareef, M. M. Islam, and A. Mohamed, "A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles," *Renew. Sust. Energ. Rev.,* vol. 64, pp. 403-420, 2016.

[110] C. Botsford and A. Szczepanek, "Fast charging vs. slow charging: Pros and cons for the new age of electric vehicles," in *International Battery Hybrid Fuel Cell Electric Vehicle Symposium*, Stavanger, Norway, 2009, pp. 1-9.

[111] M. C. Falvo, D. Sbordone, I. S. Bayram, and M. Devetsikiotis, "EV charging stations and modes: International standards," in *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Ischia, Italy, 2014, pp. 1134-1139.

[112] M. Aziz and T. Oda, "Simultaneous quick-charging system for electric vehicle," *Energy Procedia,* vol. 142, pp. 1811-1816, 2017.

[113] J. S. Jin, "Installing Public Electric Vehicle Charging Stations: A Site Suitability Analysis in Los Angeles County, California," MSc Thesis, Facult. USC Grad. School, Univ. Southern California, Los Angeles, CA, 2016.

[114] V. Badallaj, “How many charging stations for Electric-cars are needed in Oslo by 2020?,” MINF Thesis, Dept. Inform. Fac. Math. Nat. Sc., Univ. Oslo, Oslo, Norway, 2019.

[115] M. U. Mutarraf, Y. Terriche, K. A. K. Niazi, J. C. Vasquez, and J. M. Guerrero, “Energy storage systems for shipboard microgrids—A review,” *Energies*, vol. 11, no. 12, p. 3492, 2018.

[116] L. Balko, B. Urbanic, Z. Frankova, H. Viegas, N. Westphal, and S. Hristov, “Infrastructure for Charging Electric Vehicles: More Charging Stations but Uneven Deployment Makes Travel across the EU Complicated,” European Court of Auditors, Luxembourg, no. 01786074 [Online], 26 Oct 2021. Available: https://op.europa.eu/en/publication-detail/-/publication/b22d29c8-df94-11eb-895a-01aa75ed71a1/language-en [Accessed: 15-Nov-2022].

[117] International Energy Agency, “Global EV Outlook 2022.” [Online]. Available: https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf [Accessed: 10-May-2023].

[118] A. Kiani, “Electric vehicle market penetration impact on transport-energy-greenhouse gas emissions nexus: A case study of United Arab Emirates," *J. Clean. Prod.*, vol. 168, pp. 386-398, 2017.

[119] S. Bridge. (2020, Feb 6) *Dubai to add 60 new electric car charging stations in 2020* [Online]. Available: https://www.arabianbusiness.com/gcc/uae/438415-dubai-to-add-60-new-electric-car-charging-stations-in-2020. [Accessed: 19-Apr-2021].

[120] P. C. Philip, F. Subaihi, S. Musgun, S. Ghebretatios, and F. Alnajjar, “Solar Car Parking for Maximum Power Utilization at the United Arab Emirates University: Case Study,” in *Proceedings of the ICR’22 International Conference on Innovations in Computing Research*, Athens, Greece, 2022, pp. 454-464.

[121] S. D. Jenkins, J. R. Rossmaier, and M. Ferdowsi, “Utilization and effect of plug-in hybrid electric vehicles in the United States power grid,” in *2008 IEEE Vehicle Power and Propulsion Conference*, Harbin, China, 2008, pp. 1-5.

[122] J. Kester, L. Noel, G. Z. de Rubens, and B. K. Sovacool, “Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion,” *Energy Policy*, vol. 116, pp. 422-432, 2018.

[123] S. Alotaibi, S. Omer, S. Aljarallah, and Y. Su, “Potential implementation of EVs–Features, Challenges and User perspective,” in *2021 IEEE Green Energy and Smart Systems Conference*, Long Beach, CA, 2021, pp. 1-10.

[124] C. Weiller and A. Neely, “Using electric vehicles for energy services: Industry perspectives,” *Energy*, vol. 77, pp. 194-200, 2014.

[125] Tesla. (2023). *Powerwall modes* [Online]. Available: https://www.tesla.com/en_gb/support/energy/powerwall/mobile-app/powerwall-modes. [Accessed: 21-May-2022].

[126] Ali, H.; Hussain, S.; Khan, H.; Arshad, N.; Khan, I. Economic and Environmental Impact of Vehicle-to-Grid (V2G) Integration in an Intermittent Utility Grid. In Proceedings of the International Conference on Smart Power & Internet Energy Systems (SPIES), Bangkok, Thailand, 15–18 September 2020; pp. 345–349.

[127] B. K. Sovacool, J. Kester, L. Noel, and G. Z. de Rubens, “Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review,” *Renew. Sust. Energ. Rev.*, vol. 131, pp. 109963, 2020.

[128] A. B. Britto and K. Krannich, (2011-2022). *What is vehicle to grid technology?* [Online]. Available: https://www.elektrobit.com/trends/vehicle-to-grid-technology/ [Accessed: 15-Dec-2022]

[129] M. Coffman, P. Bernstein, and S. Wee, "Electric vehicles revisited: a review of factors that affect adoption," *Transport Reviews,* vol. 37, no. 1, pp. 79-93, 2017.

[130] Z.-Y. She, Qing Sun, J.-J. Ma, and B.-C. Xie, "What are the barriers to widespread adoption of battery electric vehicles? A survey of public perception in Tianjin, China," *Transport Policy,* vol. 56, pp. 29-40, 2017.

[131] V. Singh, V. Singh, S. Vaibhav, "A review and simple meta-analysis of factors influencing adoption of electric vehicles," *Transp. Res. D. Transp. Environ.,* vol. 86, Art. No. 102436, 2020.

[132] P. Plötz, U. Schneider, J. Globisch, E. Dütschke, Who will buy electric vehicles? Identifying early adopters in Germany. *Transp. Res. Part A Policy Pract.*, vol.67, pp. 96-109, 2014.

[133] N. Pearre, W. Kempton, R. Guensler, V. Elango, "Electric vehicles: How much range is required for a day's driving?," *Transp. Res. C. Emerg. Tech.*, vol. 19, pp. 1171-1184, 2011.

[134] K. Palmer, J. Tate, Z. Wadud, J. Nellthorp, "Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan," *App. Energy,* vol. *209,* pp. 108-119, 2018.

[135] O. Egbue, and S. Long, "Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions," *Energy policy,* vol. 48, pp. 717-729, 2012.

[136] E. Narassimhan, and C. Johnson, "The role of demand-side incentives and charging infrastructure on plug-in electric vehicle adoption: analysis of US States," *Environ. Res. Lett.,* vol. 13, no. 7, pp. 074032, 2018.

[137] K. Chidambaram, B. Ashok, R. Vignesh, C. Deepak, R. Ramesh, T. M. Narendhra, et.al., "Critical analysis on the implementation barriers and consumer perception toward future electric mobility," *Proc. I.Mech.E. Part D. J. Automobile Engineering*, pp. 09544070221080349, 2022.

[138] L. Tie, "Status analysis and development planning for the network of charging stations," *Eur. J. Elec. Eng.*, vol. 20, p. 485, 2018.

[139] O, Hafez, K. Bhattacharya, "Optimal design of electric vehicle charging stations considering various energy resources," *Renew. Energy*, 107, pp. 576-589, 2017.

[140] D. Yu, M. P. Adhikari, A. Guiral, A. S. Fung, F. Mohammadi, and K. Raahemifar, "The impact of charging battery electric vehicles on the load profile in the presence of renewable energy," in *2019 IEEE Canadian Conference of Electrical and Computer Engineering*, Edmonton, AB, 2019, pp. 1-4.

[141] H. Quak, N. Nesterova, and T. van Rooijen, "Possibilities and barriers for using electric-powered vehicles in city logistics practice," *Transp. Res. Proc.,* vol. 12, pp. 157-169, 2016.

[142] P. Ninh, K. Bentzen, and M. S. Laugesen, "Why should transportation companies join Public Private Partnership (PPP) proposed by the public sector to support the implementation process of Freight Electric Vehicles (FEVs) in Copenhagen Municipality," *NSR, Activity,* vol. 7, no. 4, 2014.

[143] EDF.(2020). *All about electric car batteries* [Online]**.** Available online: https://www.edfenergy.com/electric-cars/batteries [Accessed: 15-nov-2022].

[144] A. M. Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, and V. Esfahanian, “A review of Battery Electric Vehicle technology and readiness levels,” *Renew. Sust. Ener. Rev.*, 78, pp. 414-430, 2017.

[145] D. Coffin, J. Horowitz, “The supply chain for electric vehicle batteries,” *J. Int'l Com. & Econ.* vol. 1, 2018.

[146] BYD. (n.d) *Tang Model* [Online]. Available: https://www.bydauto.eu/tang.html [Accessed: 15-nov-2022].

[147] S. Edelstein. (2018). *Chinese startup aims to set design direction for autonomous cars* [Online]. Available: https://www.digitaltrends.com/cars/byton-k-byte-concept/ [Accessed: 15-nov-2022].

[148] R. Hensley, J. Newman, M. Rogers, M. Shahinian, “Battery technology charges ahead,” *McKinsey Q.*, vol. 3, pp. 5-50, 2012.

[149] K. Smith, “Battery Lifespan,” National Renewable Energy Lab Report [Online] Available: https://www.nrel.gov/transportation/battery-lifespan.html [Accessed: 21-May-2022].

[150] Weather Online. (1999-2023). *Climate of the World, Saudi Arabia* [Online]. Available: https://www.weatheronline.co.uk/reports/climate/Saudi-Arabia.htm [Accessed: 15-nov-2022].

[151] K. Reddy, “Energy sources and multi-input DC-DC converters used in hybrid electric vehicle applications–A review,” *Int. J. Hydrog. Energy*, 43, pp. 17387-17408, 2018.

[152] Battery University. (2019, Nov.28) *Battery Aging in an Electric Vehicle (EV)* [Online]. Available: https://batteryuniversity.com/learn/article/bu_1003a_battery_aging_in_an_electric_vehicle_ev [Accessed: 15-nov-2022].

[153] Deng, Jie, et al. "Electric vehicles batteries: requirements and challenges." *Joule* 4.3 (2020): 511-515

[154] Nissan Motor. Electric vehicle lithium-ion battery. Available: https://www.nissan-global.com/EN/INNOVATION/TECHNOLOGY/ARCHIVE/LI_ION_EV/ [Accessed: 15-nov-2022].

[155] M. Moses. (2020). *Electric cars with the longest range* [Online]. Available: https://www.edfenergy.com/for-home/energywise/electric-cars-longest-range [Accessed: 15-nov-2022].

[156] WATTEV2BUY. (2015-2020). *NIO ES8 EV 7 Long Range, BEV Pure electric vehicle* [Online]. Available: https://wattev2buy.com/electric-vehicles/nio-electric-vehicles/nio-es8-ev-crossover-specs-price-battery-range/ [Accessed: 15-nov-2022].

[157] US Department of Energy, Office of Energy Efficiency & Renewable Energy. (n.d.). *Alternative Fuels Data Center* [Online], Available: https://afdc.energy.gov/fuels/electricity_infrastructure.html [Accessed: 15-nov-2022].

[158] S. Rumale, H. Al Ashkar, T. Kerner, F. Koya, and M. Eitzenberger, “Design and implementation of an on-board vehicle CHAdeMO interface for Vehicle-to-Grid applications,” in *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020)*, Trivandrum, India, pp. 1-6, 2023.

[159] Nissan UK. (n.d). *New Nissan Leaf, Prices & Specifications* [Online]. Available: https://www.nissan.co.uk/vehicles/new-vehicles/leaf/prices-specifications.html#grade-LEAFZE1A-2|overview. [Accessed: 28-Jan-2023].

[160] EDF. (n.d) *GoElectric EV Tariffs for your car and home* [Online]. Available: https://www.edfenergy.com/electric-cars/tariffs [Accessed: 15-nov-2022].

[161] Zethmayr, J. "Charge for less: An analysis of hourly electricity pricing for electric vehicles," *World Electr. Veh. J.* vol.10, 2019.

[162] O. Travesset-Baro, M. Rosas-Casals, and E. Jover, "Transport energy consumption in mountainous roads. A comparative case study for internal combustion engines and electric vehicles in Andorra," *Transp. Res. D. Transp.Environ.,* vol. 34, pp. 16-26, 2015.

[163] M. Keyser, A. Pesaran, Q. Li, S. Santhanagopalan, K. Smith, E. Wood, et.al., "Enabling fast charging–Battery thermal considerations," *J. Power Sources,* vol. 367, pp. 228-236, 2017.

[164] P. Sun, R. Bisschop, H. Niu, and X. Huang, "A review of battery fires in electric vehicles," *Fire Technol.,* vol. 56, no. 4, pp. 1361-1410, 2020.

[165] G. Haddadian, M. Khodayar, and M. Shahidehpour, "Accelerating the global adoption of electric vehicles: barriers and drivers," *Electr. J.,* vol. 28, no. 10, pp. 53-68, 2015.

[166] A. T. Halawani and F. Rehimi, "Evaluation of the intention to shift to public transit in Saudi Arabia," *Transp. Res. D. Transp. Environ.,* vol. 94, p. 102809, 2021.

[167] E. Ludlow, M. Martin, (2021, Jan. 7). *Saudi-backed Lucid in talks for electric car factory near Jeddah* [Online]. Available: https://www.bloomberg.com/news/articles/2021-01-07/saudi-backed-lucid-in-talks-for-electric-car-factory-near-jeddah [Accessed: 21-May-2022].

[168] Dubai Electricity & Water Authority (2013). *Display EV Green Charger locations* [Online]. Available: http://www.dewa.gov.ae/en/consumer/ev-community/ev-green-charger-stations. [Accessed: 19-Apr-2021].

[169] SASO. "Technical regulations for electric vehicles, Saudi Standards, Metrology and Quality Organization," Regulation no.170 [Online] May 17 2019. Available: https://saso.gov.sa/en/Laws-And-Regulations/Technical_regulations/Documents/TR%20-%20Electric%20Vehicles.pdf [Accessed: 03-Nov-2022].

[170] Ministry of Transport and Logistic Services (2019, Apr. 9). *Saudi Transportation Ministry: 18 Million Road Trips in August* [Online]. Available: https://mot.gov.sa/en/MediaCenter/News/Pages/NEWS1078.aspx. [Accessed: 28-Mar-2021].

[171] M. Hussain (2020, Jun23) *Saudi Arabia to set maximum limit on car ownership* [Online]. Available: https://www.drivearabia.com/news/2020/06/23/saudi-arabia-to-set-maximum-limit-on-car-ownership/ [Accessed: 15-nov-2022].

[172] S. Al-Fouzan, "Using car parking requirements to promote sustainable transport development in the Kingdom of Saudi Arabia," *Cities,* vol. 29, pp. 201-211, 2012.

[173] A. M. Elshurafa and N. Peerbocus, "Electric vehicle deployment and carbon emissions in Saudi Arabia: A power system perspective," *Electr. J.*, vol. 33**,** pp.106774, 2020.

[174] T. Alquthami, A, Alsubaie, M. Alkhraijah, K. Alqahtani, S. Alshahrani, M. Anwar, "Investigating the Impact of Electric Vehicles Demand on the Distribution Network" *Energies*, vol.15, pp.1180, 2022.

[175] M. M. Rahman, G. A. Ghazi, E. A. Al-Ammar and W. Ko, "Techno-Economic Analysis of Hybrid PV/Wind/Fuel-Cell System for EVCS," in *2021 International Conference on Electrical, Communication, and Computer Engineering (ICECCE),* Kuala Lumpur, Malaysia, 2021.

[176] S. Alotaibi, S. Omer, Y. Su, “Identification of Potential Barriers to Electric Vehicle Adoption in Oil-Producing Nations—The Case of Saudi Arabia,” *Electricity*, vol. 3, no.3, pp. 365-395, 2022.

[177] H. S. Das, M. M. Rahman, S. Li and C. W. Tan, “Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review” Renew. Sust. Energ. Rev., vol. 120, pp.109618, 2020.

[178] Natural Resources Canada. (2005, Dec. 31) *RETScreen Software Online User Manual* [Online]. Available: https://publications.gc.ca/collections/collection_2008/nrcan/M39-115-2005E.pdf [Accessed: 28-Jan-2023].

[179] G. Leng, N. Meloche, A. Monarque, G. Painchaud, D. Thevenard, M. Ross, et.al. “Clean Energy Project Analysis: RETScreen Engineering & Cases Textbook-Photovoltaic Project Analysis,” CANMET Energy Technology Center, 2004.

[180] RETScreen, “Natural Resources Canada”, Available: http://www.retscreen.net./ [Accessed: 10-May-2023].

[181] Florida Solar Energy Centre. (2014). *Types of PV Systems* [Online]. Available: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/types_of_pv.htm [Accessed: 15-Nov-2022].

[182] RETScreen International, “Clean energy project analysis: RETScreen engineering & cases textbook” Minister of Natural Resources, Canada, Catalogue no. M39-99/2003E-PDF, 2011-2004.

[183] M. Susten. (2020, Aug.). *What is a Distributed Solar Power Generation?* [Online]. Available: www.mahindrasusten.com/blog/what-is-a-distributed-solar-power-generation [Accessed: 15-Nov-2022].

[184] Chen, Yuche, and Marc Melaina. "Model-based techno-economic evaluation of fuel cell vehicles considering technology uncertainties." *Transportation Research Part D: Transport and Environment* 74 (2019): 234-244.

[185] Aniegbunem, George, and Andrea Kraj. "Economic Analysis of Sustainable Transportation Transitions: Case Study of the University of Saskatchewan Ground Services Fleet." (2023).

[186] Mirzahosseini, Alireza Hajiseyed, and Taraneh Taheri. "Environmental, technical and financial feasibility study of solar power plants by RETScreen, according to the targeting of energy subsidies in Iran." *Renewable and Sustainable Energy Reviews* 16.5 (2012): 2806-2811.

[187] Hussein, Ibrahem M., and Ali T. Al-Awami. "Reliability Assessment of Sustainable Photovoltaic-Electric Vehicles System." *2017 9th IEEE-GCC Conference and Exhibition (GCCCE)*. IEEE, 2017.

[188] S. Rehman, M.A. Ahmed, M.H. Mohamed and F.A. Al-Sulaiman, “Feasibility study of the grid connected 10 MW installed capacity PV power plants in Saudi Arabia,” *Renew. Sust.Energ. Rev.*, vol. 80, pp.319-329, 2017.

[189] B. Imteyaz, D.U. Lawal, F. Tahir, and S. Rehman, “Prospects of large-scale photovoltaic-based power plants in the Kingdom of Saudi Arabia,” *Eng. Rep.*, vol. 3, no. 9), pp.e12398, 2021.

[190] Bustos, F., et al. "Sensitivity analysis of a photovoltaic solar plant in Chile." *Renewable Energy* 87 (2016): 145-153.

[191] Hasan, Md Rabiul, and Choudhury Abul Anam Rashed. "Economic Feasibility and Environmental Aspects of an Electric Vehicle by using Standalone Photovoltaic Energy." *Power (watt)* 300.270: 310.

[192] S. Vanderstoep and D. Johnston, “Research Methods for Everyday Life: Blending Qualitative and Quantitative Approaches,” John Wiley & Sons, 2009.

[193] A. Ghazi, K. Petersen, R. Reddy, H. Nekkanti, “Survey research in software engineering: problems and strategies,” *IEEE Access,* vol.7, pp. 24703-24718, 2017.

[194] J. Cummings, C. Sibona, “Crowdsourcing surveys: alternative approaches to survey collection,” *J. Inf. Sys. App. Res.* Vol. 10, pp. 44–54, 2017.

[195] Kumar, R. *Research Methodology: A Step-by-Step Guide for Beginners*, 3rd ed. London, UK: SAGE, 2011.

[196] P. Ralph, E. Tempero. “Construct validity in software engineering research and software metrics,” in *Proc. 22nd Int. Conf. Eval. & Assess. in Soft. Eng. 2018 - EASE ’18*, Trondheim, Norway, 2018, pp. 13–23.

[197] Thabane, L. *et al.* (2010) “A tutorial on pilot studies: The what, why and how,” *BMC Medical Research Methodology*, 10(1). Available at: https://doi.org/10.1186/1471-2288-10-1.

[198] S. Aljarallah, R. Lock, “An investigation into sustainable e-government in Saudi Arabia,” *Electronic J. e-Govt.***,** vol. 18, pp. 1–17, 2020.

[199] V. Braun, V. Clarke, “Using thematic analysis in psychology,” *Qual. Res. Psych*, vol. 3, pp. 77-101, 2006.

[200] V. Makrakis, N. Kostoulas-Makrakis, “Bridging the qualitative–quantitative divide: Experiences from conducting a mixed methods evaluation in the RUCAS programme,” *Eval.Program Plann.* vol. 54, pp. 144-151, 2016.

[201] R. Swanson, E. Holton, *Research in Organizations Foundations and Methods of Inquiry*. San Francisco, CA, USA: Berrett-Koehler, 2005.

[202] A. Field, Discovering Statistics Using IBM SPSS Statistics, 4th ed.; SAGE: London, UK, 2013.

[203] General Authority for Statistics. (2021). *Saudi Arabia population* [Online]. Available: https://www.stats.gov.sa/en/43 [Accessed: 15-nov-2022].

[204] Y. Rosseel, “Lavaan: An R package for structural equation modelling,” *J. Stat. Soft.* vol. 48, pp.1-36, 2012.

[205] H. Wickham, W. Chang, L. Henry, T.L. Pedersen, K. Takahashi, C. Wilke, et. al. *Ggplot2: Elegant Graphics for Data Analysis*, New York, NY, USA: Springer-Verlag, 2016.

[206] G. Sullivan, A. Artino, “Analyzing and interpreting data from Likert-type scales,” *J. Grad. Med. Ed.* vol. 5, pp. 541–542, 2013.

[207] R. Faria, P. Marques, P. Moura, F. Freire, J. Delgado, and A. T. De Almeida, 2013. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews,* 24**,** 271-287, 2013.

[208] Nahdi Parts. (2023) *Nahdi Parts* [Online]. Available: https://nahdiparts.com [Accessed: 15-nov-2022].

[209] Pitstop Arabia. (2022) *Pitstop Arabia* [Online]. Available: https://www.pitstoparabia.com/en [Accessed: 15-nov-2022].

[210] Riyadh Traffic Department, Ministry of Interior. (2023). *Riyadh traffic* [Online]. Available online: https://www.moi.gov.sa/wps/portal/Home/sectors/publicsecurity/traffic/trafficriyadh/ [Accessed: 15-nov-2022].

[211] Arabian Drive. (2008). *Arabian Drive* [Online]. Available: https://arabiandrive.com [Accessed: 15-Nov-2022].

[212] Tesla. (2023). *Model 3* [Online]. Available: https://www.tesla.com/en_AE [Accessed: 15-Nov-2022].

[213] Abdul Latif Jameel. (2022). *Toyota* [Online]. Available: https://www.toyota.com.sa/en [Accessed: 15-Nov-2022].

[214] S. Millen, and E. Page, "Transport and environment statistics 2021 annual report," D. f. Transport, ed., UK Government, 2021.

[215] Department of Transport Ireland Gov.ie. (2021) *The benefits of switching to an electrical vehicle* [Online]. Available: https://www.gov.ie/en/publication/fabfa-electric-vehicles/?referrer=http://www.gov.ie/en/service/electric-vehicle-grant-scheme/# [Accessed: 15-Nov-2022].

[216] P. Weldon, P. Morrissey, M. O'Mahony, "Long-term cost of ownership comparative analysis between electric vehicles and internal combustion engine vehicles," *Sustain. Cities Soc.*, vol. 39, pp. 578-591, 2018.

[217] P. Lane, H. McKenna, A. A. Ryan, P. Fleming, "Focus group methodology," Nurse Res.(through 2013) vol. 8, no. 3, pp. 45, 2001.

[218] M. Q. Patton, *Qualitative research & evaluation methods: Integrating theory and practice*. USA: Sage publications, 2014.

[219] P. F. Colaizzi, "Psychological research as a phenomenologist views it," in *Existential-Phenomenological Alternatives for Psychology,* R.S. Valle, M. King, Eds., New York: Oxford University Press, 1978, pp.48-71.

[220] J. Hair, J. Wolfinbarger, D. Ortinau, R. Bush, *Essentials of marketing research*, 2nd ed. New York: McGraw-Hill/Irwin, 2010.

[221] ACWA Power, (2019, nov. 25). *ACWA connects the first renewable energy project in the kingdom, Sakaka PV IPP, to the national electricity grid, commencing initial production* [Online]. Available: https://www.acwapower.com/news/acwa-power-connects-the-first-renewable-energy-project-in-the-kingdom-sakaka-pv-ipp-to-the-national-electricity-grid-commencing-initial-production/#:~:text=Al%20Jouf%2C%20KSA%2C%2025%20November,Arabia%20%2D%20to%20the%20national%20grid [Accessed: 15-Nov-2022].

[222] Y. Pan, L. Liu, T. Zhu, T. Zhang, and J. Zhang, "Feasibility analysis on distributed energy system of Chongming County based on RETScreen Software," *Energy*, vol. 130, pp. 298–306, 2017. doi:10.1016/j.energy.2017.04.082.

[223] Stobierski, Tim. (2020). *Harvard Bussiness School. Cashflow vs profit: what's the difference?* [Online]. Available: https://online.hbs.edu/blog/post/cash-flow-vs-profit#income [Accessed: 15-nov-2022].

[224] M.M. Rafique, H.M. Bahaidarah, "Thermo-economic and environmental feasibility of a solar power plant as a renewable and green source of electrification," *Int. J. Green Energy*, vol. 16**,** pp.1577-1590, 2019.

[225] R. Burgess, M. Greenstone, N. Ryan, and A. Sudarshan, "The consequences of treating electricity as a right," *J. Econ. Perspect.*, vol. 34, no. 1, pp. 145-169, 2020.

[226] E. Dreibelbis. (2022). *PCMAG. How to Easily Estimate Charging Costs for an Electric Vehicle* [Online]. Available: https://uk.pcmag.com/cars-auto/143307/how-to-easily-estimate-charging-costs-for-an-electric-vehicle [Accessed: 15-nov-2022]

[227] Electric Nation. (2020-2022). *The future of vehicle to grid EV charging* [Online]. Available: https://electricnation.org.uk/2020/09/02/the-future-of-vehicle-to-grid-ev-charging/ [Accessed: 15-nov-2022].

[228] G. Payne. (2019). *Understanding the true value of V2G [Online]*. Available: https://www.cenex.co.uk/app/uploads/2019/10/True-Value-of-V2G-Report.pdf.

[229] I. Malmgren, "Quantifying the societal benefits of electric vehicles," *World Electr. Veh. J.*, vol. 8, no. 4, pp. 996-1007, 2016.

[230] S. Kalin, Y. Bayoumy. (2017, Sept. 26) "Saudi king decrees women be allowed to drive" [Online]. Available: https://www.reuters.com/article/us-saudi-women-driving/saudi-king-decrees-women-be-allowed-to-drive-idUSKCN1C12SB [Accessed: 21-May-2022].

[231] Arab News. (2022). *Poll reveals a crowded list of Arabs' favourite Japanese car brands* [Online]. Available: https://www.arabnews.com/node/1574736/%7B%7B [Accessed: 21 May 2022].

[232] Tesla Model 3 is Now 16th Bestselling Car in the World. Forbes. 2021. Available online: https://www.forbes.com/sites/jamesmorris/2021/05/29/tesla-model-3-is-now-16th-bestselling-car-in-the-world/ (Accessed: 21 May 2022).

[233] Tesla Model 3. Electric Vehicle Database. Available online: https://ev-database.org/car/1555/Tesla-Model-3 (Accessed: 21-May-2022).

[234] Natural Resources Canada, "Learn the Facts: Fuel consumption and CO2" [Online] Available:https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_6_e.pdf, 2012. [Accessed: 15-nov-2022].

[235] J. Pimentel, "A note on the usage of Likert scaling for research data analysis," *USM R&D Journal*, vol. 18, no. 2, pp. 109–112, 2010.

[236] M. Adhikari, L. Ghimire, Y. Kim, P. Aryal, and S. Khadka, "Identification and analysis of barriers against electric vehicle use." *Sustainability*, vol. 12, no. 12, pp. 4850, 2020.

[237] S. Steinhilber, P. Wells, and S. Thankappan, "Socio-technical inertia: Understanding the barriers to electric vehicles," *Energy Policy*, vol 60, pp. 531 – 539, 2013.

[238] P. Lévay, Y. Drossinos, and C. Thiel, "The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership," *Energy Policy*, vol. 105, pp. 524 – 533, 2017.

[239] B. Sovacool & R. Hirsh, "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition," *Energy Policy*, vol. 37, pp. 1095 – 1103, 2009.

[240] A. Palomino and M. Parvania, "Advanced charging infrastructure for enabling electrified transportation," *Electr. J.*, vol. 32, pp. 21 – 26, 2019.

[241] L. Dulău and D. Bica, "Effects of electric vehicles on power networks," *Procedia Manuf.*, vol. 46, pp. 370 – 377, 2020.

[242] C. Jackson, "Expanding access to electric vehicles in California's low-income communities," *J. Sci. Policy Gov.*, vol. 18, 2021.

[243] F. Gandoman, A. Ahmadi, P. Bossche, J. Mierlo, N. Omar, A. Nezhad, H. Mavalizadeh, C. Mayet, "Status and future perspectives of reliability assessment for electric vehicles," *Reliab. Eng. Syst. Saf.*, vol. 183, pp. 1–16, 2019.

[244] Broadbent, G.H.; Metternicht, G.; Drozdzewski, D. An Analysis of Consumer Incentives in Support of Electric Vehicle Uptake: An Australian Case Study. World Electr. Veh. J. 2019, 10, 11.

[245] J. Ruan, P. Walker, N. Zhang, and J. Wu, “An investigation of hybrid energy storage system in multi-speed electric vehicle,” *Energy*, vol. 140, pp. 291–306, 2017.

[246] B. Sandén, *Systems Perspectives on Electromobility 2013*, Sweden: Chalmers Publication Library, 2013.

[247] T. Yuksel, J.J. Michalek, “Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States,” *Environ. Sci. Technol*, vol.49, no. 6, pp.3974-3980, 2015.

[248] B. Schoettle and M. Sivak, “Resale Values of Electric and Conventional Vehicles: Recent Trends and Influence on the Decision to Purchase a New Vehicle,” University of Michigan: Ann Arbor, MI, USA, SWT-2018-4, 2018.

[249] Our Energy Policy. (2013, April). Global EV outlook: understanding the electric vehicle landscape to 2020 [Online]. Available: https://www.ourenergypolicy.org/wp-content/uploads/2013/09/GlobalEVOutlook_2013.pdf [Accessed: 21-May-2022].

[250] Cover Hound. (n.d.). *Counting the cost of electric cars* [Online]. Available: https://www.coverhound.com/insurance-learning-center/counting-the-cost-of-electric-cars [Accessed: 30-May-2022].

[251] A. Ferscha, K. Zia, A. Riener, and A. Sharpanskykh, “Potential of social modelling in socio-technical systems,” *Procedia Comp. Sci.*, vol. 7, pp. 235 – 237, Jan. 2011.

[252] S. Carley, R. Krause, B. Lane, and J. Graham, “Intent to purchase a plug-in electric vehicle: A survey of early impressions in large US cites,” *Transp. Res. Part D Transp. Environ.*, vol. 18, pp. 39 – 45, 2013.

[253] J. Cansino, A. Sánchez-Braza, and T. Sanz-Díaz, “Policy instruments to promote electro-mobility in the EU28: A comprehensive review,” *Sustainability*, vol. 10, no. 7, pp. 2507, 2018.

[254] Y. Liang, J. Su, B. Xi, Y. Yu, D. Ji, Y. Sun, C. Cui, and J. Zhu, “Life cycle assessment of lithium-ion batteries for greenhouse gas emissions,” *Resour. Conserv. Recycl.*, vol. 117, pp. 285 – 293, 2017.

[255] A. Awasthi, V. Cheela, I. D’Adamo, E. Iacovidou, M. Islam, M. Johnson, T. Miller, K. Parajuly, A. Parchomenko & L Radhakrishan, “Zero waste approach towards a sustainable waste management,” *Resour. Environ. Sustain.*, vol. 3, pp. 100014, Mar. 2021.

[256] Saudi Electricity Company. (2019, March). *Questions and answers about electric voltage change from 127/220 volts to 230/400 volts* [Online]. Available: https://www.se.com.sa/ar-sa/MarketingPrintMaterial/NewID/Questions%20and%20Answers%20about%20Electric%20Voltage%20Change.pdf, [Accessed: 05 May 2022].

[257] J. Krane, “Climate strategy for producer countries: the case of Saudi Arabia,” in *When Can Oil Economies Be Deemed Sustainable?*, G. Luciani, and T. Moerenhout, Eds. Singapore: Palgrave Macmillan imprint, 2020, pp. 301.

[258] GIS Geography. (2022, Nov. 7). *Map of Saudi Arabia* [Online]. Available: https://gisgeography.com/saudi-arabia-map/ [Accessed: 15-nov. 2022].

[259] A.A. Imam, Y.A. Al-Turki, and K.R. Sreerama, “Techno-Economic Feasibility Assessment of Grid-Connected PV Systems for Residential Buildings in Saudi Arabia—A Case Study,” *Sustainability*, vol. 12, pp. 262, 2020.

[260] Government of Canada. (2022, Oct. 31). *RETScreen Innovation Lab* [Online]. Available: https://www.nrcan.gc.ca/energy/energy-offices-and-labs/canmetenergy/canmetenergy-varennes/retscreen-innovation-lab/23359 [Accessed: 15-nov-2022].

[261] Mobility House, (2022). *Seven things that I need to consider when buying a charging station for my electric car* [Online]. Available: https://www.mobilityhouse.com/int_en/knowledge-center/6-things-to-consider-when-buying-a-charging-station-for-my-electric-car [Accessed: 15-nov-2022].

[262] R. Fu, D.J. Feldman and R.M. Margolis, "US solar photovoltaic system cost benchmark: Q1 2018" National Renewable Energy Lab, Denver, CO, USA, No. NREL/TP-6A20-72399, 2018.

[263] F. Kane. (2021, Jan. 29). *Saudi Crown Prince unveils plan to make Riyadh one of world's 10 largest city economies* [Online]. Available: https://arab.news/53dnt [Accessed: 03-Feb-2023].

[264] Ministry of Municipal and Rural Affairs. (2019). *Riyadh city profile* [Online]. Available: https://unhabitat.org/sites/default/files/2020/03/riyadh.pdf [Accessed: 19-Feb-2023].

[265] M.C. Peel, B.L. Finlayson, and T.A. McMahon, "Updated world map of the Köppen-Geiger climate classification," *Hydrol. Earth Syst. Sc.*, vol. 11, no. 5, pp.1633-1644, 2007.

[266] VectorStock (2023). *Map of Riyadh, Saudi Arabia* [Online]. Available: https://www.vectorstock.com/royalty-free-vector/map-of-riyadh-saudi-arabia-vector-14722990 [Accessed: 15-nov-2022]

[267] Climatemps.com. (2009-2017). *Riyadh climate & temperature* [Online]. Available: http://www.riyadh.climatemps.com/ [Accessed: 15-nov-2022]

[268] YEN. (2022). *Global Financial Centres Index* [Online]. Available: https://www.longfinance.net/programmes/financial-centre-futures/global-financial-centres-index/gfci-31-explore-data/gfci-31-rank/ [Accessed: 15-nov-2022].

[269] Vision 2030 Kingdom Saudi Arabia. (2022). *Green Riyadh* [Online], Available: https://www.vision2030.gov.sa/v2030/v2030-projects/green-riyadh/ [Accessed: 15-nov-2022]

[270] F.A. Al-Mubarak, A.M. Al-Sayari, H.S. Al-Sayari, A.M. Al-Athel and K. A. Al-Juffali, "57th Annual Report," Saudi Central Bank, Riyadh, Saudi Arabia, no. 1442H, 2021 [Online]. Available: https://www.sama.gov.sa/en-US/EconomicReports/AnnualReport/ANNUAL_Report_57th_2021.pdf [Accessed: 15-nov-2022]

[271] A. B. Alsaud, H. Yas, and A. Alatawi, "A new decision-making approach for Riyadh makes up 50 percent of the non-oil economy of Saudi Arabia," *Journal of Contemporary Issues in Business and Government Vol*, vol. 27, no. 1, 2021.

[272] S.M. Shaahid, L.M. Al-Hadhrami, and M.K. Rahman, "Economic feasibility of development of wind power plants in coastal locations of Saudi Arabia–A review," *Renew. Sust. Energ. Rev.*, vol. 19, pp.589-597, 2013.

[273] D. Feldman, V. Ramasamy, R. Fu, A. Ramdas, J. Desai and R. Margolis, "US solar photovoltaic system and energy storage cost benchmark: Q1 2020," National Renewable Energy Lab, Golden, CO, United States, No. NREL/TP-6A20-77324, 2021.

[274] IRENA, "Renewable Power Generation Costs in 2020", International Renewable Energy Agency [Online], 2021. Available: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020 [Accessed: 15-nov-2022].

[275] H. Walker, E. Lockhart, J. Desai, K. Ardani, G. Klise, O. Lavrova, et.al., "Model of operation-and-maintenance costs for photovoltaic systems" National Renewable Energy Lab, Golden, CO, United States, No. NREL/TP-5C00-74840, 2020.

[276] K. Kurokawa, M. Ito, K. Komoto, P. Vleuten, and D. Faiman, “Energy from the desert. Very large-scale photovoltaic systems: socio-economic, financial, technical and environmental aspects,” Report International Energy Agency, Japan, IEA -PVPS T8-01:2015, 2015.

[277] Richie, Hannah. (2020, Feb. 10). *What are the cleanest sources of energy? Our World in Data* [Online]. Available: https://ourworldindata.org/safest-sources-of-energy [Accessed: 15-nov-2022].

[278] International Trade Administration (2021, Sep. 13). *Saudi Arabia Carbon Trading Platform* [Online]. Available: https://www.trade.gov/market-intelligence/saudi-arabia-carbon-trading-platform [Accessed: 15-nov-2022].

[279] M. Milousi, M. Souliotis, G. Arampatzis, and S. Papaefthimiou, “Evaluating the Environmental Performance of Solar Energy Systems Through a Combined Life Cycle Assessment and Cost Analysis,” *Sustainability*, vol. 11, no. 9, p. 2539, May 2019, doi: 10.3390/su11092539.

[280] E. Hyde (2023, Feb. 7). What is fast charging? What is rapid charging? What is ultra-rapid charging? EV charging speeds explained, [Online]. Available: https://www.drivingelectric.com/charging/117/what-is-fast-charging-what-is-rapid-charging-what-is-ultra-rapid-charging-ev-charging [Accessed: 15-nov-2022]

[281] C. Nelder and E. Rogers, “Reducing EV charging infrastructure costs,” Rocky Mountain Institute [Online], Available: https://rmi.org/ev-charging-costs, 2019. [Accessed: 15-nov-2022].

[282] M. Brander, A. Sood, C. Wylie, A. Haughton and J. Lovell, “Technical Paper, Electricity-specific emission factors for grid electricity,” Ecometrica, [Online], 2011. Available: https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf [Accessed: 15-nov-2022].

[283] U.S. Environmental Protection Agency. (2022). *Greenhouse Gases Equivalencies Calculator- Calculation and References* [Online]. Available: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references [Accessed: 15-Nov-2022].

[284] R. Hein, P.R. Kleindorfer, and S. Spinler, “Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems,” *Technol. Forecast. Soc. Change*, vol. 79, no. 9, pp.1654-1671, 2012.

[285] M.A. Alghoul, F.Y. Hammadi, N. Amin and N. Asim, “The role of existing infrastructure of fuel stations in deploying solar charging systems, electric vehicles and solar energy: A preliminary analysis,” *Technol. Forecast. Soc.Change*, vol. 137, pp.317-326, 2018.

[286] Z. Liao, M. Taiebat, and M. Xu, “Shared autonomous electric vehicle fleets with vehicle-to-grid capability: Economic viability and environmental co-benefits” *Appl. Energy*, vol. 302, pp.117500, 2021.

[287] NEOM. (n.d). *NEOM is real* [Online]. Available: https://www.neom.com/en-us. [Accessed: 18-Feb-2022].

[288] NEOM. (n.d). *The LINE* [Online]. Available: https://www.neom.com/en-us/regions/theline. [Accessed: 18-Feb-2022].

Appendixes

Appendix A - Electric Vehicles Future in Saudi Arabia

INFORMATION FOR PARTICIPANTS

Dear participant,

I am a postgraduate student and doing a research in renewable energy technology. This survey is aimed to investigate the state quo of vehicle usage behaviour for drivers in Saudi Arabia. Furthermore, it explores the generic knowledge of Saudi citizens and their intention to adopt electric vehicles in Saudi Arabia. Equally focused at adoption of renewable energy systems to support both electric grid and electric vehicles, thereby providing clean and green solutions.
The survey contains of 25 questions and should not be taken more than 15 minutes to be completed. However, I would like to inform you in prior that this study is purely an academic exercise and will neither expose the participants to any injury/risk nor impact in any way on the project under study. Please be assured also that every information you will give shall be treated with anonymity and confidentiality. It may also be used as data for any relevant academic publications.

I truly value the information you will be provided. Your responses and honest information will contribute to my analyses and suggest new lines of approach to the PhD study I undertake.
Should you require further explanations or any concern, feel free to contact me at: saleh.alotaibi@nottingham.ac.uk

Saleh Alotaibi

ELECTRONIC CONSENT

Please select your choice below:

Clicking on the “agree” button below indicates that:

- You understand the purpose and nature of this survey and you are participating voluntarily.
- You can withdraw from the survey at any time, without any penalty or consequences.
- You are at least 18 years of age.
- You are driving your own car.

If you do not wish to participate in the survey, please decline participation by clicking on the “disagree” button

☐ Agree

☐ Disagree

Before you take a part of this survey we would like to define some terms as following:

Terms	Definition
Conventional vehicle	A vehicle which has ONLY a fuel motor and runs on diesel or petrol.
Electric vehicle	A vehicle which has ONLY electric motor and runs on electricity, using energy stored in rechargeable batteries.
Hybrid vehicle	A vehicle which has electric and fuel motors and runs on both electricity and fuel, with unchangeable batteries.
Vehicle-to-grid V2G	A technology that enables energy to be fed back to the power grid from the battery of an electric vehicle, to support the electric grid when there is demand.

1. **What is your gender?**

☐ Male

☐ Female

2. **Your age**

☐ 18 - 29

☐ 30 – 39

☐ 40 - 49

☐ Above 50

3. **What is your marital status?**

☐ Single

☐ Married

☐ Other; please specify _____Click or tap here to enter text.

4. **What is your nationality?**

☐ Saudi citizen

☐ Non-Saudi citizen

5. **Where is your residency?**

☐ Central Region

☐ Eastern Region

☐ Western Region

☐ Northern Region

☐ Southern Region

6. **What is your highest level of education? (Select only one)**

☐ Below high School

☐ High school

☐ Diploma

☐ Bachelor's degree

☐ Higher degree

☐ Other; please specify _____Click or tap here to enter text.

7. **How would you describe your current employment status? (Select only one)**
   ☐ Student

   ☐ Employed in public sector

   ☐ Employed in private sector

   ☐ Self-employed

   ☐ Retired

   ☐ Other; please specify _____Click or tap here to enter text.

8. **What do you expect your combined family annual income to be?**
   ☐ Under SAR 50,000

   ☐ SAR 50,001 – SAR 100,000

   ☐ SAR 100,001 – SAR 200,000

   ☐ SAR 200,001 – SAR 400,000

   ☐ SAR 400,001 – SAR 800,000

   ☐ Over SAR 800,000

   ☐ I would rather not say

   ☐ Other; please specify _____ Click or tap here to enter text.

9. **How many cars do you own?**
   ☐ 1

   ☐ 2

   ☐ More than 2

10. **What types of vehicles do you have?**
    ☐ Conventional (diesel/petrol) vehicle

    ☐ Hybrid vehicle

    ☐ Electric vehicle

11. **Which brand name, year model and engine size do you normally drive on a daily basis? For example: Toyota Camry - 2016 - 4 Cylinder**

    _____**Click or tap here to enter text.**

12. If you have more than one car, which one do you normally drive on a daily basis?

_____Click or tap here to enter text.

13. On average, how many kilometres do you travel every day?

☐ Under 25 km

☐ Between 26 and 50 km

☐ Between 51 and 100 km

☐ Between 101 and 150 km

☐ Above 150 km; please specify _____Click or tap here to enter text.

14. How much do you spend weekly on your vehicle fuel?

☐ Under SAR 50

☐ Between SAR 51 and SAR 100

☐ Between SAR 101 and 150 SAR

☐ Between SAR 151 and 200 SAR

☐ Between SAR 201 and 300 SAR

☐ Between SAR 301 and 500 SAR

☐ Above 500 SAR; please specify _____Click or tap here to enter text.

15. What time do you normally park your car for the longest period throughout the workdays for the summer and winter seasons? (More than one option can be selected for each season)

	Between 12:00 AM and 7:00 AM	Between 8:00 AM and 2:00 PM	Between 3:00 PM and 6:00 PM	Between 7:00 PM and 11:00 PM
Summer	☐	☐	☐	☐
Winter	☐	☐	☐	☐

16. What time do you normally park your car for the longest period throughout the weekends for the summer and winter seasons? (More than one option can be selected for each season)

	Between 12:00 AM and 7:00 AM	Between 8:00 AM and 2:00 PM	Between 3:00 PM and 6:00 PM	Between 7:00 PM and 11:00 PM
Summer	☐	☐	☐	☐
Winter	☐	☐	☐	☐

17. Describe your awareness with regard to the following statements.

Questions	No idea	Very little	Acceptable	Good	Very good
Electric vehicle (EV) in general (how it works, components of EV, etc.)	☐	☐	☐	☐	☐
Type of EV	☐	☐	☐	☐	☐
Brand of EV	☐	☐	☐	☐	☐
EV batteries (types, capacity)	☐	☐	☐	☐	☐
Saudi government goals in EV	☐	☐	☐	☐	☐
EV prices	☐	☐	☐	☐	☐
Environmental benefits of using EV	☐	☐	☐	☐	☐

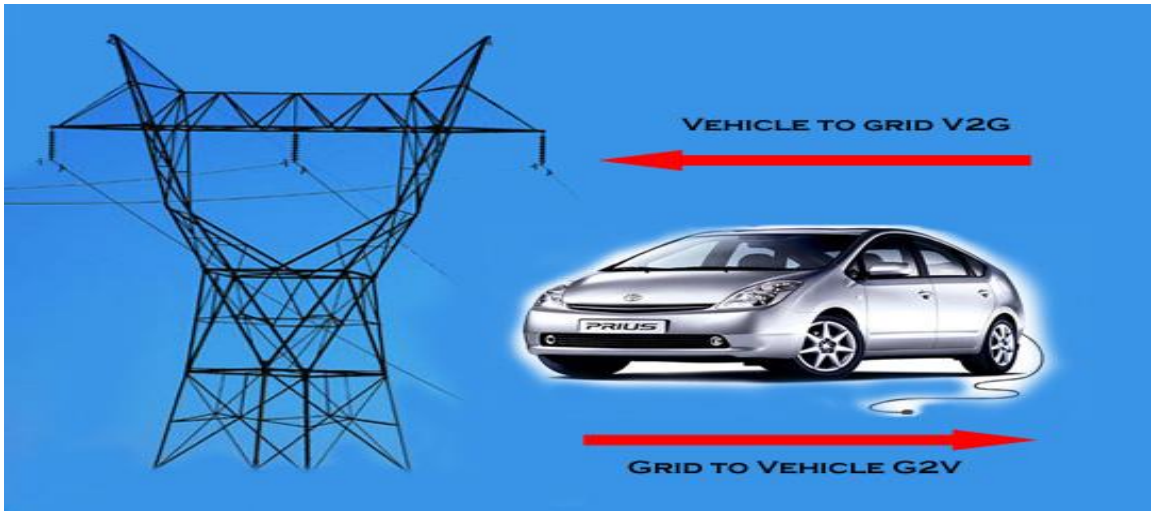
18. Are you willing to use an electric vehicle instead of a conventional vehicle?

☐ Yes

☐ No

☐ Other; please specify _____ Click or tap here to enter text.

Vehicle-to-grid is a technology that enables energy to be fed back to the power grid from the battery of an electric vehicle, to support the electric grid when there is electricity demand **in the grid.**



19. If you received more economic benefit from using a vehicle-to-grid, would you be interested in using vehicle-to-grid technology?

☐ Yes

☐ No

☐ Other; please specify _____ Click or tap here to enter text.

20. Please indicate how much you agree with the following statements concerning buying an electric vehicle in Saudi Arabia?

EV barriers and challenges	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
The infrastructure is incomplete in the Saudi Arabia, such as charging stations	☐	☐	☐	☐	☐
We do not need electric vehicles, as we are in one of the biggest petroleum-producing countries	☐	☐	☐	☐	☐

The cost to charge an electric vehicle will be higher than the fuel costs for a petrol or diesel vehicle	☐	☐	☐	☐	☐
Electric vehicles cost about the same to buy as petrol or diesel vehicles	☐	☐	☐	☐	☐
Electric vehicles are new technology and it too early to trust it like a conventional vehicle	☐	☐	☐	☐	☐
Electric vehicles are expensive to maintain	☐	☐	☐	☐	☐
Electric vehicles can only be used for shorter distances of travel	☐	☐	☐	☐	☐
Electric vehicles are dangerous due to the use of rechargeable batteries	☐	☐	☐	☐	☐
Duration of charging is longer in electric vehicles	☐	☐	☐	☐	☐
The terrain and weather conditions of Saudi Arabia are not suitable for EVs	☐	☐	☐	☐	☐

21. Are there any other issues that you are aware of which are not mentioned above (please specify)?

Click or tap here to enter text.

22. How important are these factors in your opinion when considering buying an electric car?

Questions	Very important	Important	Moderately important	Slightly important	Not important
The initial purchase cost	☐	☐	☐	☐	☐
Performance – speed	☐	☐	☐	☐	☐
Maintenance costs (battery replacement, service, spares, accessories)	☐	☐	☐	☐	☐
High resale value	☐	☐	☐	☐	☐
Government grants, discounts and initiatives	☐	☐	☐	☐	☐
Cost involved in charging	☐	☐	☐	☐	☐
Environmental benefits	☐	☐	☐	☐	☐
Aesthetics (style, size, design, safety, etc.)	☐	☐	☐	☐	☐
How far you could travel before it needs recharging	☐	☐	☐	☐	☐
Brand (USA, Japan, Europe, China)	☐	☐	☐	☐	☐
Car insurance price	☐	☐	☐	☐	☐

Availability of charging stations	☐	☐	☐	☐	☐

23. Are there any other features important for you that are not mentioned above, (please specify)?

Click or tap here to enter text.

24. What is the maximum price that you may be willing to pay for an electric vehicle?

☐ SAR 70,000 – 100,000 SAR "with less battery range"

☐ SAR 100,001 – SAR 150,000 "with medium battery range"

☐ SAR 150,001 – SAR 250,000 "with high battery range"

☐ SAR 250,001 – SAR 500,000 "with high battery range and advanced specifications"

25. Are there any other factors that are important to you (please specify)?

Click or tap here to enter text.

Appendix B – Solar Panel Module Characteristics

Table A.0.1 Datasheet for the PV Panels

Technical Specifications		
STC rated output (Pmpp)*	340 Wp	345 Wp
Rated voltage (Vmpp) at STC	37.33 V	37.38 V
Rated current (Impp) at STC	9.11 A	9.23 A
Open circuit voltage (Voc) at STC	46.16 V	46.37 V
Short circuit current (Isc) at STC	9.62 A	9.67 A
Module efficiency	17.60%	17.80%
Rated output (Pmpp) at NMOT	237.4 Wp	240.9 Wp
Rated voltage (Vmpp) at NMOT	34.10 V	34.15 V
Rated current (Impp) at NMOT	6.96 A	7.05 A
Open circuit voltage (Voc) at NMOT	42.36 V	42.55 V
Short circuit current (Isc) at NMOT	7.44 A	7.48 A
Temperature coefficient (Pmpp)	- 0.408%/°C	
Temperature coefficient (Isc)	+0.050%/°C	
Temperature coefficient (Voc)	- 0.311%/°C	
Nominal module operating temperature (NMOT)	46±2°C	
Maximum system voltage (IEC/UL)	1000VDC or 1500VDC	
Number of diodes	3	
Junction box IP rating	IP 67	
Maximum series fuse rating	15 A	

Table A.0.2 Datasheet for the Inverter

Technical Specifications	
Max. Efficiency	99.00%
European Efficiency	98.80%
Max. Input Voltage	1,500 V
Max. Current per MPPT	22 A
Max. Short Circuit Current per MPPT	33 A
Start Voltage	650 V
MPPT Operating Voltage Range	600 V ~ 1,500 V
Rated Input Voltage	1,080 V
Number of Inputs	12
Number of MPP Trackers	6
Rated AC Active Power	90 kW
Max. AC Apparent Power	100 kVA
Max. AC Active Power (cosϕ=1)	100 kW
Rated Output Voltage	800 V, 3W + PE
Rated AC Grid Frequency	50 Hz / 60 Hz
Rated Output Current	65 A
Max. Output Current	72.9 A
Adjustable Power Factor Range	0.8 LG ... 0.8 LD
Max. Total Harmonic Distortion	＜3%

Table A 0.3 Solar Tracker information

Rating Type	NX Horizon
Maximum input voltage	30 VDC
Range of input operating voltage	10–25 VDC
Maximum input current (DC)	2 A
Operating frequency range or single frequency	N/A
Normal operation temperature	–30°C to 50°C (–22°F to 122°F)