Modelling of The Saudi Arabia Energy System with The Future 100% Renewable Energy Systems Scenarios for Power Supply for All Sectors Coupled with Transport Sector Electrification

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

Signed:

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List of Abbreviations

ARAMCO – Saudi Arabian Oil Group

BCM – Billion Cubic Meters

CCS – Carbon Capture and Storage

CCGT – Combined Cycle Gas Turbine

CCPP – Combined Cycle Power Plant

CM – Cubic Meter

CO2 – Carbon Dioxide

CSP – Concentrated Solar Power

DHI – Diffuse Horizontal Irradiance

DNI – Direct Normal Irradiance

ECRA – The Old Name for WERA (Water and Electricity Regulatory Authority)

EPR – Energy Price Reform

EV – Electric Vehicle

GCC – Gulf Cooperation Council

GHI – Global Horizontal Irradiance

GT – Gas Turbine

GW – Gigawatt

H2 – Hydrogen

HFO – Heavy Fuel Oil

HRSG – Heat Recovery Stream Generator

ICE – Internal Combustion Engine

IEA – International Energy Agency

IPP – Independent Power Producer

IRENA – International Renewable Energy Agency

IWPP – Independent Water and Power Producer

KAPSARC – King Abdullah Petroleum Studies and Research Centre

KM – Kilometre

KPI – Key Performance Indicator

KWh – Kilowatt Hour

LCA – Life Cycle Assessment

LDV – Light Duty Vehicle

LPG – Liquefied Petroleum Gas

LPEC – Low Primary Energy Conversion

MCM – Million Cubic Meters

MERRA – The Modern-Era Retrospective Analysis for Research and Applications

Mtoe – Million Tonne of Oil Equivalent

MW – Megawatt

MWh – Megawatt Hour

NREL – National Renewable Energy Laboratory

NREP – National Renewable Energy Program

O2 – Oxygen

OCGR – Open Cycle Gas Turbine

PP – Power Plant

PV – Photovoltaic

RES – Renewable Energy System

SAM – System Advisor Model

SEEP – Saudi Energy Efficiency Program

SWCC – Saline Water Conversion Corporation

TFC – Total Final Consumption

TJ – Terajoule

TWh – Terawatt Hour

UNESCO – United Nations Educational, Scientific and Cultural Organization

V2G – Vehicle to Grid

Abstract

Saudi Arabia depends on fossil fuels for its energy production. Oil and natural gas are the primary natural resources used. In 2018, the total CO2 emissions were 491.7 Mt, which indicates that Saudi Arabia is one of the top CO2-emitting countries in the world. This work investigated possible pathways to 100% renewable energy supply by 2050 for the power from entire sectors with transport electrification. Three main gaps were identified: lack of a comprehensive dataset representing the current energy system, a validated hourly model, and a modelling study exploring 100% renewable options. To address these gaps, research was divided into two parts. First, comprehensive data gathering, review, and analysis were carried out for all energy sectors in the Kingdom. In this part, data collection and calculations were carried out for each sector in the Kingdom, providing the correct and validated information. In addition, the dataset was used to create a comprehensive energy balance block diagram of the entire Kingdom's sectors. A comprehensive review and dataset were conducted to fix the lack of data and clarity in several parts of the Saudi energy system. Then, in the second part, the new data set created was used to inform and validate the energy model of Saudi Arabia, allowing future scenarios in 2050 to be assessed from technical and economic perspectives. After the energy model was created and validated with actual data, 100% RES using solar photovoltaic, wind, and battery storage was investigated for power from all sectors. First, each RES technology was studied and simulated solely and assessed from a technical and economic perspective with limitations. Then, different combinations of RES are evaluated based on the same criteria and selected based on the limitations of the previous system in a series of gradual, cumulative improvements to reach the final optimal system. The renewable energy systems are compared and evaluated, and the final optimal system is identified. A green hydrogen power plant was created as a backup system to work in case any shortage occurs due to unusual events and changes in 2050. The backup system used green hydrogen, which was 100% generated from the surplus power of the renewable energy system through electrolysers. The passenger vehicle fleet of the transport sector in the Kingdom was 100% electrified using the surplus power generated from the renewable energy system in 2050. It was found that the combination of photovoltaics located in the Tabuk region, wind turbines located in NEOM city, and battery storage in addition to a green hydrogen backup plant was the optimal solution to supply the entire Kingdom power in 2050, technically and economically. In addition, carbon dioxide emissions were reduced by 60% in 2050 in the Kingdom with the renewable energy

systems scenario compared to the same year in the business-as-usual scenario. Finally, the results are discussed, and the conclusion is carried out. The limitations of this work, future work, and recommendations were identified. The contributions of the work in directly addressing the identified gaps are discussed.

CHAPTER 1

Introduction

1.1 Introduction & Background

Kingdom of Saudi Arabia Energy demand is increasing rapidly. It is the second biggest producer of oil in the world, and at the same time, it is the largest consumer of petroleum in the Middle East [1]. In 2017, Saudi Arabia ranked as the 10th largest global consumer of primary energy, with a total consumption of 266.5 Mtoe [2]. In 2018, the total primary energy supply in Saudi Arabia amounted to 213.6 Mtoe, consisting of 62.9% oil and 37% natural gas, with negligible reliance on renewable energy sources (RES) [3]. This great demand is due to extreme climate conditions, rapid economic growth, rising population, and developments in infrastructure. In addition, the abundance of oil resources and the subsidised energy prices had a significant impact on the increasing demand since Saudi Arabia has the second largest proven oil reserves in the world, 267,026 million barrels, after Venezuela in 2020 [4]. In addition, in 2018, Saudi Arabia held the 5^{th} largest proven reserves of natural gas in the world, totalling 9,000 km^3, after Russia, Iran, Qatar, and the United States [5]. This growth in energy demand has resulted in significant GHG emissions. In 2017, Saudi Arabia ranked among the top ten global contributors to CO2 emissions, with a total output of 620 Mt [6]. To date, it remains the largest emitter of CO2 in the Middle East. GHG gas emissions are not the only challenge; Saudi Arabia's economy, which mainly relies on oil and gas, has been dramatically impacted by several pandemics over the last few years. The most recent COVID-19 pandemic had a profound impact on the Saudi Arabian economy, leading to a collapse in oil prices. Revenues saw a significant decline in 2020 due to historically low oil prices and a reduction in economic activity. According to the quarterly budget performance report [7] released by the government, oil revenues dropped by 24% in the first quarter of 2020 (the beginning of the coronavirus pandemic) compared to the first quarter of 2019, from 169 billion riyals ($ 45 billion) to 128 billion riyals ($ 34 billion). The country faced a deficit of 34 billion riyals ($9 billion) in the first quarter of 2020, and its foreign exchange reserves fell dramatically, reaching their lowest point in the past nine years.

The growing reliance on petroleum and natural gas has led to climatic change and economic and political concerns. These concerns are forcing the Kingdom to change its improper energy structure. There are few studies on Saudi Arabia’s total energy structure and the potential for future change. The Kingdom needs a more studies on changing its improper energy structure and finding the opportunities and potential for enhancing this structure in the entire country. One of the Kingdom's most promising RES technologies is solar power, which is harnessed through PV panels (Photovoltaic). Several researchers have proven that abundant solar energy can produce sufficient power to run extensive areas and buildings. However, fewer studies still exist on using solar power on a country scale. In addition, wind power has a significant potential, especially near shores, as shown in the upcoming sections.

1.2 Problem Statement (Problem Formulation)

As mentioned in the introduction, Saudi Arabia is the largest oil consumer in the Middle East. Saudi Arabia holds 15% of the total world-produced oil reserves. It is the largest exporter of crude oil and the second-largest producer of total petroleum liquids after the United States. Oil is the primary resource used for energy, power production, and transportation, which is convenient due to its vast abundance. This has led to high CO_2 emissions, as Saudi Arabia is one of the top 10 countries in the world in terms of CO_2 emissions. With such a huge country and high use of fossil fuels for energy, it is essential to address this issue and find solutions, especially knowing that Saudi Arabia is one of the participating countries in the Paris climate agreement, which aims to limit global warming to well below 2, preferably to 1.5 degrees Celsius**,** compared to pre-industrial levels. To accomplish this long-term temperature goal, countries aim to reach the worldwide peak of greenhouse gas emissions as soon as possible to achieve a climate-neutral world by mid-century. Another interesting reason for conducting this research is that, although Saudi Arabia is one of the largest consumers of fossil fuels for energy, being the largest in the Middle East with vast reserves of crude oil, it also holds one of the most promising and abundant clean energy alternatives: solar power. There are several renewable energy resources available in the country. However, several studies have accepted solar energy as a key energy source for the future energy mix. Saudi Arabia has massive potential for utilising solar and wind energies for several reasons, such as geographical location, which will be discussed in detail, along with the potential for other renewable energy resources in the upcoming sections.

Several studies have addressed the current energy system and the potential for renewable resources. However, most of these studies focus on the potential of solar or the potential of a RES technology rather than the total transition of different sectors into RES in the future year targets such as 2030 and 2050, and for the power and transport sectors [8][9][10]. For example, researchers studied the potential of CSP (concentrated solar power) on the city scale in the Kingdom from an electricity perspective [11]. Some studies have been conducted on the potential for solar PV and wind but for small-scale areas in the country or city scale [12], as shown in Chapter 3. In addition, studies on the other potential for renewable resources, the fuel and energy in the Kingdom, transportation analysis, and energy breakdown. Some of these studies focused on technology review on one part of the RES [13][14]. However, a limited number of studies include energy analysis for a country scale for the future with different energy sectors, including supply and demand, electricity, transportation, fuel distribution, and CO2 emissions, as shown in detail in Chapter 3. Research such as [15] studied the 100% RES transition pathway in Saudi Arabia for 2050. However, this research focused on power, desalination, and industrial gas. The highest oil product consumers, such as those in the transport sector, were omitted, which is vital when speaking about the 100% transition towards RES in Saudi Arabia. Other studies and research are explained in detail in Chapter 3, along with their limitations.

To summarise, the fundamental problems that necessitate this research are:

1. Global warming is one of the leading world concerns—the considerable greenhouse gas emissions by the Kingdom of Saudi Arabia.
2. The country's significant dependence on fossil fuels as the leading supplier of its energy system and the unavailability of energy supply mix technologies, including RES, affect the economy, especially with the fluctuations of oil prices in different political situations or global pandemics, such as the most recent global pandemic of COVID-19, as mentioned earlier.
3. Saudi Arabia is late in the RES marathon compared to the other countries. Only in the last five years has it started to build RES for a country-scale future after introducing Vision 2030.
4. Saudi Arabia is not only blessed with enormous oil resources. It also has one of the most significant available solar energies globally, and this is a big challenge: having such a vast, clean, and renewable energy source and not utilising it on a country scale, especially with

the excellent availability of areas in the Kingdom, as it is geographically the largest country in the Middle East and the 12th largest country in the world.

5. A key rationale for this research lies in the scarcity of comprehensive studies on the future potential of RES in Saudi Arabia, particularly those conducting detailed technical and economic analyses on a country scale. Unlike many countries that have already outlined RES targets for 2030 and 2050, Saudi Arabia lacks a robust, country-wide energy model that integrates both supply and demand across different sectors. This gap includes the absence of models that assess various energy sources such as electricity, oil, and natural gas, while exploring various 100% RES scenarios. There is a pressing need for a framework that evaluates these potential systems not only from a technical perspective but also from economic and environmental perspectives, incorporating different future pathways to inform long-term strategic planning for a sustainable energy transition.
6. To the best of our knowledge, no existing quantitative computational model thoroughly examines the future potential of RES in Saudi Arabia for target years, such as 2050. This includes a detailed analysis of the Kingdom's key supply and demand sectors, specifically power and transport. A comprehensive model that integrates these sectors and evaluates the transition to RES from technical, economic, and environmental perspectives is lacking, underscoring the need for a robust computational approach to explore sustainable energy pathways nationally.
7. Previous studies have either focused on a single part of the energy system or multiple parts, but for a small-scale system. So far, there has not been a complete study of the whole energy system that examines the potential for cross-sector coupling and future 100% RES solutions in 2050 on a national scale with technical, economic and environmental evaluations, recommendations and limitations. This is the knowledge gap to be addressed in this work.

1.3 Research Questions

Saudi Arabia has only recently started planning to transition towards RES. This research aims to help contribute to the knowledge of that and help to find solutions to the problems mentioned in the last section. This research seeks to contribute to answering the following questions:

1. How can one of the biggest oil-dependent countries transition towards renewable and sustainable energy systems? In a country with a significant dependency on fossil fuels and massive availability of renewable alternatives, what would be the situation if the dependency

on fossil fuels for energy is reduced to 50%? to 0% for the power sector and the power & transport sectors?

2. How is the energy transition currently envisioned in the context of the Saudi Arabian Energy system?
3. What are the challenges facing the transition of the Saudi Arabian energy system towards a renewable and sustainable energy system?
4. What is the optimal future RES for Saudi Arabia? How can this system be determined? What are the advantages, challenges, and limitations of this system?
5. What are the recommendations for designing the future sustainable energy system for Saudi Arabia?
6. What gaps exist in research about Saudi Arabia's specificity in the energy field, and how could they be tackled?
7. What is the optimal energy system combination from techno-economic and environmental perspectives?

1.4 Aim

This research aims to contribute to knowledge by addressing the research questions outlined in Section 1.3 and tackling the issues and gaps highlighted in Section 1.2. This involves developing a comprehensive understanding of Saudi Arabia's current energy landscape, focusing on identifying sustainable pathways for transitioning to RES. Specifically, this study seeks to construct a detailed energy model of Saudi Arabia's existing power and transport sectors, integrating data from all relevant energy sectors. This model will serve as a foundation for simulating and evaluating future energy systems, considering both renewable and non-renewable configurations for target years like 2050.

Through a quantitative computational approach, this research seeks to evaluate prospective energy systems from technical, economic, and environmental perspectives. This includes determining optimal configurations of RES solutions specifically for Saudi Arabia, with the goal of developing scenarios in which RES sources fully satisfy projected energy demands by 2050. The outcomes of this analysis will be used to inform policymakers, provide evidence-based recommendations and highlight the limitations of different energy scenarios. Ultimately, this research aims to contribute key insights through a validated dataset, a reliable energy model, and scenario analyses tailored to Saudi Arabia's specific energy context.

An aim has been to deliver helpful knowledge through an informed dataset, model, and scenarios for the Saudi Arabia energy system.

1.5 Overall Approach of This Research

To accomplish the overall aim, the research was structured around the following key steps, as outlined in the chapters of this thesis:

- (Chapter 2) To inform the analysis, it was essential to investigate the current energy system and bring together and synthesise available fragments of information from reputable sources to build a comprehensive knowledge base and dataset representative of Saudi Arabia's current energy system. The energy demands were compiled, and the current supply systems were detailed. An extensive dataset and whole energy balance diagram were the key outputs from this stage, intended to be a valuable contribution to knowledge and made available to others, e.g. to directly inform policy and to be used to inform the energy system model developed and deployed later in this work.
- (Chapter 3) in this chapter, the energy modelling strategy and methodology were then determined based on the research and modelling requirements for both the current and potential future energy systems. The key performance criteria and parameters to evaluate and compare the performance of the current energy system and future options, as well as the objective functions to be derived from the modelling, were specified. Several methods and tools were reviewed, and the modelling methodology was justified and documented to be used as a platform for the investigations.
- (Chapter 4) The technical knowledge base and the modelling methodology were used to establish and validate a baseline model for Saudi Arabia’s energy system and investigate various RES options. Individual technology options were evaluated technically, several combined technology scenarios were explored, and the outcomes were assessed. The key findings from the modelling investigation relevant to future policy for Saudi Arabia were summarised, as well as future work that could further build on the modelling methods and investigation.

- (Chapter 5), in this chapter, the economic analysis employed a rigorous and systematic approach to evaluate both the current energy framework and the projected 2050 RES scenarios for Saudi Arabia. Individual RES technologies, as well as various hybrid configurations, were assessed from a comprehensive economic perspective. This evaluation utilised a set of critical economic indicators, including total investment costs, annual investment costs, operation and maintenance (O&M) costs, and the Levelized Cost of Energy (LCOE), forming a robust methodological framework for cost assessment. By calculating the LCOE and examining the investment and operational costs in detail, this study identified the most economically viable pathways for transitioning to a 100% RES by 2050. This analysis provided nuanced insights into the financial implications and investment requirements, supporting informed decision-making for future sustainable energy policies. This structured and systematic approach not only quantifies the economic feasibility of each technology and scenario but also enhanced the clarity and reliability of the research findings, ensuring that they contribute significantly to the knowledge base on Saudi Arabia's energy transition.

- (Chapter 6) The recommended optimal RES for Saudi Arabia in 2050 was then summarised and evaluated with other RES solutions based on the final technical and economic evaluation results. The contributions to knowledge from both the whole energy system synthesis, the model development and validation, and the modelling investigation were identified and discussed together with limitations and extensions of the work in this thesis that can be addressed in future work to build further on these outputs.

In the first step (Chapter 2), the aim was to investigate the current energy system of the Kingdom for a reference year, specifically 2017, as it was the most recent year with the most available data. The reference year of 2017 was selected, as the entire Kingdom's energy system was simulated for comparison with the new energy solutions projected for 2050. This comparison included the installed energy systems, the total primary energy supply, CO2 emissions, consumption patterns, and system costs, etc. 2017 was chosen as the reference year because it was the most recent year with complete data available at the time of writing this thesis. Later years, such as 2018 and 2019, had critical missing data, including the hourly electrical demand for the entire country and some fuel and industry consumption figures. Therefore, 2017 was the optimal choice for this analysis.

It is essential to build one solid review of the current energy system, including all sector's demands and supply, as many parts of the Saudi system were unclear or have missing information. Some data was also misleading and did not provide a clear understanding of the system. Thus, building a solid knowledge base and dataset representative of Saudi Arabia's current energy system was essential, representing each sector in detail with the correct collected and calculated data. The key outputs from the first step were a comprehensive dataset and whole energy system diagram (energy balance) made available to others, e.g. directly inform policy, and to be used to inform the energy system models developed and deployed later in this work.

In the second step (Chapter 3) of this thesis, the energy modelling strategy and methodology were determined based on the research and modelling requirements of the current and potential future energy systems. The key performance criteria/parameters to be used to evaluate and compare the performance of the current energy system and future options and objective functions to be available as outputs from the modelling were specified. Several methods and tools were reviewed, and a modelling methodology was justified and documented to be used as a platform for the investigations.

In the third step of this thesis, detailed in (Chapter 4), the foundational knowledge base, validated dataset, and systematic modelling methodology were applied to construct and authenticate a baseline energy model for Saudi Arabia's energy system, with the reference year set to 2017. This baseline model was instrumental in setting a credible foundation for investigating a range of future RES configurations for the power sector in 2050, evaluated primarily from a technical perspective. Two advanced energy modelling tools were employed to develop and validate the model: EnergyPLAN by Aalborg University, combined with the System Advisor Model (SAM) by NREL labs. Together, they facilitated the creation of a comprehensive and validated model of Saudi Arabia's current energy system, which then served as the basis for simulating and evaluating potential renewable energy scenarios for the future target year of 2050. This methodological framework allowed for the detailed assessment of individual RES options and the exploration of several hybrid configurations. The outcomes of this model provided key technical insights, synthesised to highlight the most promising options for future policy in Saudi Arabia. Additionally, recommendations made regarding potential future research directions that could enhance the current modelling framework and expand on the technical investigation conducted in this thesis.

In the fourth step of this thesis, detailed in (Chapter 5), a comprehensive economic analysis of both the current energy system and the future simulated RES for Saudi Arabia in 2050 was conducted. This chapter systematically evaluated key economic assumptions, including investment costs, operational and maintenance costs, interest, and discount rates. These economic inputs were critical in understanding the financial viability of each RES configuration. Chapter 5 aimed to provide a detailed assessment using a set of economic metrics, including the total investment costs, total annual costs, and LCOE. This analysis built upon the technical evaluations from Chapter 4, integrating both technical and economic criteria to deliver a holistic view of the most feasible and cost-effective RES configurations for 2050. The outcomes were carried out to highlight the economic efficiency of each scenario, identifying the optimal RES pathways for Saudi Arabia by balancing both technical performance and financial sustainability. In addition, Chapter 5 not only reviewed and evaluated the energy systems from an economic perspective but also discussed the assumptions and financial parameters in depth, ensuring transparency and clarity in the economic assessment. Combining these financial analyses with the technical evaluations, this chapter aimed to provide robust recommendations for policymakers regarding the optimal configuration of a 100% RES, supporting Saudi Arabia's strategic transition towards sustainable energy.

In the fifth step of this thesis, outlined in (Chapter 6), the research synthesized the contributions to knowledge derived from the entire energy system analysis, model development, validation, and simulation investigations. This chapter emphasised the significance of the research outputs, summarising how the methodological framework has advanced understanding in the field of renewable energy for Saudi Arabia. It highlighted the identification and selection of the optimal RES for 2050, evaluated and validated through the findings from the technical and economic assessments conducted in Chapters 4 and 5.

Chapter 6 also acknowledged the current study's limitations, provided a critical reflection on the research scope, and identified areas where future investigations could expand or enhance the findings. This included potential extensions in modelling techniques, simulations, real-world data accuracy, and broader scenario analyses that could further contribute to sustainable energy planning for Saudi Arabia. Additionally, it assured the importance of the validated model and its application to future studies, serving as a robust foundation for ongoing energy system optimisation.

This chapter thus summarised the synthesis of the research, affirmed its relevance and impact, and pointed towards future opportunities for refinement and development within the field of RES.

1.6 Contributions from This Work

The primary contributions of this research are multi-faceted, reflecting its comprehensive approach to evaluating Saudi Arabia's energy system and planning for a sustainable future:

1. The Development of a Comprehensive Dataset: This research has developed a detailed and accurate dataset covering all sectors of the Saudi energy situation, including demand and supply metrics for various fuels, the power sector, transportation, industry, desalination, and water management. This dataset offers a complete overview of the country's energy dynamics, highlighting the interconnections between different sectors. A key contribution of this dataset is the energy balance block diagram of the entire Kingdom, developed from scratch by the author. Additionally, supplementary calculations, analyses, and data are made publicly accessible through Microsoft Excel, EnergyPLAN, and SAM files hosted on GitHub, encouraging further research and analysis.
2. The Validated Computer Model of Saudi Arabia's Energy System: The second significant contribution is the development and validation of the detailed computer model of Saudi Arabia's complete energy system. This model includes energy demands, supply sources, power generation, fossil fuel dynamics, the transport and industrial sectors, cost structures, and CO2 emissions. It provides a robust tool for assessing future energy scenarios from technical, economic, and environmental perspectives. The validated model is publicly available for free, supporting transparent and reproducible research efforts.
3. The Development of 100% Future RES Scenarios for 2050: The final key contribution is the development of future energy scenarios detailing how Saudi Arabia could transition to a 100% RES for the power and transport sectors by 2050. These scenarios, coupled with specific recommendations and noted limitations, provide a strategic foundation for future policy-making, infrastructure design, and decision-making processes. These scenarios aim to guide the country in aligning with ambitious sustainability targets, such as those for 2050. Aside from select data from the Saudi Water and Electricity Regulator Authority (WERA), all data used in this thesis is publicly accessible for further research, facilitating wide-ranging academic and policy discourse. Some data from WERA was restricted for public access and used exclusively within this research in compliance with WERA's conditions.

Through its dataset, validated model, and scenario analyses, this research contributes significantly to the body of knowledge on sustainable energy transitions in Saudi Arabia.

1.7 Scope of The Thesis

This section illustrates the research components that were initially considered but ultimately not carried out due to constraints or limitations:

1. 2030 as an intermediate target year: The year 2030 was identified as a significant step for analysing and simulating future energy scenarios, with an intended focus on achieving 50% RES supply and 50% electrification of the transport sector. This was envisioned as a stepping stone towards the 2050 target of 100% RES and complete passenger vehicle electrification. The methodology planned for 2030 mirrored that of the 2050 analysis, involving extensive hourly simulations across multiple parameters. Each simulation entailed processing 8,784 hourly data points, a time-intensive task requiring comprehensive analysis, calculations, and graphical visualisations. Due to the extensive effort needed for these detailed simulations and data processing, the 2030 analysis was not completed within the project’s timeframe.

2. Desalination sector analysis: A focused analysis of the desalination sector was planned, explicitly addressing the shift from fossil fuels to synthetic gas produced from surplus RES for fuel needs. Given the Kingdom’s substantial reliance on desalination and its status as one of the world's largest consumers of energy for water production, this sector holds critical importance. However, there had been significant challenges in data collection. Data on the hourly behaviour of desalination, including fuel consumption by type, freshwater generation, saltwater processing and other data, was either unavailable, classified, or restricted to specific entities. As a result, the planned in-depth analysis of the desalination sector's transition to RES was not feasible within the scope of this thesis.

3. Grid stability with 100% RES: Achieving grid stability under 100% RES currently requires support from conventional fossil-fuel-based power plants. This research assumed that future advancements in non-fossil fuel grid stabilising technologies and control systems would emerge by 2050, allowing for a fully sustainable energy grid. However, the design and evaluation of non-fossil fuel stabilising systems are beyond the scope of this thesis. Future studies must explore and develop these technologies to achieve complete RES implementation.

4. Fuel consumption in other sectors: While this thesis focused on RES solutions for the power demands across all sectors in the Kingdom and specifically targeted the transport sector's

fuel consumption, it did not extend to other sectors like industry and desalination. The potential replacement of natural gas in industrial applications with alternatives like biogas or synthetic gas remains an area for future research. This decision to limit the study was based on the availability of reliable data and the need to concentrate efforts on achievable and impactful targets. Future work could build on the findings of this thesis to explore comprehensive RES solutions for other sectors in terms of their fuel consumption.

CHAPTER 2

Saudi Arabia Energy System: Development of The Knowledge Base and Dataset.

2.0 Introduction

This chapter comprehensively reviews Saudi Arabia's current energy system by consolidating information from various credible sources to present a holistic view. The analysis includes a detailed examination of each energy sector and its interrelations with different fuel resources such as crude oil, oil derivatives (gasoline, diesel, kerosene, and heavy fuel oil), electricity, and natural gas. The outcome of this synthesis is a comprehensive dataset and an energy balance diagram in Figure 2 representing the complete energy landscape of the Kingdom.

The chapter is structured as follows: It begins with a general overview of the Kingdom's energy framework. This is followed by an in-depth exploration of energy demand across various sectors. Finally, the chapter concludes by addressing the current energy supply situation, offering a clear understanding of the dynamics between supply and demand within Saudi Arabia's energy system. The comprehensive dataset generated from this analysis forms the foundation for further modelling and scenario projections discussed in subsequent chapters.

2.1 Saudi Arabia Energy System: Overview

Saudi Arabia is a heavy consumer of fossil fuels for the entire energy sector. Power stations heavily use fossil fuels in addition to transport and industry sectors. Oil and natural gas provide Saudi Arabia's primary energy supplies. Looking into the energy system of the Kingdom in 2017, from a broad point of view, oil and natural gas were the primary resources used for energy production; 67.5% of the total primary energy supply was oil, and the remaining 32.5% was from natural gas [16] while coal and other energy resources such as biomass or biofuel were not utilised.

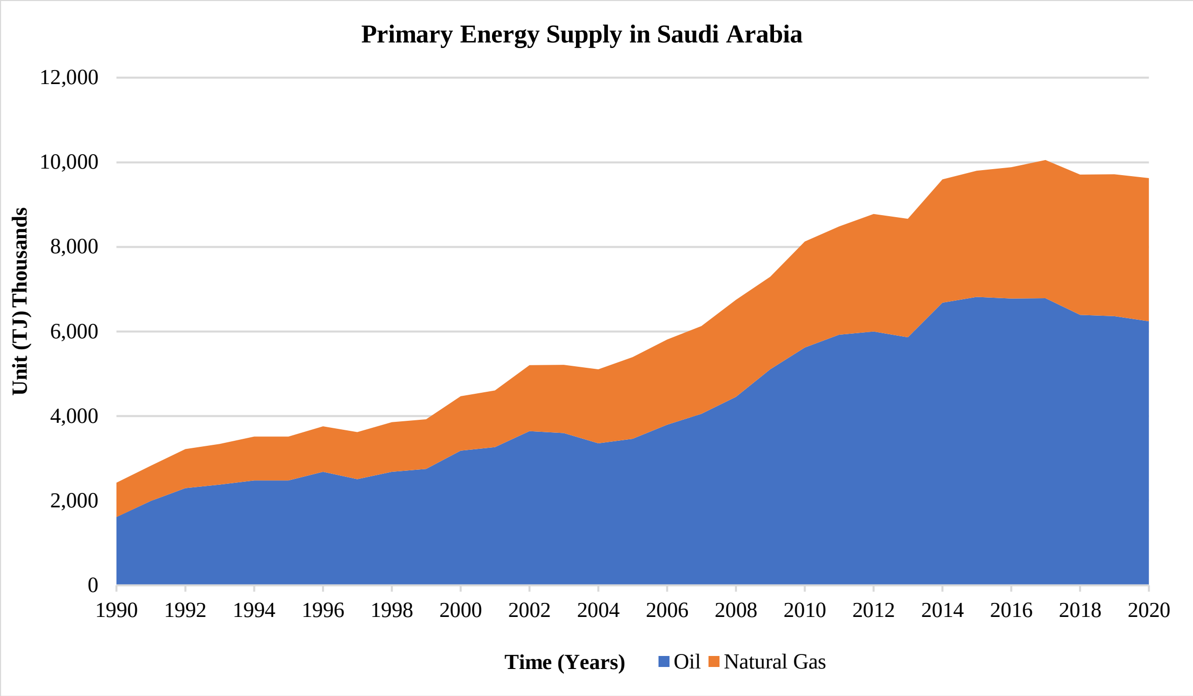

Figure 1 Total primary energy supply by source in Saudi Arabia [17].

In Figure 1, oil and gas are the Kingdom's primary energy supply resources, with almost no use of other resources. The use of oil and natural gas has been increasing over the last few years. Oil and oil products supplied most of the Kingdom's primary energy, accounting for 6,786,736 TJ (67.5%), followed by energy from natural gas at 3,266,096 TJ (32.5%) [18].

2.1.1 Design and Structuring of Saudi Arabia's Energy Balance Diagram (Figure 2)

Figure 2, presented below, was accurately constructed to provide a comprehensive overview of the dataset and logical framework for Saudi Arabia's energy system. Developed by the author, this figure represents a significant contribution to the study by visually depicting a detailed energy balance block diagram for Saudi Arabia's energy system in 2017. It maps out the intricate relationships between various energy resources (fuels and electricity) and different sectors within the Kingdom. A higher-resolution version of this diagram can be found in the appendix.

The data utilised for Figure 2 were sourced from IEA and WERA. The IEA's fuel balance data, primarily in Microsoft Excel format, served as a foundation for aligning and integrating the sector-specific energy flows of the Kingdom into a single block diagram. This diagram illustrates the interactions between various energy resources and their respective origins (such as production, imports, and conversion) and destinations, highlighting the flow from source to end-use.

Key components of this figure include the origins of energy resources—like crude oil, natural gas, and electricity—and their pathways through the Kingdom's sectors. These sectors range from industrial and residential to agricultural, commercial, and public services. For instance, power plants are shown using various fuel sources such as crude oil, natural gas, fuel oil, and diesel to generate electricity, which is then distributed to different end-users, with the residential sector identified as the largest electricity consumer. The diagram also demonstrates how crude oil, locally produced in quantities of 21,116,751 TJ, is allocated: part of it is exported, part is directly utilised in power and desalination facilities, and part is sent to local refineries. In the refineries, crude oil is converted into other fuels like fuel oil, diesel, bitumen, and naphtha, which are subsequently used in various applications, including power generation. This visual framework is instrumental in understanding the Kingdom's energy landscape, showing the complex dynamics of energy flows and sectoral interactions, and is a vital reference point for subsequent energy system modelling and scenario development.

2.1.2 Analysis of Saudi Arabia's Energy Balance Diagram and Consumption Dynamics

Discussing the data in Figure 2, in 2017, the Kingdom produced about 21.1 million TJ of crude oil, with more than half exported, making the Kingdom one of the world's largest net producers and exporters of crude oil. The remaining crude oil was primarily allocated to oil refineries, amounting to 5.3 million TJ for the production of oil products, and to power stations, totalling 0.88 million TJ (0.63 million TJ for standalone power stations and 0.25 million TJ for desalination stations). Oil refineries are the primary producers of oil products in the Kingdom, with only minimal amounts imported. The quantity of oil products is approximately 5.5 million TJ, including motor gasoline, jet kerosene, diesel, LPG, fuel oil, other kerosene, and oil products. In comparison, imports of oil products did not exceed 1 million TJ. Most oil products are set for export purposes. Meanwhile, the remaining quantity was allocated to transportation, power generation, industry, and non-energy applications, with the transport sector consuming the largest share of oil products, reaching 2 million TJ across the Kingdom. Transport sector is the largest consumer of motor gasoline, totalling 1.09 million TJ (54%). Power stations, including standalone and cogeneration, are supplied by crude oil, petrol, diesel, and natural gas as the primary fuel inputs to produce electrical power. The total fuel input to all power stations totalled 3.8 million TJ, with the total generated electricity of 1.36 million TJ, indicating a combined efficiency of roughly 35% for the power stations in the Kingdom. After accounting for network losses and internal use, the final produced electricity is distributed to the end-user sector. The residential sector is the largest consumer of electrical energy in the Kingdom, consuming 0.516 million TJ (47% of the final end-user electrical demand), followed by the commercial and public services sectors with 0.425 million TJ, and the industrial sector with 0.147 million TJ. Agriculture and other sectors show lower electricity consumption patterns.

The absence of electrical demand for the transport sector is worth mentioning as most of the Kingdom's transport sector is supplied by oil products. In recent years, negligible electric vehicles emerged in the Kingdom as a personal option, not an official government decision and plan. In addition to the transportation and power generation sectors, oil products are also consumed across various sectors in the Kingdom, including industry and residential sectors. The highest consumption of oil products is for liquefied petroleum gas (LPG) used for cooking, as well as kerosene fuels, which are used for heating in the few colder areas during the winter.

A substantial amount of oil products is consumed for non-energy use purposes. According to the IEA, 'non-energy use' refers to *"fuels that are used as raw materials in various sectors and are not consumed as fuel or transformed into another fuel"* [19]. Fuels such as LPG, ethane, bitumen, naphtha, and other oil products are utilized as chemical feedstocks and non-energy products, as Saudi Arabia has a large petrochemical industry. In addition, both oil products and natural gas are used as raw materials to produce several synthetic products. Natural gas is 100% produced domestically (3.26 million TJ) and not imported. It is primarily consumed in power stations; approximately 65% of the natural gas is consumed by power stations, while the remainder is used for the industry sector, followed by non-energy use.

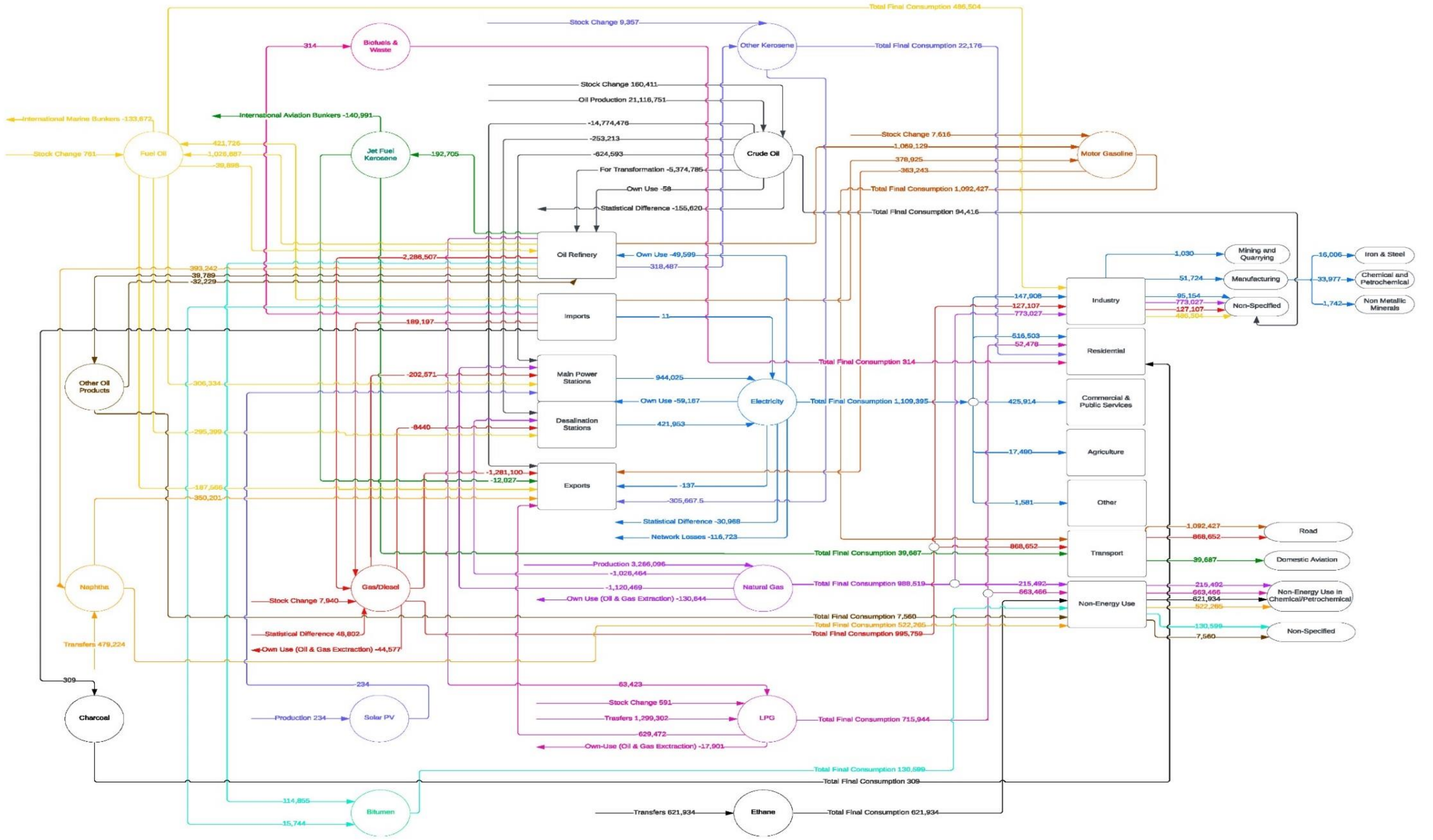

Figure 2 Detailed block diagram of the energy balance in Saudi Arabia, including fuels, supply, and demand sectors [Author: constructed from IEA as the primary reference and WERA]

2.2 Saudi Arabia: Energy Demand

2.2.0 Overview

Saudi Arabia's energy demand is divided into three key categories: oil, natural gas, and electricity. This demand encompasses not only the total final consumption by end-users or specific sectors but also the broader energy requirements of the entire Kingdom. This includes the energy needed for power generation, oil refining, and other conversion processes. Oil demand consists of both crude oil and refined oil products. In 2017, the Kingdom's primary energy supply sources were oil and natural gas, which supplied all energy demands, from end-user consumption to conversion demands in power stations and refineries. Notably, no utilisation of alternative energy sources like coal or renewables, such as solar power, across any sector in the Kingdom due to Saudi Arabia's abundant oil and natural gas reserves.

In the recent years, from 2017 to 2024, the Kingdom has initiated large-scale RES projects to diversify its energy mix in alignment with its "Vision 2030" strategy, directed by the Crown Prince. This plan aims to reduce greenhouse gas emissions and increase the contribution of renewables to the energy supply by 2030. Subsequent sections will elaborate on these initiatives.

Figure 3 illustrates the breakdown of energy consumption by type for different sectors within Saudi Arabia in 2017. Power generation facilities are the largest consumers of crude oil and natural gas, using 877,806 TJ and 2,146,933 TJ, respectively, along with moderate amounts use of refined oil products. The transport sector predominantly consumes oil derivatives, including motor gasoline, diesel, and jet kerosene. Natural gas is the dominant energy source in the industrial sector, supplemented by oil products, crude oil, and electricity for various industrial purposes, such as mining, manufacturing, and other unspecified activities. In the manufacturing sub-sector, iron and steel production consumed 16,006 TJ of electricity, while the chemical and petrochemical production consumed 33,977 TJ, as detailed in later sections.

Non-energy use refers to the consumption of fuel resources for non-energy-related purposes, such as using oil products and natural gas as raw materials in chemical and petrochemical production. Although non-energy use is not associated with fuel combustion or transformation into another fuel, it is included in the analysis to understand fuel distribution in Saudi Arabia comprehensively. However, non-energy use is often excluded from an energy systems perspective since it does not involve burning fuels for energy generation.

In the same figure, the residential sector is the largest electricity consumer, accounting for 47% of the total end-user electricity demand, driven by significant air conditioning needs, particularly during the summer months—a topic discussed in more detail in subsequent sections. Additionally, in a few areas, the residential sector uses oil products, such as LPG, for cooking and kerosene for minimal heating needs during winter.

The "own use of energy" category includes the energy consumed by energy-producing sectors for operational purposes, such as heating, lighting, pumping, and equipment operation in extraction, distribution, and processing facilities. This includes the electricity utilised by power plants and the natural gas used in oil and gas extraction processes, as defined by ISIC Rev. 4 Divisions 05, 06, 19, and 35, Group 091, and Classes 0892 and 0721 [20].

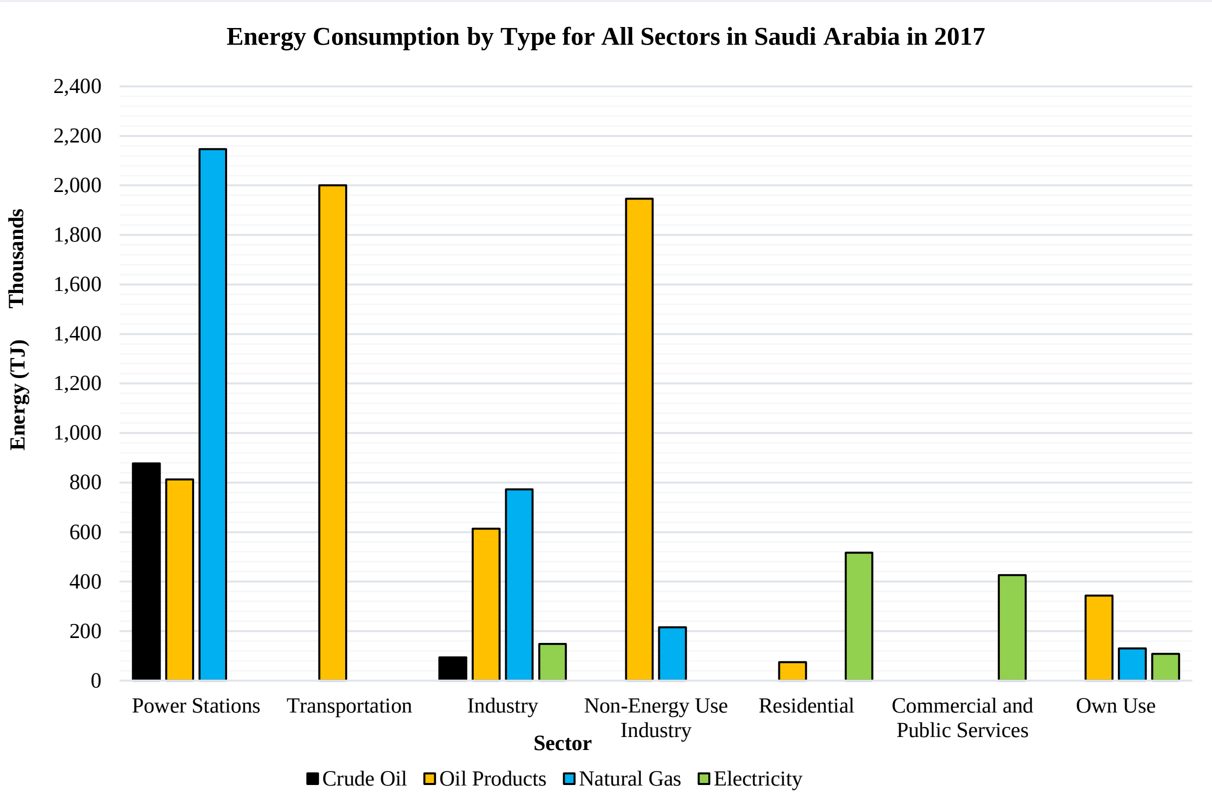

Figure 3 Energy consumption by type for all sectors in Saudi Arabia in 2017 [Author: constructed from Figure 2 and IEA]

2.2.1 Electricity

The demand for electricity in Saudi Arabia has grown significantly since the establishment of the electricity sector in the 1970s. Figure 4 illustrates the rapid growth in the Kingdom's total electricity demand over the past three decades. Several studies attribute this rise to substantial population growth and government-regulated energy prices. Additionally, the surge in electricity consumption has been driven by Saudi Arabia's economic expansion, which was strongly influenced by historically high international oil prices and substantial local fuel subsidies. These factors collectively contributed to the sharp increase in electrical demand across the country.

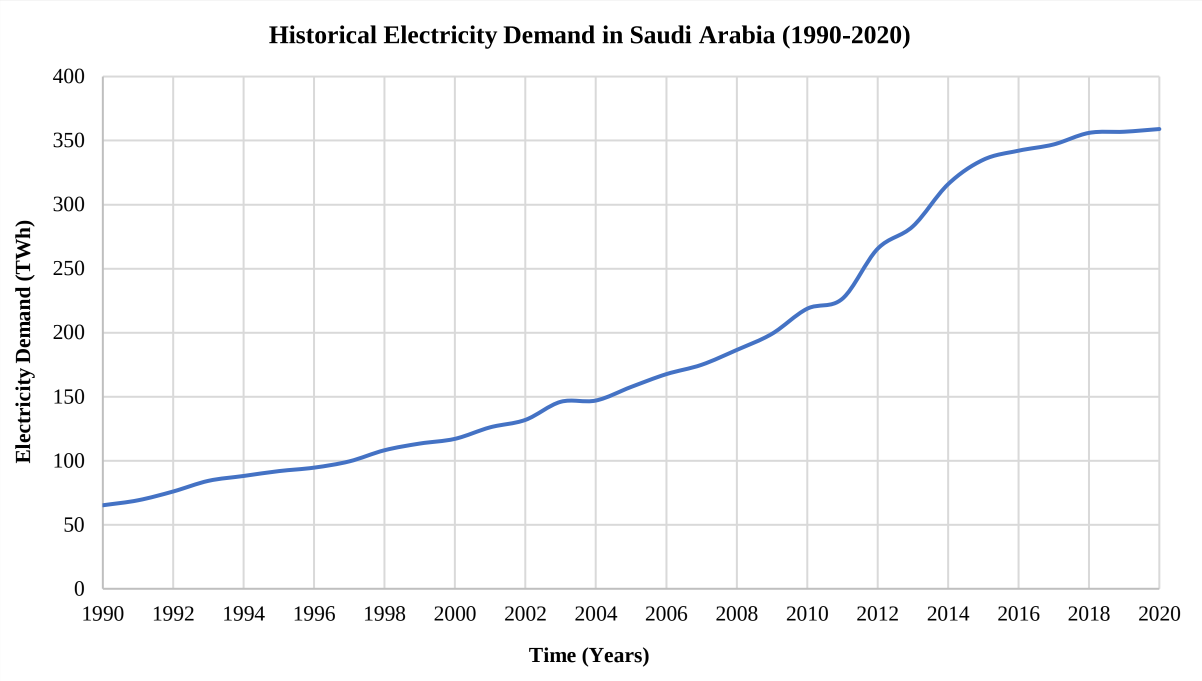

Figure 4 Electricity demand in Saudi Arabia (1990 – 2020) [21]

Figure 4 shows the annual electrical demand of Saudi Arabia from 1990 to 2020. The gradual growth of electrical demand over the years, population increase and rapid expansion, are essential factors affecting the development. The electrical demand in 2017 was 347 TWh as shown in the Figure, slightly different from the electrical demand value of 379 TWh used in the EnergyPLAN model, which is shown more frequently later in this thesis. This is because, in Figure 4, IEA calculated the electricity demand of all sectors in addition to their own use without the network losses as follows: all sector's demand is 308.1 TWh + own use of electricity= 30.2 TWh + a statistical difference in the IEA's data = 8.6 TWh. The total then = 347 TWh, as shown in the graph. If the network losses of 32.4 TWh are added, the new total will equal to 379.4 TWh, the value used in the energy model as shown in the later sections. In 2017, the total electricity demand in Saudi Arabia reached 347 TWh [21], with a peak load of 62,121 MW recorded in the summer of August 22, 2017 [22].

Saudi Arabia ranks as the eleventh largest electricity consumer globally [23], with consumption levels comparable to more populous nations like Mexico, which had a population of 128,932,753 in 2020, compared to Saudi Arabia's 34,813,871 [24]. The electrical demand of the Kingdom is also similar to more advanced economies such e.g. as Italy, who's in 2020 their total Gross Domestic Production (GDP) was 1,888,709 million $ compared to 700,117 million $ in Saudi Arabia [25].

Unlike the general energy consumption trend in other countries, Saudi Arabia's energy consumption has increased faster than its GDP, indicating an increased energy intensity. Driven by rapid economic growth, the expansion of the industrial sector—particularly through the development of petrochemical cities—population growth, low electricity tariffs, and high electricity consumption for air conditioning, especially during the summer months, electrical demand in the Kingdom increased by approximately 75% between 2009 and 2019. Peak load is expected to reach 74,168 MW in 2025, 83,855 MW in 2030, and 103,228 MW in 2040 [26]. Electrical consumption has been increasing annually, but few drops in the electrical consumption occurred, such as in 2020, when electrical consumption witnessed a sharp decrease of 3.6% compared to 2019 due to the COVID-19 pandemic and commercial and industrial institutions remained temporality closed during the nationwide lockdown [27]. Most of the Kingdom's electrical demand occurs in the summer. Usually in August of each year, as shown in the hourly electrical demand for the year 2017 in Figure 5.

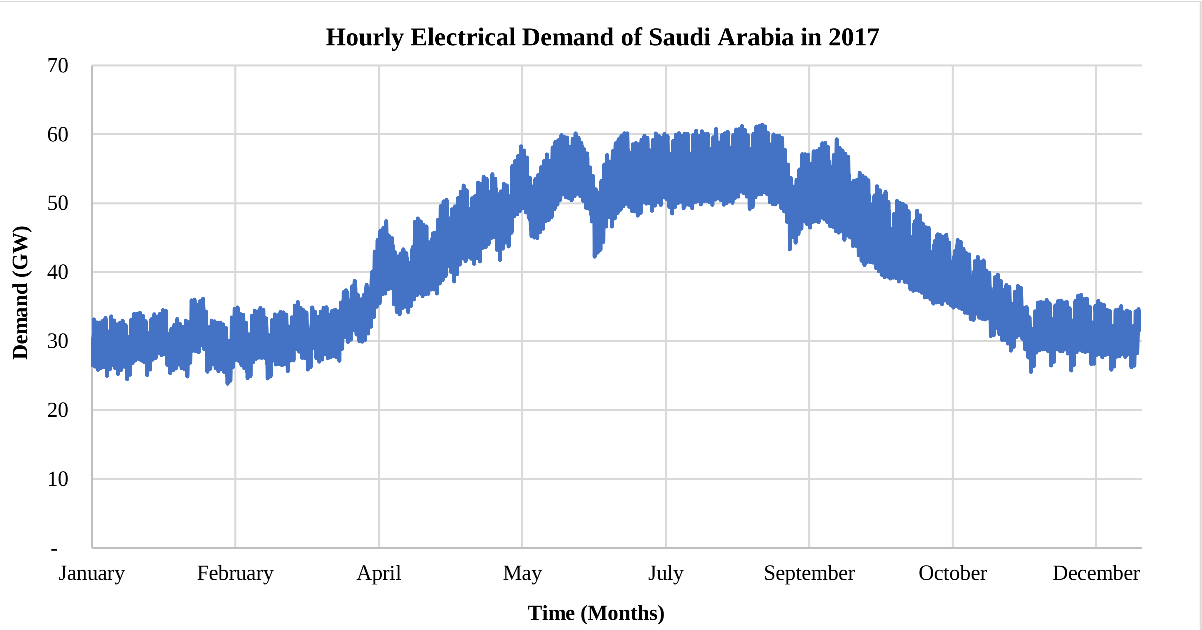

Figure 5 Electrical demand of Saudi Arabia in 2017 [28] [Author: constructed from Excel file taken from official source in the Kingdom]

Figure 5 illustrates the obvious seasonal variation in hourly electricity demand in Saudi Arabia, highlighting that the highest demand period extends from April to October. Electrical consumption nearly doubles in the summer compared to winter months, primarily due to the intensive use of air conditioning systems as temperatures reach extreme levels. This seasonal peak in demand is driven by the country's harsh climate, particularly during summer when temperatures can rise to 53°C. The middle regions, including the area around the capital, experience scorching and arid conditions, while the coastal areas in the east and west are characterised by intense heat and humidity. Consequently, air conditioning becomes essential in maintaining comfortable living conditions.

In terms of sectoral consumption, the residential sector is the dominant consumer of electricity, followed by the industrial and commercial sectors, as illustrated in Figure 6. The residential sector’s high consumption is mainly due to the significant air conditioning requirements throughout the hot months, making it a crucial factor in the country’s energy demand profile.

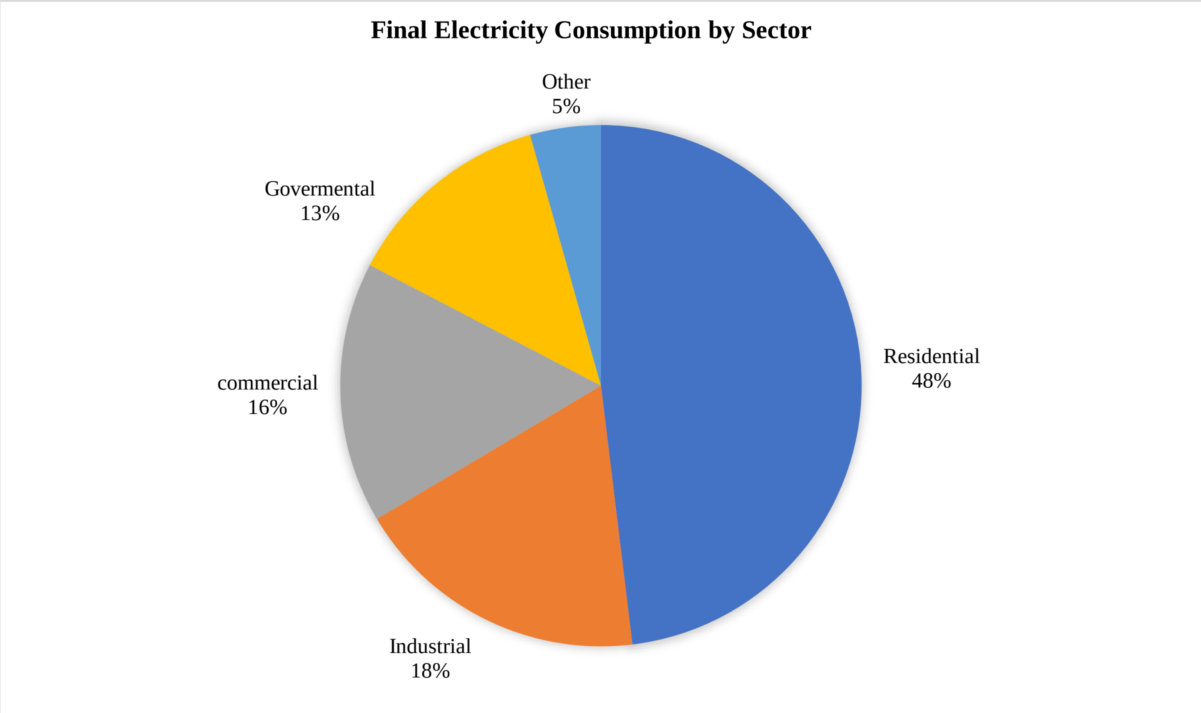

Figure 6 Saudi Arabia final energy consumption by sector [29]

In Figure 6, the residential sector emerges as the dominant electrical power consumer in Saudi Arabia, accounting for nearly half of the total electricity generated nationwide. This is followed by the industrial and commercial sectors, respectively. According to sources such as IEA, the residential sector's electricity consumption reaches 47%, with the commercial and industrial sectors trailing behind. Notably, there is no recorded electrical demand from the transportation sector, as it relies entirely on oil-based products for energy needs, as detailed in subsequent sections.

Electricity in residential, commercial, and governmental buildings is primarily used for cooling, lighting, and powering electrical appliances. Approximately 70% of the electricity consumed within these buildings is dedicated solely to cooling purposes [30]. This heavy cooling demand is especially pronounced during the summer months across all regions of the Kingdom. In contrast, heating requirements are minimal and restricted to limited locations, primarily during winter, including Riyadh—situated in the heart of the desert—and some northern areas, as shown in Figure 7 [31][32].

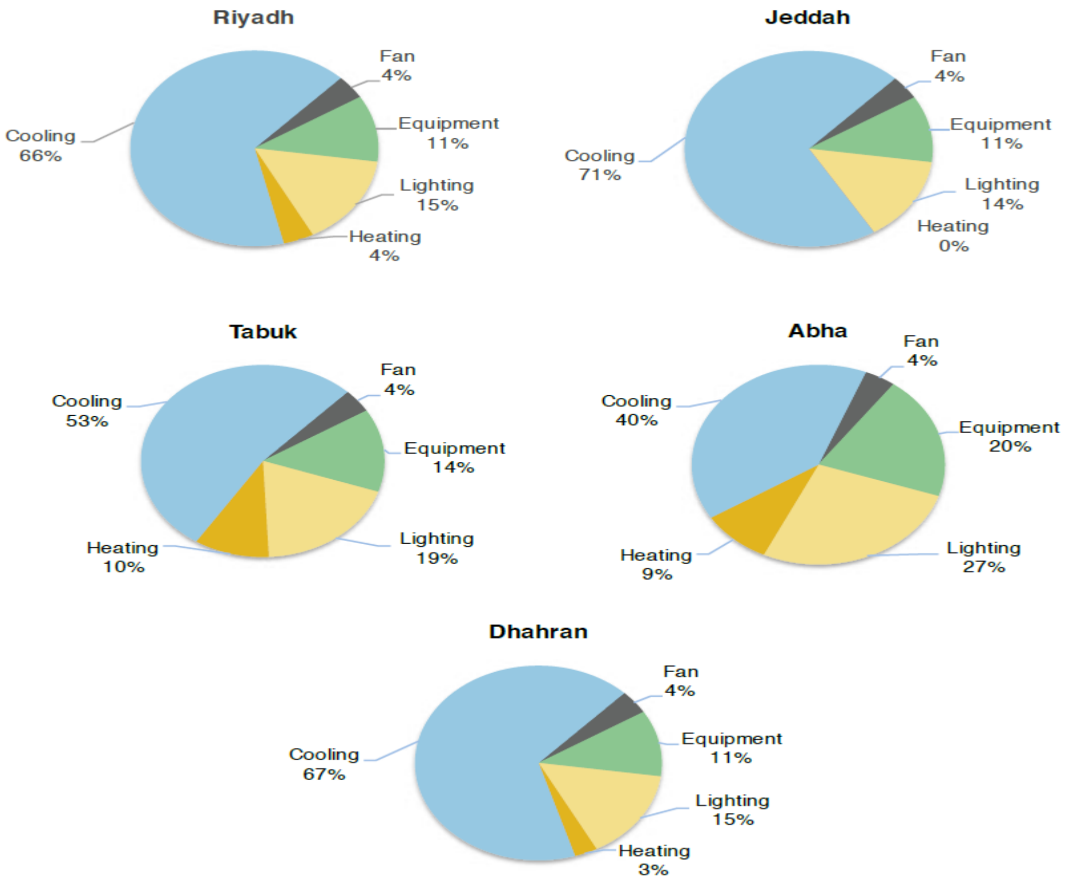

Figure 7 Saudi Arabia's annual energy consumption of a typical two-stories villa of 525 m2 in five different climate zones [31][32]

Figure 7 illustrates the distribution of electrical energy usage for a typical two-story villa across five distinct climatic regions within Saudi Arabia. Air-conditioning is the main electricity consumer in every zone, regardless of the regional climate. In contrast, heating demands are minimal, with specific areas, such as the west (Jeddah), registering 0% heating consumption, while northern regions (Tabuk) exhibit a modest 10%. After air-conditioning, lighting constitutes the second-largest electrical energy expenditure.

Both cooling and heating fall under the broader electrical demand category, with cooling exclusively powered by electricity. A variety of cooling systems are deployed throughout the Kingdom. Individual direct expansion systems are mainly utilised in residential buildings, including window units and split-unit air conditioners. Figure 8 highlights the prevalence and types of cooling devices used in the residential sector [33]. In the industrial sector, air-cooled chiller units are commonly utilized for cooling purposes.

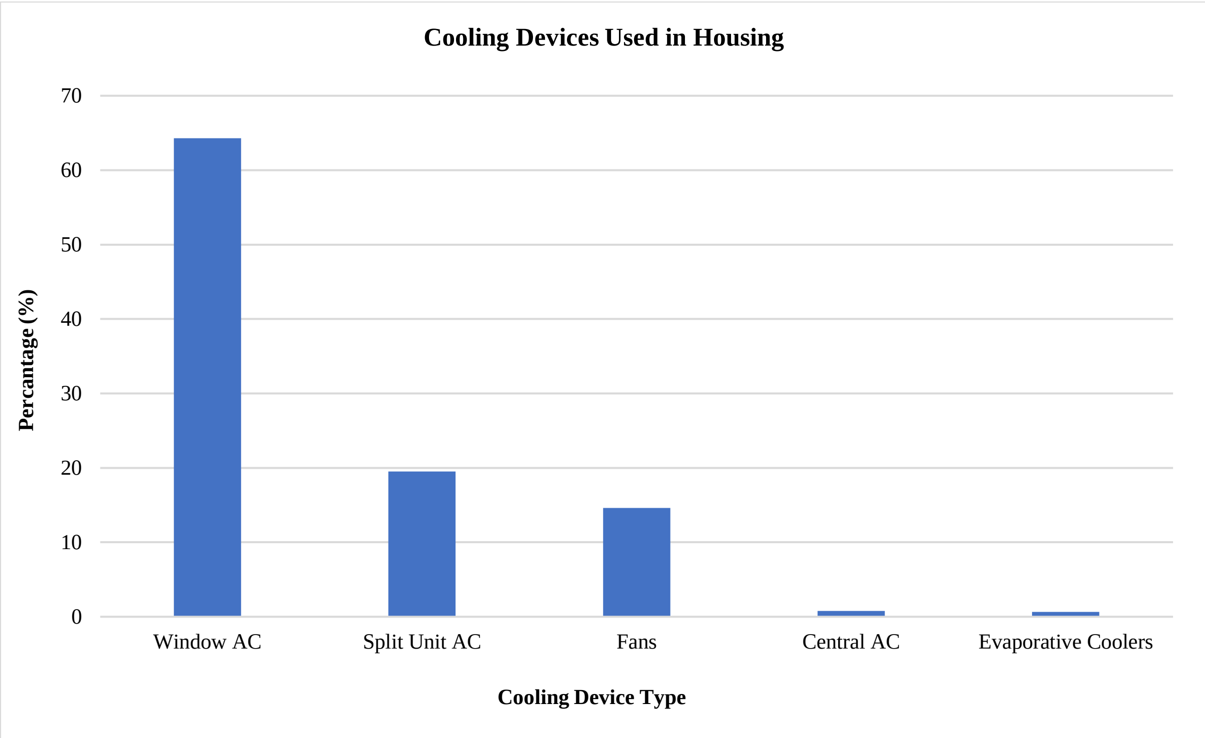

Figure 8 Cooling devices used for housing in Saudi Arabia in 2017 [Author: constructed from [33]]

In the residential sector, the operation hours of air conditioners significantly differ between summer and winter. During the winter season, air conditioners are typically used for about 20 hours per week on average. However, usage intensifies for the rest of the year, averaging 60 hours per week, or roughly 8.5 hours per day. This marks a threefold increase in operating time compared to the winter months, indicating a substantial rise in electrical demand during the summer. In total, there are approximately 26,034,896 air conditioners in use, highlighting the heavy electrical load during the hotter months.

In contrast, electrical heating usage peaks in winter, averaging 56 hours per week. For the remainder of the year, heating devices operate for around 12 hours per week, catering to the limited regions in Saudi Arabia that experience cooler temperatures. Approximately 7.5 million heating devices are in use, highlighting the more constrained and seasonal nature of heating demands in the Kingdom [34].

2.2.2 Transport Sector and Electric Vehicles

- Transport Sector

Globally, the transport sector is expanding rapidly, and transport demand is expected to increase by 80% to 130% above today's levels [35]. Many sources expect that the transport sector alone could consume more than one-third of the global energy supplies (including more than half of the oil produced). Most of the demand is expected from regions with high population and economic growth, such as the Middle East, China, Russia, and India. Several reasons drive this expansion, including population growth, urbanisation, increase in all travel modes, megacities, and the quality of life. The challenges relating to unpredicted increases in oil products demand, local air pollution, urbanisation, noise, and economics will be compounded if we stay at the same pace. Considering these challenges, the transport sector faces an essential question of how technologies could emerge in the following years and how the new technologies and solutions will mitigate the problem and satisfy the future additional demand.

Saudi Arabia has witnessed the same global trend of transport sector expansion, leading to increased national transportation and fuel demand. Transport energy demand has been growing over the last decades in the Kingdom. Transport energy demand in the Kingdom has been growing over the past decades. The demand for oil products in transportation nearly tripled from 1990 to 2020, increasing from 686,806 TJ in 1990 to 1,712,055 TJ in 2020 [36]. Figure 9 shows the Kingdom's demand for transportation oil products over the last twenty years.

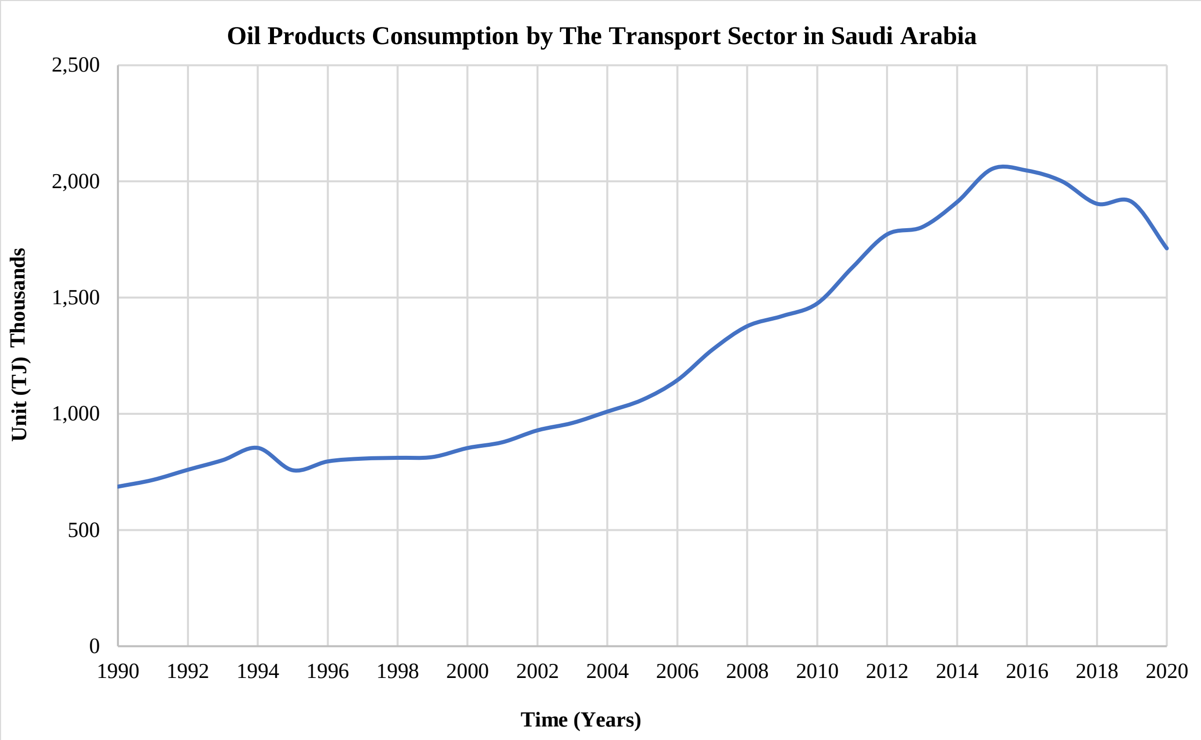

Figure 9 Transport sector's oil products demand in Saudi Arabia [36].

Even though transportation fuel demand has been increasing for years. It witnessed a sharp drop in 2019 and 2020 in the national and international lockdown and restriction periods because of the global COVID-19 pandemic, which also affected the transportation fuel demand.

Saudi Arabia has supported road transport by keeping petrol prices low compared to the world. Even with increasing oil prices, the demand for oil products for transportation was inelastic due to increased prices [37] and limited alternative options for passenger transport in the Kingdom. Road support and low petrol prices are not the only reasons for the higher transportation demand. Population growth, rapid economic expansion, urbanisation, and climate are directly related to the increased fuel demand. Climate with extreme temperatures, especially during summer, directly affects almost all the sectors in the Kingdom (Transport, residential, industry, power generation, buildings). The extreme weather forces the population to use transportation. Walking and biking are very limited in the Kingdom in this climate, especially in summer. Personal and light-duty vehicles have the highest share of gasoline and diesel demands since Saudi Arabia is a private car-oriented society, primarily because of the lack of efficient public transportation. In addition, higher transportation demand could be caused by adopting "supply side" tactics. Usually, transportation strategies adopt a "supply-side" policy, which covers the increased transportation demand by supplying more. According to the "predict and provide" viewpoint, transportation engineers would predict transport expansion trends based on demographic variations and car ownership and only give the road facilities to match this growth. This methodology does not consider the high cost associated with the supply for this predicted expansion. Demand is a function that refers to the relationship between price and consumption, but transport planning often calculates demand at zero price, free roads and parking. The experiences of many cities reveal that as capacity increases, demand increases at a similar rate [38].

Looking at the Saudi Arabia transport sector in 2017, which is the reference year for this thesis. Oil products completely drove the sector with a total demand of 2,000,766 TJ (47.8 Mtoe), including road transport (personal vehicles, light duty vehicles, trucks, buses, and public transport), Air transport, and marine transport, with no use of electric cars and negligible use of hybrid vehicles. The total transportation fuel demand included motor gasoline, diesel, and jet kerosene, with motor gasoline taking the most significant share by more than half of the total fuel demand for transportation. Figure 10 illustrates the breakdown of fuel demand for the transportation sector in the Kingdom in 2017.

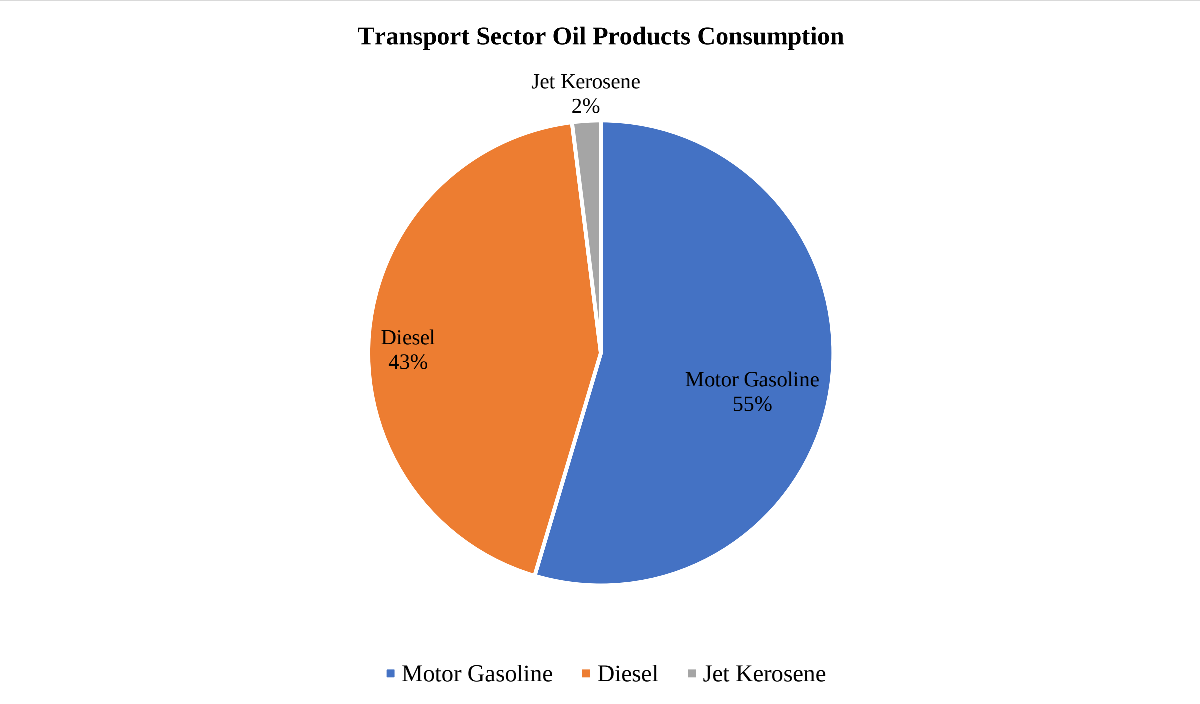

Figure 10 Oil products demand for transportation sector in Saudi Arabia in 2017 [Author: constructed from [39]].

In 2017, the transport sector in Saudi Arabia primarily relied on oil products to meet its energy needs. **Motor gasoline** constituted the largest share, accounting for more than half of the sector's total energy consumption, with a total usage of 1,092,327 TJ. **Diesel** was the second most significant fuel, representing 43% of the transport demand, with a consumption of 868,652 TJ. **Jet kerosene** had the smallest share, comprising only 2% of the total demand, at 39,687 TJ. This makes the transport sector the largest consumer of oil products in the Kingdom compared to other sectors. For a comprehensive view, Figure 11 illustrates the broader consumption patterns of oil and oil products across Saudi Arabia in 2017.

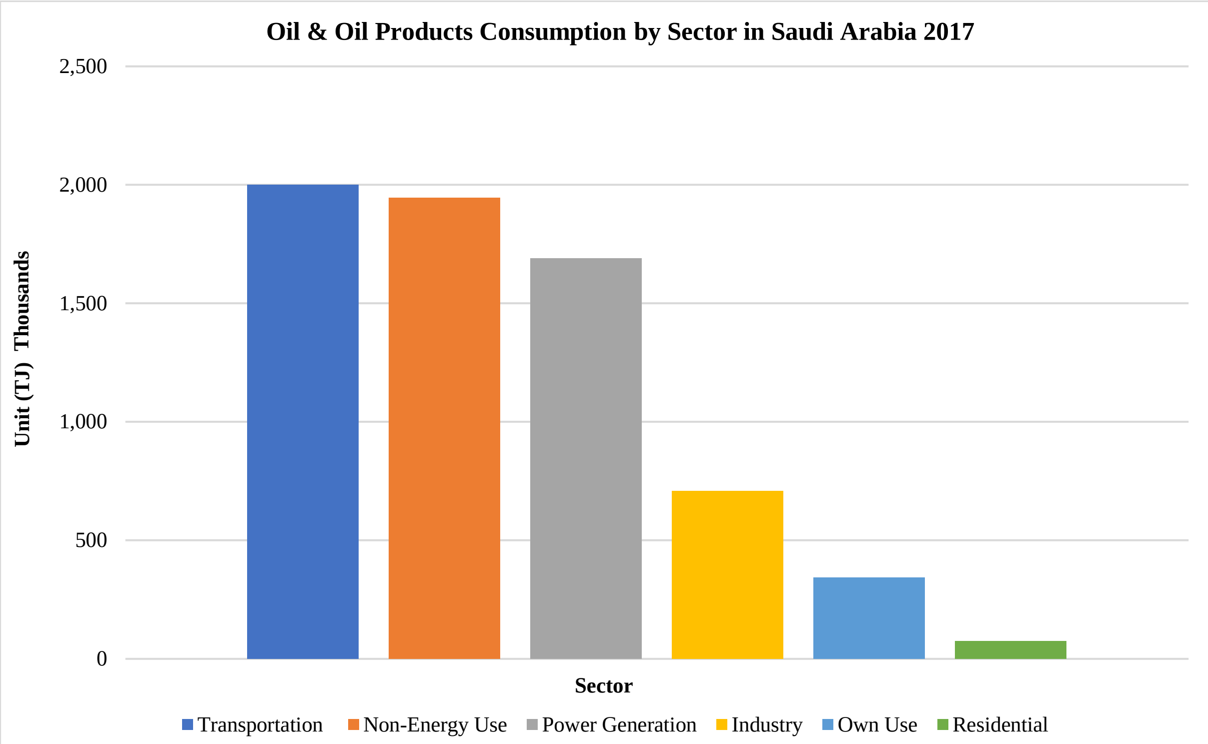

Figure 11 Oil consumption by sector in Saudi Arabia in 2017 [Author: constructed from [40],[41] and Figure 2]

Figure 11 shows the consumption of oil and oil products by different sectors in Saudi Arabia in 2017. The transportation sector had the highest consumption of oil and oil products in the Kingdom, with 2,000,766 TJ of oil products. This was subsequently followed by non-energy use and power generation, with power stations utilizing both crude oil and oil products, amounting to 1,690,550 TJ. This highlights the importance of including the transportation sector in the analysis and development of a new energy strategy for the Kingdom.

- Electric Vehicles

In Saudi Arabia, the demand for EVs has historically been negligible, primarily due to the country's long-standing dependence on fossil fuels, specifically gasoline and diesel, for transportation. This reliance has been facilitated by the local abundance of oil resources, with government subsidies maintaining historically low fuel prices for decades. As a result, the transportation sector has consistently utilised internal combustion engines (ICEs), making it the most significant consumer of fossil fuels among all sectors. The turning point for EV adoption in the Kingdom came with the launch of the Crown Prince's Vision 2030**,** which aims to diversify the economy and reduce fossil fuel consumption by 50% in 2030.

A critical component of this vision is the gradual integration of RES and the promotion of sustainable transportation alternatives, including EVs. The Vision 2030 initiative marks the first significant effort to introduce EV technology nationally, reflecting a broader shift towards sustainable energy practices in Saudi Arabia. The absence of a significant electric vehicle market in Saudi Arabia before 2020 can also be attributed to the minimal presence of RES infrastructure. Historically, the country did not deploy RES nationally until the launch of Vision 2030, which emphasises reducing carbon emissions and diversifying energy sources.

The initiatives and efforts of the electric vehicle's introduction and deployment in recent years are discussed in the supply section. In addition, it includes the challenges of electric vehicle deployment in the Kingdom.

2.2.3 Industry

Between 1986 and 2017, industrial energy consumption in Saudi Arabia (excluding feedstock) increased more than tenfold. Figure 12 shows the industrial energy demand from 1990 to 2019.

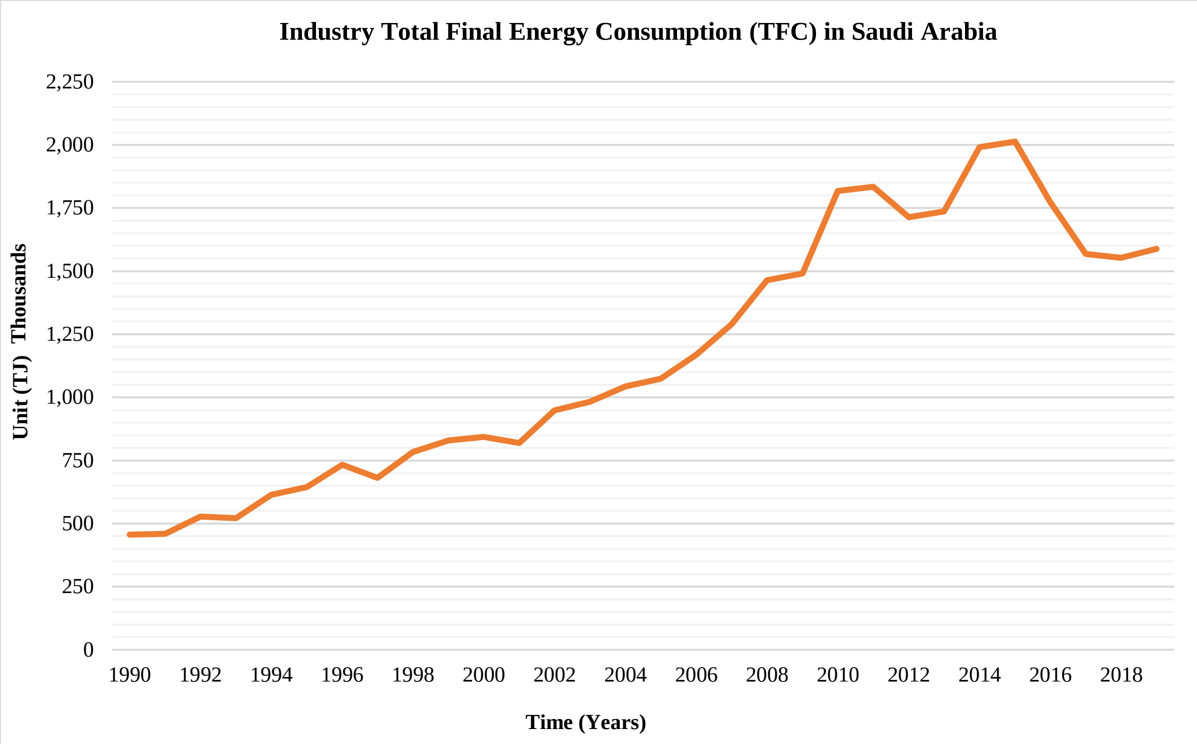

Figure 12 Industry Total Final Consumption (TFC) in Saudi Arabia [Source: IEA]

In Figure 12, industrial energy use in Saudi Arabia has shown a steady and rapid increase since 1986. However, there have been some declines, notably in 2015 and 2016, which were attributed to the first attempt at energy price reform in 2015. Saudi Arabia implemented the first stage of its energy price reform on December 29, 2015, with economic implications for households and businesses across all sectors of the economy. The energy price reform programme aims to raise domestic energy prices to international benchmarks, which will increase government revenues, stimulate productivity, and encourage investments that will help Saudi Arabia diversify its energy mix. According to the decomposition analysis, higher industrial energy prices in 2016 reduced the sector's energy consumption by 6.9%, resulting in energy savings of approximately 3 Mtoe. Nevertheless, industrial energy consumption appears to have recovered in 2017, with faster growth seen in that year [42].

In 2017, Saudi Arabia's industrial energy consumption reached 1,628,962 (39 Mtoe), representing approximately 24% of the total final energy consumption in the Kingdom [43, Figure 2]. The total final energy consumption represents the energy consumed by the final consumer or (end-user) such as fuel (oil products) consumed by the transport sector, electricity consumed by the residential sector, fuel used by industry to produce and manufacture different products such as steel, chemicals, cement etc. Figure 13 shows the energy consumption breakdown for the industrial sector in the Kingdom in 2017.

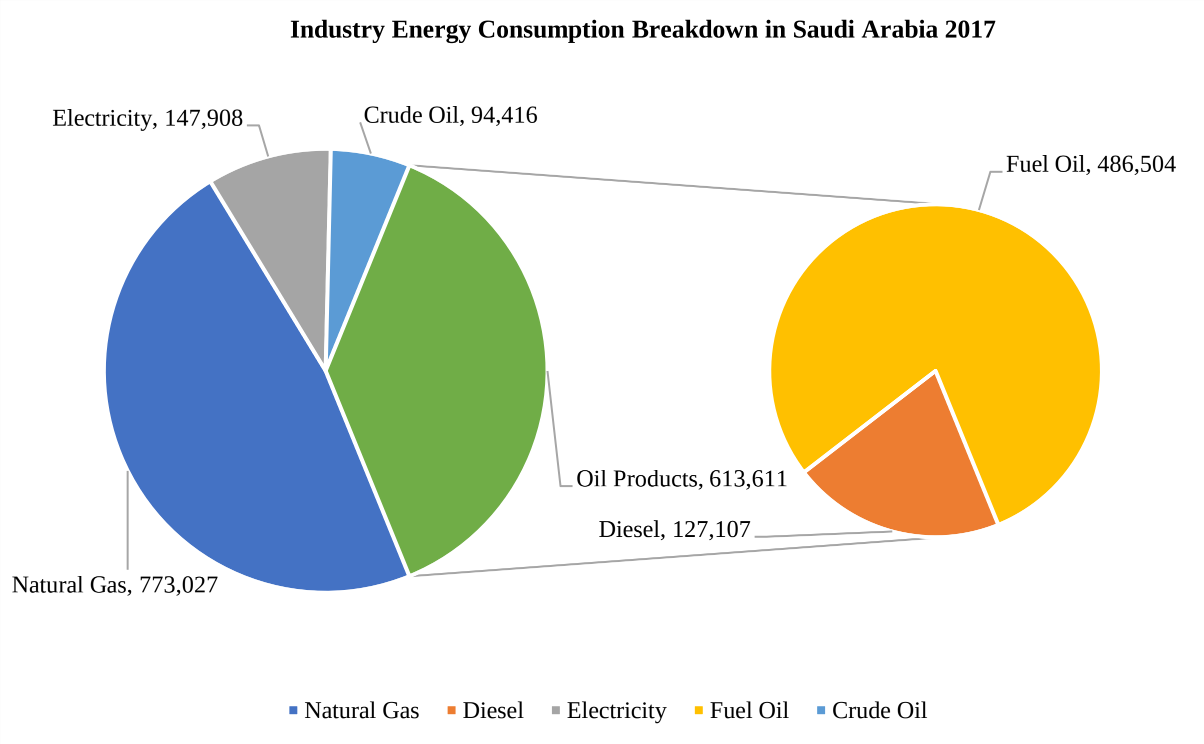

Figure 13 Industry energy consumption breakdown in Saudi Arabia 2017 [Author: constructed from [43] and Figure 2]

Figure 13 shows the energy resource types consumed by the industry sector in the Kingdom in 2017. Natural gas had the highest share of consumption, representing 47%, followed by the consumption of oil products, electricity, and crude oil. In addition to crude oil, the industry sector consumes oil products such as diesel of 127,107 TJ and fuel oil of 486,504 TJ [43]. These fuels are used in different parts of the industry, with the industry in Saudi Arabia mainly consists of mining and quarrying, manufacturing, and other non-specified industries. Manufacturing includes different products such as iron & steel, chemical & petrochemical, which consumed most of the electrical energy supplied for manufacturing with an amount of 33,977 TJ, non-metallic minerals, cement, plastics, etc.

Notably, the resources consumed by the industry sector, as shown in Figure 13, are only used for the production and manufacturing of different industries, as mentioned earlier, such as in furnaces and other different machines, and not used as raw materials or feedstock. Industry sector in the Kingdom consumes more oil products and natural gas but not as a fuel. These fuels are consumed as raw materials (feedstock) in the industry for different products and manufacturing and are not consumed as a fuel or transformed into another fuel. Almost all the feedstock in the Kingdom is used by industry as raw materials to produce different chemicals and petrochemicals [44]. Some reference, such as IEA, refers to that in a separate sector or division as "non-energy use industry". If the non-energy use fuel demand is added to the industry demand, it would give the actual industrial energy and fuels demand in the Kingdom. Figure 14 shows the actual energy demand of the industrial sector in the Kingdom compared to other sectors energy demand.

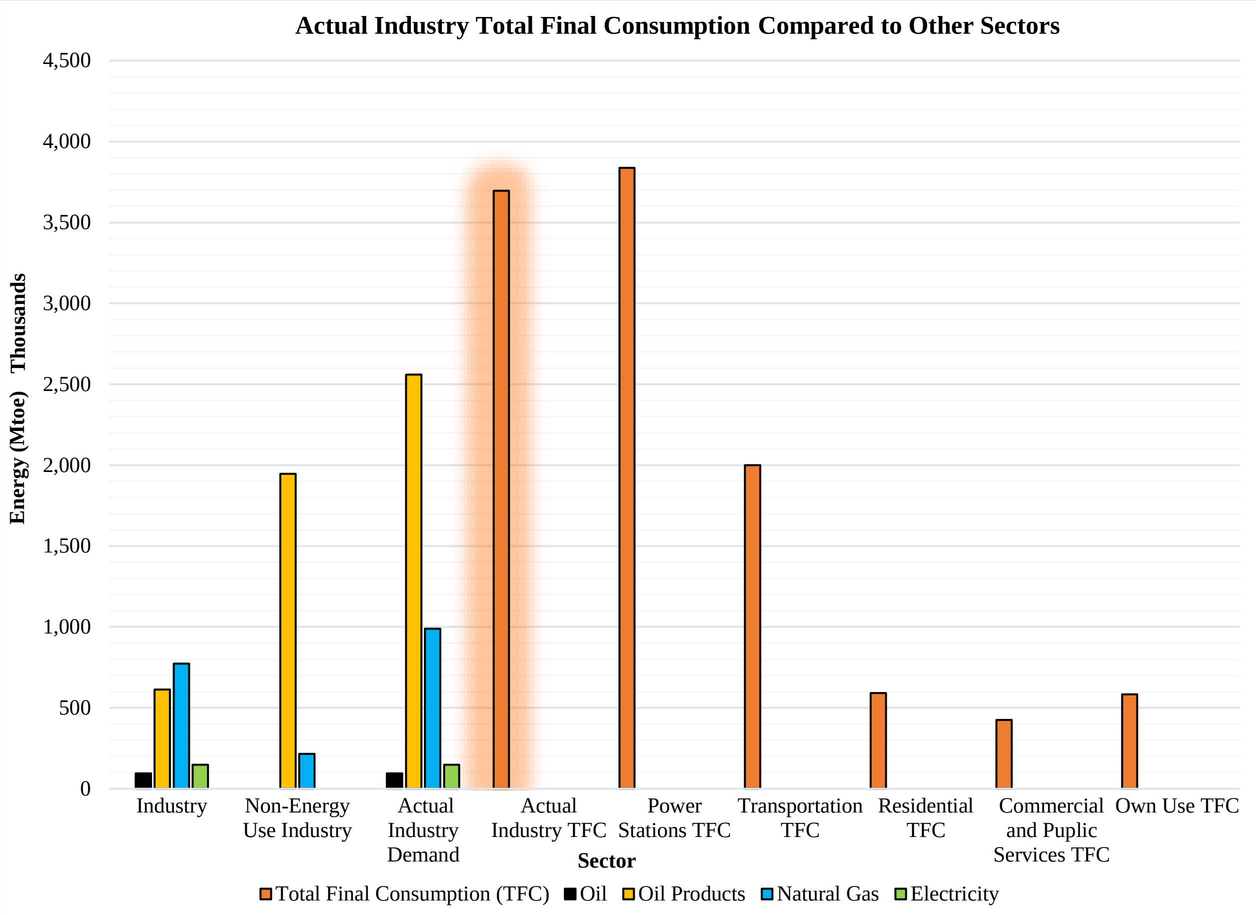

Figure 14 Actual demand of the industrial sector in the Kingdom compared to other sectors in 2017 [Author: constructed from IEA and Figures 2,3,11,13]

Figure 14 shows the actual industry total final consumption (TFC) compared to other sectors' demand in the Kingdom. Actual Industry TFC represents the sum of the industry & non-energy use demands of oil, oil products, natural gas, and electricity. Industry's TFC is the second largest demand after power stations demand. The industrial sector demand has increased rapidly since 1976, when the government established the Saudi Basic Industries Corporation (Sabic) to diversify the economy. Its initial goal was to boost the manufacturing capacity of industries related to the petroleum industry. Since then, rolled steel, iron, chemicals and petrochemicals, fertilisers, pipes, copper wire and cable, truck assembly, refrigeration, plastics, aluminium products, metal products, and cement have all been produced, with many of these products being linked to Sabic.

The Kingdom also manufactures and produces metals, non-metallic minerals, rubbers, and vehicle tyres. Furniture manufacturing, publishing, and baking have all been small businesses. Industries in ISIC Rev. 4 Divisions 22, 31 and 32, such as the manufacturing of jewellery, bijouterie and related articles, the manufacture of medical and dental instruments and supplies, and the manufacture of games and toys, are also produced in the Kingdom [45]. It is difficult for countries to provide industrial fuel breakdown for each industry separately. Most countries resources provide the aggregate industrial consumption of fuels.

2.2.4 Water

Desalination plays a crucial role in Saudi Arabia's energy and water sectors. Many standard references, including those from institutions like the IEA, do not consider desalination as a separate entity in their discussions of national energy systems, even in countries heavily reliant on desalination. They often merge desalination data with that of other Independent Power Producers (IPPs), obscuring the specific impact of desalination on the national energy landscape. In Saudi Arabia's context, it is vital to differentiate the desalination sector due to the Kingdom's status as one of the world's leading operators of Independent Water and Power Plants (IWPPs).

Understanding the Kingdom’s reliance on desalination requires an appreciation of its geographical and demographic context. Saudi Arabia is situated in the Middle East between latitudes 16° and 33° N and longitudes 34° and 56° E, covering approximately 80% of the Arabian Peninsula—the largest peninsula on the globe [46]. The country features a harsh desert climate, with extremely hot and dry summers and colder winters in some regions. The Kingdom encompasses around 2,150,000 km^2 and, as of 2021, has a population growth rate of 1.5% [47].

The rapid urbanisation in Saudi Arabia has had significant implications for water demand. Urbanization has surged from 49% in 1970 to 85% in 2021 [48], driving an increase in domestic, industrial, and agricultural water consumption. Since the 1970s, the Kingdom has experienced accelerated development across all sectors, leading to a corresponding rise in water demands. Studies indicate that domestic water usage jumped from 200 million m^3 per year in 1970 to 2,063 million m^3 per year by 2010, marking an annual increase of 6% [49].

The industrial sector—comprising water-intensive industries such as petrochemicals, steel, and iron—has also seen significant growth in water consumption. From 1990 to 2010, water demand in this sector increased from 190 million to 800 million m^3 per year, with an annual growth rate of 7.5% [49]. Agriculture remains the dominant water consumer, driven in part by government subsidies aimed at supporting rural development between 1974 and 2006. These policies led to a surge in irrigated areas, particularly for water-intensive crops like wheat, expanding from 400,000 hectares in 1971 to 1,620,000 hectares by 1992 [49]. In 2010, agricultural water consumption reached 15,000 million m^3 per year.

A separate report from the Saudi Ministry of Environment, Water, and Agriculture, although limited to Arabic and lacking comprehensive historical data, highlights water demand trends over the last decade [50]. Figure 15 provides a breakdown of the annual water demand by sector in the Kingdom, emphasizing the growing importance of accurately measuring and understanding desalination's role in Saudi Arabia's energy ecosystem.

This level of specificity is necessary to grasp the implications of desalination on the Kingdom's energy system, given its substantial footprint in both the national energy strategy and resource allocation.

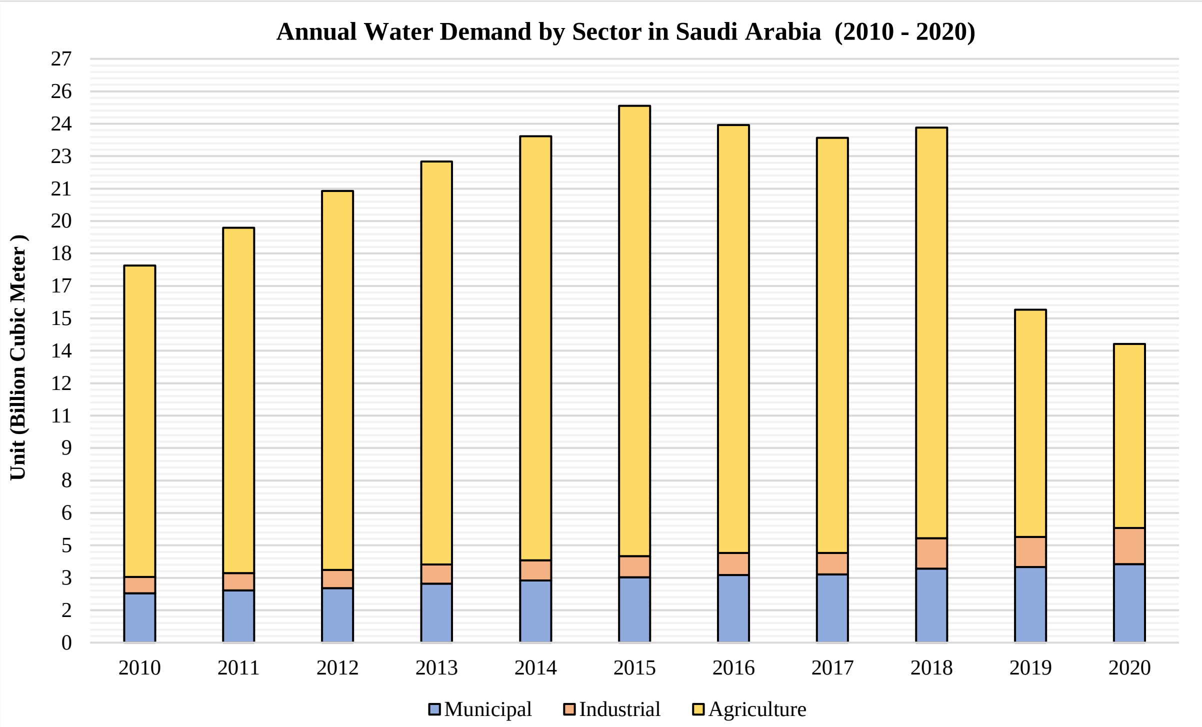

Figure 15 Annual water demand with each sector's share of the total demand in Saudi Arabia from 2010 to 2022 [Author: constructed from [50]]

Figure 15 illustrates the primary water consumers in Saudi Arabia, with water demand distributed across the municipal, industrial, and agricultural sectors. The agricultural sector accounts for the largest share, consuming approximately 80% of the total water demand in most years. In 2017, for instance, the total water demand was 23,350 million m^3, with municipal demand reaching 3,150 million m^3 (13.5%), industrial demand at 1,000 million m^3 (4.3%), and agricultural demand comprising 19,200 million m^3 (82.2%). Municipal water demand is the second largest, followed by industrial, where both demands are significantly lower than the agricultural demand. The Saudi government realised the huge agricultural demand and made several attempts to decrease it over the years.

A recent initiative took place in 2019 when the government introduced the 'Qatrah' program, implementing various strategies aimed at reducing water consumption across both industrial and municipal sectors. It aims to reduce water consumption to 150 litres per person daily by 2030. In addition, strategies and a few initiatives were applied in the past years to reduce agriculture water consumption, such as a massive reduction of the production of intensive water crops like wheat and a switch to importing, using modern farming machines to improve the overall efficiency and make the use of water more sustainable.

Wheat production fell from a peak of 4,142,000 Mt in 1992 to 1,000,000 Mt in 2022, while the imports increased from 75,000 Mt in 2007 to 3,000,000 Mt in 2022 [51][52]. After 2015, the total agricultural water consumption started to decline due to the substantial decrease in agricultural water use, particularly after 2019, following the initiation of the government program to decrease forage cultivation [53].

The Kingdom's water demand has reached concerning levels. Over recent years, water demand per capita has risen, reaching 265 Liters per capita per day in 2017 and 278 Liters in 2018 [54], making it one of the highest rates globally. High water demand is not the only challenge. Despite huge water demand, the Kingdom is one of the poorest nations in terms of renewable water resources. The Kingdom is located in an extreme desert environment and has no natural surface watercourses such as rivers or lakes, and its renewable water resources are minimal. The country is also characterised by high evapotranspiration rates, given the high temperatures most of the year. According to the UNESCO Relative Water Stress Index, the country is in a condition of extreme water scarcity [55]. The entire area of Gulf countries suffers from extreme water scarcity. Figure 16 shows the renewable water resources per capita for Saudi Arabia and the Gulf countries in 2018.

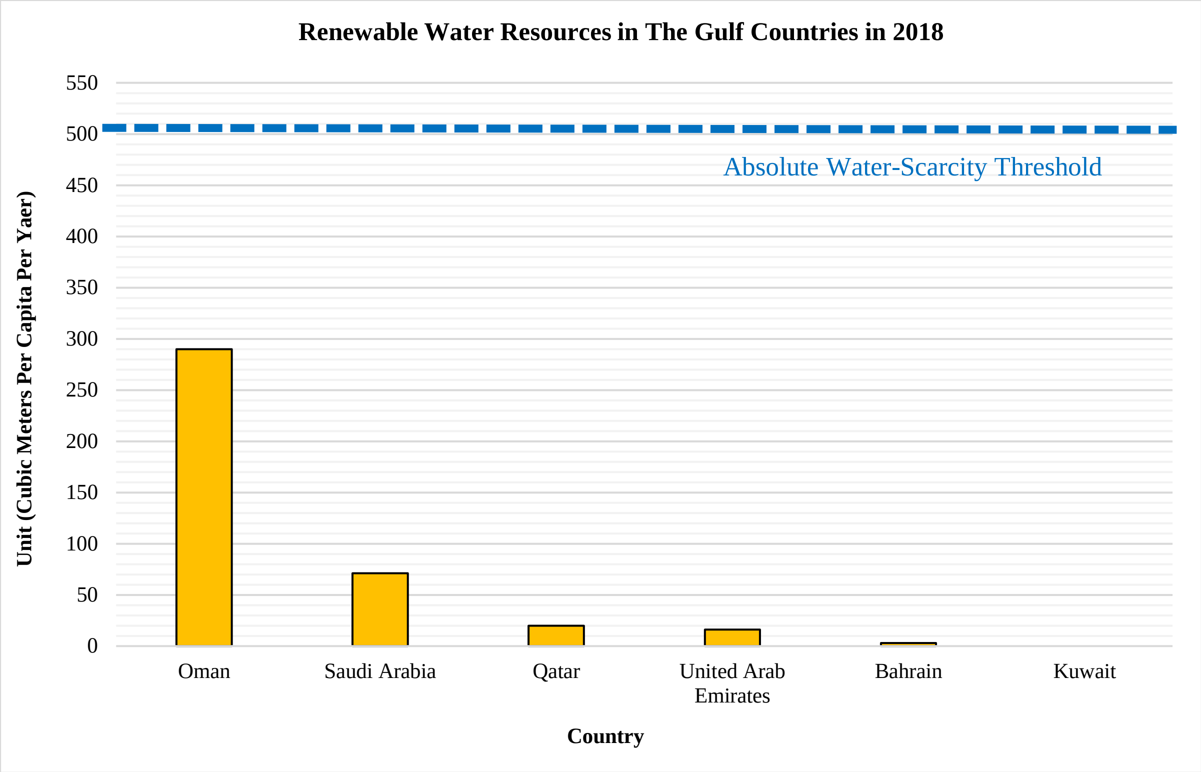

Figure 16 Renewable water resources in Saudi Arabia and neighbour Gulf countries in 2018 [Author: constructed from [56]]

Figure 16 shows the amount of renewable water resources in the Kingdom is minimal. It is far below the absolute water scarcity level set by the United Nations [57]. All the other Gulf countries in the area have the same issue. Although Oman has more renewable water resources than other neighbours, it is still far below the absolute water scarcity level, which means that the country suffers from extreme water scarcity. Rain is also scarce in almost all regions in the Kingdom. The county's average precipitation is 59 mm/y [58], with an occasional maximum annual rainfall of 550 mm in the southwestern region. Saudi Arabia uses two conventional and two non-conventional water resources to supply its expanding water demand (domestic, industrial, and agricultural). Conventional resources are surface water and groundwater, while non-conventional resources are desalinated seawater and treated wastewater.

- Ground Water

Groundwater is the primary and reliable source of water in the Kingdom. Groundwater is divided into non-renewable deep groundwater or deep fossil aquifer groundwater and renewable groundwater in fractured Precambrian basement and shallow alluvial aquifers, primarily in the country's west and southwest. Non-renewable or fossil groundwater is formulated in the deep sandstone aquifers, which are confined in sand and limestone formations of a thickness of about 300 metres at a depth of 150-1,500 metres. The deep rock aquifers are sedimentary in origin, usually sandstone and limestone, extending over thousands of square kilometres with very poor natural recharge. Isotopic analysis shows that the non-renewable groundwater in the upper aquifers is 10,000–32,000 years old [59]. Today, these fossil aquifers are considered "storage dominated rather than recharge-flux dominated" as only a tiny fraction of total groundwater storage is due to recharge [60]. Shallow water is a renewable form of groundwater comprising shallow, unconfined alluvial aquifers located mainly in the western and southwestern regions of the country. They recharge from infiltrating the annual orographic rainfall in the coastal mountains [59]. Estimated reserves of ground water varied between different literatures. It is estimated that groundwater resources, most of them are fossil water sources, equal to approximately 2,185,000 million. m^3 of which 250,000 million m^3 to 870,000 million m^3 are economically extractable groundwater and approximately 4,000 million m^3 are renewable shallow-water aquifers with an annual recharge of 1,196 million m^3[59][61][62].

- Renewable Water

Renewable natural water resources in the Kingdom, such as surface water, shallow groundwater, and stormwater, are scarce and limited. Saudi Arabia has no perennial rivers or lakes. Except for the mountainous areas in Saudi Arabia's southwest, surface water resources are scarce and non-existent. Run-off occurs primarily as intermittent flash floods and is affected by rainfall patterns and topographic features in Saudi Arabia. Because of the low rainfall amounts in most of the Kingdom, surface runoff was limited. The annual precipitation averages around 59 mm [58]. The yearly evaporation rate ranges from 2,500 to 3,000 mm/year [63].
In Saudi Arabia, the average annual volume of rainwater is estimated to be 126.8 billion m^3 [64]. Because of the flat nature of most Saudi Arabian lands and the high evaporation rate, it isn't easy to harvest and utilise surface water runoff directly. Only a small part of this water recharges groundwater resources. The annual runoff volume is estimated to be 5,000 million m^3 with 780 million m^3 produced on the Arabian shelf and the remaining amount in the Kingdom's western coastal areas. In 2020, the total number of dams built was 532, with a total storage capacity of 2,334,721,694 million m^3 [65]. These dams were built to recharge groundwater and control flooding.

- Wastewater Reuse

The increased water demand combined with the extreme water scarcity and the limited water supply options in the Kingdom have brought attention to wastewater treatment and reuse.

Wastewater treatment is a process used to remove contaminants from wastewater and convert it into an effluent that can be returned to the water cycle. Once returned to the water cycle, the effluent creates an acceptable impact on the environment or is reused for various purposes [66]. Groundwater resources, desalinated water, and treated wastewater fill the gap between water supply and demand. Therefore, wastewater treatment plants are essential to bridge this gap.

Treated wastewater is considered an essential part of Saudi Arabia's water resources and a significant source of non-potable water demands, such as agricultural, industrial, and commercial uses. By 2025, the Ministry of Water and Electricity hopes to provide complete sewage collection and treated wastewater services to every city with a population of more than 5,000 people [67]. Treated wastewater has been successfully used for landscaping activities, irrigation of agriculture, industry, and commercial enterprises, and the remainder is discharged into groundwater recharge in the Kingdom [68]. A small fraction of the treated wastewater is reused. The remaining wastewater is typically discharged into wadis and sand dunes. Wastewater in the Kingdom includes sanitary, industrial, and agricultural wastewater as mentioned in the definition of wastewater by the water law of 2020 in the Kingdom as follows '*'Treated Water: Sanitary, industrial, or agricultural wastewater that is treated by biological, physical, industrial, or natural methods through removing its contaminants to make it safe for the environment or to be reused in urban, industrial, or agricultural purposes, based on the degree of treatment''* [69].

In 2020, the total treated wastewater totalled 1,868.5 million m^3/y from 116 wastewater treatment plants. The total average treated wastewater reached 1 million m^3/d with the reused water amount of 0.92 million m^3/d until the end of 2020, indicating that only 18.2% of the total average treated wastewater was reused [70]. Municipal wastewater treatment is critical because it is a renewable water resource that is increasing as the population grows. Total municipal wastewater increased steadily between 2007 and 2018, from approximately 2,125 to 2,884 million m^3, and it is expected to rise dramatically between 2025 and 2050, reaching 5,090 million m^3 due to population growth. Similarly, the volume of treated water increased by nearly 200% between 2007 and 2018, from 811 to 1,710 million m^3. Although the growth of treated water is expected to reach about 4% per year between 2025 and 2050, total effluent of wastewater is expected to be 28% higher in the same period [71]. Several wastewater treatment plants with varying capacities are operational in Saudi Arabia, including some long-established facilities and others currently under development. One notable example is the large-capacity treatment plant in Madinah, which has a treatment capacity of 460,000 m^3/d and utilizes media filtration technology.

The output of this water treatment plant is used for agriculture irrigation. Some plants are used for irrigation and ground water recharge, such as the one on the capital of the Kingdom in Riyadh with a design capacity of 400,000 m^3/d and activated sludge technology. Smaller plants output is usually used for landscape irrigation and industrial such as the Taif wastewater treatment plant used for landscape irrigation with a design capacity of 190,000 m^3/d and activated sludge technology and Jubail treatment plant used for industrial sector demand with design capacity of 115,000 m^3/d with tertiary treatment technology [72]. In 2018, agriculture irrigation followed by landscape irrigation represented approximately two-thirds of the total treated water reuse, with the industrial water reuse demand represented 13%, as shown in Figure 17.

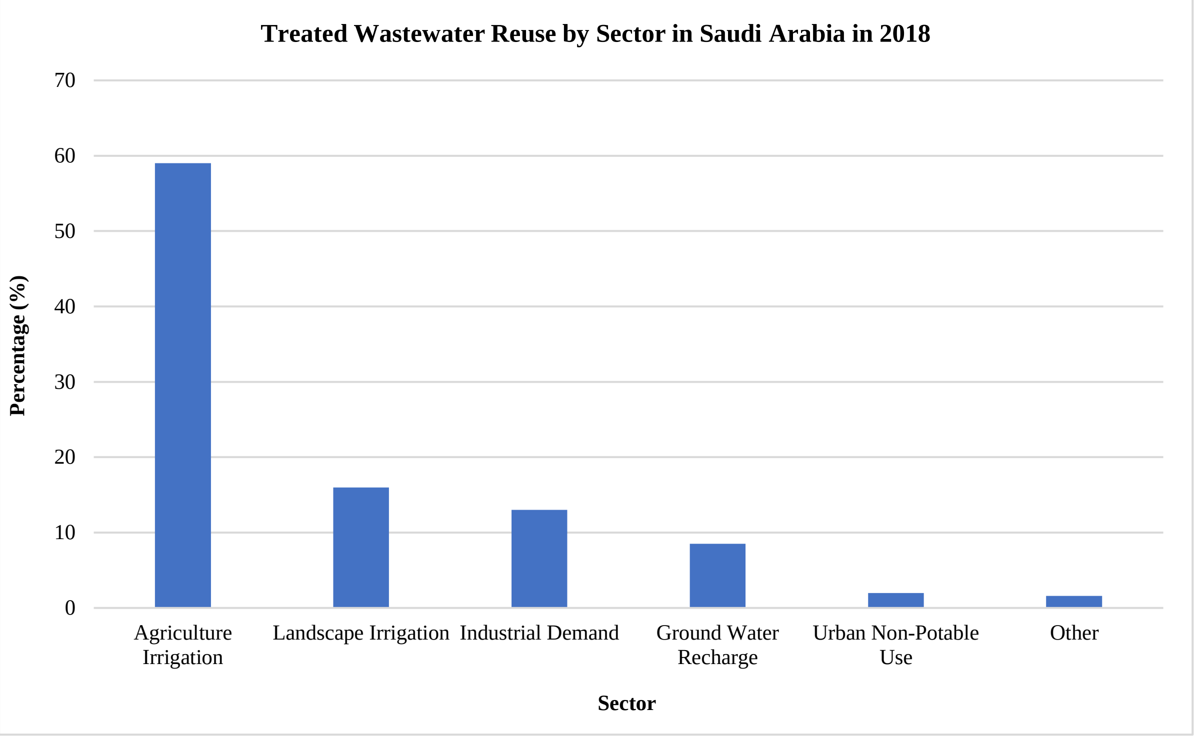

Figure 17 Treated wastewater reuse by sector in Saudi Arabia in 2018 [73].

2.2.5 Desalination

Desalination is a crucial sector in Saudi Arabia, the largest producer of desalinated water worldwide, generating 7.6 million m^3 daily [74]. This reliance on desalination stems from the Kingdom's arid desert climate, characterised by extreme water scarcity, minimal precipitation, and rapid population growth, making the country heavily dependent on non-renewable groundwater resources and energy-intensive seawater desalination facilities. Saudi Arabia's desalination efforts have a long history, dating back to the early 1900s when a coal-fired distillation unit operated by a non-governmental organisation began producing 300 m^3 of freshwater per day in Jeddah, located along the Red Sea coast [75].

Currently, Saudi Arabia contributes 18% of the world's desalinated water production, accounting for 43% of the desalination output in the GCC region [76]. This substantial share emphasizes the critical role of desalination in the Kingdom's water supply strategy. The increase in desalination capacity has been a direct response to rising municipal water demands, with production growing annually to meet the needs of the expanding population. Figure 18 illustrates the yearly increase in desalinated water output, reflecting the Kingdom's continuous efforts to address water scarcity.

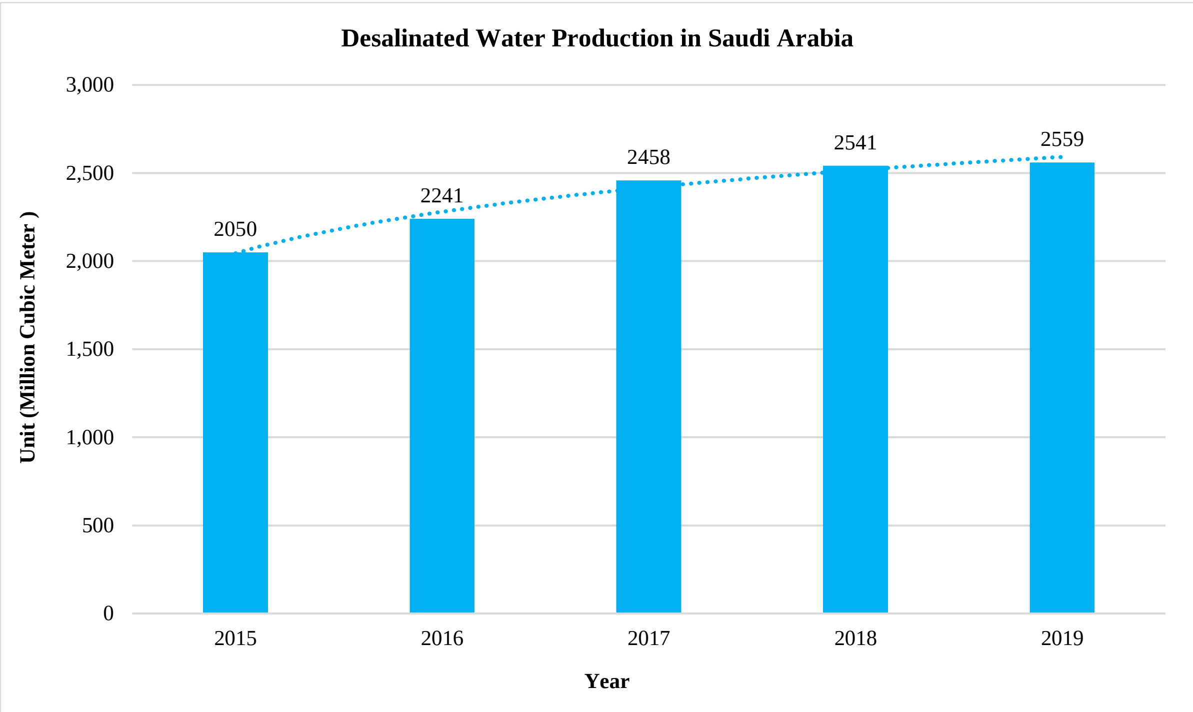

Figure 18 Annual desalinated water production in Saudi Arabia [77]

Figure 18 illustrates the steady annual growth in desalinated water production, reaching 2,559 million m^3 in 2019. This desalinated water primarily serves municipal needs, supplying 63% of the total water demand for urban sectors. The remaining 37% of municipal water demand is met through non-renewable groundwater and surface water sources, as shown in Figure 19.

This reliance on desalinated water highlights its critical role in meeting the urban water requirements within the Kingdom.

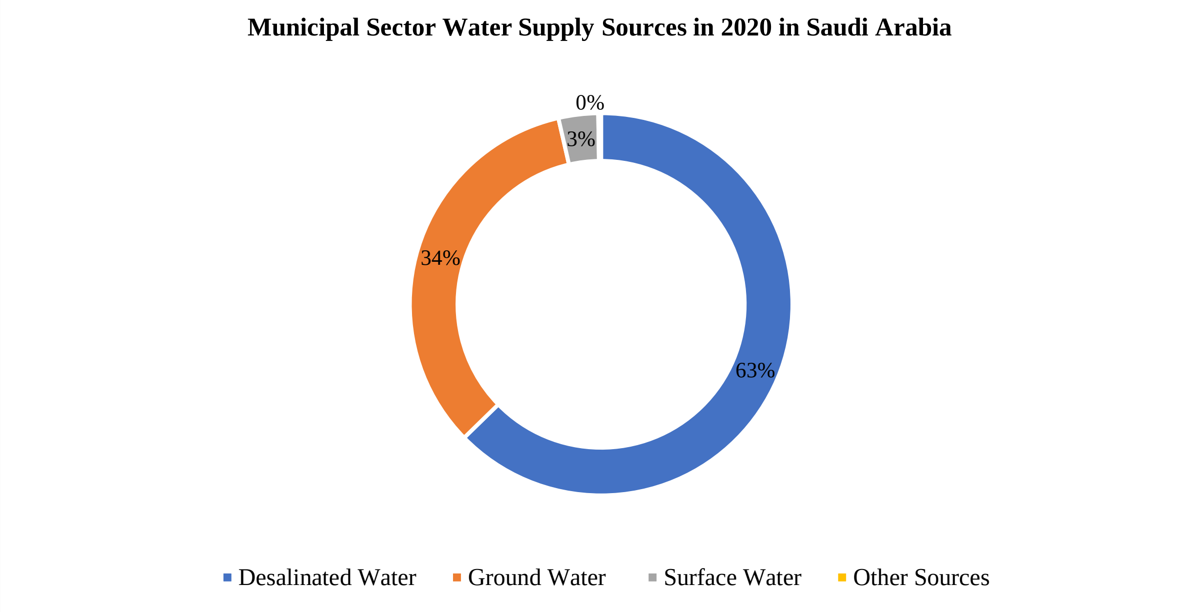

Figure 19 Municipal sector water supply sources in 2020 in Saudi Arabia [78]

Figure 19 shows that 63% of the Kingdom's municipal water demand is supplied by desalinated water, followed by non-renewable groundwater use in 2020.

Desalination is an energy-intensive process that is very costly and unsustainable. The energy requirement varies depending on the technology and fuel used in desalination. MED, MSF, and RO are the primary desalination technologies used in Saudi Arabia. Multiple effect distillation (MED) and multi-stage flash distillation (MSF) are usually integrated with power generation (cogeneration). At the same time, reverse osmosis (RO) uses electrical power through the grid or from neighbouring power stations. Multi-effect distillation (MED) is a thermal desalination process that utilises multiple stages (or "effects") to evaporate and condense seawater. In each effect, a part of the vapour generated from boiling seawater is used to heat the incoming feedwater, enhancing energy efficiency. This process involves sequential evaporation and condensation stages, which optimise the use of thermal energy.

MED is particularly advantageous in scenarios where waste heat is available, or energy costs are high, as it can be highly efficient under these conditions [79]. MSF is another thermal desalination technique that operates by rapidly flashing seawater into vapour in multiple stages. The process involves heating seawater and passing it through a series of chambers at progressively lower pressures. Each stage causes a portion of the seawater to flash into steam, which is then condensed to produce fresh water. MSF is known for its robust operation and is widely used in large-scale desalination plants due to its higher water production rates and reliability [80].

RO is a membrane-based desalination process that removes dissolved salts and other impurities from seawater by applying pressure to force them through a semi-permeable membrane. The membrane allows water molecules to pass through while blocking salt and other contaminants. RO is recognised for its energy efficiency compared to traditional thermal processes, particularly when operated with advanced membrane materials and energy recovery systems. This process is widely employed in both small and large-scale desalination applications due to its relatively lower operational cost and effectiveness [81].

The limited available data has made it difficult to accurately determine fuel consumption in desalination processes. References, such as the IEA, do not have information about the energy consumed for desalination only. IEA reports the desalination combustible fuel input under the ‘’Auto producer’’ term in addition to the other auto producers in the Kingdom. In Figure 2, the ‘’desalination’’ term was assumed instead of ‘’auto producer’’ since the vast majority of auto producers are desalination plants in Saudi Arabia. IEA also reported the desalination consumption of electricity under ‘’commercial and public service’’ in addition to other commercial and public services, which made it difficult to know the exact desalination fuel and electricity consumption. Sources such as the Saudi Arabian Oil Company (ARAMCO) only have detailed energy consumption data on desalination. However, they are classified and unavailable to everyone, such as this internal report [82] in 2010.

The only available data was from WERA in their annual report, which shows the fuel consumption for both power generation and cogeneration. However, even the cogeneration fuel consumption data is slightly misleading and cannot be taken if we talk about desalination since the term ‘’cogeneration ‘’ mentioned in the report includes both cogeneration of desalination (power and water production) and cogeneration of steam (power and steam production) as some stations produce process steam for oil refineries along with the power. We have calculated the fuel consumption for desalination purposes by identifying and categorising each desalination cogeneration plant one by one and adding all the fuel inputs for each desalination cogeneration plant from the ECRA report in one summary in Table 1. However, not all the cogeneration plants show the required data on their official websites. Thus, some of the missing information about the purpose of the plants and the fuel type was taken from official sources in the Kingdom.

Table 1 Summary of the cogeneration desalination producers in the Kingdom their fuel consumptions in 2019.

Desalination Cogeneration Producer		Fuel Consumption (Trillion BTU)			
		Natural Gas	Crude Oil	HFO	Diesel
1	Jubail Water & Power Company (JWAP)	212	0	0	0
2	Shuaibah Water & Electricity Company (SWEC)	0	122	0	0
3	Shaqaiq Water & Electricity Company (SQWEC)	0	59	0	0
4	Saline Water Conversion Corporation (SWCC)	543	63	91	7
5	Rabigh Arabian Water and Electricity (RAWEC)	0	0	104	0
6	Power & Water Utility Company for Jubail & Yanbu (MARAFIQ)	24	40	38	0
Total		779	284	233	7
Gross Total		1,303			

Table 1 shows the producers of desalinated water from cogeneration and desalination plants in the Kingdom in 2019. Total desalination fuel consumption in the Kingdom is 1,303 trillion BTU divided by type into 779 trillion BTU of natural gas, 284 trillion BTU of crude oil, 233 trillion BTU of heavy fuel oil (HFO), and 7 trillion BTU of diesel. Natural gas had the highest share, with approximately 60% of the total consumption. In addition, the Saline Water Conversion Corporation (SWCC) was the highest consumer of fuel energy among all producers since SWCC is the largest producer of desalinated water in the Kingdom, with 65.6% of the total water production [83]. On average, the MED technology consumption is approximately 2 kWh/m^3, 4 kWh/m^3 for MSF [84], and 2.5-4 2 kWh/$m^3$for RO desalination [85].

The share of desalination fuel consumption to the total fuel consumption in the Kingdom is difficult to find. Two sources must be incorporated with each other. IEA has the final fuel consumption by sector but does not have any data about desalination separately. The ECRA and the summary in Table 1 have the desalination data only, and there is no information on the consumption of other sectors. The only link between the references is the fuel consumption for all power plants, including all standalone power plants, cogeneration, and desalination plants, which equals to 3,973 trillion BTU in 2019 from ECRA [86]. In IEA, the total fuel consumption for all power cogeneration plants is 3,512 trillion BTU (88.5 Mtoe) [87], which is very close to the ECRA's Figure. Both references have common data (total fuel consumption from all power cogeneration stations) and thus, other data can be incorporated. This means the fuel consumption of the desalination and cogeneration plants from Table 1, and ECRA can be compared to the total fuel consumption from all sectors in the Kingdom from IEA. The total fuel consumption for all sectors in IEA can be found by looking at IEA's Sankey diagram of Saudi Arabia in 2019. A summary of the Kingdom's fuel consumption by sector based on this diagram is shown in Table 2.

Table 2 Total fuel consumption by sector in 2019 in Saudi Arabia

Total Fuel Consumption in 2019 (Trillion Btu)	
All power and cogeneration plants	3,512 (88.5 Mtoe)
Industry	1,389 (35 Mtoe)
Transport	1,813 (45.7 Mtoe)
Non-Energy Use	2,097 (52.4 Mtoe)
Residential	71.4 (1.8 Mtoe)
Own Use	389 (9.8 Mtoe)
Bunkers	274 (6.9 Mtoe)
Total	9,545

Table 2 shows the total fuel consumption from all sectors in the Kingdom, including natural gas, oil, and oil products, which was 9,545 trillion BTU in 2019. Thus, the share of desalination's fuel consumption to the total fuel consumption in the Kingdom can be calculated as 1,303 / 9,545 = 14%. The desalination sector consumes 14% of the total fuel demand by all sectors in the Kingdom. To incorporate desalination energy consumption into the total energy consumption by sector in 2017 in Figure 3, the same calculations of Tables 1 and 2 were carried out but for 2017, which is the reference model year of this project and incorporated into Figure 3. The result is shown in Figure 20. The Figure shows the energy consumption of all sectors in the Kingdom, including the desalination sector, separately after applying the calculations in Tables 1 and 2 for 2017 and incorporating data into Figure 3. Desalination consumed around 16 % of the total fuel (oil, oil products, and natural gas) consumed by all sectors in Saudi Arabia in 2017, slightly higher than the consumption in 2019. The electricity consumption of desalination plants is difficult to determine or calculate due to the lack of available data. In

IEA, the estimated electricity consumption of desalination plants is reported in the ‘’commercial and public service’’ (with the other commercial and public services consumption) and ‘’own use’’.

In conclusion, the desalination sector presents the most significant challenge in terms of available information, as the data is often imprecise, aggregated with other variables, or classified and not accessible to the public. To add the entire desalination sector to the energy model, hourly data on all fuel consumption, water production, and consumption are needed. The problem is that all these required data are not available, either because they are classified or because they are not available as mentioned in the scope. Thus, this review of the desalination sector serves as the initial step in contributing to knowledge, pending the availability of hourly data. Once the required hourly data is obtained, it will be incorporated into the energy model to explore potential solutions for desalination energy supply in 2050, such as synthetic gas. However, desalination power consumption was entirely considered in the energy model, along with the total power consumption from all sectors in the Kingdom, in order to develop the future RES for the Kingdom in 2050.

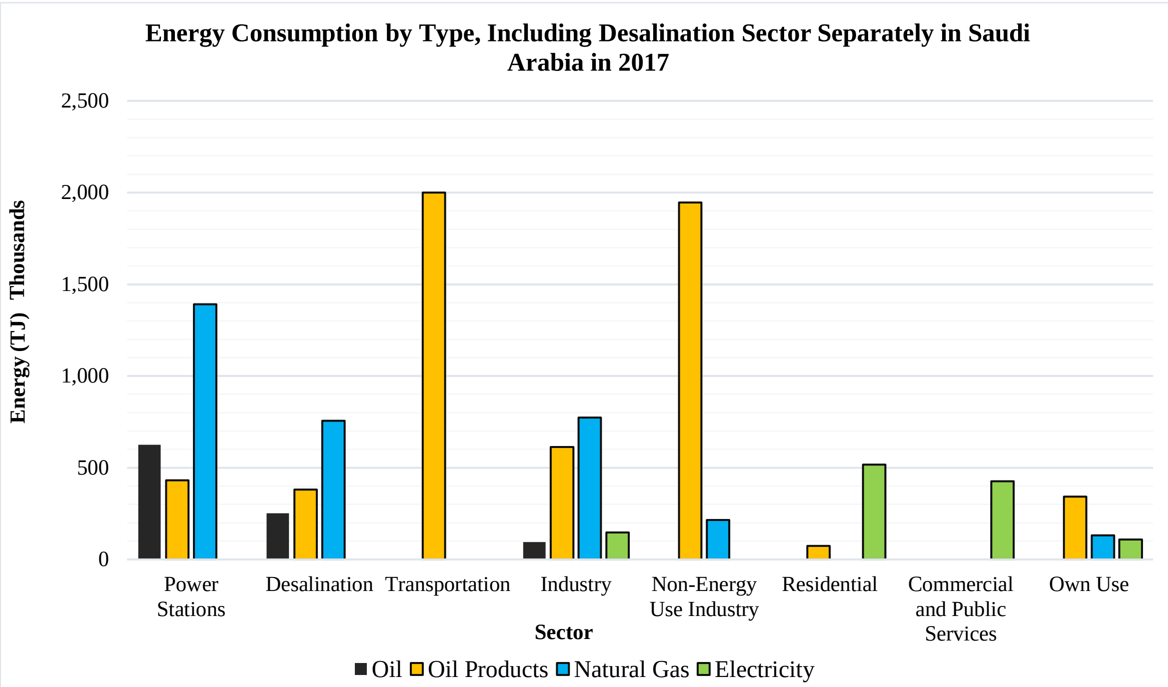

Figure 20 Energy consumption by type, including the desalination sector, separately in 2017 for all sectors in Saudi Arabia [Author]

2.3 Saudi Arabia: Energy Supply, Transport & Hydrogen Deployment

2.3.1 Energy Supply: Power Generation and Desalination

In 2017, the traditional power stations entirely generated the Kingdom's electrical energy using fossil fuels as the supply source. The Kingdom had an electricity generation capacity of 88.6 GW from 80 power plants, varying between IPPs and IWPPs. The electrical generation capacity covered the total Kingdom's energy demand, which peaked at 62 GW in August 2017. The majority of power plants are located in the eastern province (Jubail, Dammam, Ahsa), western province (Jeddah, Mecca, Madinah) and the central province (Riyadh). Saudi Electricity Company (SEC) is the leading electricity producer in the Kingdom, as 66% of the total electricity generating capacity is provided by SEC, followed by 9% from SWCC [88].

Different technologies are used in the power stations. The technologies used in electricity generation by capacity range from high-efficiency combined cycle units (19 %), single-cycle gas turbines (40 %), steam turbines (41%), and diesel generators [89]. Figure 21 illustrates that steam and gas turbines are the primary technologies used in power stations, followed by combined cycle units. The contributions of steam turbines, gas turbines, and combined cycle units were 36.1 GW, 35 GW, and 17.2 GW, respectively. Diesel generator units had a tiny share of 0.5 GW in total generation capacity.

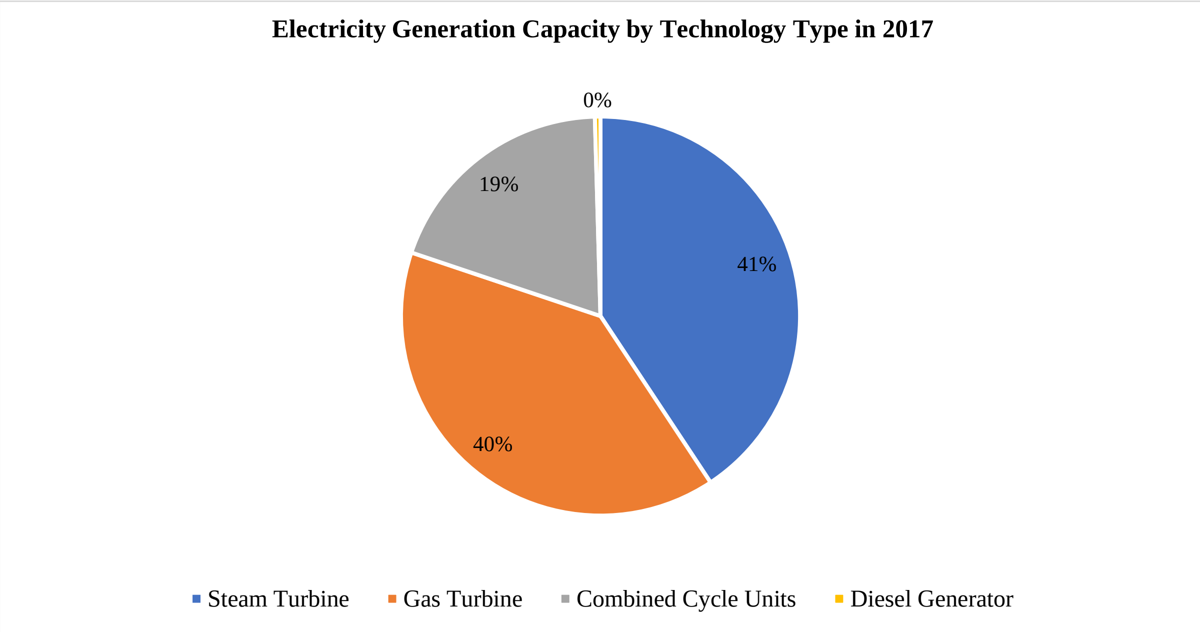

Figure 21 Electricity generation capacity by technology type in 2017 in Saudi Arabia [Author: constructed from [89]].

The overall power generation efficiency is around 32% [90], lower than the world average. The power plants' gross efficiency is 35% in some sources, such as IEA, when calculated by dividing the electricity output by the fuel input of power stations. This efficiency could be improved when replacing the retiring power stations with modern high-efficiency combined cycle gas turbines, which can deliver seasonal efficiencies of 45%-50% based on the Kingdom’s climate conditions [91]. Other sources, such as ECRA, indicate that the fuel consumed in all power stations, including cogeneration and desalination, amounted to 4,230 million BTU in 2017, with 60% of the fuel consumed for electricity generation alone, while 40% was used for cogeneration and seawater desalination [92].

Power stations utilized crude oil, natural gas, HFO, and diesel as input fuels. Among these, natural gas was the most consumed fuel for electricity generation and seawater desalination in the Kingdom, as shown in Figure 22. The figure highlights Saudi Arabia's heavy reliance on natural gas for power and desalination, with consumption reaching 2,273 trillion BTU, accounting for 53.7% of the total fuel used by power and desalination plants. HFO had the second-highest consumption at 927 trillion BTU, followed by crude oil at 831 trillion BTU and diesel at 200 trillion BTU.

As outlined in the demand sections, the power generation and desalination sectors in 2017 were entirely dependent on fossil fuels, including oil, oil products, and natural gas. Only in recent years has the Kingdom begun integrating RES into its total energy mix, aligning with the goals of Vision 2030. A key objective of this vision is to phase out oil in power generation, targeting 50% of total electricity production from renewable sources, with the remaining half supplied by natural gas.

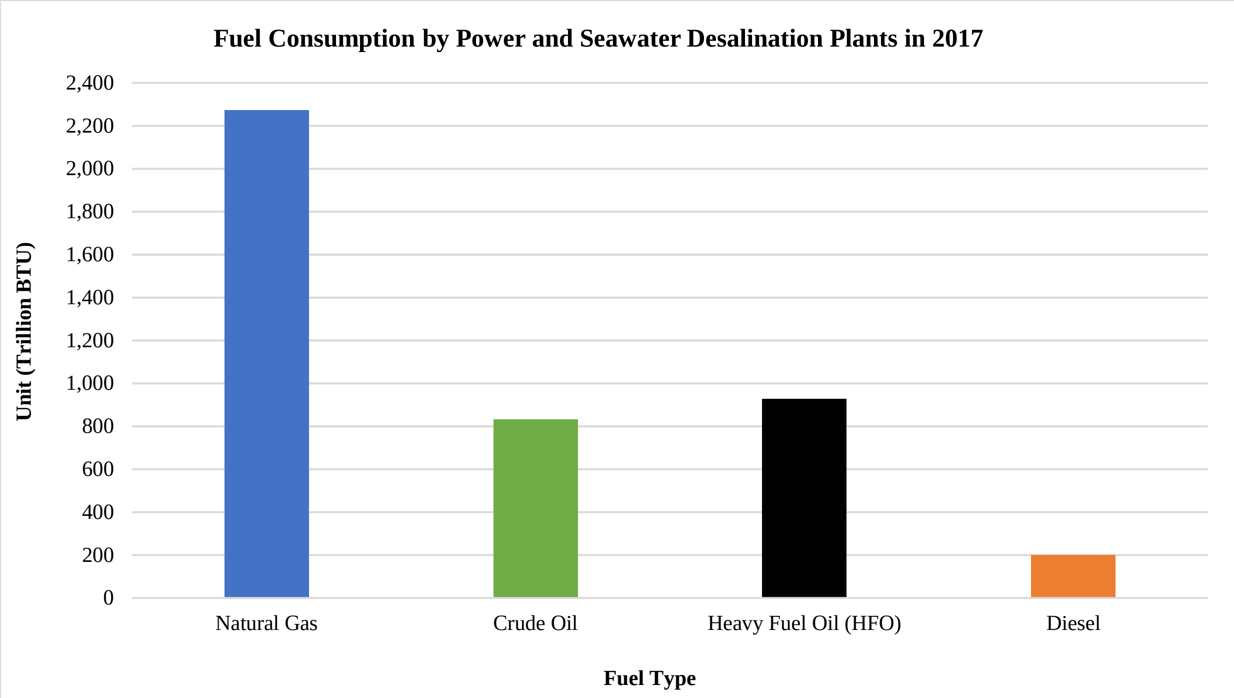

Figure 22 Fuel consumption by power and seawater desalination plants in 2017 [93]

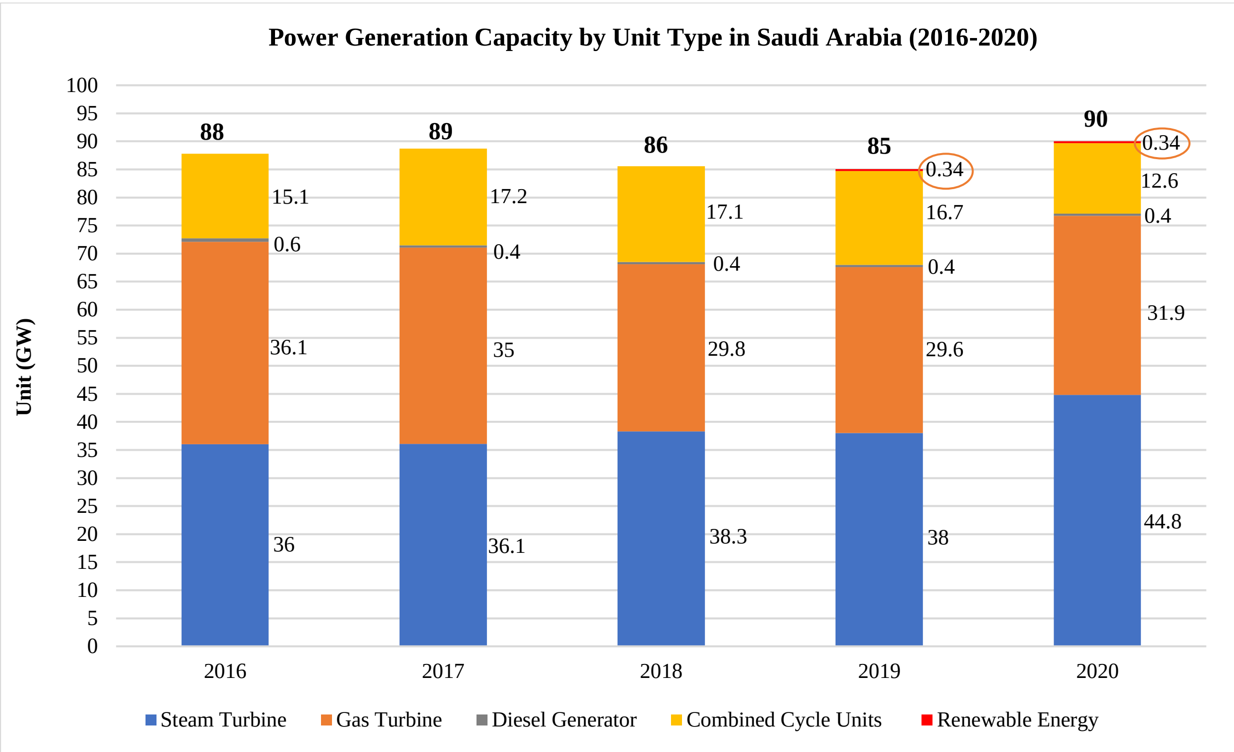

Figure 23 Power generation capacity by unit type in Saudi Arabia (2016-2020) [94]

Figure 23 illustrates that the Kingdom began incorporating RES into its total generation capacity alongside conventional resources starting in 2019. However, other sources, such as the IEA, indicate that solar energy first emerged in the Kingdom in 2017, as mentioned earlier. The share of RES is new and growing. The Kingdom started constructing large scale solar PV and wind projects in recent years only. These projects are being built under the National Renewable Energy Program (NREP), a strategic initiative under Vision 2030 and the King Salman Renewable Energy Initiative. The program aims to maximise the potential of RES in Saudi Arabia. The program sets out an organised and specific road map to diversify local energy sources, stimulate economic development and provide sustainable economic stability to the Kingdom, considering the goals set for Vision 2030, which include establishing the RES industry and supporting the advancement of this promising sector while working to fulfil the Kingdom's commitments to reducing carbon dioxide emissions.

In 2018, under the NREP, Saudi Arabia successfully launched two RES projects in the northern region of Al-Jouf: Sakaka, a 300 MW solar PV powerplant, awarded to AWCA Power, the Dumat Al-Jandal 400 MW onshore wind farm project. The 300 MW Sakaka IPP PV solar project is the first-ever utility-scale RES project under NREP of Saudi Arabia. The Renewable Energy Projects Development Office (REPDO) awarded ACWA Power the contract at a world record-breaking tariff of US cents 2.3417/kWh (8.781 halalas/kWh). The plant will cover an area of six square kilometres at Al Jouf. With an investment of US $302 million, this project is the first of a series of projects under the Saudi NREP, which aims to produce 9.5GW of RES by 2023 [95].

The 400 MW Dumat Al Jandal wind power plant, developed by a consortium led by Masdar and EDF Renewables, has been recently connected to the Kingdom’s grid and started generating electricity. The project consists of 99 onshore wind turbines with a power capacity of 4.2 MW each [96]. The Kingdom has other ongoing RES plants. In 2022, Saudi Arabia launched five projects to produce electricity using RES, a total capacity of 3,300 MW. The Saudi Power Procurement Company launched the projects as part of the fourth stage of NREP, which is under the supervision of the Ministry of Energy. The five projects, as reported by the Saudi Press Agency (SPA), including three wind farms and two solar energy plants, can generate a total capacity of 3,300 MW of energy. The wind energy projects in Yanbu, Al-Ghat and Waad Al Shamal have a total production capacity of 1,800 MW, distributed as 700 MW, 600 MW and 500 MW, respectively. The two solar energy projects, based in Al Hinakiyah and Tabarjal, will have the capacity to produce 1,500 MW in total, distributed as 1,100 MW and 400 MW, respectively. Water desalination projects using solar power projects were also inaugurated by the crown prince in November 2018 [97]

2.3.2 Electric Vehicles Deployment: Recent EVs Deployment Initiatives and Challenges

- EVs Deployment Initiatives in Saudi Arabia

As mentioned in the demand section, Saudi Arabia had no electric vehicles (EVs) for decades. It is only in recent years that EVs have begun to be gradually promoted. The Saudi government is actively promoting EVs in alignment with Saudi Vision 2030, a comprehensive strategy aimed at diversifying the economy away from oil dependence and reducing greenhouse gas emissions. Several policies have already been developed to support the adoption of EVs [98]. In accordance with Vision 2030, the Saudi Green Initiative (SGI) was launched in 2021, unveiling the first wave of over 60 initiatives with investments exceeding SAR 700 billion to meet its objectives. Saudi Arabia aims to reduce carbon emissions by more than 278 million tons per annum by 2030, with a long-term goal of achieving net zero emissions by 2060. A key focus of the SGI is the promotion of EVs within the country. Specifically, the Kingdom plans to ensure that at least 30% of vehicles in Riyadh are electric-powered by 2030, which aligns with global efforts to phase out ICE vehicles. As part of this initiative, the Saudi government announced an agreement with Lucid Motors in 2024 to acquire a minimum of 50,000 EVs, potentially increasing to 100,000 over the next decade, to electrify its fleet. Following a partnership established in late 2021, ABB, a Swiss company and global leader in EV charging solutions, has also begun supplying Electromin, a Saudi e-mobility solutions provider, with EV chargers for installation at 100 gas stations nationwide [99].

- EVs Deployment Challenges in Saudi Arabia

Despite the enormous initiatives the Kingdom promotes for deploying EVs by 2030 and 2050, deploying EVs in Saudi Arabia presents several challenges, ranging from infrastructural and technological to economic and cultural aspects. These challenges are discussed in detail below:

1. Infrastructure Development**:** A significant challenge is the need for extensive EV charging infrastructure. Currently, Saudi Arabia has limited EV charging stations, and developing a widespread network is essential to support the growing number of EVs. This involves substantial investment and planning to ensure chargers are accessible in urban and rural areas alike.
2. Electric Grid Capacity: The increased demand for electricity to charge EVs could strain the current overloaded electric grid. Upgrading the grid to handle this additional load while

ensuring reliable and efficient power distribution is critical. This includes integrating RES sources to sustainably power the EV charging network.

3. Economic Factors: The cost of EVs is still relatively high compared to traditional ICE vehicles. This price difference can be a barrier to widespread adoption. Incentives such as subsidies, tax breaks, and financial support for EV buyers can help mitigate this issue, but these require careful economic planning and policy implementation.
4. Public Awareness and Acceptance**:** There is a need to educate the public about the benefits of EVs, including environmental impact and long-term cost savings. Cultural resistance to change, especially in a region historically dependent on oil, can slow the adoption rate. Public awareness campaigns and demonstration projects are necessary to build consumer confidence and interest in EVs.
5. Technical Skills and Workforce Development**:** Deploying and maintaining EVs and their infrastructure requires a skilled workforce. There is a need for training programs and educational initiatives to develop the necessary technical skills among local engineers and technicians. Partnerships with international experts and companies can help bridge this skills gap.
6. Regulatory and Policy Framework**:** Clear and supportive regulatory frameworks are essential for the successful deployment of EVs. This includes setting standards for EVs and charging infrastructure, creating policies that encourage investment, and establishing guidelines for the disposal and recycling of EV batteries. Effective regulation ensures a smooth transition to an EV-dominated transportation sector. [100-106].

2.3.3 Hydrogen Deployment: Initiatives and Challenges

- Green Hydrogen Deployment Initiatives in Saudi Arabia

Saudi Arabia's current hydrogen demand is zero; it is still unused as a fuel resource in any sector. However, due to abundant renewable energy sources, the country plans to be one of the largest net green hydrogen producers and exporters globally by 2050. The Kingdom has recognised the necessity of diversifying its energy mix and reducing its reliance on oil and gas. In response, the Kingdom has initiated several measures to enhance energy efficiency, increase RES capacity, and explore new energy sources such as hydrogen. Saudi Arabia has set ambitious targets for deploying RES, with plans to increase the share of RES in its energy mix to 50% by 2030.

In 2019, Prince Abdulaziz bin Salman, the Minister of Energy, announced the National Hydrogen Strategy, aiming to position Saudi Arabia as a leading player in the global hydrogen market. This strategy focuses on producing blue hydrogen from natural gas, utilising carbon capture and storage.

CCS technology, as well as green hydrogen from RES. The plan targets the production of 1.2 million tons of green hydrogen annually and aims to supply 10% of the global demand for hydrogen by 2030. Moreover, the Saudi Arabia Public Investment Fund (SAPIF) has been investing in various energy projects worldwide, including a joint venture with Power and Air Products to develop a $5 billion green hydrogen-based ammonia production facility in NEOM, Saudi Arabia. This facility will have a capacity of 1.2 GW and is expected to produce 650 tons of green hydrogen per day [107].

Saudi Arabia's energy policy is shifting towards a more diversified and sustainable energy mix, emphasising the increase in RES capacity and the exploration of new energy sources such as hydrogen. The National Hydrogen Strategy and the country's investments in global hydrogen projects demonstrate a commitment to becoming a significant player in the hydrogen market and contributing to the global transition to a low-carbon economy. Below are some of the hydrogen initiatives the country has taken for sustainability in the future [107]:

1. In 2020, the country launched its National Hydrogen Strategy with the aim of becoming a significant net exporter of hydrogen by 2030.
2. In 2021, the country established a Hydrogen Centre of Excellence to promote the development of renewable energy investigation

- Green Hydrogen Deployment Challenges in Saudi Arabia

Hydrogen energy holds promise for several applications, including transportation and electricity generation. In transportation, hydrogen fuel cell vehicles offer a zero-emission alternative to traditional internal combustion engines [108]. Hydrogen can be utilised in fuel cells to generate electricity, with water being the only byproduct [109]. Additionally, hydrogen can replace natural gas for power generation [110].

Despite its potential, hydrogen energy faces significant challenges that must be addressed to become a viable and widespread energy source. A primary obstacle is the development of infrastructure for the production, transportation, and storage of hydrogen in Saudi Arabia [111]. The current infrastructure and distribution networks for hydrogen in Saudi Arabia are limited, making transportation and storage both costly and challenging. Furthermore, the econremainability of hydrogen energy compared to other energy sources remains uncertain, as the costs associated with production and distribution are still relatively high [208]. Despite these challenges, several studies, such as [112], have highlighted the excellent potential for deploying hydrogen in Saudi Arabia in the future, not only for domestic use but also for large-scale export. This is especially relevant in the futuristic city of NEOM, where most of the RES projects are being developed in the north near the city. These projects aim to support electricity production as the primary input to electrolysers, with the availability of running water serving as the secondary input.

This thesis employed green hydrogen for electricity production in a backup power plant with the 100% RES in 2050, as discussed in detail in upcoming sections 4.4 and 5.6. In the hydrogen backup power plant, the electricity input for hydrogen production was entirely supplied from the surplus energy output of the final 100% RES solution.

2.4 Saudi Arabia Energy System, Outcomes and Contributions

This chapter addresses a significant gap in characterising Saudi Arabia's energy system by developing a comprehensive dataset and knowledge base on energy flows, as shown in Figure 2 with the energy balance block diagram. This synthesis establishes a foundational analysis that underpins this thesis's modelling of current and future scenarios for renewable integration and sustainable energy systems.

Key findings from the previous sections include a detailed review of the Kingdom's energy sector, analysing demand and supply on a sector-by-sector basis. The demand side was thoroughly examined across fuel types of power stations (broken down by technology and fuel types). In specific cases, such as desalination, calculations were performed to yield a robust demand assessment. The supply side further explores components like EV and hydrogen deployment initiatives and their associated challenges, essential for constructing a comprehensive energy model for Saudi Arabia.

However, data limitations posed challenges: some information was unclear, misleading, or restricted from public access, with certain parts unavailable or classified. To address these challenges, the review consolidated information from diverse sources and employed manual calculations where data were incomplete, resulting in a reliable, thorough dataset that eliminates inaccuracies. This comprehensive review not only supports the energy model in this thesis but also provides future researchers with a reliable reference.

Additionally, the second key contribution is a novel resource in Figure 2, an energy balance block diagram developed exclusively for this research. This diagram captures the relationships across all sectors and energy resources, such as oil products, natural gas, and electricity, within the Kingdom's energy landscape. For transparency and accessibility, all data used in this thesis—including Microsoft Excel files, Word documents, and hourly data across various model parameters—have been made available on GitHub, supporting open-access use and facilitating future research.

CHAPTER 3

Renewable Trends in S.A. and Modelling Methodology

3.0 Introduction

In Chapter 3, the nascent renewable energy and energy modelling trends are reviewed to inform the selection of appropriate RES technologies for Saudi Arabia's context and modelling tools relevant to the current and future energy systems and discuss the KPIs that will be used to assess any proposal. Based on these inputs, a modelling methodology for the work of this thesis is established.

3.1 Current Literature Trend Review

3.1.1 Limitations in The Current Literature About General Transitioning Towards RES Topic for The Future in Saudi Arabia, Showing the Lack of Planning Studies on the 100% Transition Towards RES for Different Sectors on a Country Scale in Future Target Years, and Their Limitations.

This section elaborates on the trends and most relevant scientific literature regarding the transition to RES and energy planning approaches for sustainable energy systems. It also shows the lack of similar studies on the 100% transition towards RES in a large country scale for a future target year. Various studies have been conducted on the transition towards RES in Saudi Arabia. However, **most studies focus on the potential of solar or the potential of RES technology rather than the total transition of all sectors into RES in future year targets such as 2030 and 2050**. Studies such as [113] aim to review the status, growth, potential, resources, sustainability performance, and prospects of RES technologies in the Kingdom, in alignment with Saudi Vision 2030. [114] explored the potential of a hybrid RES consisting of wind turbines and PV combined with pumped hydro energy storage, aiming to replace costly and short-lifetime batteries in small-scale areas of northern Saudi Arabia. However, this study focuses solely on small-scale areas and does not address other sectors. [115] studied the future performance of solar and wind energy with the behaviour of temperature for three selected sites in the Kingdom using Monte Carlo Simulation (MCS) and Brownian Motion (BM) based on historical data. However, this study focused on the behaviour of the RES technology instead of the total transition of the country towards RES and including other sectors.

[116] studied the feasibility of a 100% RES in the Middle East and North Africa region (MENA) in 2030. However, the research only considered three sectors: power, non-energetic industrial gas and seawater desalination. Although this study is similar to both the topic and analysis of this thesis, this study focused on a more general picture like the MENA region with interconnection between more than 14 countries rather than a specific, closed, standalone system for a country like Saudi Arabia. Involving multiple countries makes the practical application of this work challenging, due to several factors such as differing policies, demands, logistics, and decision-making processes. Another limitation is that this study included sectors such as desalination and industry. However, it did not include the transport sector, the highest consumer of oil products in Saudi Arabia, the biggest country in these interconnections in the MENA region. [117] studied the potential of power generation and hydrogen production by solar and wind energy resources at different locations in the Kingdom, where these locations represent different solar radiation and wind speed potentials using the HOMER tool for the simulations. However, this study was conducted for a typical house demand and not for the large-scale country demand with different scenarios for the future, including more than one sector.

Some studies focused on reviewing technology in one part of the RES. [118] conducted a comprehensive technology review on the electrical energy storage systems for RES use in Saudi Arabia. This included all types of energy storage such as mechanical (pumped hydro, flywheel, compressed air energy system), electrical (Superconducting magnetic energy storage), chemical (lead acid batteries, nickel-cadmium batteries, sodium sulphur batteries, Vanadium redox batteries). The review concluded that the most promising storage technology for RES management in Saudi Arabia is vanadium redox flow batteries based on factors such as efficiency, lifecycle, and per-cycle cost.

Another study [119] comprehensively reviewed the future desalination technology combined with the best renewable solar energy for Saudi Arabia. Each scenario includes a few parameters, such as the availability of fossil fuels, the renewables target (%), and the RES technologies used, such as solar PV in the scenario set 1 and wind power in scenario set 4.

The other direction of studies for the transition towards RES in Saudi Arabia focuses on simulation and future scenarios from different perspectives and criteria such as technical feasibility, techno-economic, socio-political, and environmental. **The body of research conducted in this area, particularly relating to Saudi Arabia, is relatively limited and**

sparse. Especially with future energy scenarios and modelling, since the Kingdom is a major oil producer with at least a quarter of the world's proven oil reserves, raising significantly less need for RES. With the limited number of studies on this direction, most focus solely on the electricity sector or one or two sectors in the Kingdom, not as one integrated system of all sectors. [120] studied the role of battery and water storage on the 100% RES transition pathway in Saudi Arabia in 2050. The study focused solely on the power, desalination, and non-energetic industrial gas sectors without considering other sectors, such as transportation, the highest consumer of oil products, in future scenarios. The LUT energy system transition model was utilised in this study to design and analyse the energy transition. They concluded that PV single-axis tracking combined with battery storage could achieve 100% RES for the power sector in 2040 in Saudi Arabia. The problem in this study is that several factors affect the process of generating power from PV solar panels on a country scale, particularly Saudi Arabia, which has not been considered in this study. The low mean capacity factor of the PV panels, especially with the Kingdom's dust conditions, which decrease the power generation, the extreme summer temperatures, which also reduce the system efficiency, the higher need for cleaning, the intermittency, and the panels' lifetime. Thus, counting on solar only for the entire Kingdom's demand is challenging. There is no doubt that solar energy is a must in Saudi Arabia due to the vast solar energy abundance and high solar irradiance, as the Kingdom lies in the centre of the world's ''sunbelt'' area. **However, as shown in this thesis, the optimal mix of RES technologies,** including solar, wind, and storage, is required to help achieve the optimal technical, economic, and environmental goals.

[121] developed different future energy scenarios for Saudi Arabia. The developed RES scenarios include four sets. Each set contains two future energy scenarios (a total of 8 scenarios). These scenarios were developed by utilising Delphi technique, described as an interactive group process to bring together expert opinions on a particular issue. This technique is an expert-based method of eliciting, collating, and refining anonymous group judgements on a complex subject, typically through circulating several sequential questionnaires (or rounds). In other words, it is a multi-stage approach, with each stage (i.e., a Delphi round) building on the results of the previous one. Repeat rounds of this process occur until an overwhelming opinion is reached. The limitation of this study lies in the use of this technique, which provides more subjective information than precise, quantitative data. Although the study included quantitative data within the scenarios, this information was simple, limited, and heavily based on assumptions. Additionally, computer models were not employed to analyse the Kingdom's

energy system. Only a few tools, such as RETscreen International Clean Energy Analysis Software, were used to calculate specific, simplified data, such as life cycle costs.

3.1.2 RES Technologies Considered in This Thesis.

Solar and wind energy have been established as highly promising renewable resources in Saudi Arabia, with solar energy being particularly prominent. The Kingdom's unique geographical location and vast land area contribute significantly to its exceptional solar potential. Solar energy has increasingly become a key technology in the Kingdom, which ranks among the highest globally in terms of solar resource availability, as evidenced by numerous scholarly studies, including [122], [123], [124], and many others. These abundant solar resources are clearly illustrated in the Solar Atlas maps, which highlight Saudi Arabia's exceptional solar potential. As such, solar energy technologies should be prioritized in any project or research focused on renewable energy supply in the Kingdom. This includes two primary solutions: PV systems and CSP technologies.

PV was considered as the first RES technology for this project. This is due to substantial-high-quality studies, research, and projects on PV in Saudi Arabia for different small-scale applications. PV has proven to be an outstanding technology for the Kingdom in hundreds of papers and projects. In addition, the GIS PV potential map indicates that the highest power potential could be utilised from PV in the northern region near Tabuk as the yearly total yield could reach 2,045 to 2,118 kWh/kWp. Tabuk and the areas of the north have some of the best direct normal irradiances in the world. Several papers, such as [125], has proven the same region as one of the best to consider PV and CSP power plants. DNI could reach 9.5 kWh/m^2/day, while GHI reaches 8.3 kWh/m^2/day. These levels exceed the required level for viable solar energy electricity systems. For the PV potential, studies such as [126] employed solar PV and wind for the entire MENA region as the predominant energy sources in all the studied scenarios, representing more than 90% of the total generation capacity for 100% RES scenarios in 2030. [127] conducted a techno-economic feasibility study of installing 10 MW grid-connected PV power plants at 44 locations in Saudi Arabia and found it technically and economically feasible.

[128] studied the techno-economic analyses of 67 MW and 144 MW PV power plants. The results were compared with the diesel power plants in two cities in the Kingdom of Saudi Arabia. The feasibility analysis aims to show the technical and economic viability of replacing

conventional fossil fuel-based plants with clean production systems in the country. The technical and financial indicators of the PV panel-based power generation system presented in this study indicated the viability of a solar project in the climatic conditions of Saudi Arabia. Several other studies and research have proven the viability, technical and economic feasibility of PV power plants in Saudi Arabia. However, relying solely on PV systems to meet the entire energy demand of Saudi Arabia is not feasible in practice, despite claims in studies such as [129] suggesting that the country could be powered entirely by single-axis PV systems and battery storage. The author of this thesis agrees with the study in [129] that PV systems and battery storage can be deployed on a large scale in Saudi Arabia. However, it is disagreed that this combination alone could fully power the Kingdom. This is due to the same technical reasons mentioned in [130]; some are the low mean capacity factor of 0.27-0.28 with the dust conditions in Saudi Arabia, the cleaning requirement increased costs. The author also suggests alternative solutions, such as high-efficiency combined-cycle power plants with carbon capture, as more viable than a 100% PV and battery storage system for the Kingdom. However, this recommendation contradicts one of the core objectives of this thesis—eliminating fossil fuel use in power plants and CO_2 emissions by 2050.

Given these considerations from various studies, **wind power was considered** as a key future renewable energy source alongside PV. This approach ensures that the Kingdom's energy demand does not rely solely on PV and battery storage. The integration of wind power will reduce the dependency on PV systems and enhance the reliability of the hybrid energy system in real-world applications. Additionally, wind power is a compelling option because Saudi Arabia has excellent wind resources, particularly along its northern, northwestern, and western coastal regions. Wind has proven to be an excellent renewable energy source by many research papers in Saudi Arabia. These studies have demonstrated the feasibility of harnessing wind power in northern Saudi Arabia, such as Tabuk and Alwajh, and the new futuristic NEOM city is being developed now, where these locations have the best wind speeds and power potential. Studies such as [131] assessed the feasibility of Saudi Arabia's first large utility-scale wind farm, the 400 MW Dumat Aljandal Wind Farm, located in the northern part of the Kingdom. Utilizing SAM program, the study concluded that the project is viable for extensive utility-scale deployment, marking it as the largest wind farm in the region. This project is a part of the

Saudi Arabian government's plan to diversify its energy mix to reach 50% of the electricity supply from RES by 2030.

Another study [132] identified optimal locations for wind farms in Saudi Arabia during the summer, focusing on areas with wind speeds exceeding 9 m/s for at least half of the time. The study also assessed the risk of wind turbine disruption, finding that these locations have a disruption probability of less than 1%. This analysis was conducted using Bayesian Spatial Extremes, ensuring low-risk conditions for wind turbine operations. The most suitable locations were found on the western coast of Saudi Arabia, predominantly in the northwest near the futuristic NEOM city. Paper [133] conducted an analytical assessment of the feasibility of wind energy in Saudi Arabia’s envisioned NEOM city. By applying a method that minimizes the mean squared error between the Weibull distribution and the empirical distribution, the study determined the wind speed pattern in the city. The findings concluded that wind farms are both technically and financially viable for commercial use in NEOM city.

One of the limitations of wind energy studies and this thesis is the absence of actual measured data for wind turbine production in regions with high wind potential. Although Saudi Arabia has begun developing large-scale renewable energy projects in recent years, such as the 400 MW wind farm connected to the grid in 2022, there is still a lack of readily available hourly production data for researchers and engineers. This data gap hinders precise assessments and optimization of wind energy systems in the country. In addition to the discussed studies, Figure 55 shows the mean power density from the Global Wind Atlas with the latest 2023 update, indicating a great wind potential, especially in NEOM city.

Battery Storage was considered in this study as the solution for intermittency, which will result from the hybrid system of PV+Wind. Battery storage was incorporated into the system design due to its demonstrated superior ability to address intermittent and small-scale energy deficits throughout the year, compared to PV and wind technologies. The energy required to compensate for these deficits is sourced from the surplus power generated by the PV and wind systems, as will be elaborated in the following sections.

CSP was not considered and out of this study's scope for several reasons. One of the most important reasons is CSP’s less technological maturity than PV worldwide and in Saudi Arabia. While there have been notable advancements in CSP technology in recent years, it remains comparatively less developed than solar PV or wind power. Consequently, there may be a perception of elevated risks associated with CSP, resulting in slower rates of adoption and constrained investment. In addition, the first reason is the vast spread of PV over CSP globally. PV is one of the fastest-growing RES technologies and plays an increasingly important role in the global energy transformation. By the end of 2020, the total installed capacity of solar PV systems worldwide had reached 710 GW, while the global installed capacity of CSP was approaching 7 GW. Approximately 125 GW of new solar PV capacity was added in 2020, the largest capacity addition of any renewable energy source [134]. In 2022, with the latest IREANA data, the total installed PV capacity reached 1,055 GW compared to 6.6 GW for CSP worldwide [134].

In terms of investments and costs, CSP systems are usually more costly to build and operate compared to other RES options like solar PV. This is because CSP setups require more intricate designs, specialised parts, and additional systems for storing heat, all of which drive up the initial expenses. As a result, many projects find CSP less financially attractive. PV power plants offer significantly lower investment costs compared to CSP plants, making them more appealing to investors. This is particularly evident in the dramatic decline in PV prices over the last decade, which dropped by 82% from 2010 to 2019, compared to a 47% reduction in CSP costs during the same period. The significant global investment in RES is highlighted by the annual financial commitment data from IRENA [135], which shows that in 2022, PV energy received a total of 298.21 billion USD—approximately 60% of the global annual investment in RES. This represents the highest financial commitment to any renewable energy source worldwide. The second highest annual financial commitment was for wind, at 140.70 billion USD (28%), while for CSP, it did not exceed 9.3 billion USD (2%)

CSP power plants, along with their heat transfer fluids as well as thermal energy storage systems, face a range of technological and economic challenges. Economically, these challenges involve high initial capital expenses, unpredictable pricing, financing difficulties, limited scalability, fluctuating material prices, availability concerns, and ongoing operational costs. On the technological front, issues include the variability of solar resources, grid integration complexities, corrosion risks, thermal stability concerns, and the intricate nature of system setups. These hurdles emphasise the need for continuous innovation and investment in CSP technology to enhance cost-effectiveness and efficiency. Moreover, addressing these challenges is crucial for facilitating large-scale deployment involving technological advancements and economic considerations. Additionally, governmental support and regulatory frameworks are essential to foster the development of concentrated solar power technology and expedite the transition towards a future powered by clean energy sources [136].

The variability of solar resources caused by meteorological conditions, like clouds and dust, can hinder the efficiency of CSP facilities. Similarly, thermal energy storage technologies within CSP plants may suffer from thermal losses and system complexity, posing challenges to their effectiveness. Integrating CSP plants into the grid can be challenging due to their inherent unpredictability, requiring regular maintenance to maintain efficiency. Furthermore, the high construction costs, uncertain electricity prices, and financing difficulties faced by CSP plants, coupled with the lack of economies of scale in the early stages of the industry, contribute to the comparatively higher cost of CSP-generated power when compared to other RES sources [137][138][139].

In terms of water consumption, numerous CSP technologies utilise steam cycles or alternative heat transfer fluids to produce electricity. These configurations necessitate substantial quantities of water for cooling and steam generation purposes. In arid locales, water scarcity presents a potential constraint to the viability of CSP facilities, as they may encounter competition with essential water demands or difficulties in ensuring sufficient water availability, such as in Saudi Arabia, as shown earlier in section 2.2.4. This poses a serious problem as most CSP plants are in hot, dry regions with limited water resources. CSP plants diverge from traditional gas or coal-fired power stations by utilising mirrors to concentrate solar energy heating water to generate steam, which then powers turbines for electricity production. Following steam utilisation, cooling is necessary to condense it back into water for the cycle to restart. This cooling phase is responsible for most of the water consumption in CSP plants, involving evaporation and what's known as drift and blow-down losses. Consequently, CSP plants can consume up to 3,500 Liters of water per MWh of electricity generated, in contrast to approximately 1,000 Liters/MWh for contemporary natural gas-fired power plants. Although cooling represents CSP plants' primary water consumption process, it is not the sole one. The routine cleaning of concentrator mirrors also necessitates significant water volumes, particularly in arid, dusty regions [140].

Green hydrogen power plant was considered in this study due to its critical role as a backup power source alongside a 100% RES. Furthermore, its immense potential, as evidenced by hundreds of studies, underscores its viability for future applications, including replacing fossil fuels in power generation and transportation. Papers such as [141–143] have extensively highlighted these prospects. Research such as [144] has identified Saudi Arabia's potential to emerge as a global leader in green hydrogen production, consumption, and export. Similarly, [145] emphasizes the pivotal role of green hydrogen in the Kingdom's energy transition. In [146], the study explores the feasibility of solar-based hydrogen production through water electrolysis using PV systems in the NEOM green city, further underscoring the country's prospects in advancing green hydrogen technologies. They concluded that NEOM city in Saudi Arabia has enormous potential in producing green hydrogen as it will be the world's largest producer. This is because of the vast amount of solar radiation in the northern part of Saudi Arabia and NEOM, in addition to being close to a source of water for the process of hydrogen separation from water using electrolysis. Other studies such as [147] has also studied the potential of green hydrogen in Saudi Arabia, which could be the best in the world economically. This research [148] assessed the green hydrogen production both technically and economically in the Middle East in PV power stations and found it feasible.

One of the technical aspects that makes Saudi Arabia one of the largest producers of green hydrogen globally is the huge solar irradiance, among the highest irradiance in the world. 2,500 $kWh/m^2/year$. This high availability of energy makes solar PV and CSP technologies very effective; thus, solar energy can be harnessed efficiently for electrolysis.

Second, the existence of specific regions with very high wind potential complements solar power and allows for continuous hydrogen production [149].

Third, Saudi Arabia's extensive existing oil and gas infrastructure provides a significant advantage, as it can be adapted for hydrogen production, storage, and transportation, thereby reducing initial investment costs [150]. Furthermore, the well-established logistics and distribution networks can efficiently support hydrogen delivery and export.

Fourth, the Kingdom's advanced desalination capabilities ensure a steady supply of water for hydrogen production without depleting freshwater resources. With access to both the Red Sea on the west and the Arabian Gulf on the east [151], Saudi Arabia is uniquely positioned to utilize seawater for this purpose.

Fifth, the country's strategic location near major energy markets in Europe and Asia allows it to capitalize on geographic proximity for hydrogen exports.

Sixth, its access to global shipping routes, complemented by well-developed port facilities, ensures the efficient export of hydrogen and ammonia to international markets.

Lastly, robust government support underpinned by Saudi Vision 2030 fosters a favourable environment for RES and hydrogen projects. Financial incentives and progressive regulatory frameworks further encourage investment in hydrogen infrastructure and renewable energy systems.

EV technology was examined in this study as a key solution, leveraging Saudi Arabia's abundant RES resources alongside the significant potential and advantages of EV deployment. As highlighted in research such as [152], which investigated the integration and deployment of EVs within the Saudi electric power system. The adoption of EV technology offers numerous technical benefits for the Kingdom. First, Saudi Arabia's substantial solar and wind energy resources present an opportunity to power EV charging stations, contributing to a sustainable energy ecosystem. Second, in a 100% RES generation scenario, a significant amount of surplus energy is produced by RES power plants. This surplus, if not utilised, poses grid balancing challenges. Integrating EVs into the system offers dual benefits by consuming this excess energy, which is especially advantageous in Saudi Arabia, as EV demand can be met through surplus energy generated from 100% RES, as detailed in Chapters 4 and 5, thereby reducing greenhouse gas emissions from internal combustion vehicles. Furthermore, incorporating EV technology is essential for mitigating the surplus energy generated from RES plants, critical in preventing grid instability and ensuring system balance.

3.2 Overall Methodology Steps of This Research (Dataset and Data Gathering, High-Level Approach to Modelling, Modelling Tools Selection, Future Energy Systems Scenarios)

3.2.1 Research Design

The research is grounded in addressing key problems related to Saudi Arabia's dependence on fossil fuels, high CO2 emissions, and the underutilisation of its vast RES resources. The aim is to propose a technically and economically viable solution for transitioning to a 100% RES by 2050, focusing on both the power and transport sectors.

In response to the problem formulation (as outlined in Section 1.2), this study employs a quantitative computational methodology. This methodology is driven by the need to explore future RES scenarios using validated data and advanced modelling tools, bridging the knowledge gaps related to:

1. The lack of comprehensive studies that cover all sectors, including electricity, transportation, and fuel distribution.
2. The need for an energy model that assesses cross-sector energy demand and supply under different scenarios.
3. The absence of studies that provide in-depth technical, economic, and environmental analysis of RES transitions for Saudi Arabia on a country-wide scale for a future target year.

This design is specifically tailored to address the identified gaps by creating a robust energy model that can simulate various energy scenarios for 2050. The methodology also links directly to the research questions outlined in Section 1.3, particularly in determining how Saudi Arabia can transition towards RES and what the optimal energy system combination will be from a techno-economic and environmental perspective.

3.2.2 Step 1: Methodological Framework for Building a Comprehensive Dataset to Support Long-Term Energy Scenario Analysis

To answer the research questions outlined in this thesis and to bridge the significant gaps found in previous studies, this research employs a comprehensive data collection methodology. This step serves as the critical foundation for developing an accurate and validated dataset that would act as the primary input for subsequent modelling and simulation efforts. The dataset not only enables the construction of a reliable energy model for Saudi Arabia but also supports the analysis of various RES scenarios for 2050.

- Link to The Overall Research and Future Modelling

The comprehensive dataset collected in this step directly addresses the central research problems—Saudi Arabia's reliance on fossil fuels, high CO_2 emissions, and the underutilization of RES resources. The data assembled in this phase is essential for constructing an accurate reference model of Saudi Arabia's current energy system, which is foundational for simulating future energy scenarios and assessing their feasibility from technical, economic, and environmental perspectives. This step directly supports the overall aim of the research: to explore sustainable RES pathways for Saudi Arabia, specifically for the target year of 2050. By providing validated data for the power and transport sectors, this dataset enables the creation of a dynamic energy model that is used to simulate and optimize various 100% RES configurations, forming the core of the modelling phase in Step 2.

- Challenges and Methodological Strategy

Due to the fragmented and often incomplete nature of the data available for Saudi Arabia's energy landscape, this phase required a multi-layered strategy involving both quantitative and qualitative data collection:

1. Primary Data Collection:

Data was gathered from official government sources, including the General Authority of Statistics, Saudi Ministry of Energy, Saudi Ministry of Environment, Water & Agriculture, KAPSARC, and the Saudi Ministry of Finance. These institutions provided a sector-specific breakdown of energy consumption, production, and resource availability across Saudi Arabia. This primary data was crucial for constructing the initial reference model of Saudi Arabia's energy system, ensuring that the research addresses existing gaps in data accuracy and completeness.

2. Direct Communication and Validation:

In cases where data was unavailable or classified, direct communication with key stakeholders within relevant departments was pursued. This strategy was necessary to obtain access to otherwise inaccessible information, improving the dataset's accuracy. Validation from industry insiders helped resolve discrepancies between different sources, ensuring the dataset's integrity before it was used as input for the energy model.

3. Secondary Data Collection and Cross-Referencing:

Secondary data sources, including academic journals, industry reports, and peer-reviewed research papers, were utilized to fill remaining gaps and verify the accuracy of collected data. This involved a meticulous process of cross-referencing multiple sources to construct a comprehensive and consistent dataset. These secondary data points were essential for understanding less documented sectors like industrial gas, desalination, and transport, which are critical for building a holistic model of Saudi Arabia's energy system.

- From Data Collection to Energy Modelling

The validated dataset developed through this methodology was not only used to address the research gaps but also acted as the primary input for the subsequent modelling phase. The data served as the backbone for constructing a detailed energy model using tools like EnergyPLAN and SAM, allowing the study to simulate and optimize various RES scenarios. This transition from comprehensive dataset collection to energy modelling marks a shift from understanding the current state of Saudi Arabia's energy system to projecting its future state under different RES configurations.

The development of this dataset directly supports the technical and economic assessments conducted in later steps, answering key research questions regarding the best approaches for transitioning Saudi Arabia to a 100% RES. By establishing a solid data foundation, this step ensures that the modelling and simulations are both credible and accurate, contributing to the study's overall goal of designing a sustainable energy future for Saudi Arabia.

3.2.3 Step 2: Advanced Energy System Modelling Approach for Long-Term RES Scenarios in Saudi Arabia in 2050

To achieve the overarching aim of this thesis, analysing various 100% RES solutions for Saudi Arabia by 2050 to identify the optimal configuration from both technical and economic perspectives, a robust modelling approach was employed. This research not only seeks to determine the optimal RES combination but also aims to provide recommendations and limitations for policymakers, contributing to the broader knowledge base on RES transitions. The complexities inherent in transforming a country's energy system, particularly one as fossil fuel-dependent as Saudi Arabia, necessitate a methodology that is both precise and comprehensive. This phase of the research focuses on leveraging advanced energy modelling techniques to simulate future RES scenarios, providing detailed technical and economic insights that inform policy-making and long-term planning.

- Linking the Modelling Approach to the Research Goals

The use of a modelling approach in this study is a direct response to the research questions and the identified gaps in the literature. As outlined in the Problem Statement (Section 1.2), Saudi Arabia faces significant challenges in diversifying its energy mix and reducing CO_2 emissions due to its heavy reliance on fossil fuels. This research seeks to explore how a country with abundant renewable resources can transition to a sustainable energy system by 2050, aligning with global climate goals such as those outlined in the Paris Agreement. Energy modelling offers a powerful methodology for exploring these questions because it allows for the simulation of various future energy scenarios under different technical, economic, and policy conditions. This aligns with the research objective of evaluating the feasibility and performance of RES in Saudi Arabia's unique context. The choice to use a modelling approach is based on its ability to:

1. Integrate multiple energy sectors (electricity, transport, industrial gas, and more) into a unified simulation, providing a comprehensive view of the entire energy system.
2. Evaluate different combinations of RES technologies, including PV, wind, battery storage, and green hydrogen-backed power, to determine the optimal mix for 2050.
3. Provide a quantitative basis for decision-making, ensuring that policy recommendations are grounded in data-driven analysis rather than speculative assumptions.

- Justification for Utilizing Computer-Based Energy Modelling

To the best of our knowledge, no previous studies have applied a comprehensive computer-based model to the long-term energy planning and policy-making of Saudi Arabia's energy system, specifically for target years such as 2050 including power from all sectors with cross sector coupling including transport sector electrification using the surplus energy resulted from the 100% RES and evaluating the entire system technically, economically, and environmentally. This research fills that gap by using advanced modelling techniques to simulate the country's energy transition pathway, thereby providing a unique contribution to the field. Energy modelling was chosen for its ability to:

1. Capture the complexities of integrating intermittent renewable resources, such as solar and wind, into a traditionally fossil-fuel-based system.
2. Enable long-term projections, assessing the sustainability of various scenarios over decades, which is essential for setting reliable energy policies and strategies for 2050.
3. Facilitate an in-depth technical and economic analysis, identifying the strengths, weaknesses, opportunities, and challenges associated with each RES configuration.

- Why Modelling Was Essential for This Research?

Given the scale and scope of Saudi Arabia's potential energy transition, traditional methods of energy analysis were inadequate. A modelling approach provides several distinct advantages:

1. Scenario Analysis: By simulating various configurations of RES, modelling allows for a comparative assessment of different pathways toward achieving a 100% RES. This study

utilizes combinations of RES technologies including solar PV, wind, battery storage, and green hydrogen-backed CCP plants to assess which configurations offer the best balance between cost, reliability, and sustainability.

2. Dynamic Flexibility: Modelling tools like SAM and EnergyPLAN offer the ability to adjust parameters dynamically, such as technology costs, energy demand, and policy incentives, to test how different variables impact the feasibility of achieving a sustainable energy system.

3. Data Integration: The dataset developed in Step 1 serves as the primary input for the modelling phase, ensuring that the simulations are based on validated, comprehensive data that accurately represents the current energy landscape in Saudi Arabia. This connection between data collection and modelling is crucial for ensuring the reliability of the projected scenarios.

- Modelling as a Bridge to the Next Phases of Research

This modelling phase not only serves as a foundational step for assessing various future energy scenarios but also sets the stage for the subsequent phases of research, where the focus shifts to optimizing the energy system configurations identified through the simulations. The outcomes of this phase will directly inform the optimization process, where the technical and economic performance of each scenario is evaluated in detail. The objective is to identify the optimal RES configuration for Saudi Arabia's energy transition, providing clear policy recommendations backed by solid technical and economic evidence.

By integrating advanced modelling techniques with a validated dataset, this phase is instrumental in achieving the thesis's overarching goal: to provide a sustainable and economically viable energy roadmap for Saudi Arabia by 2050. This approach not only contributes to the academic understanding of RES transitions in the Middle East but also offers actionable insights for policymakers, aligning with the broader objectives of Vision 2030 and the international commitments under the Paris Agreement.

3.2.4 Step 3: Methodology for Selecting Energy Modelling Tools for 2050 RES Analysis

3.2.4.1 EnergyPLAN Selection Methodology and Criteria

The complexity of transitioning Saudi Arabia to a 100% RES by 2050 requires a comprehensive and sophisticated approach to energy system modelling. This step outlines the methodology used to select the appropriate modelling tools for this task, with a specific focus on the criteria and rationale for choosing EnergyPLAN as the primary tool, supported by SAM for detailed RES analysis.

Energy systems are intricate structures designed to operate seamlessly based on various interdependent technologies, regulations, inputs, and outputs. As energy systems transition to RES, their complexity increases as they must deal with new energy carriers, variable RES sources, resource limitations, and fluctuating demand. Responding to these changes necessitates the development of technical alternatives that consider all facets in this concept scoping study for future energy systems. This tool must be capable of identifying and quantifying alternatives based on the concept scoping study and the following criteria:

- Include the entire energy system in accordance with the Smart Energy System concept, which is essential for comparing the large-scale integration of RES sources in power, desalination, transportation, and industrial sectors.
- Consider all energy sub-sector demands, such as electricity, cooling, residential, industry, and transport.
- Optimize the combination of energy technologies used based on both technical (such as technical capacity) and economic aspects (such as investment and energy costs)
- Support hourly resolution to analyse the impact of fluctuating RES and seasonal variations in production and demand.
- Include radical technological changes essential for achieving all types of renewable and sustainable energy systems.
- The ability of creating different energy scenarios for long-term future energy planning.
- The ability to simulate 100% RES.

The range of possible tools that meet these criteria and the research objectives have been reviewed and narrowed down. This research [153] conducted a comprehensive review of various computer tools available for analysing the integration of RES. In addition, references [154- 158] have been reviewed, and 37 energy modelling tools have been identified and reviewed. The results from the completed reviews of energy modelling tools in [153-158] and the explanation of the applicability of EnergyPLAN and SAM are as follows: This review highlights the diverse range of energy tools available, each varying in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil. Examining their typical applications can provide a comprehensive understanding of these tools. The BCHPScreening Tool, HOMER, HYDROGEMS, and TRNSYS16 are primarily used for stand-alone RES applications, such as single buildings, local communities, or individual projects, which is not suitable for this thesis as these tools do not fulfil the earlier mentioned criteria, i.e. cannot simulate 100% RES for the entire country of Saudi Arabia. EnergyPRO evaluates the feasibility of new power plants or CHP facilities for the electricity sector, while WASP assesses the need for new power capacities. ProdRisk and EMPS optimise hydropower operations, and AEOLUS examines the impact of fluctuating RES on conventional generation. ORCED simulates electricity dispatch and EMCAS models electricity markets. Thus, while all these tools are focused on the electricity sector, their specific objectives differ significantly. These tools also do not fulfil the earlier selection criteria in this thesis, such as the inability to simulate the entire energy sectors for a large-scale system (country scale) and the inability to simulate this system with 100% RES.

All other tools incorporate the heat or transport sectors and the electricity sector in their analyses, each with varying considerations. Tools like BALMORAL, GTMax, RAMSES, and SIVAEL account for district heating along with the electricity sector, while E4cast, EMINENT, and RETScreen encompass all aspects of the heat and electricity sectors. This integration enhances the use of CHP and thermal storage to manage fluctuating RES. These tools did not simulate 100% RES and focus more on the heating and district heating sectors that do not exist in Saudi Arabia. Saudi Arabia has only cooling demand with negligible heating demand supplied by electric heaters with no CHP's or district heating. PERSEUS, STREAM, and the WILMAR planning tool extend their scope to include the transport sector through electric vehicles, enabling a more comprehensive energy system analysis. This broader approach offers more options to increase system flexibility and renewable energy penetration. MiniCAM and UniSyD3.0 further expand the transport sector to include hydrogen and electric vehicles, providing additional flexibility options for the energy system. Conversely, Invert, H2RES, and SimREN focus only on one transport technology: biofuels for Invert and hydrogen vehicles for H2RES and SimREN, with no electric vehicle use, which is required in this thesis.

The remaining tools, such as COMPOSE, EnergyPLAN, ENPEP-BALANCE, IKARUS, INFORSE, LEAP, MARKAL/TIMES, Mesap PlaNet, MESSAGE, NEMS, and PRIMES, are capable of accounting for all technologies across the electricity, heat, and transport sectors. Of these tools, only EnergyPLAN, Mesap PlaNet, INFORSE, and LEAP have successfully simulated 100% RES. It is important to mention other factors must be considered when selecting an energy tool. For instance, seven tools have been used to simulate 100% RES:

EnergyPLAN, H2RES, Invert, Mesap PlaNet, INFORSE, LEAP, and SimREN. Among these, only EnergyPLAN, Mesap PlaNet, H2RES, and SimREN used time steps of one hour or less, making them more suitable for optimising the energy system to accommodate RES fluctuations [153].

Finally, the other factors that could influence the choice of an energy tool include the technologies and sectors considered, economic capabilities, tool accessibility (e.g., cost), existing user base, type of tool, future support, and previous studies. Among the final five selected tools, EnergyPLAN fulfilled all the abovementioned criteria and included all energy sectors such as the power sector, industry, and transport, with different fuel types and electricity. In terms of economic capabilities, EnergyPLAN is capable of economic analysis for the entire simulated 100% RES with the selected sectors. In terms of tool accessibility, EnergyPLAN is free tool and available to anyone from Aalborg University at no costs. In terms of previous studies, EnergyPLAN tool has enormous number of high-quality papers in reputable journals. The EnergyPLAN tool has been used in research and papers from more than 30 countries, including governments and researchers, with excellent support from Professor Henrik Lund and the EnergyPLAN team in Alborg, as well as documents and training courses.

Based on these review results, and for the objective of this research and required criteria, EnergyPLAN stood out for several reasons: It successfully balances technical accuracy with economic considerations, enabling a nuanced evaluation of various RES scenarios. It supports long-term planning for 100% RES systems, a critical aspect for Saudi Arabia's 2050 targets. Its focus on operational optimization of energy systems allows for a more realistic assessment of grid stability and sectoral integration. EnergyPLAN, which can meet these modelling requirements, has been chosen for this work.

In addition to the earlier mentioned reasons, EnergyPLAN was specifically chosen for this research because of its ability to align with the overall research goals, facilitating the technical and economic evaluation of different RES scenarios to determine the optimal energy configuration for Saudi Arabia by 2050, provide a system-wide perspective, capturing the interactions between different energy sectors and supporting the development of holistic policy recommendations. EenrgyPLAN also allow for a detailed analysis of 100% RES solutions, identifying challenges and opportunities for RES integration across the Saudi energy system, and serve as a bridge between the quantitative dataset collected in Step 1 and the modelling approach established in Step 2, ensuring that the scenarios are both data driven and reflective of real-world conditions.

EnergyPLAN is an energy modelling tool developed by the Department of Development and Planning at Aalborg University to aid in scenario and investment analysis. EnergyPLAN uses a bottom-up method to perform hourly simulations for a horizon of one year. Typically, it is utilised to simulate, plan, and design energy strategies on regional and national scale for energy systems, including all electricity generation technologies and demand sectors. EnergyPLAN allows for the simulation of electricity imports and exports and includes a vast array of technologies for the sectoral integration of energy systems. These characteristics facilitate the incorporation of greater proportions of variable renewable energy into energy systems. The simulations can be evaluated based on technical and operational criteria such as excess electricity generated, total primary energy, or CO2 emissions, as well as economic criteria including investment costs, operation and maintenance costs, fuel costs, carbon, and taxes. EnergyPLAN is deterministic inputs/outputs simulation model.

In contrast to linear optimization, dynamic programming, and stochastic programming, the calculation is based on analytical programming. It focuses more on operational optimization of a group of given energy units unlike the other models that optimise investment in the system. It focuses more on operational optimization of a given group of energy units rather than other models that optimise system investment. The hourly display of results and the hourly variation of demand and production are among the benefits of the analysis for the integration of RES, as the fluctuation of RES and demand must be accounted for in the hourly domain. Otherwise, results may lead in the wrong direction due to the exclusion of hourly balancing problems, which would be more significant for a high level of RES integration if hours are aggregated.

Another essential advantage of this tool that it can facilitate the design of 100% RES. The concept of 100% RES has undergone tremendous increase among researchers in the last decade. EnergyPLAN have been widely used among researcher whether for a national or local scale, focusing on system or holistic focus on the energy system and the synergies between different sectors. Another key advantage of EnergyPLAN is that significant research has been conducted on various energy subjects using this tool. Subjects include but not limited to:

1. 100% RES plan for several countries and towns [158 – 164]
2. The integration of high share of RES with a single technology or more [165 – 170]

3. Energy storage technologies to assist the integration of RES [171-177]
4. Hydrogen power plants [184]
5. Transport solutions including electrification, V2G and synthetic fuels [178-182].

3.2.4.2 SAM Selection Methodology

Within the research framework of this study, EnergyPLAN was identified as the primary energy mode simulation tool. However, its dependence on predefined hourly distribution files for RES technologies introduced certain limitations. These constraints necessitated the integration of an additional tool to enhance flexibility and precision. Despite EnergyPLAN's strengths, it does not allow for the detailed specification and customization of RES, a critical factor for this study focused on Saudi Arabia. In regions like Europe or the UK, extensive localized data for RES resources are readily available. In contrast, Saudi Arabia's renewable datasets are more limited, creating a gap that required a more systematic approach to accurate energy system design. Thus, the inclusion of SAM, developed by the NREL, was essential to overcome these challenges and support a comprehensive analysis of 100% RES scenarios by 2050.

A core challenge in relying solely on EnergyPLAN is its need for predefined hourly behaviour data for technologies like solar PV and wind power, lacking the flexibility to design RES with specific parameters such as:

- Geographic and climatic conditions (e.g., panel location, local meteorological conditions)
- Technological specifications (e.g., panel type, inverter characteristics)
- System configurations (e.g., azimuth and tilt angles)

These factors are crucial for accurately modelling RES performance within the study's research framework. In Saudi Arabia, the lack of comprehensive datasets for RES technologies necessitated a systematic approach using SAM, which provides extensive localized data sets, including:

- Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), Global Horizontal Irradiance (GHI) for solar technologies.
- Detailed design specifications that account for site-specific meteorological conditions, critical to Saudi Arabia’s diverse climate.

SAM's capacity to simulate detailed hourly generation profiles aligns with the systematic approach adopted for this study, enabling a more accurate representation of Saudi Arabia's RES potential. In this research framework, SAM was employed to design the PV RES in Saudi Arabia, generating highly detailed hourly profiles that were subsequently utilized as primary inputs for EnergyPLAN simulations. This integrated approach enabled the study to:

- Accurately assess the technical potential of various RES configurations.
- Perform in-depth technical and economic analyses of each RES scenario.
- Address the core research objective: identifying the optimal RES configuration for 2050 from both technical and economic perspectives with recommendations and limitations.

By combining SAM's ability to generate precise localized data with EnergyPLAN's system-wide simulation and optimization capabilities, the research implements a structured and systematic modelling framework that aligns with its broader goals. This two-tool strategy not only addresses data limitations but also supports the generation of high-quality, validated energy scenarios, filling critical gaps in the existing literature on Saudi Arabia's RES potential.

SAM was specifically integrated into the research framework due to its strengths in addressing unique challenges related to Saudi Arabia's RES. The choice to incorporate SAM followed a systematic selection process based on the need to:

1. Generate localized meteorological data: Saudi Arabia's diverse climate requires high-precision meteorological data for accurate energy simulations. SAM provides the necessary data to evaluate the performance of solar and wind systems under realistic local conditions.
2. Design RES with high practicality: The ability to customize RES using detailed design parameters such as tilt angles, inverter types, and panel efficiency, ensures that the simulations reflect operational conditions, a critical requirement for credible results.
3. Provide accurate input for EnergyPLAN: SAM's detailed hourly output is essential for creating reliable scenarios in EnergyPLAN, ensuring that the simulations are grounded in real-world performance data.
4. Support comprehensive economic analysis: SAM's financial modelling capabilities provide insights into investment and operational costs, which are crucial for evaluating the economic feasibility of each scenario and ensuring the study's findings are relevant to policymakers and stakeholders.

The integration of SAM within the research framework is closely connected to the study's overarching aim of exploring 100% RES solutions for Saudi Arabia. Its inclusion plays an essential role in the systematic approach applied throughout the research. The modelling approach outlined in Step 2 emphasized the need for high-resolution, localized data for accurate scenario analysis. SAM was selected to fulfil this requirement, providing precise RES profiles essential for the study's technical simulations. SAM's simulations contribute directly to the scenario evaluation phase, where different RES configurations are compared based on their technical performance and economic feasibility.

By providing detailed insights into the localized performance of the RES technologies, SAM supports the study's goal of delivering evidence-based recommendations for policymakers on region-specific deployment strategies, investment considerations, and the long-term sustainability of 100% RES solutions. The incorporation of detailed design parameters and localized meteorological data not only strengthens the study's technical findings but also ensures that its contributions to knowledge are relevant and applicable, providing value to both academic discussions and policy formulation in RES transitions.

3.2.5 EnergyPLAN Algorithms for National Energy System Simulation

EnergyPLAN is a tool designed primarily for simulating national and regional energy systems, with a focus on integrating diverse energy sectors such as electricity, heating, cooling, and transport. The tool's algorithms are structured to handle complex, multi-sectoral energy systems while optimizing either technical performance or economic objectives. Below is a detailed breakdown of how EnergyPLAN's algorithm's function.

1. Input Data Handling

EnergyPLAN begins by handling comprehensive input data to accurately represent the energy system being modelled. This includes the installed capacities of renewable and conventional energy sources like solar PV, wind, natural gas, and coal. The hourly production profiles for renewables, capturing fluctuations in energy generation across 8,784 hours of a typical year. And the sector-specific energy demands, including electricity, heating, cooling, and transport, which are fed into the model to simulate realistic energy consumption patterns.

2. Energy Demand Matching

EnergyPLAN matches energy supply to demand on an hourly basis, focusing on balancing variable RES outputs with real-time consumption needs. For RES such as wind and solar, EnergyPLAN analyses how much of the hourly demand can be covered by renewables. It identifies periods of energy surpluses (excess generation) or deficits, allowing the simulation to assess the potential for energy storage and backup generation solutions.

3. Technical Simulation

The technical simulation component of EnergyPLAN consists of several sequential steps designed to optimize the integration of renewables and manage demand:

A. Step 1 - Utilizing RES and Waste Heat: Prioritizes the use of RES and any available waste heat to meet electricity and heating demands.

B. Step 2 - Optimizing Flexible Demands: Adjusts flexible demands, such as charging electric vehicles, to periods of high renewable generation, enhancing grid stability.

C. Step 3 - Heat Production Management: Calculates heating needs and allocates resources from CHP systems, boilers, or heat pumps.

D. Step 4 - Energy Storage Optimization: Simulates the operation of energy storage solutions, including batteries, pumped hydro, Vehicle-to-Grid (V2G) systems, and thermal storage.

E. Step 5 - Balancing CHP, Hydrogen Electrolysers, and Storage: Sequentially manages CHP units, hydrogen electrolysis, and energy storage technologies to maintain supply-demand balance.

F. Step 6 - Summary of System Performance: Concludes with a summary of key metrics, such as electricity generation, energy surpluses, imports, exports, CO2 emissions, and primary energy use.

4. Economic Simulation

EnergyPLAN also includes an economic simulation module that can be activated to evaluate the financial implications of different energy scenarios: Cost Analysis which estimates operational costs, including fuel expenses and maintenance, under various configurations. Market simulation which models power plant operations within an electricity market, considering energy prices, fuel volatility, and competition. Investment Assessment which Calculates investment costs, payback periods, and potential profits, offering insights into the long-term economic viability of each scenario.

The EnergyPLAN algorithms provide a robust framework for evaluating complex energy systems. By integrating technical and economic considerations, the tool facilitates comprehensive national or regional energy planning, particularly in scenarios aiming for high shares of RES.

3.2.6 SAM's Algorithms for Detailed RES Design

SAM, developed by NREL, is a comprehensive tool designed to simulate the performance and financial feasibility of individual RES. It offers a user-driven workflow that takes the user from data input to detailed simulation results, supporting the broader system analyses conducted in EnergyPLAN. SAM algorithms when interacting with a new project are shown in the following steps.

1. SAM and Initial Setup

Upon opening SAM, the user selects the specific type of RES technology they wish to analyse—such as PV, wind, or CSP. The user also selects the analysis type, such as technical performance, economic analysis, or scenario evaluation. SAM prompts the user to choose between a range of project configurations (e.g., utility-scale PV farm, rooftop PV installation, or wind farm), each offering different parameters and design inputs. The user inputs the location coordinates, which allows SAM to retrieve localized climate data from a built-in database of meteorological datasets. This ensures that the simulation is based on realistic and location-specific environmental conditions.

2. Data Input and System Configuration

In the next step, SAM requires detailed user input to define the system's technical specifications. This includes selecting the specific components, adjusting parameters, and setting financial assumptions. First, defining system components, the user specifies details such as panel types, inverter models, turbine types, hub heights, and storage options. This step allows the user to define how the system will operate under the given conditions. Second, meteorological inputs, SAM uses the localized weather data including solar irradiance (DNI, DHI, GHI), wind speed, temperature, and humidity profiles to simulate how the system will perform over an annual cycle. Third, design adjustments, the users can manipulate system characteristics like orientation, tilt angle, tracking mechanisms, and string configurations to optimize system performance. SAM visually displays these settings, providing instant feedback on potential impacts.

3. Simulation Execution and Data Processing

Once the user has configured the system, SAM proceeds to simulate its performance. This process is entirely automated, relying on complex algorithms to manage the interactions between system parameters and environmental conditions:

- Balancing Energy Flows: SAM calculates energy flows on an hourly basis, considering the impacts of shading, temperature fluctuations, inverter efficiency, and other losses. It balances the energy input from renewable sources with storage requirements, ensuring optimal system performance.
- Validation of Inputs: During the simulation, SAM checks the consistency of input data against typical operational conditions, flagging any issues that could affect accuracy (e.g., unrealistic system parameters or incorrect climatic data).
- Hourly Simulation: The core of SAM's workflow involves generating an hourly output file for the entire simulation year, capturing fluctuations in energy production due to changing meteorological conditions. This data is critical for feeding into system-wide models like EnergyPLAN, where accurate RES profiles are necessary for high-resolution simulations.

4. Result Analysis and Output Interpretation

After conducting the simulation, SAM presents the results through a variety of graphical and numerical outputs, allowing the user to interpret system performance and economic viability which includes, the energy generation summary. It provides detailed breakdowns of energy production by source (solar, wind, etc.), including efficiency metrics, capacity factors, and expected annual yields. This helps assess the viability of different system configurations. It also includes financial outputs. The tool calculates financial metrics like net present value (NPV), and internal rate of return (IRR), based on user-defined financial assumptions. And finally, the results include scenario comparisons which allow the user to run multiple simulations with varying configurations to compare outcomes, providing insights into the best system designs for specific conditions.

3.2.7 Integration of EnergyPLAN and SAM for Synergistic Energy System Analysis

When combined, SAM and EnergyPLAN leverage their unique strengths to offer a more comprehensive simulation of RES in a national or regional context. The methodology of the cooperation is as follows:

1. One of the key strengths of SAM is its ability to generate highly detailed, hourly performance data for RES technologies (e.g., a solar PV farm or wind turbines) based on meteorological data and system specifications. This data can be exported as an hourly distribution file, a format required by EnergyPLAN for its simulations. For instance, SAM can model the hourly power output of a solar PV farm in a specific location in Saudi Arabia for an entire year, accounting for irradiance, temperature, and system losses. In terms of wind and solar data in regions like Saudi Arabia, where hourly data for RES output is often unavailable, SAM becomes essential in generating these profiles. EnergyPLAN requires this data to simulate the operation of the entire energy system, including balancing electricity supply and demand.

2. Once SAM provides the hourly output profile for a technology (such as a PV or wind farm), EnergyPLAN can integrate that data into its broader system simulation. EnergyPLAN uses SAM's detailed generation profiles to model how the RES will interact with other sectors like power generation, transportation, demands and energy storage. EnergyPLAN can then simulate how the entire energy system behaves, accounting for energy storage, grid interactions, and the balancing of flexible and non-flexible demands over the year. It calculates energy flows, CO_2 emissions, primary energy use, and system costs based on these inputs.

3. SAM provides precise generation data, while EnergyPLAN focuses on integrating that data into a broader energy system. EnergyPLAN can then simulate grid stability, managing issues like surplus renewable energy or peak demand shortfalls, and propose solutions such as energy storage or CHP integration. For example, in a scenario where excess RES energy is generated (as modelled by SAM), EnergyPLAN can simulate how that energy might be stored (in batteries or other storage systems) or exported to the grid to avoid curtailment.

4. Together, SAM and EnergyPLAN provide a robust framework for both technical performance assessment and long-term energy system planning. SAM's technology-specific modelling provides a detailed understanding of how individual RES projects perform, while EnergyPLAN's system-wide optimization helps to assess the implications of integrating those projects into the national or regional energy mix. This cooperation is especially useful for countries like Saudi Arabia, where a transition to 100% RES requires detailed analysis of individual technologies (via SAM) and how they fit into a larger system

that balances electricity demand, fuel demands, and transportation demands (via EnergyPLAN).

3.2.8 Modelling Economic Analysis Method

Economic analysis is a keystone of this research, directly following the technical evaluation phase to assess the financial feasibility of different RES scenarios for Saudi Arabia's transition to a 100% RES by 2050. The economic analysis aims to determine the most cost-effective system configuration that can satisfy both technical and financial criteria, ensuring the reliability and sustainability of Saudi Arabia's future energy landscape.

In this research, the economic analysis was integrated alongside technical outputs within the broader simulation strategy, playing a pivotal role in evaluating different RES configurations. The primary objective of the economic analysis was to identify the lowest cost system that could meet the technical goal of ensuring a 100% RES supply for the entire Kingdom. This analysis took place only after confirming that each system configuration could maintain power supply stability for one full year without any energy shortages or reliance on power imports from neighbouring countries. Once the technical requirements were satisfied, the economic performance of each configuration was assessed to determine the most cost-efficient option. Below is a detailed breakdown of the economic analysis methodology, linked to the broader research context.

1. Evaluation Criteria and Process

The economic analysis begins once potential systems have passed rigorous technical evaluations. The systems that meet the technical requirements, demonstrating a stable and reliable power supply for a full year without energy deficits, are subsequently evaluated on their economic viability. The key criteria used in this evaluation include total investment costs, an assessment of the total upfront costs required to establish each RES configuration. Annual Investment Costs, the yearly financial commitment associated with each system, including any staged investments or upgrades. Operation and Maintenance (O&M) Costs, a breakdown of variable and fixed operational expenses needed to sustain each system over its lifetime. LCOE, this metric is calculated to standardize the total costs of each system over its operational lifespan, enabling direct comparisons of cost-effectiveness. The optimal system is defined as the configuration that not only passes the technical evaluation but also offers the lowest total annual costs and LCOE, highlighting its economic feasibility.

2. Economic Inputs and Simulation Process

Prior to the economic evaluation, several crucial inputs must be determined and incorporated into the simulation tools. This includes investment costs per MW/MWh. These include capital expenditures required for each technology in the RES configurations, such as the installation of solar PV panels, wind turbines, and battery storage systems. Investment cost estimates for 2050 were drawn from reliable sources, including Aalborg University's future forecasts and reports from leading international organizations such as IEA and IRENA. O&M Costs per MW/MWh, these are divided into fixed costs (constant irrespective of output) and variable costs. Accurate O&M data for 2050 were collected from internationally recognized studies and projections.

The lifespan of each technology, such as PV panels, wind turbines, and battery systems, was factored into the cost analysis. These lifetimes are crucial for understanding depreciation, replacement cycles, and long-term financial planning. And the financial assumptions: Key economic assumptions, such as the interest rate and discount rate, were established based on reliable forecasts and justified in detail in Chapter 5. These rates impact the cost calculation by determining how future costs are discounted to their present values.

Once these inputs are established, the economic simulation is performed using EnergyPLAN, which calculates metrics like annual investment costs, O&M costs, and total annual costs for each RES configuration.

3. Manual Calculation of LCOE

After the simulation, the LCOE is manually calculated using the simulation results generated by EnergyPLAN. The LCOE is a crucial economic indicator that represents the cost per megawatt-hour of electricity generated, accounting for both capital and operational expenses over the system's lifetime. This calculation provides a standardized comparison of different RES solutions, ensuring that the most economically efficient option is selected.

4. Source and Justification of Economic Data

The economic parameters used for this evaluation were carefully chosen based on an extensive review of existing literature, including peer reviewed studies by individual researchers, as well as large-scale research projects undertaken by universities and governmental bodies. Specifically, the parameters and methods for economic assessment were drawn from foundational studies in energy system economics, including those examining both conventional and RES (e.g., studies [184-188]). By leveraging this well-established body of research, the economic analysis in this thesis aligns with best practices in the field, ensuring that the results are both scientifically robust and relevant for large scale energy planning. This approach provides a comprehensive view of the economic sustainability of transitioning to 100% RES, allowing for a thorough comparison of both conventional and renewable energy systems over their full operational life cycle. The economic data sources are as follows:

- Investment and O&M Costs in 2050: Data were sourced from credible institutions like Aalborg University, and robust databases from organizations such as IEA and IRENA.
- Battery Storage Costs in 2050: These were specifically referenced from NREL studies, focusing on future trends in storage technology and cost declines.
- Financial Assumptions: interest rates and discount rates were carefully chosen based on economic conditions specific to Saudi Arabia, as well as broader historical trends in the energy sector. These projections were selected to align with the expected economic environment of Saudi Arabia by 2050, factoring in regional economic stability, investment trends, and future financial policies that may impact RES projects. In cases where precise data were not available, conservative estimates were applied, grounded in well-established research and validated by reliable international sources. Detailed justifications for these financial assumptions, tailored to Saudi Arabia's economic context, are provided in Chapter 5.

By grounding the economic inputs in robust sources, the research aims to present a credible and transparent assessment of each RES configuration's financial viability.

3.2.9 Summary of The Step-by-Step Overall Methodology of This Work

The overall methodology of this research is divided into steps, as shown in the earlier sections. Step 1 involved conducting a comprehensive review of the entire energy sector in Saudi Arabia. This review, coupled with the development of a comprehensive dataset, served as a crucial foundation for the research. A major challenge encountered was the limited availability of accurate and consistent data regarding various aspects of Saudi Arabia's energy system, which created significant obstacles in conducting a precise assessment of the existing framework. Without addressing these data gaps, there was a high risk of generating unreliable results in future energy scenario modelling. Therefore, it was essential to construct a rich, accurate, and comprehensive dataset that could reliably represent the Saudi energy system. Moreover, this review and the resulting dataset were pivotal because they provided the foundational input for the next phase of the research, which involved the development of the energy model for Saudi Arabia. This dataset formed the basis for all subsequent energy modelling and scenario analysis in this study, making it an essential component in ensuring the validity of the overall methodology.

Step 2 involved the quantitative computational modelling approach was employed to develop energy scenarios for Saudi Arabia This approach enables the development and analysis of future energy systems from technical, economic, and environmental perspectives, ultimately supporting informed future policy making. In this method, all the datasets from step 1 previously developed and collected for Saudi Arabia's energy system were integrated into a single energy model to develop a reference model for the year 2017, representing the actual energy system in Saudi Arabia during that year.

The reference year model serves two critical purposes. First, it allows for the validation of the model, ensuring that it accurately reflects real life system behaviour. This step is crucial for confirming the reliability of the model before it is used to project future scenarios. In addition, it provides a necessary foundation for developing future energy scenarios for the year 2050. Without a validated reference model, it would be impossible to generate realistic and reliable projections of future energy systems. By using the 2017 model as a benchmark, various growth trajectories and potential policy shifts such as energy price reforms, energy efficiency measures, and RES integration can be incorporated into the analysis for 2050. These future energy scenarios for Saudi Arabia can then be thoroughly simulated, assessed, and analysed from technical, economic, and environmental standpoints, aligning with the central objectives of this thesis. Through this comprehensive analysis, the study aims to offer insights that can inform long term energy planning and policy development in Saudi Arabia.

Step 3 in the overall methodology involves selecting the most suitable modelling tools to meet the specific requirements and goals of this research. After establishing the comprehensive review and dataset in step 1, and applying the energy modelling techniques in step 2, the selection of the appropriate tools became crucial. This step ensures that the chosen energy modelling tools align with the specific objectives of the study, allowing for the accurate simulation and analysis of Saudi Arabia's energy system, both for the reference year and future scenarios. The tools were carefully selected based on their ability to handle the complexities of the energy system and their relevance to the technical, economic, and environmental analysis required to fulfil the research objectives.

Step 4 in the methodology involves developing the reference year model for 2017, validating its accuracy, and performing a comprehensive performance analysis. Following validation, growth rate factors for key sectors are calculated to project trends up to 2050 with the future polices considered. These sectors include future population growth, electricity demand, fuel demands and supplies, and potential policy changes. Such policy shifts might involve energy price reforms, energy efficiency measures, the complete elimination of CO2 emissions, and the phasing out of fossil fuels. Once these growth factors are integrated, the 2050 model is constructed with various scenarios, allowing for a detailed analysis of potential future energy systems in Saudi Arabia. This step ensures that the model reflects realistic trajectories, providing a robust foundation for scenario-based analysis.

In Step 4, the 2050 model explored several 100% RES scenarios, utilizing PV systems, wind power, and battery storage as the primary systems, with green hydrogen combined cycle power plants serving as a backup solution to address the limitations of a 100% RES, as discussed in section 4.4.4. Each RES solution was individually evaluated, followed by an assessment of various hybrid systems, including combinations such as PV+Battery, PV+Wind, Wind+Battery, and more. The evaluation process followed a sequential approach, beginning with PV as a standalone system. The system was analysed to determine if it could meet two main goals: Goal 1: Ensuring 100% supply stability throughout the entire year, day and night, in 2050, without any energy shortages or the need for power imports. Goal 2: Assessing the economic viability of the system. If multiple systems satisfied the first goal, the second goal, economic efficiency, was used to determine the most cost-effective system. Starting with PV as the sole power supply for Saudi Arabia, the system was analysed for its ability to meet these goals, and its limitations were identified. This led to the second scenario of a PV+Battery system, which was simulated and assessed in the same manner. Following the analysis of limitations, the process continued with a solo wind system, and further hybrid configurations were evaluated sequentially until the most optimal system was identified, one that met both supply stability and cost effectiveness goals.

Step 5, Practical considerations were also incorporated. For example, although a Wind+Battery system was economically more favourable than the PV+Battery configuration on paper, it was deemed impractical in real world implementation due to land limitations in Saudi Arabia. The deployment of wind energy on a large scale in Saudi Arabia is hindered by the limited availability of land in regions with optimal wind resources. These high-potential wind locations are relatively limited within the Kingdom.

Step 6, The final optimal hybrid RES was identified and evaluated. To address potential limitations of the system in 2050, a green hydrogen power plant was incorporated as a backup, operating entirely on green hydrogen produced from surplus energy generated by the hybrid 100% RES. Additionally, surplus power was utilized for electrifying the passenger vehicle fleet in the transport sector. The results were thoroughly discussed and analysed, with recommendations for future work provided. The thesis concluded with an examination of the limitations of this research, as outlined in Chapters 4 and 5.

CHAPTER 4

Modelling Investigation: Baseline, Validation and Future Scenarios

4.0 Introduction, Model Inputs, Outputs, and Included Sectors.

The chapter employed the knowledge base and modelling methodology to establish and validate a baseline model for Saudi Arabia's energy system, while exploring various RES options. Individual technology options were evaluated, several combined scenarios examined, and the outcomes assessed. The key findings from the modelling investigation relevant to future policy for Saudi Arabia are summarised, with the future work that could further build on the modelling methods and investigation. This chapter comprises several sections; in the first section, 4.1, the baseline model is developed for 2017, and the results validated against real world data. This section is divided into three subsections, each corresponding to a step of the validation process. The first subsection (4.1.0) introduces the overall validation process. The second subsection validates the EnergyPLAN tool, while the third subsection validates the SAM program against actual data. The fourth subsection presents the combined hourly results of both programs, providing the final model's performance. After developing the model for the reference year 2017, it underwent validation with real-world data, as detailed in the following sections.

- Inputs of The Energy Model.

1. The entire hourly electricity consumption from all sectors in the Kingdom, including power plants, housing, commercial and public services, industry, desalination, etc. In addition, the annual total electricity consumption from all sectors in TWh. The electricity consumption can also be divided into electricity used for electrical cooling/electrical heating/heat pumps.
2. The fuel consumption of the power plants, industrial, transport, housing (i.e. for heating) sectors and other uses by fuel type. This includes coal, oil and oil products, natural gas, biomass, and hydrogen. In the transport sector, these fuel types must be further detailed and broken into motor gasoline, diesel, and jet fuel. Some of these fuel demands must be added into hourly form for the entire year.
3. Hourly electric air conditioning consumption for the entire year and COP.

4. The country's entire condensing power plants capacities, efficiencies, transmission lines capacity
5. All the considered RES power plants capacities and the hourly generation of each technology for the entire year.
6. The type of storage (battery storage in this case) with the charge capacity, discharge capacity, efficiencies, and the storage capacity.
7. Total grid stabilisation requirements such as minimum grid stabilisation share. In addition, critical excess electricity production (CEEP) required policies, including those required when the system has surplus power generation.
8. Hourly hydrogen demand, electrolysers capacities and efficiency, hydrogen storage capacities
9. Entire system costs unit. These are the investment costs per unit, lifetime per unit, fixed O&M costs per unit. Each cost must be considered for all the model components, including condensing power plants, RES power plants, and storage: fuel costs (local and market prices) and fuel handling costs.

- Outputs of the Energy Model.

1. Primary energy supply including all types of energy resources, such as electricity, and different fuels, such as gasoline, diesel, natural gas, and biomass.
2. CO_2 emissions per as total and per sector
3. Costs of the entire system's configurations including annual investment costs, interest, fixed and variable operation and maintenance costs, annual costs, trading costs, and taxes for the entire systems configurations.
4. Energy balance of the entire energy system, including demand and supply hour by hour for the entire year.

- Sectors Included in the 2050 Decarbonizing Solutions.

For 2050 future simulations, the solutions in this thesis focused on decarbonising the entire power from all sectors in the Kingdom (including backup power plant) and the passenger vehicle fleet in the transport sector, with an increased focus on the power sector. This implies that even if the power from sectors transition to RES and the entire passenger vehicle fleet is electrified, that CO_2 emissions would be eliminated. The Kingdom has other complex fuel consumptions from the industrial sector, desalination, agriculture, etc. In addition, CO_2 emissions from heavy, light-duty trucks and aeroplanes in the transport sector. The fuel consumption of the remaining sectors, particularly desalination, is beyond the scope of this thesis due to unavailable, unclear, or classified data. Additionally, the decarbonization of these sectors was not included in the scope due to time constraints, as it would require extensive analysis and would merit a separate study. Addressing these sectors will be a focus of future work.

4.1 Baseline and Validation

4.1.0 The Three-Step Validation Process

In this chapter, the validation process of the energy model follows a three-step approach. The purpose of this process is to assess the applicability of the model tools for simulating the Saudi Arabian energy system specifically. This model uses two combined tools to give the Kingdom's final energy model. The first tool is EnergyPLAN; therefore, EnergyPLAN was validated solely against actual data as the first step in the validation process. In the second step of the validation process, the second energy tool, SAM is validated against actual data. The third and last step is the generation of hourly results from both tools combined, showing the model's performance in different hourly data. In EnergyPLAN validation process, the primary energy supply, total fuel consumption, peak electricity generation, and CO_2 emissions are compared with real life data from reliable sources such as IEA to assure the applicability of EnergyPLAN for Saudi Arabia energy system modelling. Regarding the validation process of SAM, the tool has been extensively validated through numerous studies conducted across various countries, including Saudi Arabia. However, to assure the applicability of the tool to model the Saudi Arabia RES, the energy output from the PV power plant was compared between the simulated system and the actual on the ground system from IEA.

4.1.1 EnergyPLAN Validation

After gathering all necessary input data, the reference model was simulated for the year 2017. The initial phase of results and validation involved comparing the primary energy supply from the simulation outputs with actual data from the IEA, as presented in Table 3.

Table 3 Total fuel consumption by sector in 2019 in Saudi Arabia

Primary Energy Supply (TWh)			
IEA [189] (TWh)	EnergyPLAN Simulation (TWh)	Difference (TWh)	Difference (%)
2,792.5	2,788.04	4.46	0.1 %

As shown in Table 3, the difference in the primary energy supply between the EnergyPLAN simulations and IEA is 0.1%. The simulation results represented the primary energy supply correctly. The second part of EnergyPLAN validation is a fuel balance comparison (total energy supply by fuel source), as shown in Table 4.

Table 4 Comparison of total energy supply by fuel source in Saudi Arabia in 2017 and the EnergyPLAN simulation.

Total Fuel Consumption by Fuel Type (TWh)				
Fuel Type	IEA [189] (TWh)	EnergyPLAN (TWh)	Difference (TWh)	Difference (%)
Coal	0	0	0	0
Oil & Oil Products	1,885.20	1,878.63	6.57	0.3 %
Natural Gas	907.24	909.26	2.02	-0.2 %
Biomass	0.087	0.09	0	0 %
Nuclear	0	0	0	0%
PV	0.065	0.06	0	0 %

Table 4 presents a comparison of fuel consumption in the Kingdom by fuel type, based on IEA data and EnergyPLAN simulations. The total energy supply for oil and oil products shows a difference of 0.3%, while for natural gas, the difference is 0.2% relative to the actual IEA data, indicating that the simulation accurately represents fuel consumption. Notably, in 2017, the Kingdom’s primary energy supply was limited to oil and natural gas, with no coal usage and minimal biomass and RES contributions. The third stage of EnergyPLAN validation involves comparing peak power generation capacity, as outlined in Table 5.

Table 5 Electrical energy produced from power plants in Saudi Arabia with maximum generation capacity in 2017

The Maximum Electricity Generation Capacity (MW) in 2017				
	Actual [190]	EnergyPLAN	Difference (GW)	Difference (%)
Maximum Generation Capacity	62.1 GW	63.4 GW	1.3 GW	2 %

Table 5 shows the difference in the maximum generation capacity in the same year between the actual data from the Saudi General Authority of Statistics and EnergyPLAN simulations. The difference does not exceed 2% in the generation capacity. The percentage of 2% is the highest percentage difference among all the validation parts. The simulation results correctly represented the maximum generation capacity. Notably, this is the electrical energy produced from all conventional power plants, including standalone and cogeneration plants, with negligible energy produced from solar PV. No CHP or any renewable source production other than solar, such as wind, geothermal, etc., in the reference year. The last step of the EnergyPLAN model validation is the comparison of the total CO2 emissions between the actual reference and EnergyPLAN simulation. The CO2 emissions generated from EnergyPLAN are different from the values in the actual reference, as shown in Table 6.

Table 6 CO2 emissions comparison between the actual data and EnergyPLAN simulations with non-energy use.

Carbon Dioxide Emissions (Mt)			
Actual (Mt) [191]	EnergyPLAN (Mt)	Difference (Mt)	Difference (%)
521.3	670.6	149.3	22 %

The substantial difference in CO2 emissions from EnergyPLAN compared to the actual reference is because of the demand for non-energy use. In the primary energy supply, one of the demand sectors is the non-energy use demand, which covers the fuels that are used as raw materials in the different sectors (such as the chemical and petrochemical industry) and are not consumed as a fuel or transformed into another fuel (not combusted). Between IEA and EnergyPLAN, the primary energy supply, which also contains the non-energy use, is correct, as shown in Table 3. However, when calculating the CO2 emissions, IEA did not include the non-energy use since it is not combusted demand. At the same time, EnergyPLAN assumes that all the fuels in the model are 100% combusted. Thus, it also generated CO2 emissions from the demand for non-energy use. This is one notable limitation of EnergyPLAN is its lack of functionality to selectively determine which fuels are utilized for combustion and which are excluded. To validate CO2 emissions from EnergyPLAN against the actual reference values, it was necessary to temporarily exclude non energy use demand. This adjustment involved removing 540.5 TWh of oil products and 59.85 TWh of natural gas, representing the total non-energy use demand, from the overall energy demand. The revised CO2 emissions results are presented in Table 7

Table 7 CO2 emissions comparison between the actual data and EnergyPLAN's simulations without non-energy use.

Carbon Dioxide Emissions (Mt)			
Actual (Mt) [192]	EnergyPLAN (Mt)	Difference (Mt)	Difference (%)
521.3	518.4	2.9	0.5 %

Table 7 shows the new value of CO2 emissions compared to the actual reference after removing the non-energy use demand. The difference between the results does not exceed 0.5 % indicating correct results and that EnergyPLAN can accurately simulate Saudi Arabia's energy system.

4.1.2 SAM Validation

SAM serves as an additional tool used alongside EnergyPLAN to generate results that EnergyPLAN alone cannot provide, as shown in the following hourly results. SAM has undergone extensive validation in numerous studies within Saudi Arabia, particularly for small-scale PV and wind projects, as evidenced in studies [193], [194], [195], and [196]. This paper also validates SAM by simulating a PV system with a design capacity matching Saudi Arabia's 2017 installed PV capacity of 34 MW, as reported in IRENA's 'Renewable Capacity Statistics 2023' [197]. This PV system, designed and simulated in SAM in 2017, is detailed in Table 8, while the assumed design specifications are outlined in Table 9. Specifications for the PV module and inverter are provided in Table 10

Table 8 Weather conditions and location details of the PV system in 2017

Location	
Country	Saudi Arabia
Latitude, Longitude	26.29, 50.02 Degrees
Elevation	4 Meters
Annual Averages in 2017	
Global Horizontal	5.70 kWh/m^2/day
Direct Normal (beam)	4.74 kWh/m^2/day
Diffuse Horizontal	2.44 kWh/m^2/day
Average Temperature	27.8 °C (standard deviation 6°C)
Average Wind Speed	3.5 m/s (standard deviation 1 m/s)

Table 9 PV system overview with the assumed parameters.

PV System Overview							
PV Peak Power (MW)	Tilt (Degree)	Azimuth (Degree)	Axis Type	Total Modules Number	Modules Per String in Subarray	Strings in Parallel in Subarray	Number of Inverters
34	30	180	Fixed	68,000	20	3,400	16

Table 10 PV module and inverter specifications.

PV Module Specifications	
Name	Miasole FLEX-03 500W
Nominal Efficiency	16.7 %
Maximum Power DC	501.072 Wdc
Maximum Power Voltage	62.4 Vdc
Maximum Power Current	8 Adc
Open Circuit Voltage	77.2 Vdc
Short Circuit Voltage	9.1 Vdc
Inverter Specifications	
Name	Schneider Electric Solar Inverters USA – Inc: CS2200-NA [600V]
Maximum MPPT DC Voltage	1200 Vdc
Minimum MPPT DC Voltage	906 Vdc
Maximum DC Voltage	1200 Vdc
Maximum DC Current	2147.75 Adc
Maximum AC Power	2,200,000 Wac
Maximum DC Power	2,263,730 Wdc

SAM's simulation results indicated a total energy output of 60,074,492 kWh (0.06 TWh) from the PV power plant in 2017, aligning precisely with the total PV generated energy for Saudi Arabia in 2017, as reported by the IEA in their 'Balances Table' at 0.06 TWh [198]. This alignment demonstrates SAM's capability to accurately design and simulate renewable energy systems in Saudi Arabia, even for past years.

4.1.3 Hourly Results

The third step of the validation process involves analysing the hourly results generated through the integration of EnergyPLAN and SAM, which collectively demonstrate the model's overall performance. Certain results could not be produced using EnergyPLAN alone, while others required EnergyPLAN to be included, as illustrated in the following graphs.

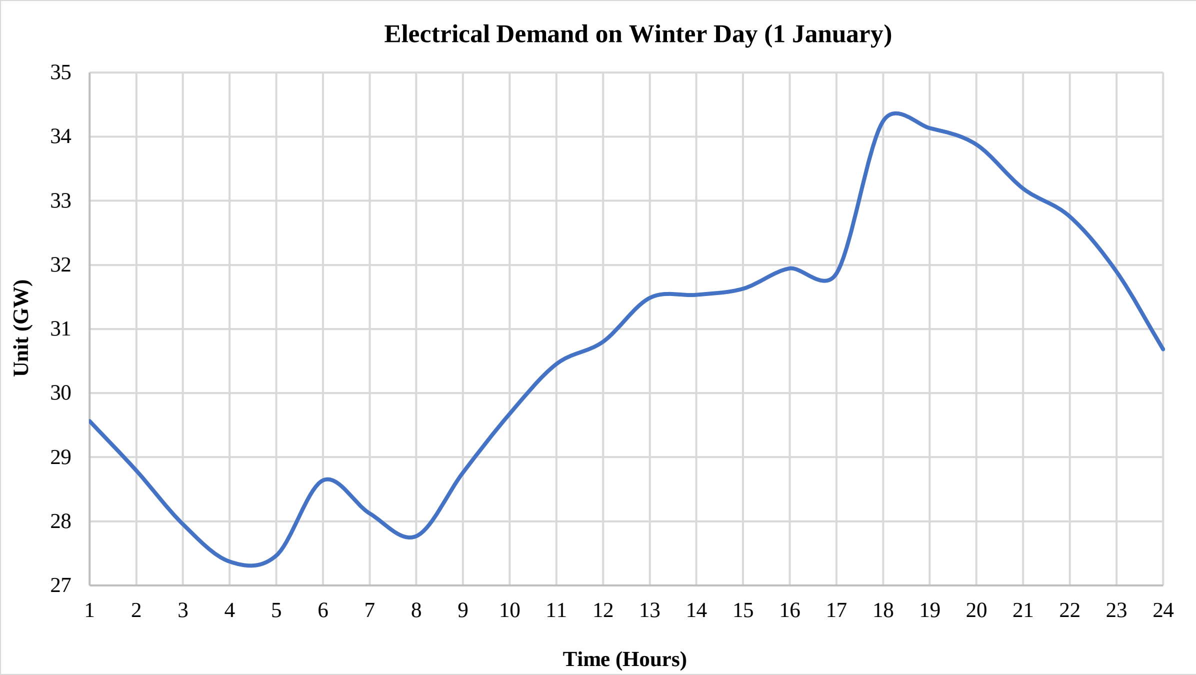

Figure 24 Electrical demand on winter day [Author: constructed from simulations]

Figure 24 shows the total electrical demand of the Kingdom on a winter day on 1/1/2017. The demand increased from 4:30 AM to 6:00 AM to 28.6 GW with a small down peak until 8:00 AM. From 8:00 AM, the demand increases steadily throughout the day up to 18:00, with the highest peak occurring at 34.4 GW. Next, the total electrical demand on summer days on 1/7/2017 is shown in Figure 25.

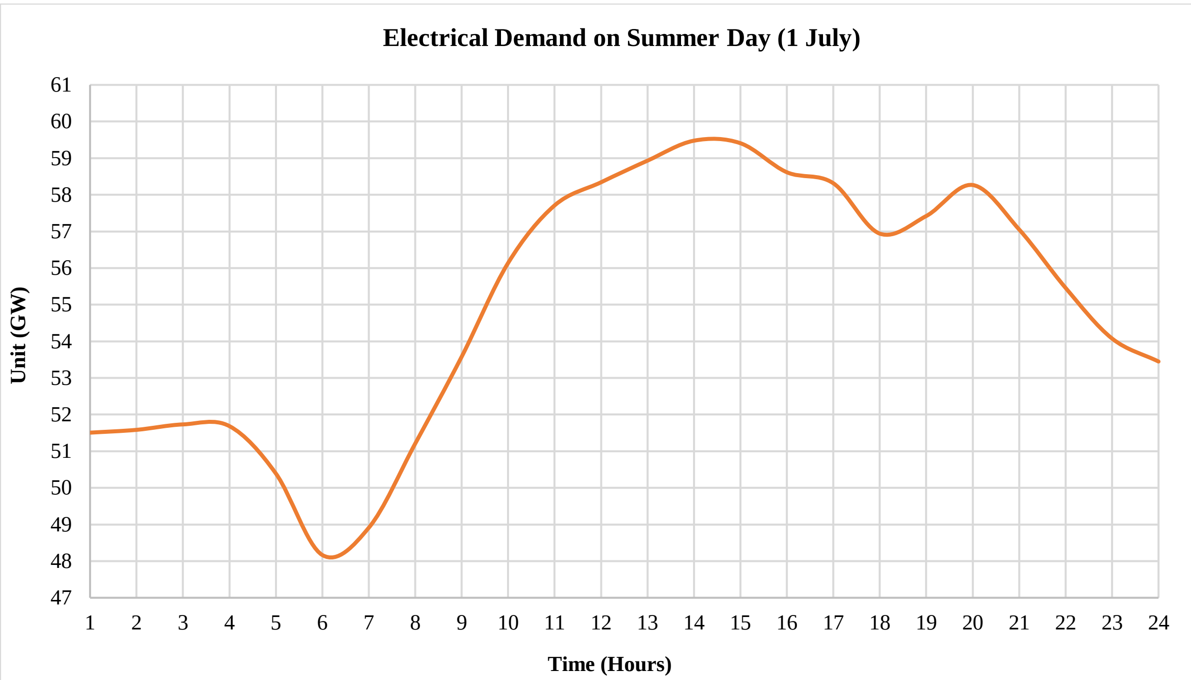

Figure 25 Electrical demand in summer day [Author: constructed from simulations]

Figure 25 illustrates a steady increase in electrical demand from 6:00 AM, reaching its peak at 59.5 GW by 2:30 PM. Compared to winter, summer demand shows notably higher peaks, with the lowest summer peak at 48 GW versus 27.5 GW in winter. The highest winter peak is recorded at 34.2 GW, while in summer, the peak rises to 59.5 GW which indicates a 42% increase, primarily driven by the increased use of air conditioning during extremely high summer temperatures.

Figure 26 illustrates the relationship between the Kingdom's total electrical demand and ambient temperature by presenting hourly temperature variations across different regions alongside electrical demand for a typical summer day. The inclusion of regional temperatures highlights the Kingdom's extensive geographic diversity, spanning five distinct regions (or six, if the Empty Quarter is included), each characterized by unique climatic conditions. Figure 26 shows a strong correlation between ambient temperatures and electrical demand on this summer day: both temperature and demand rise steadily from 6:00 AM, peaking between 2:00 PM and 2:30 PM, before declining for the remainder of the day. Notably, the western region registers the highest temperatures, while other regions show comparable temperature ranges, except for the northern region, which remains the coolest in the Kingdom.

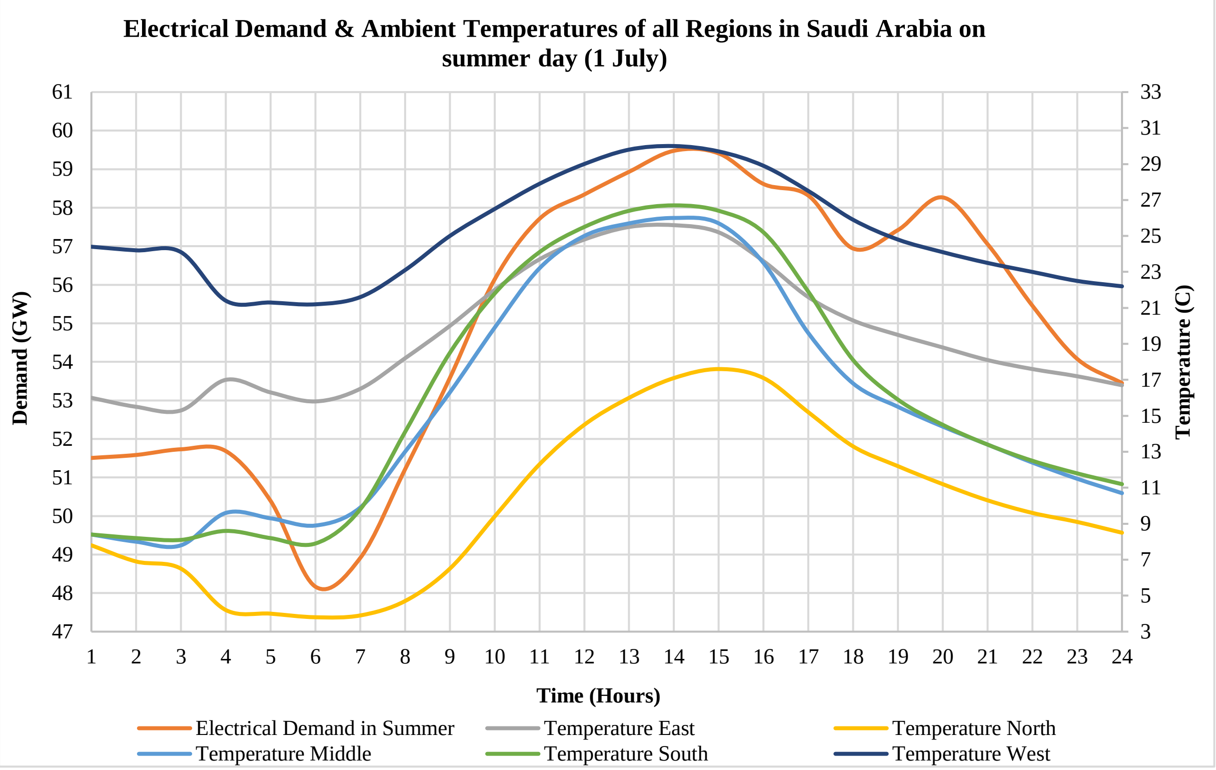

Figure 26 Electrical demand with ambient temperatures of different regions in Saudi Arabia on a summer day [Author: constructed from simulations

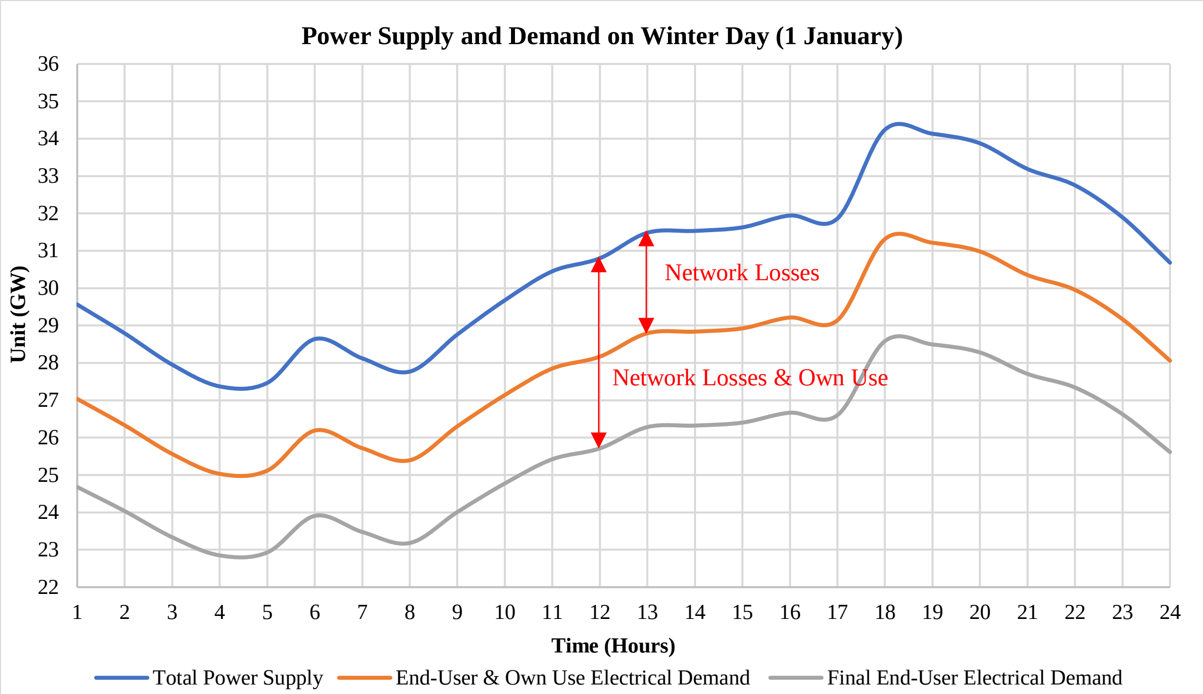

Figure 27 Power supply & demand in one winter day [Author: constructed from simulations]

Figure 27 shows the total power supplied by all power stations in the Kingdom with the final electrical demand to the end user. The end use is the different consumption sectors of industry, residential, commercial, public services, agriculture/forestry, and non-specified. In the same Figure, the electricity demand is divided into two demands. The first is the total demand of the end-user in addition to the own use of electricity, and the second demand is the final end-user electricity consumption of all sectors in the Kingdom. The definition of the own use covers *the amount of electricity used for energy-producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and distribution. It includes the energy consumed by energy industries for heating, pumping, traction, and lighting purposes* [199].

In Figure 28 below, the same results are illustrated but for a summer day in the Kingdom, illustrating the total power supply compared to the electricity demand from end-user and own use while showing the network losses. In Figure 29, hourly natural gas consumption by sector is shown. The majority of natural gas consumption is attributed to conventional power plants for electricity generation, followed by the industrial sector, non-energy uses, and own use. Total natural gas demand reaches its highest levels during the summer months, peaking at approximately 132 GW, while winter months see the lowest demand, with a peak around 92 GW. This is because natural gas consumption in power stations is directly correlated with electricity production, which in turn is influenced by electricity demand, itself closely tied to weather conditions, as demonstrated in the following graphs. In the same graph, the industry, non-energy use and own use consumptions are assumed to be constant throughout the year since no hourly information is available.

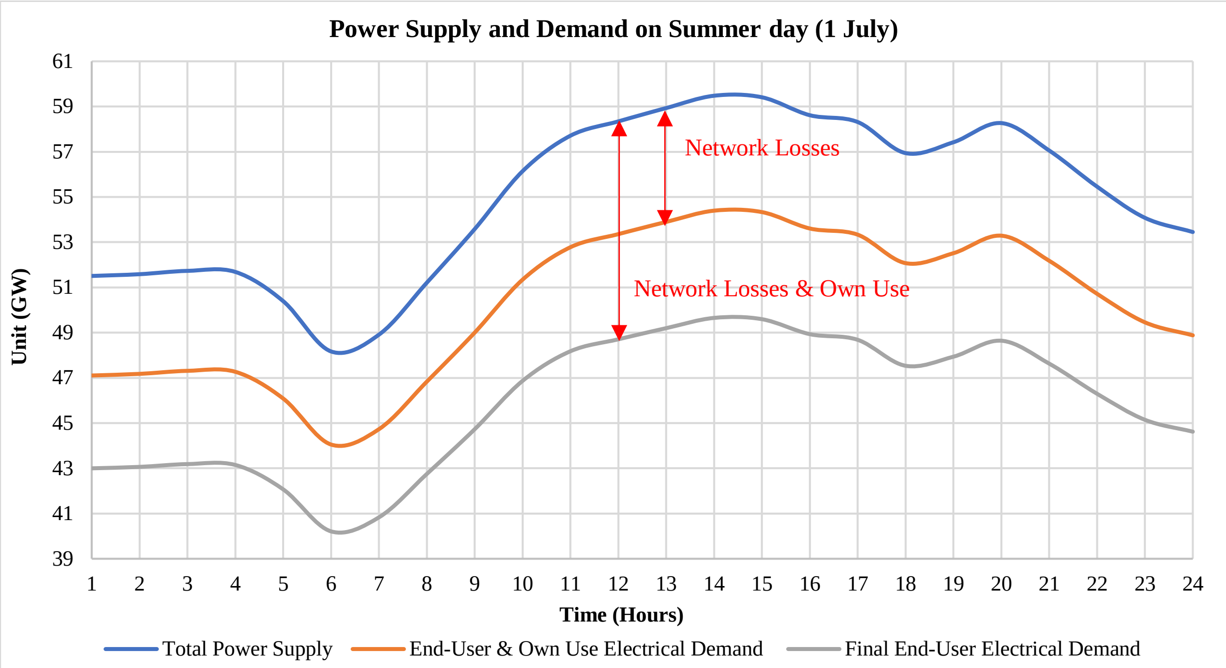

Figure 28 Power supply & demand in one summer day [Author: constructed from simulations]

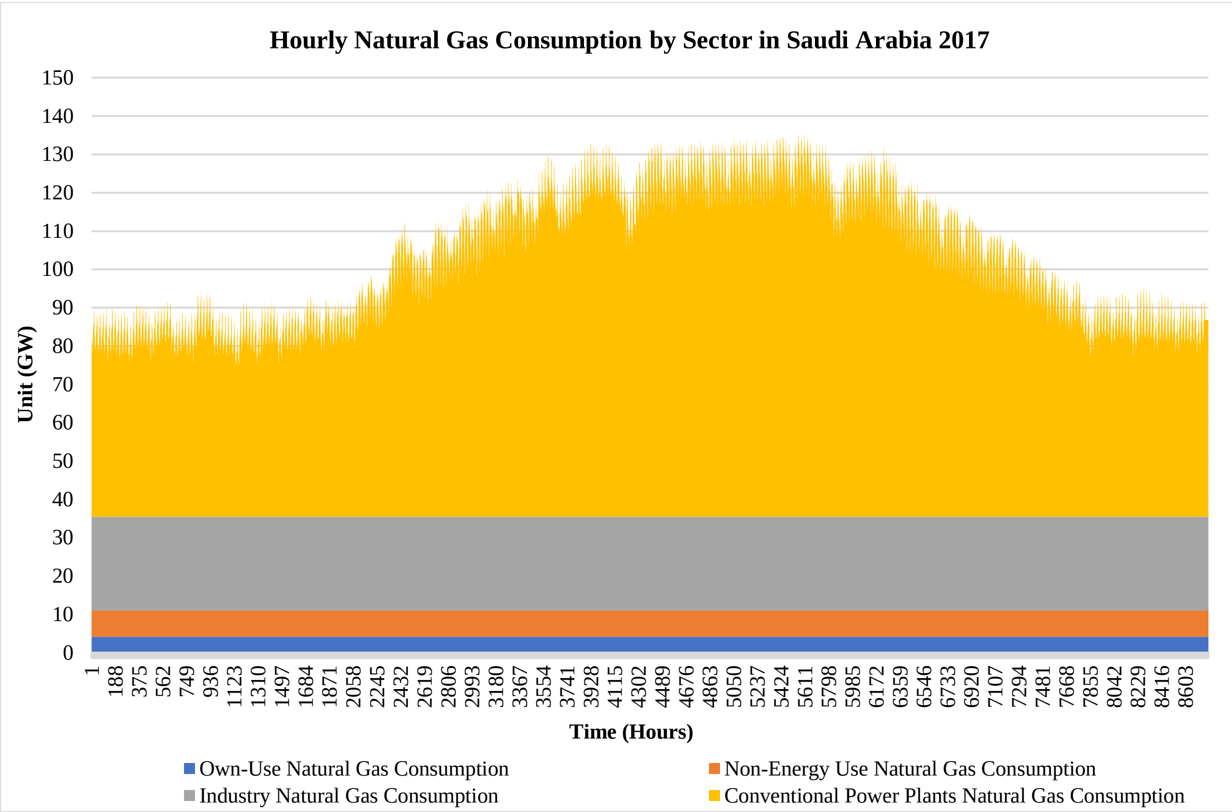

Figure 29 Hourly natural gas consumption by sector in Saudi Arabia in 2017[Author: constructed from simulations]

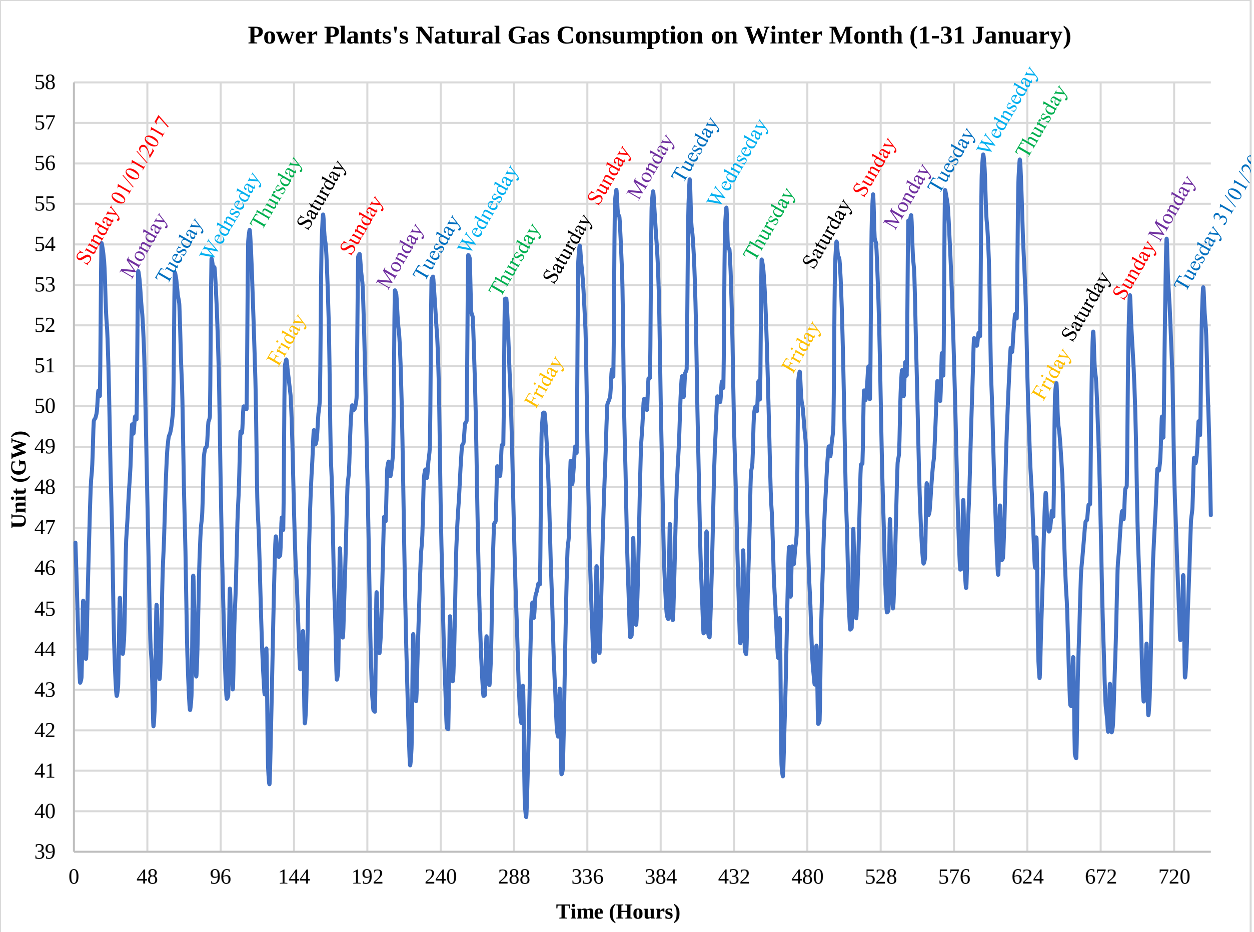

Figure 30 Power plants' natural gas consumption on winter month (1-31 January) [Author: constructed from simulations]

Figure 30 displays the gas consumption of all conventional power plants across the Kingdom during a winter month (January 1st to 30th). Gas consumption at these plants is directly proportional to the Kingdom's electrical demand, which fluctuates throughout the month. As shown in the Figure, the first day of the month is a Sunday, and the last day is a Tuesday. During this period, gas consumption peaks at an average of 52 GW to 56 GW on most days, with the lowest consumption levels observed on Fridays, ranging between 41 GW and 46 GW. This lower consumption on Fridays reflects the Kingdom's weekend schedule, which spans Friday and Saturday, with Friday marking the start of the weekend.

Fridays exhibit a unique energy consumption pattern influenced by two main factors. Firstly, a significant portion of the population spends the day outside their homes. Coastal city residents often visit the seaside for extended periods, while individuals in other regions typically spend their time in malls or exploring desert areas or camping. As a result, residential electricity demand significantly declines. Second, most commercial and public services are closed on Fridays, including the entire government sector, further reducing energy consumption. On Saturdays, consumption is higher than on Fridays but remains lower than on typical workdays, as people stay home in preparation for the upcoming workweek, and more commercial and public services operate compared to Friday.

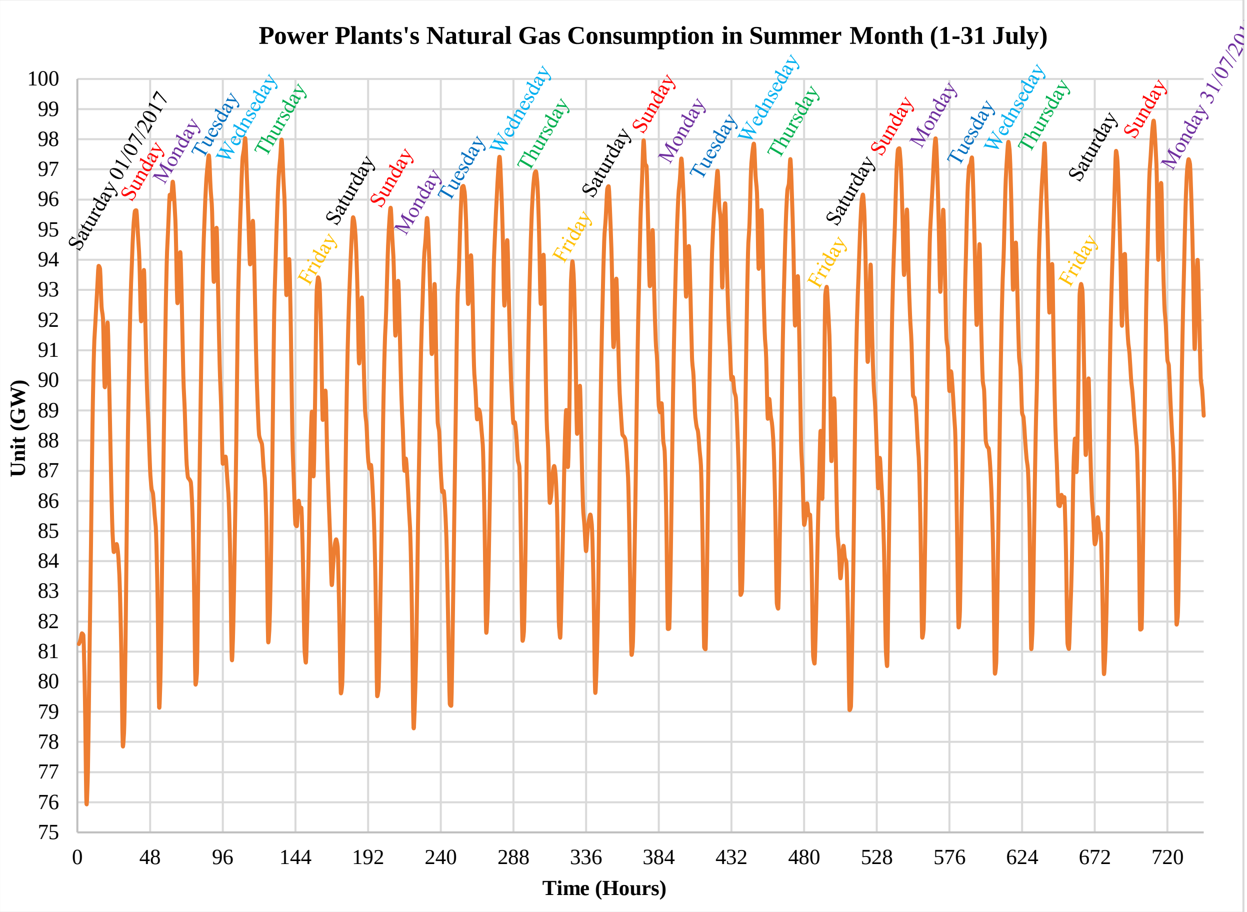

Figure 31 Power plants' natural gas consumption on summer month (1-31 July) [Author: constructed from simulations]

In summer, as shown in Figure 31, a similar pattern of gas consumption in power plants is observed, with higher consumption levels attributed to the increased use of air conditioning during the hot months. Daily consumption peaks typically range between 95 GW and 98 GW on average, except on Fridays, when the consumption is lower. The lowest points of consumption are in the range of 76 GW to 83 GW. Comparing this to winter, it can be noted that power plants' natural gas consumption is increased by around 42.5 % if the first day of each month is compared. This is primarily because of the significantly higher electricity demand due to the extensive use of air conditioning in the hot summer. Notably, a similar weekend consumption pattern is observed during the summer months. Energy demand is lowest on Fridays, with a slight increase on Saturdays. However, Saturday's consumption remains lower than that of regular working days, reflecting the same behavioural trends identified during the winter season.

In 2017, Saudi Arabia's PV capacity was only 32 MW, contributing a mere 0.06 TWh to the nation's total electricity generation. This minimal output is deemed negligible and inadequate for effectively demonstrating the model's functionality. To explore the relationship between RES and other parameters, such as the electrical supply from power stations, a 30 GW PV installation was incorporated into the model for simulation. This 30 GW power plant was positioned at the same location as the existing 32 MW PV facility in eastern Saudi Arabia, utilizing identical panels and inverters with the specifications outlined in Table 10. The configuration included an azimuth of 180 degrees and a tilt angle of 30 degrees, consistent with the original 32 MW installation. The results of this simulation are presented in Figure 32.

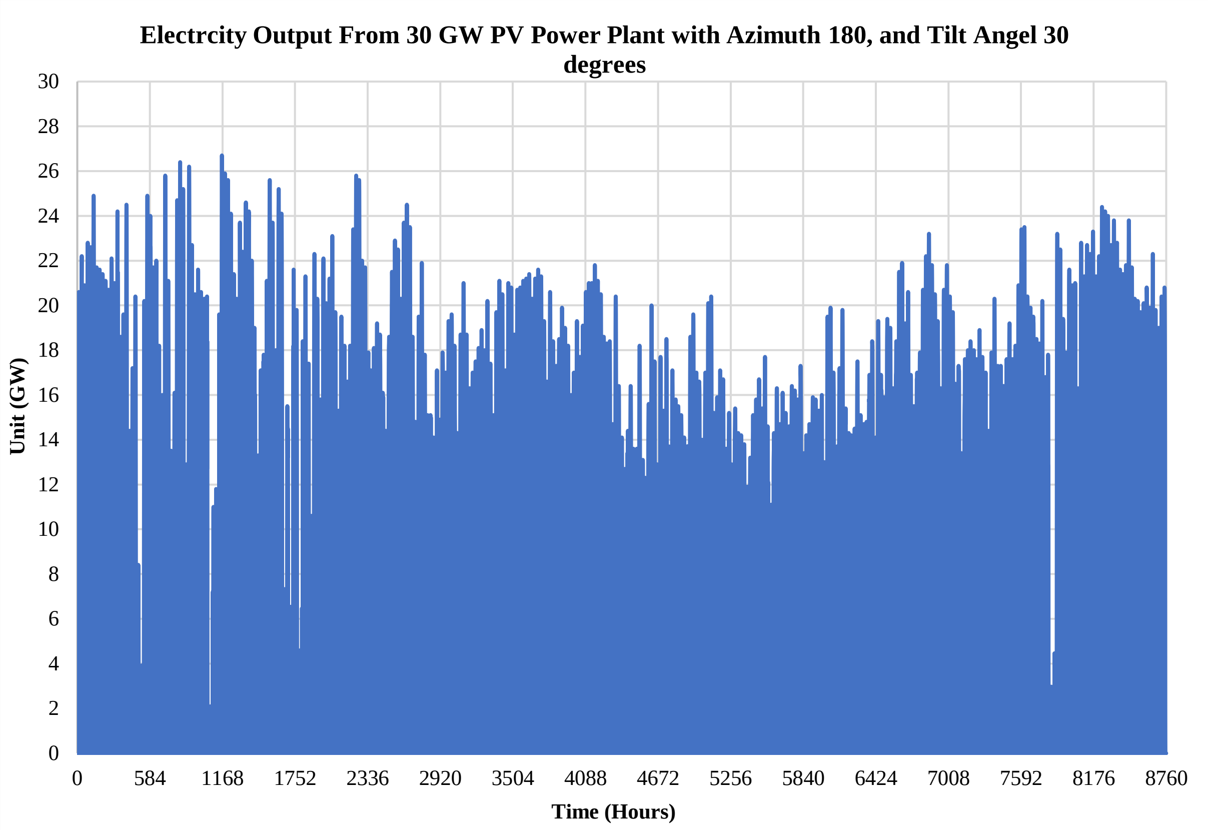

Figure 32 Electricity output from 30 GW PV power plant in Saudi Arabia in 2017, [Author: constructed from simulations]

Figure 32 shows the electricity output from the 30 GW PV power plant located in eastern Saudi Arabia at coordinates 26.29°N, 50.02°E, and 4 meters above sea level. The output shows higher peaks during winter months, reaching up to 26 GW, but with more frequent days of lower production. In contrast, summer months show fewer output peaks, with no significant gaps between days. This pattern highlights the influence of seasonal weather variations: in winter, sunlight is intermittently unavailable, resulting in visible gaps in the output graph. However, when sunlight is present, cooler temperatures enhance PV efficiency, producing higher electricity peaks. Conversely, in summer, sunlight is consistently available daily, though the warmer temperatures slightly reduce PV panel efficiency, leading to lower peaks in electricity production. A summary of key parameters for the PV power plant is provided in Table 11.

Table 11 30 GW PV Power Plant Summary

PV Power Plant Parameters Summary	
DC Capacity Factor in The Year	18.4 %
Energy Yield in the Year	1,616 kWh/kW
Performance Ratio in the Year	0.72

The performance ratio is the final yield divided by the reference yield. It accounts for the total losses in the system by converting from the nameplate DC rating to AC output. The capacity factor (CF) is defined as the actual annual AC energy to theoretical maximum energy that would have been generated if the PV system were operated at full rated power for 24 hours in a given day for an entire year [200].

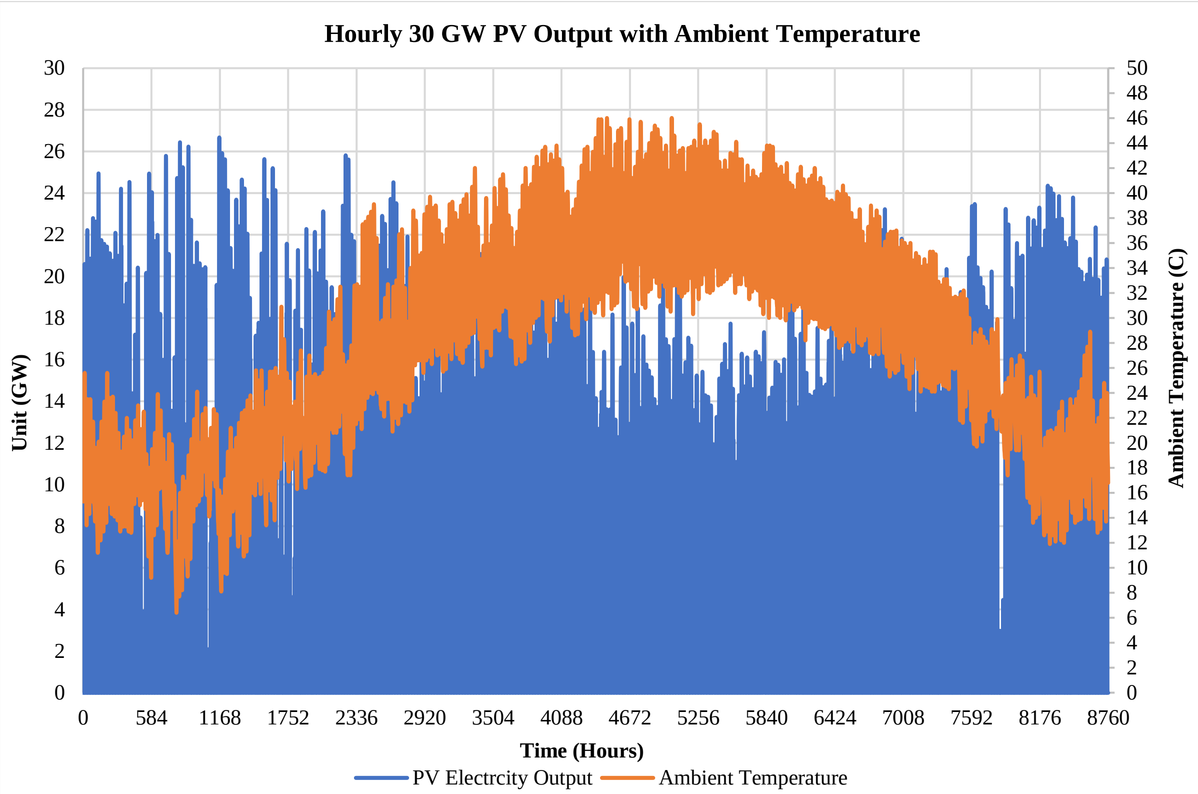

Figure 33 30 GW PV power plant with ambient temperature in Saudi Arabia [Author: constructed from simulations].

Figure 33 illustrates the relationship between the electricity output of the PV power plant and the ambient temperature for that year and location in Saudi Arabia. During winter, with temperatures ranging from 14°C to 26°C, PV output reaches its maximum production peaks.

In contrast, during the summer months, when temperatures range between 26°C and 46°C, approximately a 43% increase compared to winter, PV output peaks are lower, highlighting the significant impact of ambient temperature in Saudi Arabia. The power drop of PV panels with higher ambient temperatures is primarily due to the following technical reasons:

1. Voltage Temperature Coefficient: PV cells generate voltage based on the semiconductor properties of the materials used (typically silicon). As temperature increases, the semiconductor's energy bandgap narrows, which reduces the voltage output. This is quantified by the voltage temperature coefficient, generally around -2 mV/°C for silicon cells.

2. Increased Resistive Losses: The internal resistance of the PV cells and connections increases with temperature, leading to higher resistive losses (I^2R losses). This means more energy is lost as heat rather than being converted into electrical energy.

3. Reduced Efficiency of Charge Carriers: At elevated temperatures, the mobility of charge carriers (electrons and holes) decreases, which can reduce the efficiency of the photovoltaic process. This reduction in mobility leads to a lower current generation.

4. Temperature Effects on Cell Efficiency: The overall conversion efficiency of PV cells typically decreases as temperature rises, with efficiencies dropping by about 0.2% to 0.5% per °C increase in temperature for crystalline silicon panels.

5. Thermal Effects on Materials: Prolonged exposure to high temperatures can lead to thermal degradation of the materials used in PV cells, potentially resulting in increased defects and reduced lifespan, further impacting performance.

6. Impact on System Components: Higher temperatures can also affect the efficiency of inverters and other system components, which may further reduce the overall energy output of the PV system.

[201,202]

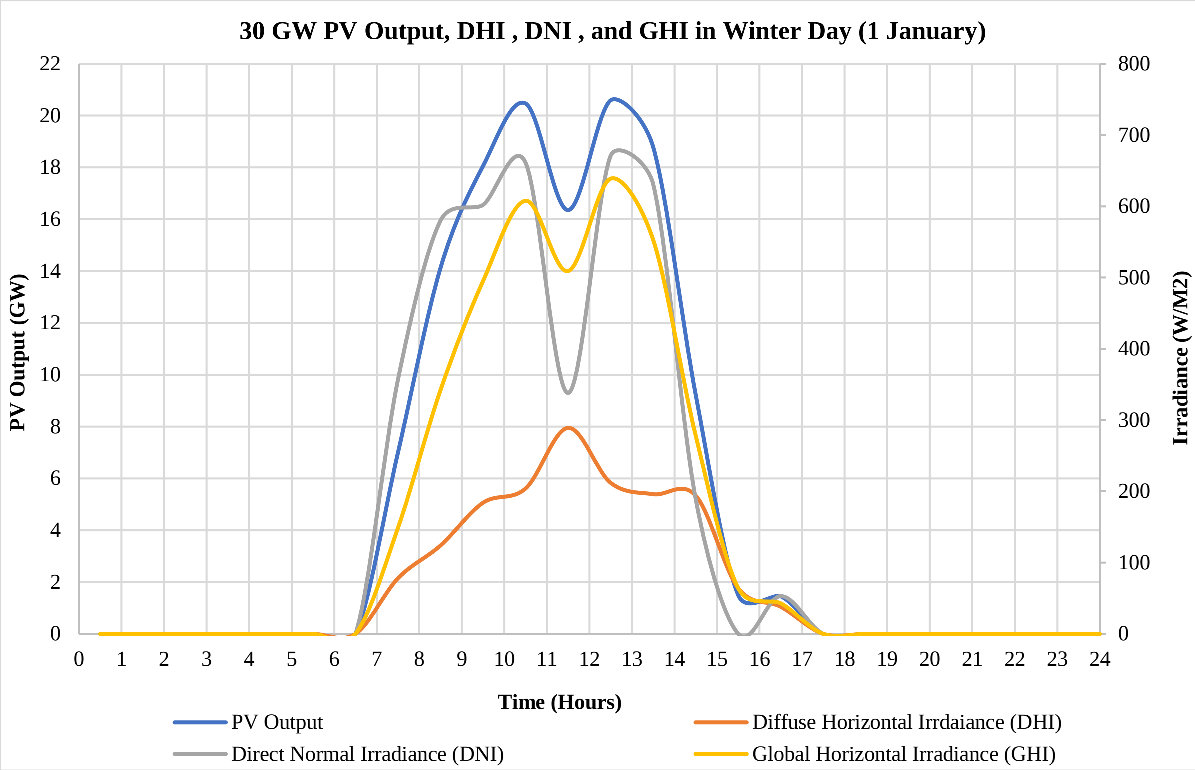

Figure 34 30 GW PV output relation with DHI, DNI, and GHI In one winter day in Saudi Arabia [Author: constructed from simulations].

Figure 34 shows the effect of the DHI, DNI and GHI on the PV electricity output in winter day in Saudi Arabia. PV output is directly proportional to solar irradiance. Solar irradiance started at 6:30 on that winter day, increasing to the peak at noon time and then decreasing gradually until 17:00. PV output followed the exact solar pattern as shown in the Figure, even the sudden drop in the PV output because of the sudden drop in solar irradiance which is probably caused by a cloud passing by. It is also noteworthy that while the DHI increased at noon, the sudden drop in PV output was primarily caused by the sudden drop in DNI and GHI. This indicates that DNI and GHI are the key parameters influencing PV output, as the decrease in these irradiance values directly led to the reduction in PV generation. In contrast, DHI increased on that day in Saudi Arabia. Further explaining about the cloud effect, Figure 35 shows the same results as Figure 34 but for three days from 1-3 January.

In Figure 35, on the second day, the impact of cloud cover is clearly observed, as the PV output drops between hours 37.50 and 38.50, coinciding with a decrease in DNI and GHI caused by a passing cloud. Following this, the PV output begins to recover and subsequently increases, before gradually declining toward the end of the day. During this decline, DHI increased, indicating that the primary factors influencing PV output are DNI and GHI. On the third day, a gradual increase in PV output was observed, corresponding with a steady rise in all types of solar irradiance, followed by a consistent decrease toward the end of the day. The sky remained clear on that day, with no sudden drops in output recorded. This suggests that winter in Saudi Arabia can feature a mix of cloudy and clear days, with occasional cloud cover influencing solar energy production.

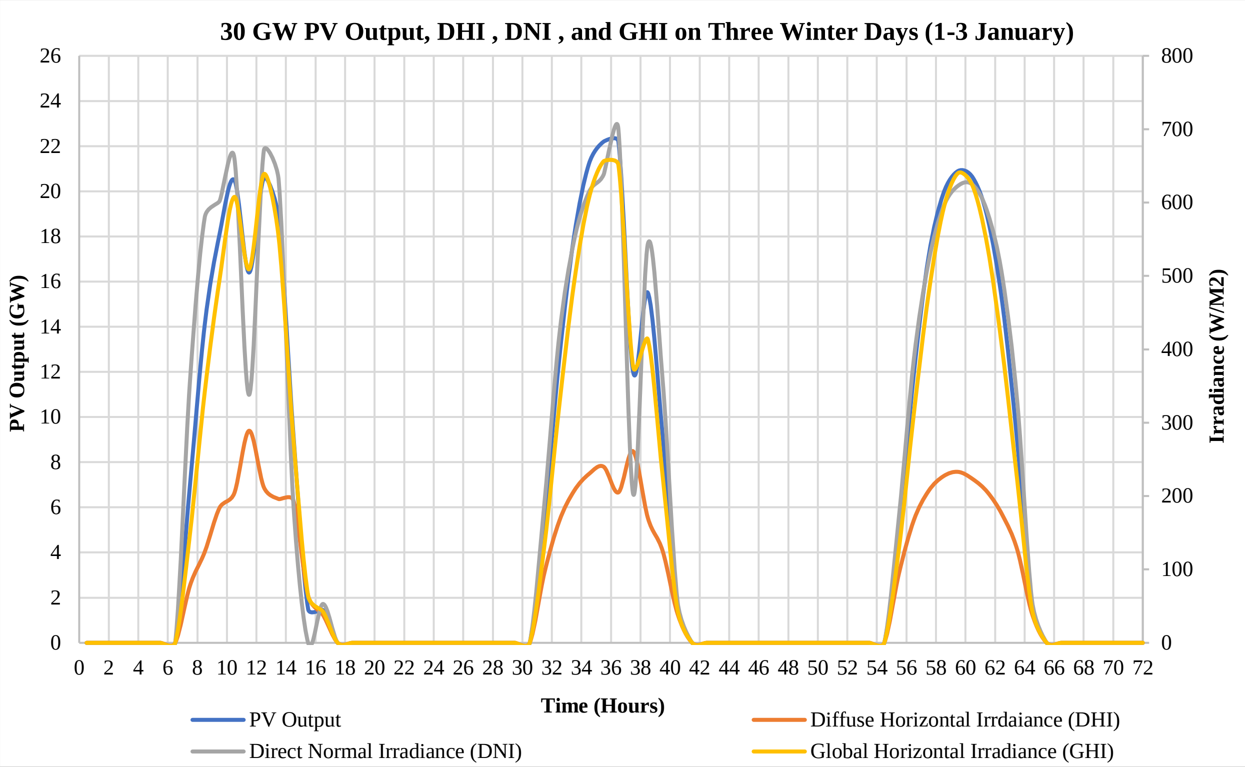

Figure 36 30 GW PV output relation with DHI, DNI, and GHI on three winter days in Saudi Arabia [Author: constructed from simulations].

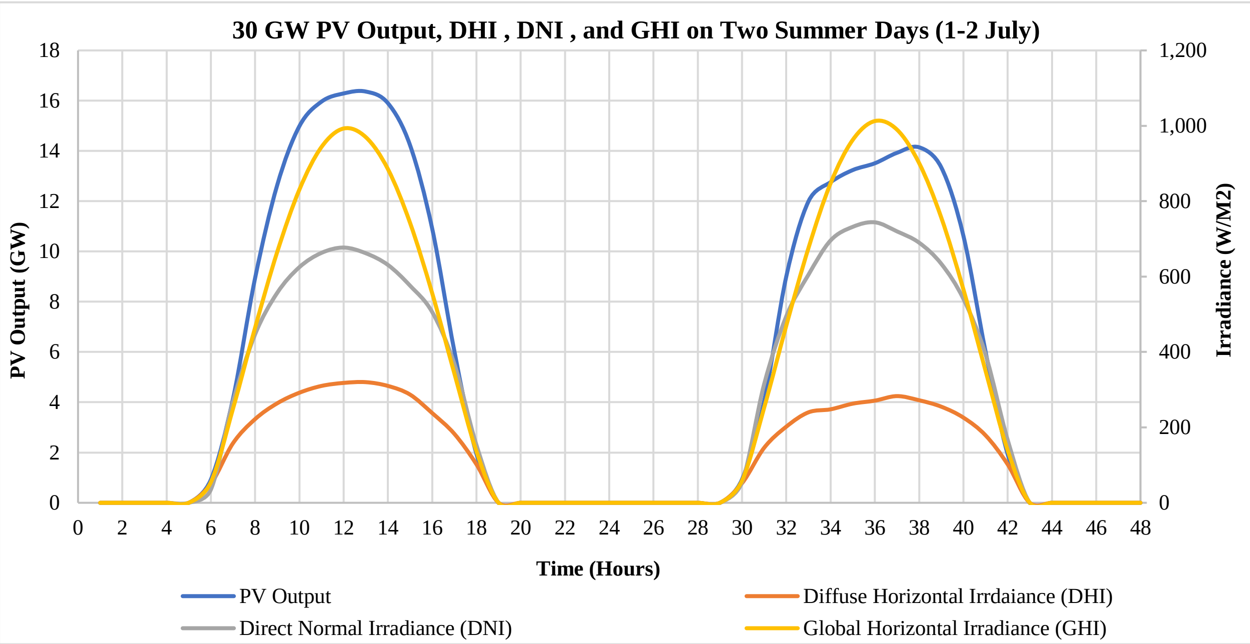

Figure 35 Figure 36 30 GW PV output relation with DHI, DNI, and GHI on two summer days in Saudi Arabia [Author: constructed from simulations].

Figure 36 illustrates the relationship between PV output and DHI, DNI, and GHI on summer days. Unlike winter, the PV output peaks are smaller in summer, despite clear skies and a smooth correlation between PV output and solar irradiance. This is attributed to the higher ambient temperatures, as shown in Figure 33. When comparing day one of each season, summer PV output peaks at 16.5 GW, while winter peaks around 20.5 GW. Additionally, clouds are less prevalent in summer, as evident from comparing days 1 and 2 across both seasons. Although PV output peaks are higher in winter, gross PV production in summer remains greater, due to longer daylight hours, higher solar intensity, and fewer gaps in availability, as shown in Figure 33.

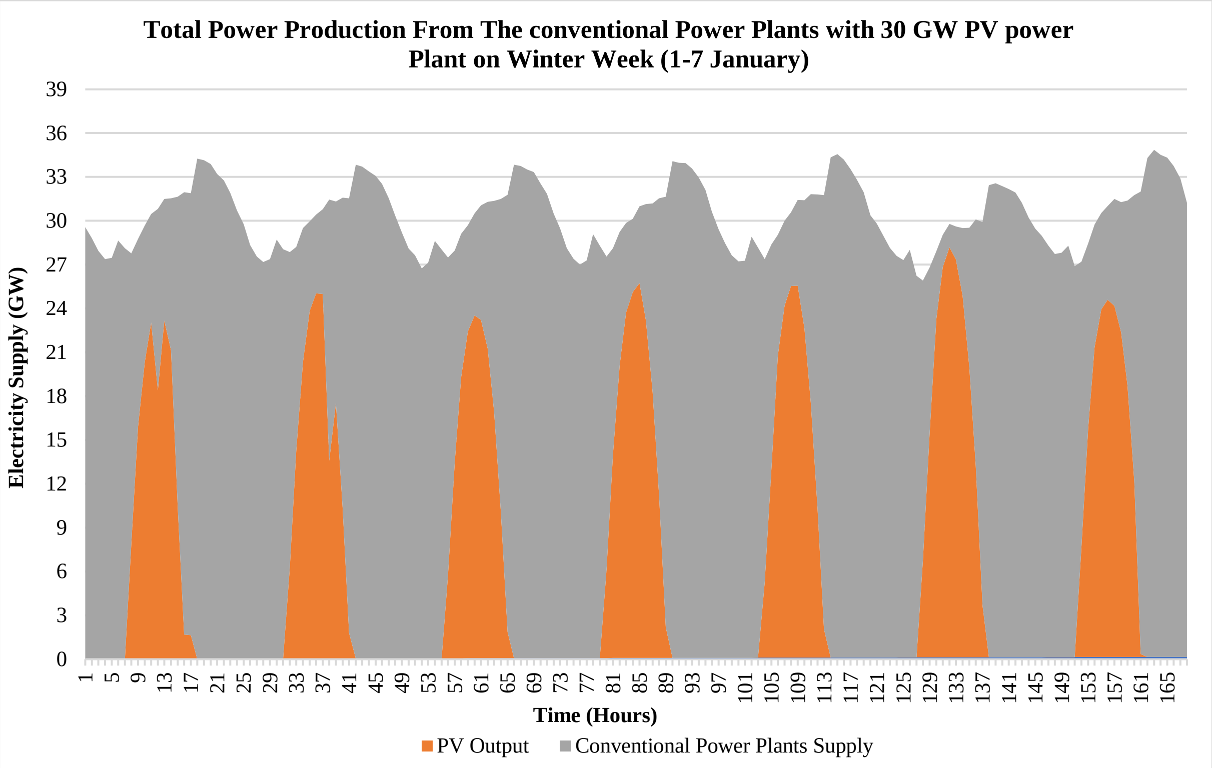

Figure 37 Total power supply from conventional power plants in addition to 30 GW PV power plant on winter week (1-7 January) [Author: constructed from simulations].

In Figure 37, the total power supply to the Kingdom is shown after the addition of the 30 GW PV in the east of Saudi Arabia. The total power supply includes the supply from all conventional power stations in the Kingdom with the contribution from the large PV power plant. The PV power plant shows a large contribution in power supply even though in the winter season. In comparison to summer (as shown in Figure 38), from graphical perspective, the PV contribution to the total power supply may appear smaller. However, this is not due to a reduced PV output, but rather because the total electricity demand in summer is significantly higher, nearly double that of winter. In the summer, the PV power plant contributed between 15 GW and 18 GW to the total electrical demand, with the remaining demand being fully met by conventional power plants.

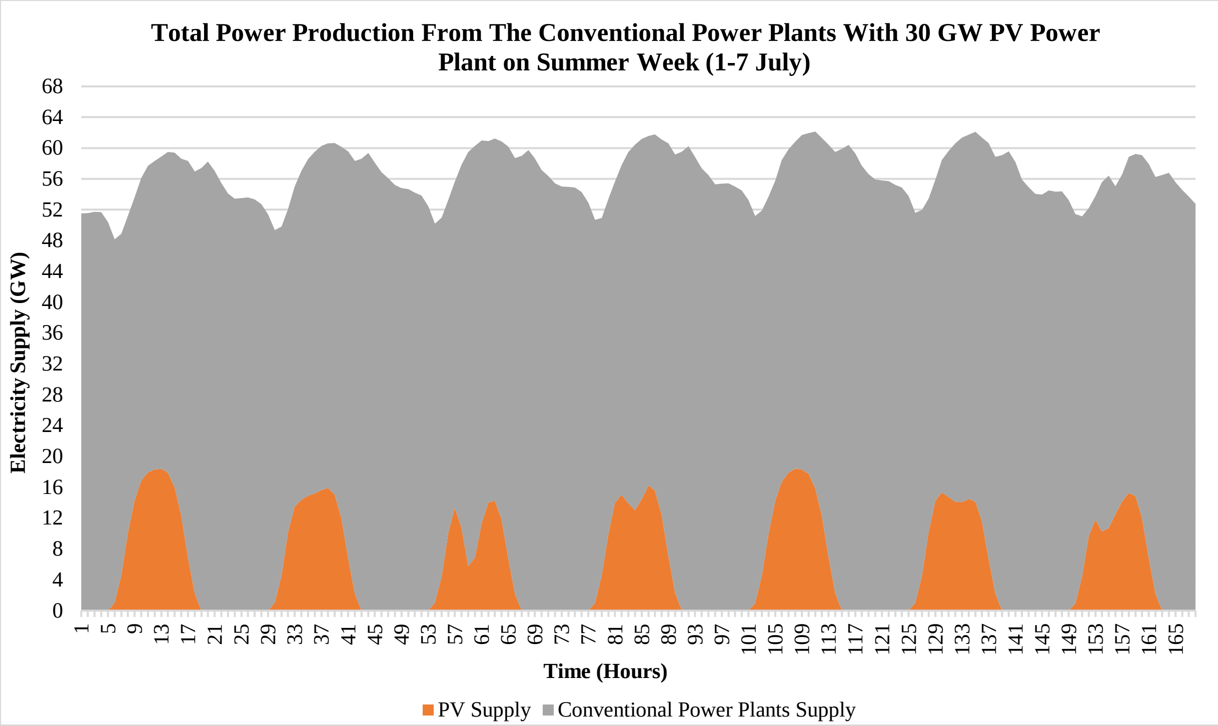

Figure 38 Total power supply from conventional power plants in addition to 30 GW PV power plant on summer week (1-7 July) [Author: simulations].

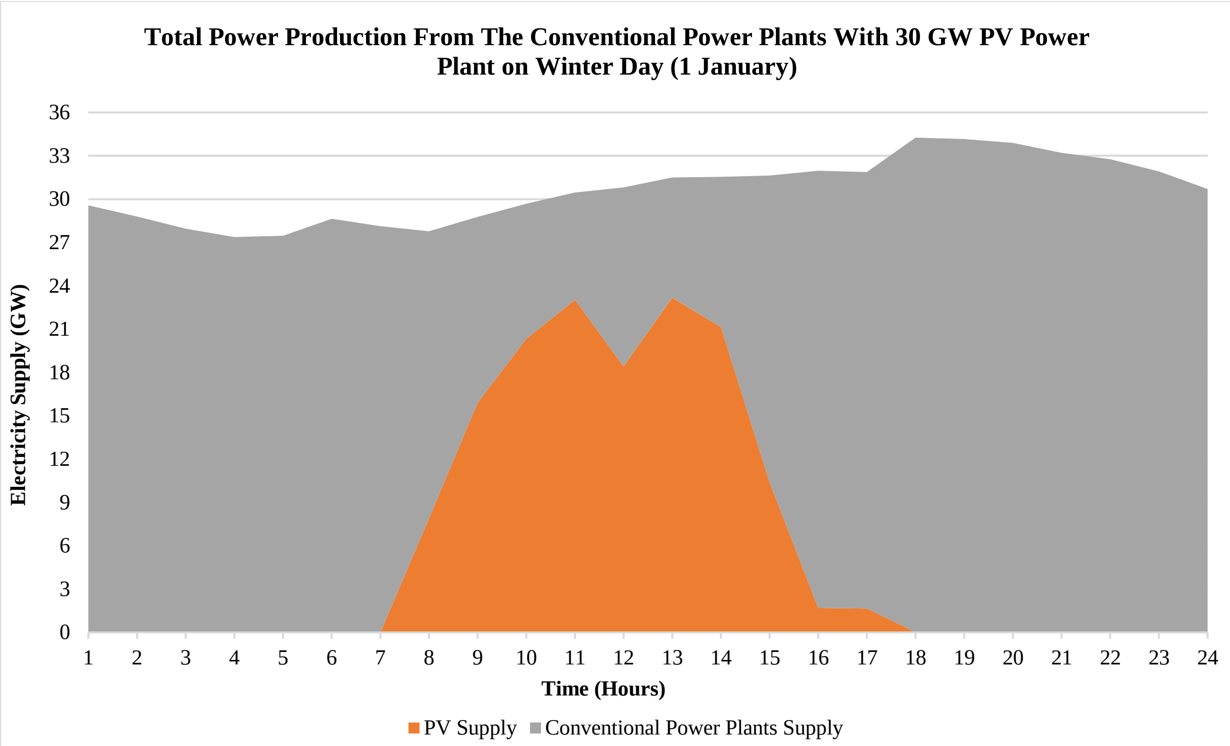

Figure 39 Total power supply from conventional power plants in addition to 30 GW PV power plant on winter day (1 January) [Author].

Figure 39 shows the contribution of the 30 GW PV power plant to the total electrical supply/demand on one winter day. As previously shown, the daily PV contribution in winter is more notable since the total electrical demand is less, with peaks reaching approximately 33 GW. In comparison, the peaks of PV production reach approximately 23 GW approximately. Figure 40 below illustrates the PV contribution to the total power supply on summer day. The maximum power supply from PV on that day reached approximately 18 GW, while the total power demand was around 58 GW. The electrical demand in summer is nearly double that of winter, which makes the contribution of PV appear smaller from a graphical perspective. The contribution of the 30 GW PV in summer and winter resulted in considerable savings in natural gas consumed by power stations with reduced CO2 emissions.

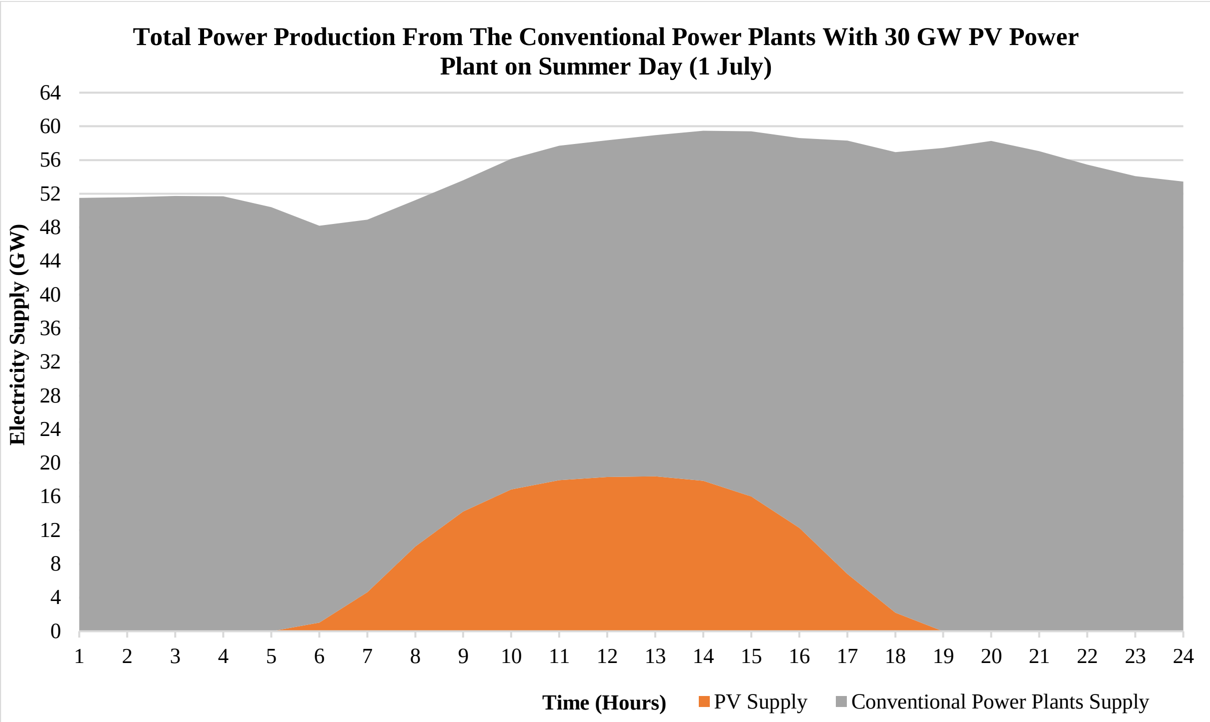

Figure 40 Total power supply from conventional power plants in addition to 30 GW PV power plant on summer day (1 July) [Author: constructed from simulations].

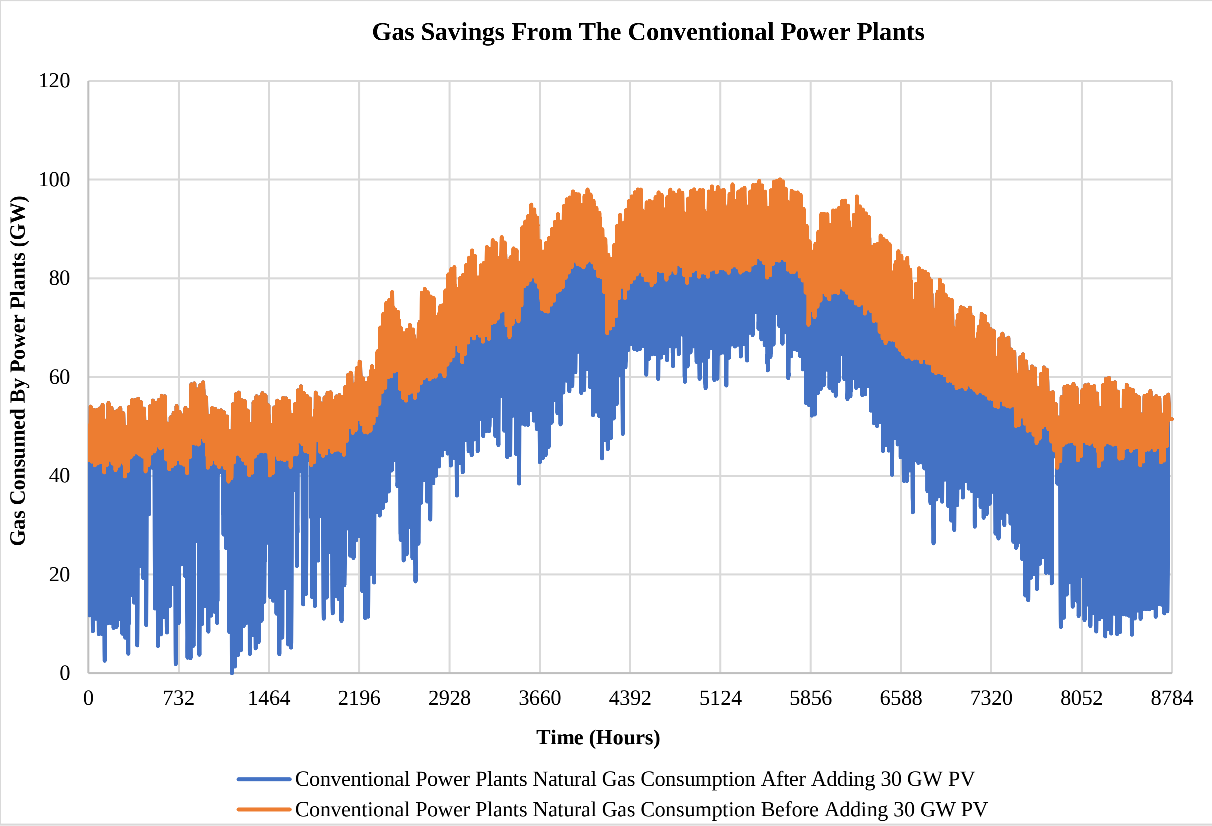

Figure 41 Conventional power plants' natural gas consumption before and after the addition of the 30 GW PV power plant in the east of Saudi Arabia [Author: constructed from simulations].

Figure 41 shows the natural gas consumption from the conventional power plants before and after the addition of the 30 GW of PV power plants. Notably, in winter, although there are higher savings peaks. However, the gross natural gas savings in the summer months are higher overall. With all validation components completed and described, the Saudi Arabia energy model is reliable and can accurately simulate future energy scenarios and policy decisions.

4.1.4 Summary, Outcomes, and Contribution to The Following Sections.

This section presents the development of Saudi Arabia's energy model for 2017, utilizing two tools, EnergyPLAN and SAM, followed by validation against actual data. The validation process consisted of three steps. The first step involved validating EnergyPLAN independently using actual data from reliable sources. This initial validation was crucial because the model incorporates multiple tools, requiring each tool to be validated separately. The second step focused on validating the SAM tool using real-world data from the IEA, alongside other validation efforts from studies that applied SAM to Saudi Arabia. The final step of the validation process involved generating hourly results from both tools to assess the model's performance across summer and winter months, days, and in annual analysis. Following the technical validation of the model, the future scenarios for Saudi Arabia in 2050 can be simulated and analysed from a technical standpoint in this chapter, with the economic analysis, assumptions, and simulation results discussed in Chapter 5

4.2 Planning the Future Energy System Scenario of Saudi Arabia: Technical Simulations and Assumptions

4.2.1 Introduction

This section describes the developed energy system scenarios for Saudi Arabia and outlines the scenario vital technical parameters and assumptions used in modelling Saudi Arabia's energy system. In contrast, the economic analysis and assumptions are carried out in Chapter 5. The future energy system scenario developed for Saudi Arabia is highlighted below:

The 2050 scenarios for a 100% RES framework model in the Saudi Arabia's energy system, include growth projections from 2017 to 2050. Additionally, this study considers the anticipated demand reductions and the potential impacts of future policies on overall energy requirements. These scenarios primarily address the power sector, incorporating the total electricity demand across all sectors within the Kingdom. The electricity demand from all sectors in the Kingdom with the total supply in 2050 are considered. In this part, the future electrical demand for the Kingdom is calculated for 2050 based on the historical year's trends and growth factors. It is assumed that by 2050, conventional condensing power plants will be completely decommissioned and replaced with RES, based on the optimal combination of RES from technical, economic, and environmental perspectives. The technical analysis is presented in this chapter, while the economic analysis is provided separately in Chapter 5. Individual RES technology, such as individual PV or wind, is also studied and analysed.

Although the 2030 analysis is not included in this study, growth factors for 2030 are considered to inform future work and provide valuable data for other researchers. These growth factors can serve as a foundational step toward analysing the 2030 energy system, should future research or analysis be conducted, ultimately contributing to the pathway for achieving a 100% RES by 2050.

4.2.2 Population & Electricity Demand Growth Assumptions for 2030 and 2050

Forecasts of population and economic growth are crucial for designing energy system models, as they significantly influence both the scale and structure of energy demand. As estimated by the United Nations in the median variant [203], with the Saudi General Authority for Statistics [204], population and populations' growth rate data are shown in Table 12 below.

Table 12 Forecasted population and population growth from 2025 to 2050 compared to 2017.

	2017	2025	2030	2035	2040	2045	2050
Population (Million)	34.19	37.98	40.46	42.75	44.88	46.78	48.37
Population Growth Rate (% per year)	2.4%	1.3%	1.2%	1%	0.9%	0.8%	0.6%

Population growth and growth rates are key factors in designing future energy models, as they directly influence the scale and structure of energy demand. For projecting future electricity demand, relying solely on historical trends, especially those prior to 2018 in the Kingdom, would not yield accurate forecasts. This is because Saudi Arabia's electricity sector is undergoing structural changes. The electrical sector's growth was rapid for decades because of government incentives through low electricity prices that were regulated. These demand trajectories were deemed unsustainable, threatening the government's fiscal sustainability and crowding out valuable fossil fuel exports.

In recent years, the authorities have launched ambitious programs to curb demand growth and reduce wasteful uses of electricity. These public action plans have reformed prices and promote efficiency measures. The Kingdom has implemented two price energy reforms (ERP) through the Saudi government's Fiscal Balance Program plants, planning to increase energy prices progressively to meet international market levels [205]. The initial wave of energy price reforms was implemented in 2016, raising electricity and fuel prices. This was followed by a second wave in 2018, which further increased the prices of oil, oil products, and electricity. For instance, electricity prices for the residential sector, the largest consumer of electricity, were 139% higher than pre-reform levels, significantly impacting demand [205]. **Thus, the historical trend before 2018 will not represent an accurate forecast of future electricity demand.**

In the period without statistical data, from 2019 to 2030, projected demand growth is significantly below its historical trend, reflecting the observed slowdown over the past years. Between 2009 and 2018, total electricity demand grew at 5.3% per year and slowed to an average rate of 2.7% per year between 2013 and 2018. In the reference scenario model, an average annual electricity demand growth rate of 1.6% is assumed for the period from 2019 to 2050, based on the findings in [206], which forecasts future electricity demand in Saudi Arabia for 2030 while accounting for the impacts of energy price reform waves. The IEA's electricity demand for 2017 and 2019 is shown in Table 13 below, along with the electricity demand forecasts for 2030 and 2050. The 2030 electricity demand projection utilizes the same 1.6% growth rate, assuming that electricity prices will remain stable at the levels established following the energy price reforms.

The Saudi authorities have also set energy efficiency measures targeting various power-consuming segments to contain electricity demand growth. The government established the SEEC to set and coordinate national programs to rationalise energy consumption in buildings, industry, and transportation. These measures are an application of the national strategy to reform the energy sector. Some of the energy efficiency measures that Saudi Arabia is using and will be using in the future, can also be found in [207] [208]. In this study, we assumed a 12.5% decrease in aggregate electricity demand of all sectors between 2030 and 2050 as [206] assumed for 2030. In addition, several researchers do not consider the network losses in the electricity energy demand. However, network losses must be added to the total electrical demand in countries with high electrical demand, such as Saudi Arabia, especially when modelling. Network losses of 9.3% were considered in the IEA's electricity demand data for 2017 and 2019 [209]. This value is also reflected in the detailed electricity balance table for Saudi Arabia on the IEA website [210]. Accordingly, the same network loss percentage of 9.3% was assumed for both 2030 and 2050 in this study. The results are shown in Table 13. In addition, it shows the electric demand in 2017 and 2019 from IEA, with the calculated demand forecasts in 2030 and 2050.

Table 13 Electricity demand in 2017 and 2019 with the forecasted electrical demand in 2030 and 2050

Year	2017	2019	2030	2050
Reference Electricity Demand (TWh)	347 [209]	356.9 [209]	424.98	583.78
Energy Efficiency Measures (-12.5%) [206]	-	-	-	510.80
Network losses (+9.3%) [210]	379.2 [210]	390.1	464.50	558.30
Final Electricity Demand (TWh)	379.2	390.1	464.50	558.30

Based on historical trends, the average annual electricity demand growth rate from 2010 to 2020 is 3.85%, according to IEA data, with electricity demand reaching 359 TWh in 2010 and 218.7 TWh in 2020 [210]. This growth rate is significantly higher than the assumed rate of 1.6%, which accounts for the effects of energy price reform waves.

4.2.3 Projected Growth Assumptions for Fuel Demands in 2030 and 2050

The other fuel demands, industry, transport, residential, and various fuel demands in the reference case in 2017 are shown in Table 14.

Table 14 Other sectors' demand by fuel type in the reference case in 2017.

Other Demands (TWh) [IEA]	2017	
Sector	Oil and oil products	Natural Gas
Industry	196.75	214.72
Non-Energy Use Industry	540.5	59.85
Own-Use	94.8	36.29
Total Industry and Various	**832**	**310.8**
Residential	**20.73**	**0**
Transport	**555.76**	**0**

For the other future demands, such as industry, transport, and non-energy use (feedstock), the average growth rate of at least few years from 2019 onward (After the second price energy reform in 2018) should be considered. However, since the IEA only provides demand data up to 2020 at the time of writing this thesis, the growth factor based on one year cannot be determined. Therefore, the average historical growth rate of oil products consumption from 2000 to 2020 was applied to the IEA energy consumption graphs. The annual growth rate of the demands was calculated using the following equations:

$$Yearly\ Growth\ Factor\ (Industry\ oil\ products) = \left(\frac{100 - 100 \times \left(\frac{304{,}443\ TJ}{441{,}552\mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right) = 1.5\ \%$$

$$Yearly\ Growth\ Factor\ (Non-Energy\ Use\ Industry\ oil\ products\ ) = \left(\frac{100 - 100 \times \left(\frac{870{,}381 TJ}{1{,}961{,}499\ \mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right)$$

$$= 2.7\ \%$$

$$Yearly\ Growth\ Factor\ (Transport\ oil\ products) = \left(\frac{100 - 100 \times \left(\frac{852{,}935\ TJ}{1{,}712{,}055\mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right) = 2.5\ \%$$

$$Yearly\ Growth\ Factor\ (Residential\ oil\ products) = \left(\frac{100 - 100 \times \left(\frac{51{,}582\ TJ}{63{,}492\mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right) = 0.93\ \%$$

$$Yearly\ Growth\ Factor\ (Industry\ natural\ gas) = \left(\frac{100 - 100 \times \left(\frac{428{,}800\ TJ}{937{,}871\mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right) = 2.7\ \%$$

$$Yearly\ Growth\ Factor\ (Non-Energy\ Use\ natural\ gas) = \left(\frac{100 - 100 \times \left(\frac{109{,}303\ TJ}{244{,}528\mathrm{TJ}} \right)}{20\ \mathrm{Years}} \right) = 2.7\ \%$$

Own-use oil products' demand growth rate was assumed as the industry oil products' demand growth rate of 1.5%. The natural gas demand growth rate was calculated in the same method as shown in the equations.

The growth rate of natural gas demand for own-use was presumed to align with the growth rate observed in the industrial sector, set at 2.7%. This growth rate was derived using the same methodology as outlined in the previously presented equations. Applying demand growth rates gives the future energy demand of the sectors by fuel type, as shown in Table 15. For the transportation demand forecast in 2030, a study conducted by 12 contributing authors [211] utilized artificial intelligence and machine learning models to predict future demand in Saudi Arabia. The resulting estimate of approximately 79 Mtoe, or around 814 TWh, closely aligns with the projected demand presented in Table 15

Table 15 Future demands forecast of other sectors by fuel type.

Other Fuel Demands (TWh)	2030		2050	
Sector	Oil and Oil Products	Natural Gas	Oil and Oil Products	Natural Gas
Industry	238.76	303.59	313.53	504.31
Non-Energy Use Industry	764.20	84.62	1269.30	140.56
Own-Use	115.04	51.31	150.84	85.18
Total Industry and Various	1,118	439	1,778	749
Residential	23.38	0	28.13	0
Transport	766.12	0	1255.37	0
Demands After Energy Efficiency Measures				
Industry	232.79	296	297.85	479.1
Non-Energy Use or Feedstock	745	82.5	1205.83	133.53
Own-Use	112	50	143.29	80.92
Residential	-	-	-	-
Transport	-	-	1054.51	-

SEEC was established in 2010 and has since focused on improving energy efficiency in the buildings, transport, and industrial sectors through numerous energy efficiency measures, as these sectors must achieve the benchmark approved by SEEC in the baseline year. This study applied a reduction in the demands, assuming two energy-efficient measure scenarios: one for 2030 and the other for 2050. In [212], the author assumes two scenarios of energy efficiency measures for the industry sector in 2030 (excluding feedstock demand). The first scenario is Low Primary Energy Conservation (LPEC), while the second is High Primary Energy Conservation (HPEC). With the LPEC, the reduction in the industry demand was assumed to be 5%, while with the higher energy efficiency measures in the HPEC, the demand reduction can reach 10%.

In this study, we assumed the LPEC scenario for the industry demand in 2030 with the HPEC for the year 2050. The demand for industry oil and oil products in 2030 was 238.76, using a growth rate of 1.5% until 2030. The energy efficiency measures are then applied to reduce the demand by 5% split between oil and natural gas (2.5% each), reducing the industry oil and oil products demand from 238.76 TWh to 232.79 TWh in 2030. The demand continues growing to 2050 with the same growth rate, resulting in the demand for oil products at 313.53 TWh and natural gas at 504.31. Energy efficiency measures of 10% were then applied to the industry demand in 2050, split between oil and natural gas (5% each), resulting in a reduction in the demand from 313.53 TWh to 297.85 TWh in oil & oil products and from 504.31 TWh to 479.1 TWh in natural gas as seen in Table 15. Although there could be a potential for additional industry demand reduction though long-run electricity price as per what this research [212] suggested. However, this is beyond the scope of this paper due to insufficient information, such as the potential for further energy price reforms.

The initiatives by SEEC also aim to improve feedstock utilisation efficiency for primary raw materials, such as hydrocarbon cracking, ammonia, methanol, propane dehydrogenation, isobutylene, and benzene-toluene-xylene. Additionally, the SEEC is developing a program to support facilities in implementing energy management systems and improving their energy performance [213]. Thus, we assumed improved feedstock utilisation efficiency by applying different energy efficiency measures using the same factors assumed for the industry sector: 5% for 2030 and 10% for 2050. Industry and non-energy use are one sector. However, IEA divides them into the industry and non-energy use sectors. In addition, in [212], the author excluded the non-energy use or ‘’feedstock’’ from the industry demand since it is out of his scope, and the energy efficiency measures were applied solely to the industry demand. Thus, the same factors were applied to the non-energy use sector. In Table 15, non-energy use demand is expected to reach 764.20 TWh of oil & oil products and 84.62 TWh of natural gas. Energy efficiency measures applied in 2030, resulted in a 5% reduction of the demand split between oil and gas (2.5% each) from 764.20 TWh to 745 TWh for oil and from 84.62 TWh to 82.5 TWh for natural gas. The demands then continue with the assumed growth rate until 2050, reaching 1269.30 TWh and 140.56 TWh for oil and natural gas, respectively. The assumed energy efficiency measures of 10% was then applied by 5% for oil and 5% for natural gas, resulting in a reduction of the demands from 1269.30 TWh to 1205.83 TWh for oil and from 140.56 TWh to 133.53 TWh for natural gas.

Energy efficiency measures were similarly applied to own use, utilizing the same reduction factors as those applied to the industrial sector. As shown in Table 15, the projected non-energy use demands are 115 TWh for oil and 51.31 TWh for natural gas. Upon applying the energy efficiency measures, demand reductions were achieved, decreasing oil consumption from 115 TWh to 112 TWh, and natural gas consumption from 51.3 TWh to 50 TWh. The demand continues to grow until 2050, reaching 150.84 TWh and 85.18 TWh for oil and natural gas, respectively. The further 10% reduction in energy demand due to improved energy efficiency is then applied, resulting in demands of 143.29 TWh and 80.92 TWh for oil and natural gas, respectively. The residential sector's oil products consumption was assumed to grow normally without energy efficiency measures. This is due to the lack of studies and analysis available about this subject in Saudi Arabia.

The SEEC also targets the transportation sector, with the SEEP instituting a comprehensive three-pronged strategy for light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs), which together represent approximately 98% of total transport demand. In 2014, the SEEP introduced the Vehicle Energy Efficiency Label for LDVs, which was subsequently updated in 2018 to include electric vehicles. In 2015, the first phase of the Tire Rolling Resistance and Wet Grip Standards for both LDVs and HDVs was launched, followed by the commencement of the second phase in 2019. Additionally, the Saudi Corporate Average Fuel Economy (CAFE) standards for LDVs were introduced in 2016 and revised in early 2021, resulting in a 16% improvement in the fuel economy of the new vehicle fleet. A third phase of the CAFE standards is scheduled for implementation in 2024. Fuel economy performance requirements were established for all incoming LDVs in 2016, contributing to a 10% enhancement in the fuel economy of the new fleet. Furthermore, all newly registered vehicles are mandated to display fuel efficiency labels, which now also include those for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Vehicles that fail to meet the minimum energy performance standards are prohibited from import. The SEEC's LDV tyre rolling resistance program is also expected to reduce fuel consumption by 2%-4% [214]. In our calculated growth rate, the period was from 2010 to 2020; thus, the improvement in 2021 and onwards did not take effect. Thus, we assumed 16% improvement in the transport demand, specifically for LDVs, s and HDVs before 2050, as shown in Table 15. In addition, the Kingdom is also moving towards electric vehicles for 2030 and 2050. However, the effect of electric vehicles inclusion will be further discussed in the results section. The reference case transport demand breakdown in 2017 was 555.76 TWh, divided into 54.60% Gasoline, 43.41% Diesel, and 1.99% Jet Kerosene. Thus, the new transport demand in 2050 was divided accordingly for EnergyPLAN inputs, resulting in 575.76 TWh of Gasoline, 457.76 TWh Diesel, and 20.98 TWh of Jet Kerosene. And for 2030, 766.12 TWh is divided into 418.30 TWh Gasoline, 332.57 TWh of Diesel, and 15.24 TWh of Jet Kerosene.

4.3 2050 Scenarios: 100% Electricity Supply from RES

4.3.1 PV / PV+Battery Storage Scenario

This section discusses the analysis of future power systems in 2050. As the first step, this section investigates the technical feasibility, advantages, and limitations of using PV power only as the main power supplier for the entire Kingdom in 2050. In the second step in this section, the same analysis and simulations are discussed for the combined system of PV+Battery storage system.

4.3.1.1 PV Potential and Location

Solar energy has been recognized as an emerging technology in Saudi Arabia, which has some of the highest solar irradiance levels globally, as evidenced by numerous studies referenced earlier. In Figure 42, the GIS PV potential map indicates that the highest power potential could be utilised from PV is in the northwest region near Tabuk as the yearly total yield could reach 2,045 to 2,118 kWh/kWp. Tabuk represents the northwest region, which has one of the best direct normal irradiances in the world. Areas with high direct irradiance are also particularly interesting for PV and CSP plants. Several research papers, such as [215], have chosen the same region as one of the optimal areas to consider PV and CSP plants in their analysis.

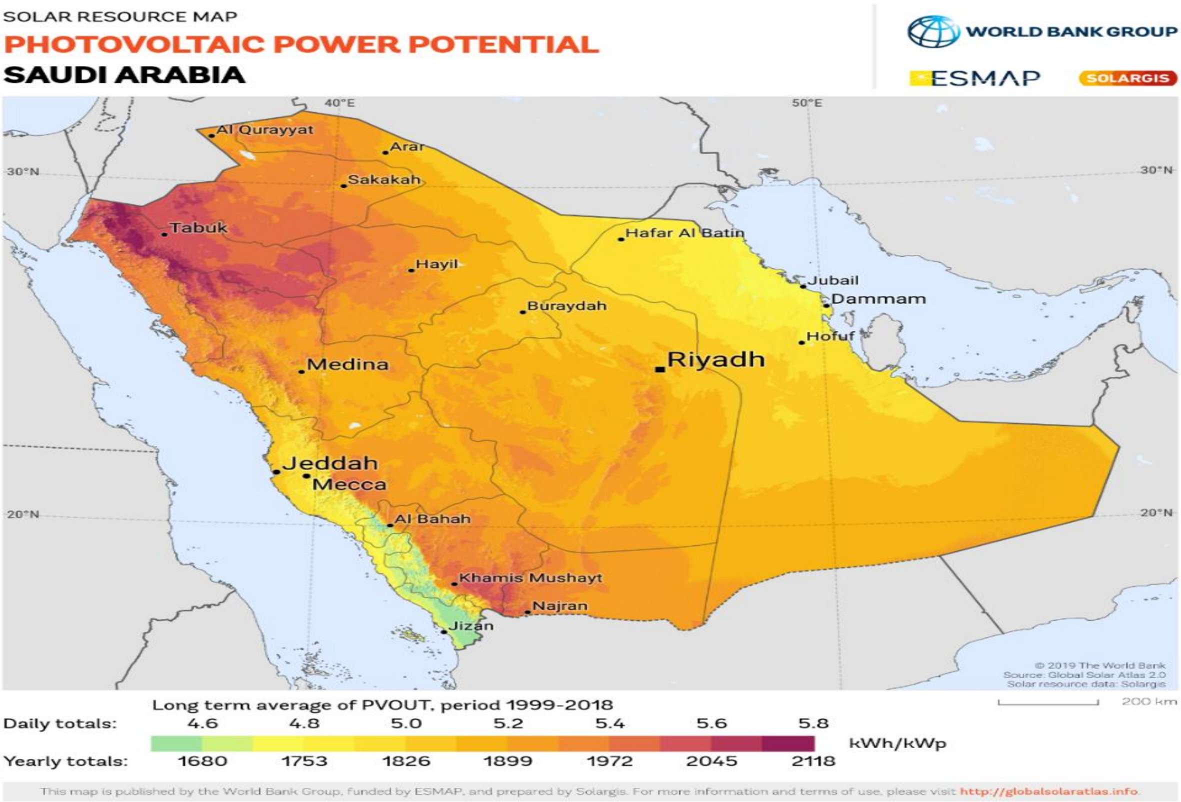

Figure 42 PV power potential map in Saudi Arabia [216].

4.3.1.2 Simulation Methodology and Results

The initial step in simulating the PV+Battery system to meet 100% of Saudi Arabia's demand by 2050 is the development of the distribution file for EnergyPLAN. As previously stated, EnergyPLAN requires the hourly distribution file of the power output generated by the PV plant in the selected location. This distribution file includes 8,784 hourly values representing the PV electrical generation over the course of the year. By doing so, the model is able to recognize the hourly generation patterns across different times of the year, enabling the user to analyse the overall relationship between supply and demand balance. This distribution file also enables the user to adjust the capacity of the power plants as needed, eliminating the necessity of designing a new power plant with a different capacity each time. The distribution file of the PV hourly output from actual operating power plants is readily accessible in many countries, particularly in Europe, where extensive data is available through databases and research papers. However, the situation is slightly different in Saudi Arabia, as there is no hourly data for the actual operating PV power plant in the Kingdom for an entire year. Few hourly data are available for small-scale projects and for a limited time, such as a week, month, or three months.

In this case, the hourly distribution file for a PV plant in the selected area of Tabuk had to be created from another source. SAM was used to simulate a 30 GW PV power plant in the selected region. In fact, before designing the final power plant, the location of the PV power plant was changed by iterations in the model to check if Tabuk is the optimal region, as mentioned in GIS data. The results comply entirely with the GIS PV potential map, as Tabuk had the highest PV output and capacity factor. The selected location data and the annual average weather data are shown in Table 16.

Table 16 Climate conditions and location details of the selected PV site.

Location	
Country	Saudi Arabia, Tabuk
Latitude, Longitude	28.37, 36.5 Degrees
Annual Averages	
Global Horizontal	6.4 kWh/m^2/day
Direct Normal (beam)	7.13 kWh/m^2/day
Diffuse Horizontal	1.65 kWh/m^2/day
Average Temperature	22.3 Celsius

For the design capacity and other design parameters, the 30 GW capacity of PV power plant was selected to indicate the technical performance parameters for the selected location. Note that SAM was used solely to find the distribution file of the PV generation for EnergyPLAN and did not include the demand file or battery storage; thus, any design capacity could be used in EnergyPLAN. For example, a 10 GW PV power plant could be modelled in SAM, and its hourly electricity output pattern would likely show minimal difference compared to the hourly output from a 30 GW power plant, particularly in terms of the overall generation pattern as the pattern will remain almost the same with the difference being in the amount of generation or the amplitude of the curve in the graph.

The azimuth is 180 degrees, with fixed-axis panels and a tilt angle of 30 degrees. The optimal tilt angle used in this region by many researchers varies between 27 to 30 degrees. In this case, 30 degrees was the optimal angle with the selected location, leading to the PV plant's best generation in one year. The simulation results are shown in Table 17.

Table 17 PV power plant simulation SAM results.

PV Plant Performance Parameters in SAM	
Annual AC Energy in One Year	54,597,120,000 kWh
DC capacity Factor in One Year	20.8 %
Energy Yield in One Year	1,820 kWh/kW
Performance Ratio in One Year	0.72

As discussed earlier in section 4.1.3, the performance ratio is defined as the final yield divided by the reference yield. It accounts for the total losses in the system by converting from the nameplate DC rating to AC output. In comparison, the capacity factor is defined as the actual annual AC energy to theoretical maximum energy that would have been generated if the PV system is operated at full rated power for 24 hours in a given day for an entire year [200].

The hourly PV electrical output was generated for one year and added to EnergyPLAN. The capacity factor shown in EnergyPLAN was slightly different (higher) than in the SAM model, and thus, a correction factor of -0.25 was used. This is because when transferring the hourly data from SAM to EnergyPLAN, it results in negligible variation in the capacity factor due to the negligible change in hours numbers between the two programs, such as 8,784 hours per year in EnergyPLAN and 8,760 hours in SAM. Although this does not affect the results, however, it is given for clarity only. The capacity factor in EnergyPLAN was 21.05%, while in SAM it was 20.8%, due to the above-mentioned reason. Consequently, a correction factor of -0.25 was applied.

The electrical demand of Saudi Arabia in 2050 in Table 13 was inserted into EnergyPLAN for simulations. The PV+ Battery system was designed to supply 100% of the electrical demand of the Kingdom every hour of the year without shortage and the need for import at any hour with the least required plant size. A parametric analysis was conducted on the PV design capacity, battery storage capacity, and charge/discharge capacities to ensure 100% demand supply under the worst-case demand/supply scenario over the course of one year. The analysis aimed to avoid supply shortages and the need for imports, utilizing only the deployed RES resources. Iterations were carried out with 1,000 MW steps for the PV capacity and 10 GWh steps for the battery storage capacity.

Initially, the PV power plant was assumed to operate at high capacity, sufficient to meet the entire grid and battery demands. The minimum required battery capacity was determined through iterative steps, progressively increasing the battery size until any supply shortage was eliminated. Subsequently, the PV capacity was gradually reduced while maintaining the minimum required battery capacity, until the lowest PV capacity was identified that still prevented any shortage. Simulations were conducted on an hourly basis for one year, and the results are presented in Table 18. This table outlines the required design parameters, size, energy specifications, and costs for the PV + Battery system that can fully cover the Kingdom's electrical demand on an hourly basis in 2050, using the smallest possible size for the RES power plants. The installed capacity of the PV panels is 577.1 GW with a minimum storage capacity of 2,039 GWh.

The battery storage charge capacity was strategically determined based on the maximum solar energy surplus that is required for storage. This design ensures that the PV power plant can produce electricity during daylight hours, meeting grid demand first, and directing the excess generation from each daytime hour into battery storage for later use. Storage charge/discharge efficiencies were assumed at 85% and 90%, respectively. The battery storage system is characterized by annual peak charge and discharge capacities of 236.8 GW and 91.4 GW, respectively. On an annual average, the system operates with charge and discharge capacities of 45.7 GW and 34.9 GW. In this scenario, surplus electricity is generated by the PV panels during the day. The total energy produced by the PV system is 1052.4 TWh. Of this, 251 TWh is used to supply the grid during daylight hours, while 401.4 TWh is directed toward meeting the storage demand.

Approximately 400 TWh of the total energy generated by the PV system was surplus, not being utilized by either the grid or the storage. Technically, this surplus production can’t be pumped into the grid as it will cause grid instability issues. Therefore, during periods of surplus energy production that exceed the grid and storage capacities, the PV power must be curtailed i.e. by adjusting the inverters to lower the DC voltage reference to the PV panels, effectively reducing output. Simulation Strategy number 1 was implemented in EnergyPLAN, where PV production is curtailed whenever the energy surplus exceeds the capacity limits of both the grid and storage systems. This method ensures that PV generation remains within feasible levels, preventing any excess that cannot be absorbed by either the grid or the storage capacity. The results, as shown in Table 18, indicate that after curtailing the PV surplus, the new energy production totals 652.6 TWh. Of this, 251 TWh is supplied to the grid, and 401.4 TWh is used to meet the storage energy demand.

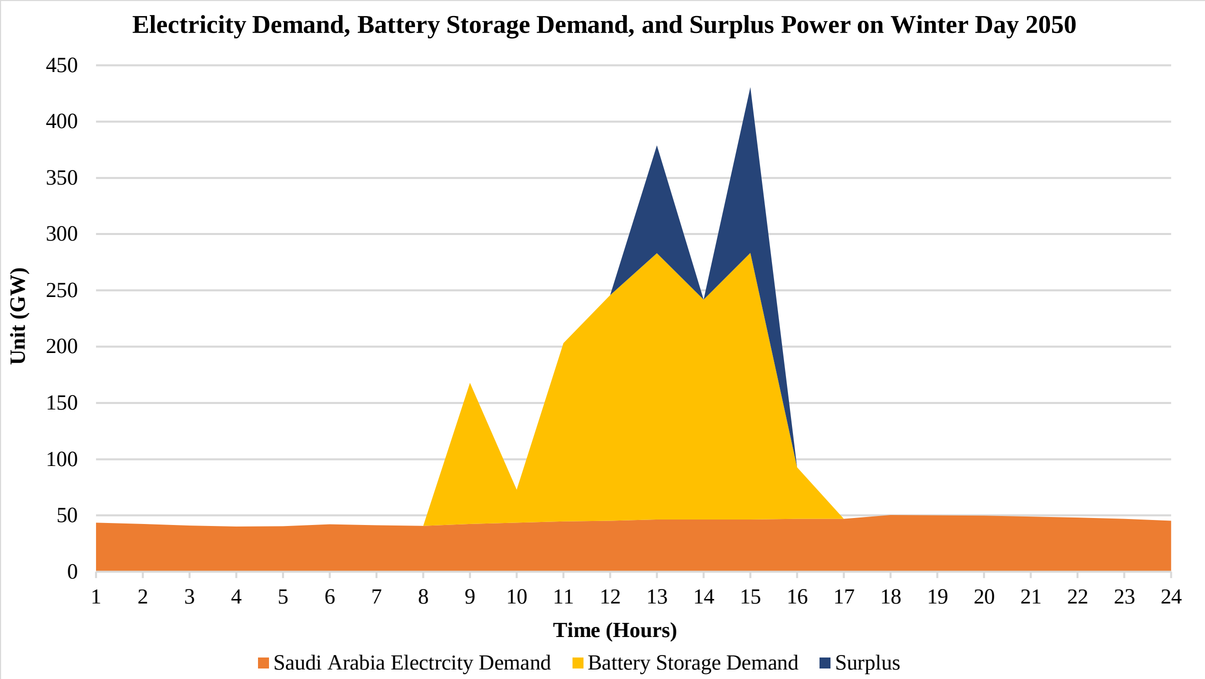

Figure 43 Electricity demand, battery storage demand, and the surplus power on winter day in 2050 [Author: constructed from simulations].

Figure 43 shows Saudi Arabia's electrical demand in 2050, along with the demand for battery storage and the surplus energy that was not used by the grid or storage. This surplus energy occurred because of two reasons. First, the PV system is designed based on the worst-case point of demand and supply. Either when the demand is very high or when the PV production is insufficient on some days. Secondly, there is substantial solar availability all year round due to the geographical location of Saudi Arabia. Although there is a surplus in many days. However, on certain days throughout the year, no surplus is generated, with all the PV generation being entirely utilized by the grid and battery storage, as illustrated in Figure 44.

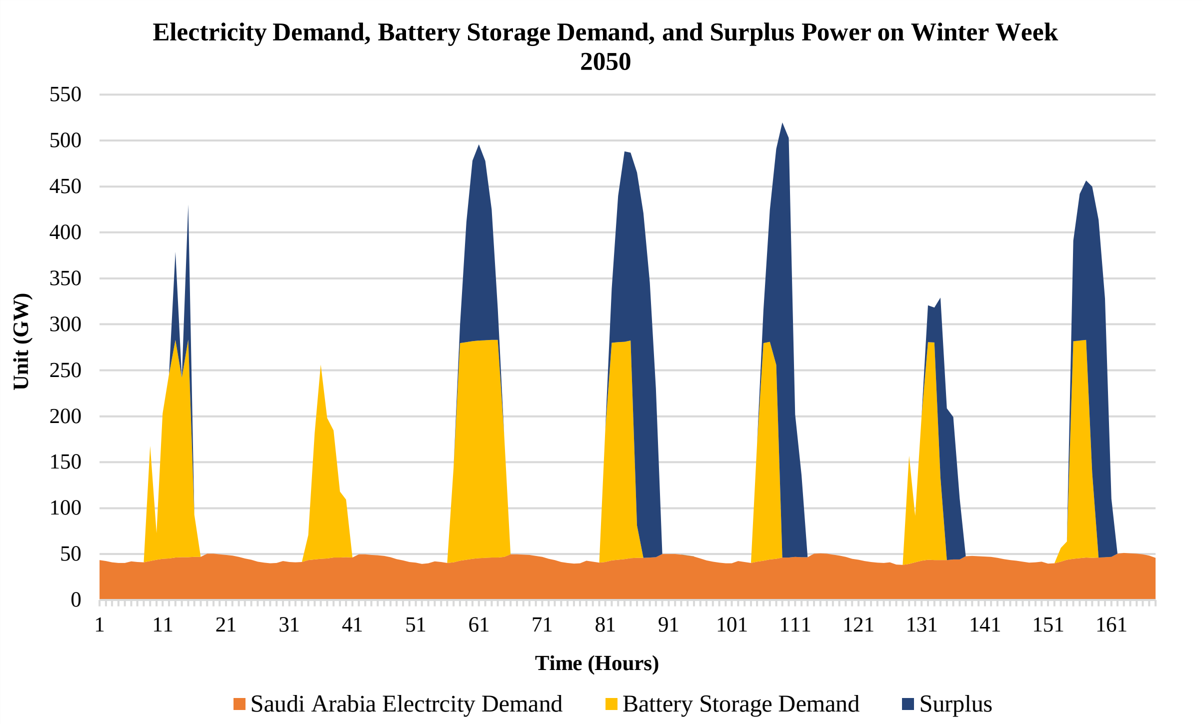

Figure 44 Electricity demand, battery storage demand, and surplus power on winter week 2050 [Author: constructed from simulations].

As illustrated in Figure 44, the electrical demand, storage demand, and surplus energy levels for the Kingdom are presented. The electrical demand fluctuates between 48 and 50 GW. On certain days, such as the first day of the week, the surplus energy is minimal, while on the second day, there is no surplus power. Throughout the weekdays, the surplus energy varies, being higher on some days and lower on others. Notably, the surplus energy is reduced in the summer due to the increased electricity demand from both the grid and the battery, as shown in Figure 45.

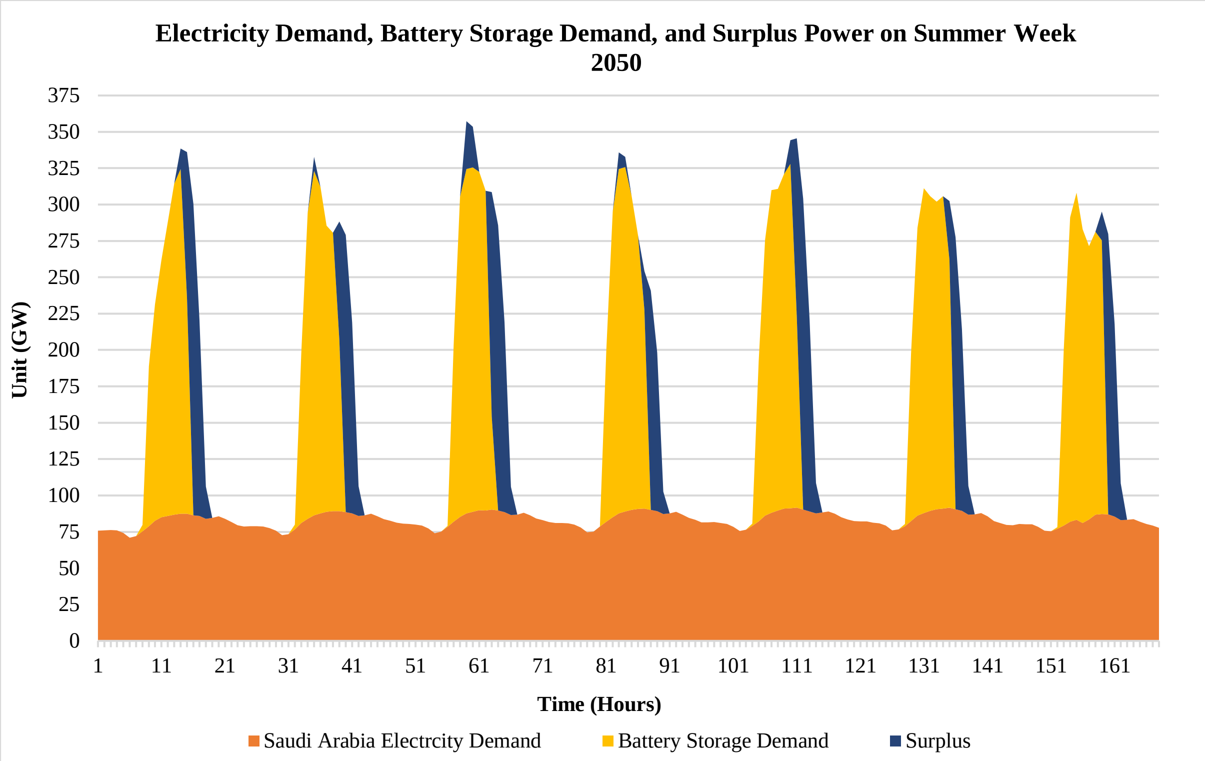

Figure 45 Electricity demand, battery storage demand, and surplus power on summer week 2050 [Author: constructed from simulations].

As illustrated in Figure 45, surplus energy is notably lower in summer compared to winter, despite higher PV production during the summer months. In summer, PV production reaches a peak of approximately 325 GW, while winter peaks are around 250 GW. This is due to the grid's higher electricity demand, which fluctuates between 70 GW to 80 GW in summer each hour, while in winter, demand peaks at 48 to 50 GW hourly. In practical application, the grid cannot take this surplus energy as it will cause huge instability and other technical issues, as mentioned earlier. Thus, PV system power generation must be curtailed after a specific generation limit to prevent further surplus to the grid. This approach has been implemented in EnergyPLAN, where surplus energy production is halted after the PV system has provided enough energy to meet the daytime grid demand and the storage discharge needs at night. This is achieved by controlling the inverters to adjust the DC voltage reference to the PV panels. Figure 46 illustrates the final system performance after curtailing PV production during surplus periods.

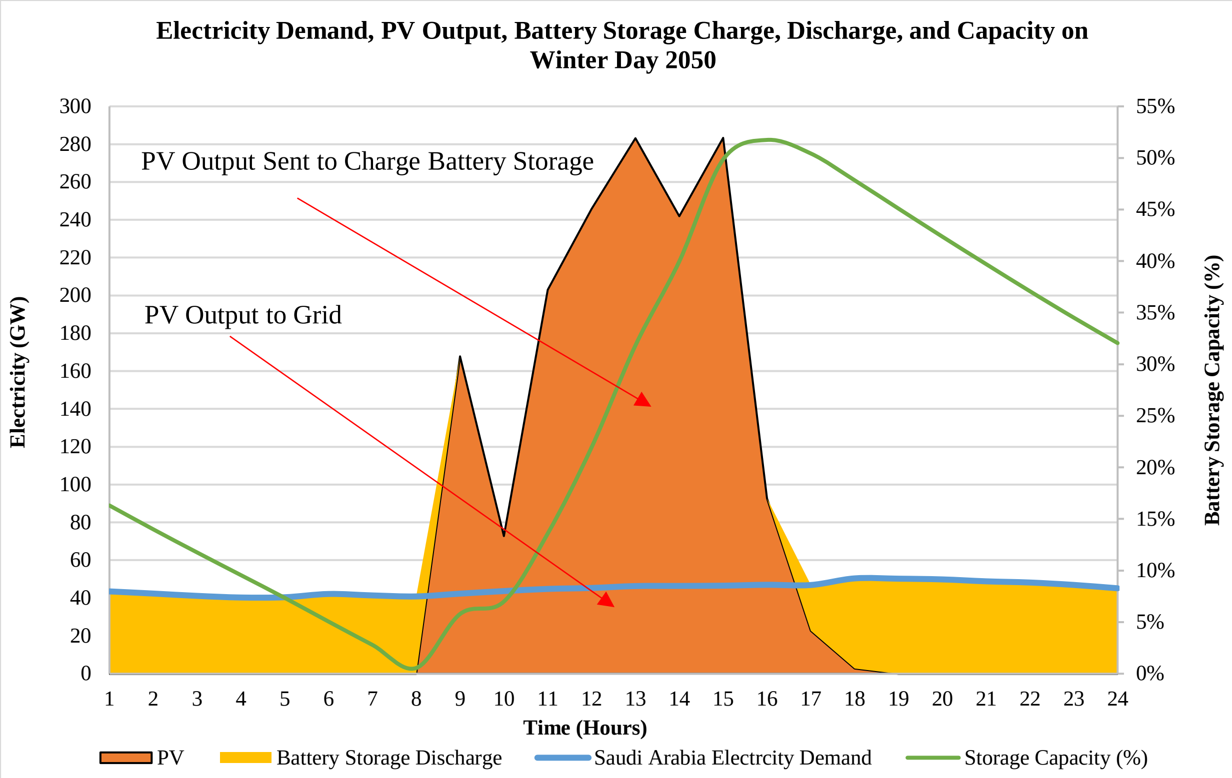

Figure 46 Electricity demand, PV output, battery storage charge, discharge, and capacity on winter day 2050) [Author: constructed from simulations].

Figure 46 shows the final system electricity flows. In Saudi Arabia, battery storage is needed on winter day to fully supply the grid demand of approximately 45 GW for 8 hours at the beginning of the day after midnight (from 1 AM to 8 AM). At the end of the day, after sunset, another 7 hours of storage supply is needed (from 17:00 to 24:00). In the late afternoon, around 17:00, the storage system is partially utilized to meet the remaining grid demand, as PV production is insufficient at this hour due to the less sun radiation. After 17:00, the storage has completely supplied the grid's demand every hour during the nighttime. In the same figure, it can be observed that there is no surplus power, as it has been effectively controlled. The grid utilised all the PV power produced during the daytime from 8:00 AM to 17:00 while the remainder of the generated energy was fully supplied to the battery storage for later discharge at nighttime. Lower PV production peaks can be noticed during random hours of the day, such as at 10:00 AM and 14:00. This is due to the passing clouds at these hours, as in winter, the sky is not entirely clear in the Kingdom. The battery storage begins charging at 08:00, coinciding with sunrise, and continues charging until 16:00, reaching 50% of its capacity. Discharging starts at 17:00 and continues until the end of the day.

However, in summer, the situation differs, Figure 47 below shows the system's performance on a summer day. Battery storage is required to supply the grid demand of approximately 70

GW to 79 GW for 7 hours at the beginning of the day after midnight (from 1 AM to 7 AM). At the end of the day, when the sunset occurs, an additional 6 hours of storage supply is needed, from 19:00 to 24:00. The storage is also partially utilized to supply the remaining grid demand when PV production is insufficient due to less sun radiation. For instance, at 19:00, the Kingdom's demand reached 84,496 MW, with PV generating only 20,992 MW, creating a shortage of 63,503 MW. This gap was bridged by the storage system. After 19:00, the storage continued to fully supply the grid's demand until 24:00, when the day ended.

In the same Figure, it can be noticed that there is no surplus power. The grid utilised all the PV power in the daytime from 7:00 AM to 19:00 while the remainder of the produced energy was fully supplied to the battery storage for later discharge at nighttime. Suppose the summer day would be compared to a winter day. In that case, the Kingdom's demand is notably higher than in winter, nearly double, due to the extensive use of air conditioning systems in every occupied building. As highlighted in earlier sections, these air conditioning systems are almost entirely powered by electricity, contributing to the increased demand during the summer months. Additionally, the duration of PV system generation is longer in summer than in winter. During summer, the PV system generates electricity for 13 hours (from 7:00 to 19:00), while in winter, the production period is shorter, limited to 10 hours a day (from 9:00 to 18:00). As a result, less storage supply duration is required in summer. In summer, 7 hours of storage energy supply is needed after midnight until sunrise, while after sunset, only 6 hours of storage supply is required.

The battery energy capacity level in this summer day did not drop below 47%, as there are higher total PV production and more hours of sunlight. In contrast, during the winter day, the storage energy level tends to approach near-empty levels due to the shorter duration of PV generation and the lower overall PV output, resulting in reduced battery charge rates. Another important point is that in summer, the absence of clouds during almost all hours of the day contributes to a more consistent and reliable PV generation, as shown in Figure 47. This results in higher and more predictable energy production compared to the winter months, where cloud cover can reduce solar output. The PV production increases gradually after sunrise until afternoon, and then it decreases gradually until the sunset without lower random drops during the day in summer.

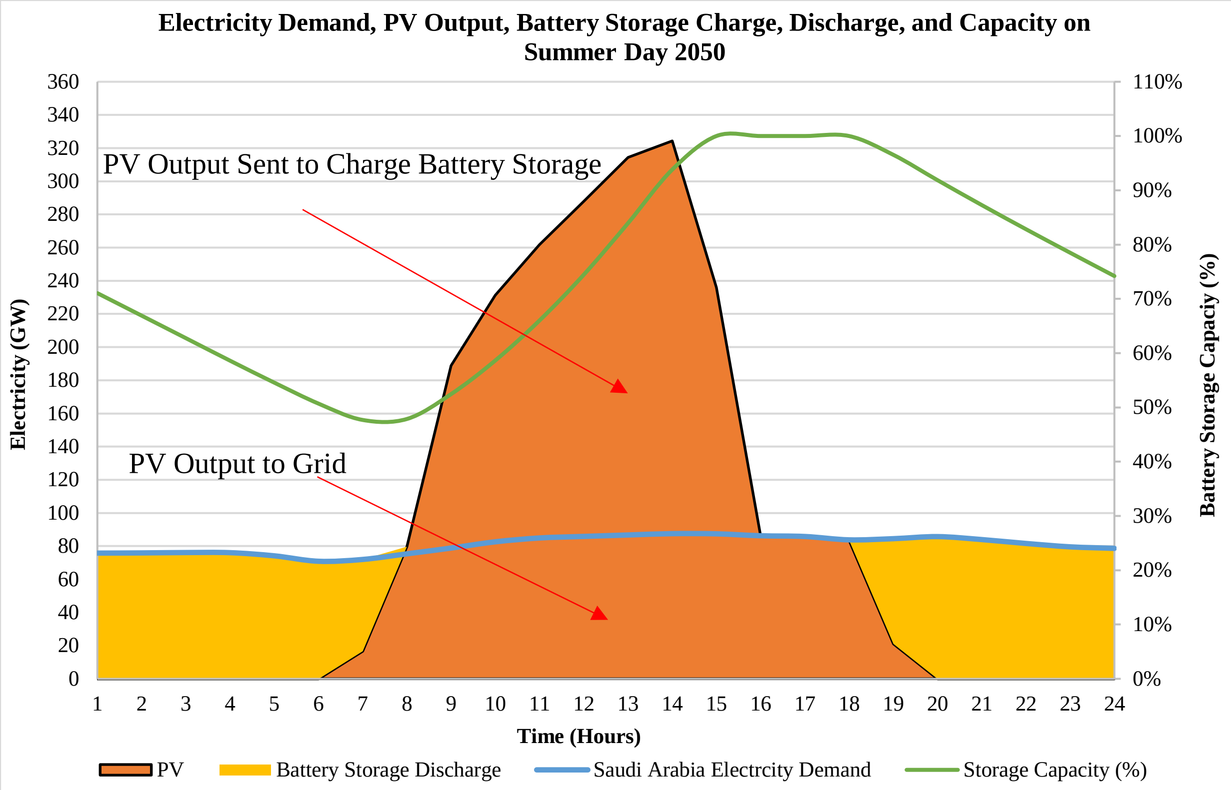

Figure 47 Electricity demand, PV output, battery storage charge, discharge, and capacity on summer day 2050 [Author: constructed from simulations].

To understand the designed capacities of the battery storage and PV system, the hourly demand for the entire year was analysed in relation to the hourly PV production, battery storage capacity, and battery charge/discharge capacities. The simulation results are presented in Figure 48 below. The worst-case hour of the year was identified: in the early morning of the summer at 7:00 AM. The worst-case hour refers to the time when the grid completely depletes the energy stored in the battery during a specific period. This situation arises when the demand exceeds the available solar generation, prompting the use of battery storage to cover the shortage, ultimately exhausting the storage capacity.

To understand why the remaining energy was fully consumed on that particular day, the hourly graph in Figure 48 includes data from two days before and two days after the worst-case day. Analysing days 1, 4, and 5, it is evident that the storage energy level does not drop below 10% to 20% on days 3 and 4 and remains around 40% on day 1. Day 3 represents the critical point where the usable energy in the storage is completely depleted. Upon examining the day prior to the depletion (day 2), we observe that the peak of the storage's usable energy amount is lower than the peaks observed on both the preceding and following days. This suggests that the storage did not charge sufficiently, resulting in insufficient energy reserves to meet the demand.

On day 1, for example, the storage was nearly fully charged, while on day 3, it had been charged to approximately 70% of its capacity. By day 5, the storage had reached about 90% of its capacity. On day 2, the maximum energy amount reached 58% of the total battery storage capacity, which is less than other regular summer days. The reason for this is shown in the same graph: the PV production. PV production that day was less than other regular summer days in both the maximum peak and the PV output power in total (the width of the PV production graph). The maximum **peak** and **duration (width in the graph)** of PV generation were lower on that day compared to all other days. This reduction was caused by passing clouds, highlighting the relationship between cloud cover and the storage capacity. **This indicates that the occasional passing clouds in summer have a more pronounced impact than in winter**. This is due to the substantially higher demand in the Kingdom during summer, meaning that any reduction in PV generation can result in more significant effects. This is further corroborated by the fact that the worst-case scenario occurred in summer, despite winter experiencing more frequent cloud cover. The worst-case point not occurring in winter highlights **the greater influence of demand and the sensitivity of the system to PV generation reductions during the summer months.**

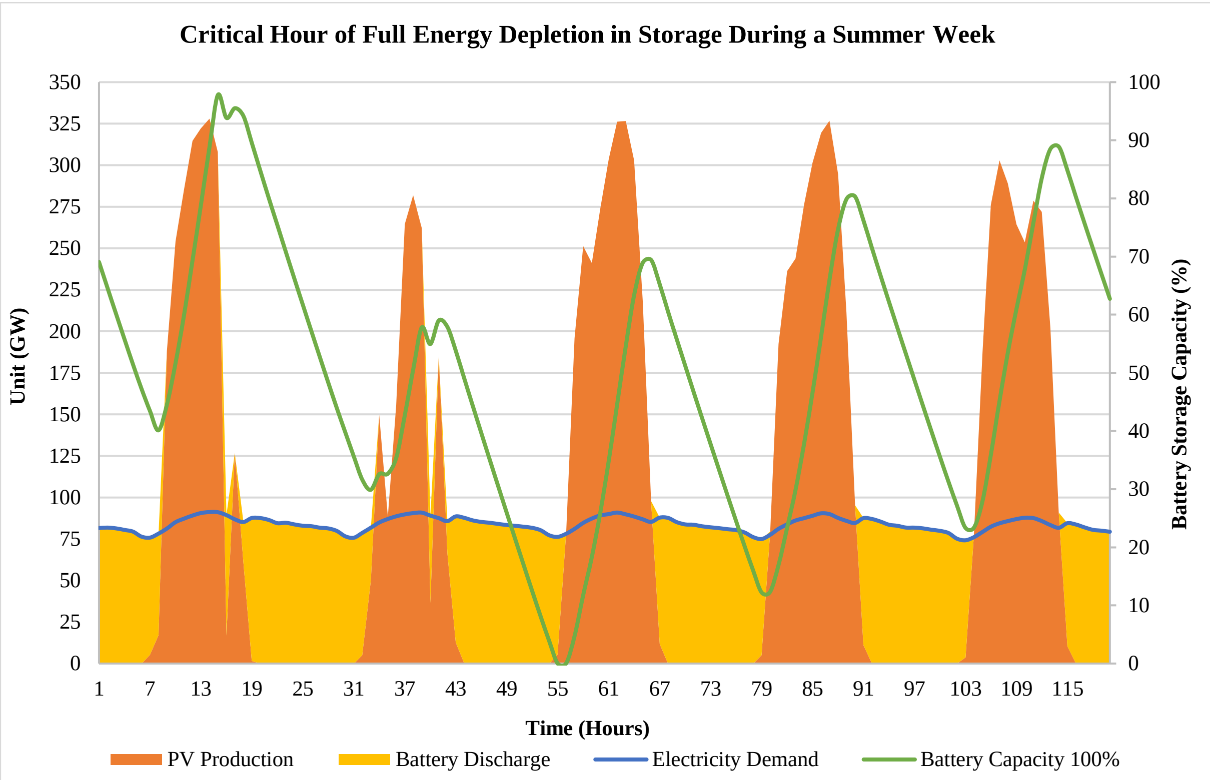

Figure 48 Worst hour point when the remainder of energy storage was fully utilised on summer week [Author: constructed from simulations].

From the above graph in Figure 48 and discussion, it can be concluded that the current designed storage capacity of 2,039 GWh is the minimum required to avoid shortage and imports in the worst-case scenario hour, which is the primary goal of this system. To validate this conclusion, the storage capacity was reduced by 1 GWh, decreasing from 2,039 GWh to 2,038 GWh. The simulation results revealed a partial shortage in grid demand at the same critical hour (Hour 55, corresponding to 7:00 AM on the third day) as observed in Figure 48. At this hour, the grid's electricity demand was 76,274 MW, while PV production contributed 5,404 MW, and the storage system discharged 69,971 MW. The combined supply from PV and battery storage amounted to 75,375 MW, resulting in a shortage of 900 MW compared to the grid demand of 76,274 MW. The simulation results for the reduced storage capacity are conveyed verbally rather than illustrated graphically, as the minimal energy deficit is not sufficiently pronounced to be clearly represented in graphical form.

The same methodology applies to the PV designed capacity of 577.109 GW. Suppose the storage capacity is returned to its original design value at 2,039 GWh, and the PV production capacity was reduced by 100 MW decreasing to 577.009 GW. In that case, the simulation results indicate that a shortage will occur at the same earlier worst point hour when the storage capacity was reduced. The demand at this hour was 76,274 MW while PV generation contributed 5,403 MW, and the battery storage system discharged 70,358 MW. The total energy supply from PV+Battery storage amounted to 75,761 MW compared to the grid demand of 76,274 MW which resulted in a shortage of 513 MW in energy supply. This means that the system has failed to achieve the first design goal; the 100% grid supply every hour in the year, day and night, without any shortage and the need for import in this closed system.

This small reduction in PV capacity is difficult to observe in graphical representations. Consequently, the PV capacity was further reduced by a larger amount—2,000 MW—resulting in a total capacity of 575,109 MW to clearly illustrate the effects. The simulation outcomes are presented in Figure 49.

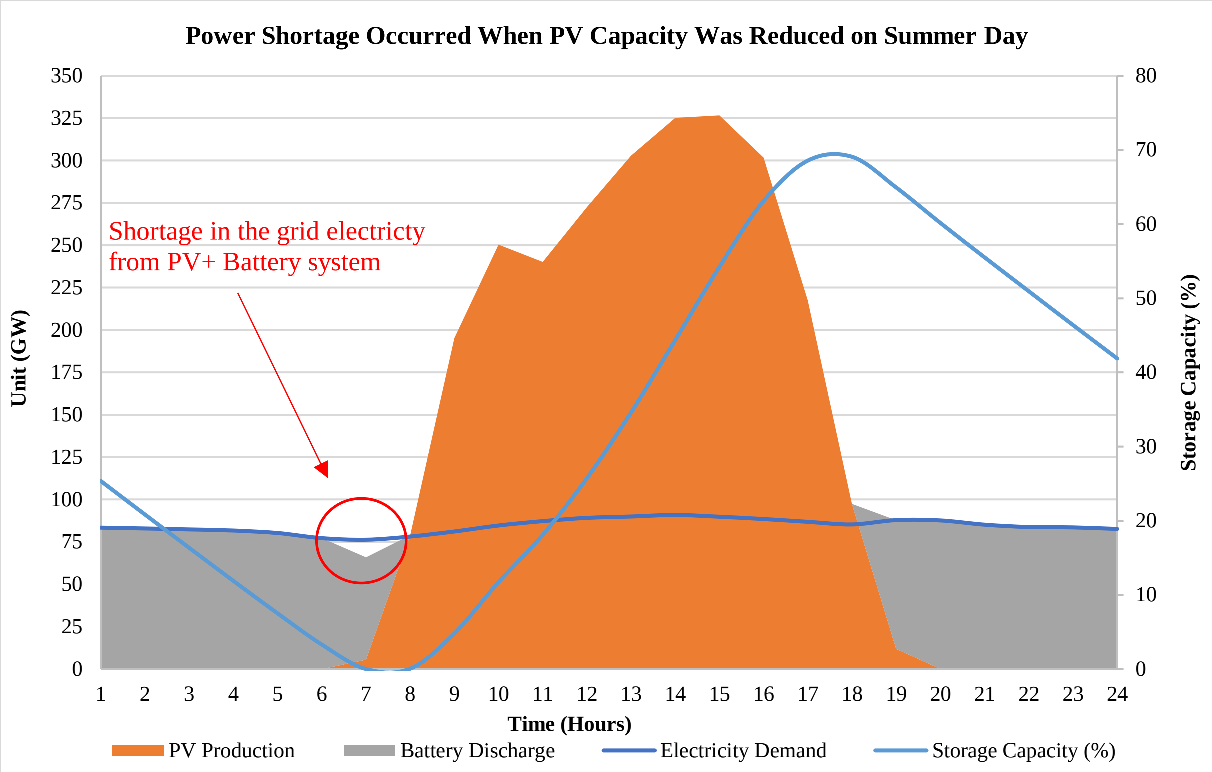

Figure 49 Shortage occurred when PV Capacity was reduced on summer day [Author: constructed from simulations].

Figure 49 illustrates the impact of reducing the PV capacity below its originally designed value. A shortage is observed during the same critical hour, at 7:00 AM. At this point, the grid demand reached 76,274 MW, while the PV production contributed 5,385 MW, and the battery storage discharged 60,576 MW before being fully depleted. The PV+Battery storage system's total energy supplied to the grid was 65,961 MW compared to the grid demand of 76,274. This resulted in a shortage of 10,313 MW in energy supply to the grid. Even if the PV designed capacity was decreased by only 1 MW, a shortage will occur, and imports will be needed. However, the PV designed capacity was reduced by 2,000 MW for more straightforward graph observation and clarity, as shown in Figure 49.

In conclusion, PV+Battery storage system was designed to fully supply the grid demand day and night without any shortage with the least power plant capacity and resources required based on the worst-case scenario day in the year as the system's primary goal.

In terms of the battery storage, to better understand the designed value of the storage capacity, it is essential to look at Figure 50 below.

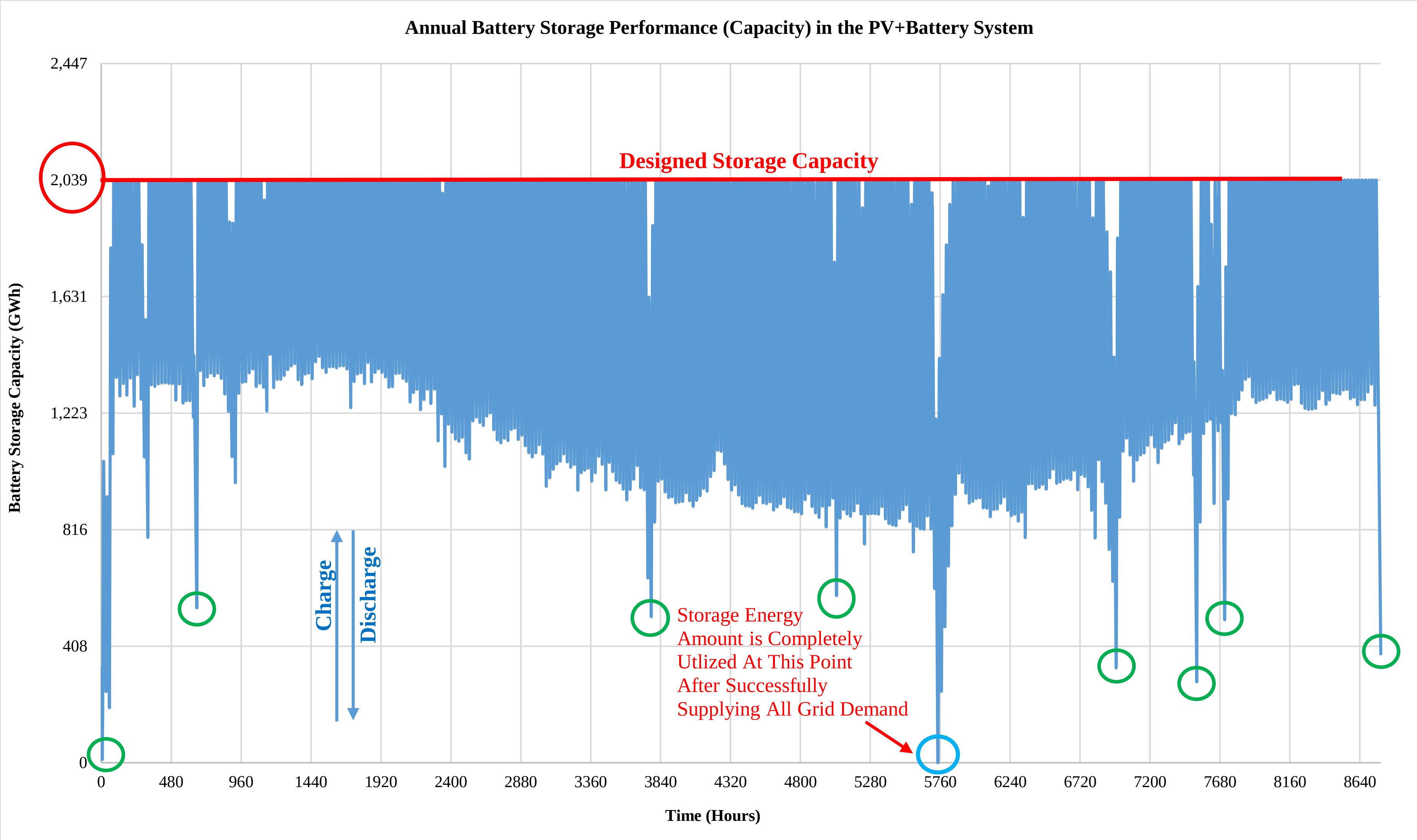

Figure 50 Battery storage hourly capacity in 2050 [Author: constructed from simulations].

Figure 50 shows the hourly battery storage capacity in GWh for the entire year. The battery storage capacity represents the final sum of the charge and discharge, including losses in each specific hour. The charge represents the energy supplied from the PV surplus, which remains after the grid demand has been fully met. This surplus is then stored in the battery. The discharge represents the energy supplied from the battery to the grid during nighttime or when the PV supply is insufficient during specific hours, such as early morning hours in Saudi Arabia. For instance, at 7:00 AM in the summer, both the PV system and the battery often simultaneously supply the grid on certain days. When PV generation is active, it prioritizes supplying the grid demand during periods of solar radiation. Any surplus energy is subsequently directed to battery storage, with a maximum charging rate of 236 GW. For example, assuming that the PV surplus at a specific hour was 114,703 MW and the storage content at the same hour was 816,734 MW. This surplus power will then be stored in the battery storage after counting the charge loss (efficiency 85%), and the new storage content will equal to 914,231 MW, calculated as follows: $114,703 \times 0.85 + 816,734$ MW = 914,231 MW. The storage will then keep the energy content until the grid is demanding, i.e., at night or early morning hours.

The discharge capacity each hour will be completely dependent on the grid demand, and it will last for approximately 15 to 16 hours on a specific day, i.e., from 18:00 on the first day up to 8:00 AM or 9:AM on the second day. Then, it will charge again on the second morning, and the same process will go on with new storage content every hour after the final cumulative result of charge/discharge/losses calculations. Throughout the year, the cumulative calculations of charge, discharge, and losses (final storage capacity in Figure 50) will fluctuate. For example, on some days, the storage content will not fall below 1,200 GWh, indicating that the storage fully received the surplus from PV and subsequently discharged the necessary energy to meet grid demand. This is especially true in winter when the demand is approximately half of that in summer, leaving around 1,200 GWh of extra energy available for use on other days.

On another day, the storage energy capacity was fully charged from the surplus energy supplied by the PV, and then, the storage discharged the required energy to meet the grid demand. Despite this, the storage content remained at a level of 407 GWh and did not drop below that. This greatly depends on the PV power availability and the grid demand each hour. During certain hours of the year, the storage energy level is fully depleted after successfully charging from PV generation and discharging to meet the grid demand during the night. For instance, on a specific day, the storage energy level reached 164,614 MW at a particular hour, while two more hours of grid demand remained before sunrise when PV generation could begin. The grid demands for these last two hours were 77,282 MW and 70,871 MW, respectively.

To meet the first hour's grid demand, the battery discharged 85,869 MW, accounting for a 10% discharge loss. This resulted in a net supply of 85,869 MW × 0.9 = 77,282 MW. Similarly, during the last hour, the required discharge from the battery was 78,745 MW. After accounting for the 10% discharge loss, the net supply was 78,745 MW × 0.9 = 70,871 MW. Consequently, the storage system successfully supplied the grid demand for these two hours before PV generation started resulting in the complete depletion of the battery storage capacity.

After supplying the remaining demand, the battery storage energy was completely depleted. Prior to the last two hours, the storage energy level was 164,614 MW, which, after subtracting the total discharge for the two hours (85,869 MW + 78,745 MW), resulted in a depletion of the battery capacity to zero. This situation was exactly what occurred in the most critical point of the year, as illustrated in the blue circle in Figure 50.

The green and blue circles in Figure 50 are the most critical hours in the year when the storage is either almost utilised or completely utilised after the successful grid supply without any shortage and needed energy imports. The decreased designed battery storage, even by 1 GWh, will lead to immediate shortage in all the critical hours starting from the most critical to the least critical as the designed capacity is decreased. The first shortage will occur in the most critical point, which is in highlighted the blue circle, then to the first green circle to the left at the beginning of the year, and the procedure will go on. From a graphical perspective, decreasing the storage size will lead to the same battery storage capacity ‘’pattern’’ as shown in the graph **but with** a lower-level line. The same pattern will occur, but it will fall below the x-axis, indicating that negative values will be present on the x-axis. These negative numbers in the graph represent a shortage. In other words, an energy that is required to be supplied by the storage at a specific hour, but the storage is depleted and unable to provide it.

The storage capacity of 2,039 GWh represents the minimum required capacity, determined after accounting for all cumulative calculations of charging, discharging, and losses across every hour of the year. For instance, if the designed capacity was reduced to 1,631 GW, the entire graph would shift downward. This would result in lower stored energy from the first hour of the year, with energy accumulation occurring hour by hour and day by day. Eventually, this would lead to a critical demand point where the storage would be unable to supply sufficient energy. The same with the designed charge capacity, which is the minimum charge capacity (energy input) required to complete the balance between input, output energies, and losses. As is shown in the Figure 51.

In Figure 50, upon examining the graph, it is observed that in approximately 90% of all hours, the storage level did not drop below 815.6 GW, suggesting that the storage capacity is larger than necessary. Therefore, the designed storage capacity could be reduced. However, decreasing the storage will lead to a shortage in all critical hours of the year, which violates the primary goal of this system, which is the system's ability to maintain grid demand all hours of the year without any shortage or import. This also indicates the **limitation** of using PV+Battery system alone to 100% supply a huge country demand such as Saudi Arabia. Since increasing the battery storage resources will be at significantly higher level to only supply some critical points in the year.

To understand the causes of the critical points mentioned earlier. It is essential to know that these critical points occur because of three reasons. The first reason is the higher demand beyond the storage and PV supply capabilities. The second reason is reduced PV production, which can occur due to cloud cover or a temporary stop in generation. The last reason is because of both reasons, one and two, as shown in Figure 51 below. In this Figure, the hourly data of the entire week when the critical point occurred (days before and days after the critical point so it can help in understanding) are shown. These hourly data are the battery storage charge rate, discharge rate, and battery storage capacity. Looking at the blue curve representing the battery storage capacity, on Day 1, the battery storage capacity was 1,362 GW at 1:00 AM, as indicated on the right-hand y-axis. The battery storage was discharging power to meet the grid demand until 9:00 AM, with a remaining capacity of 816 GW. At this point, its status changed from discharging to charging, as the PV power plant began generating electricity. The battery was then recharged until 15:00, reaching its full capacity of 2,039 GW. The battery then discharged power to grid demand at 19:00 for 13 continuous hours (from 19:00 to 7:00 AM the next morning.

The same procedure of the first day occurred in the remainder of the days as shown in the graph. In the second day, the battery discharged the power to the grid demand and reached a minimum capacity of 864 GW with a maximum energy capacity of 2,039 GW again. In the regular days of operation as the first three days; it can be noticed from the graph, that the battery is charging to full capacity (when the blue curve hits 2,039 GW at the red line), and at the same time, the remainder of energy storage is also at the same level. On the critical point day, a noticeable difference is observed in all the curves compared to other typical operational days. The first difference is in the storage capacity curve (blue), where the battery did not reach its maximum designed capacity of 2,039 GW. Instead, it only charged up to 1,203 GW, which is nearly half of the required energy storage, reflecting a significantly lower peak than on regular operational days. This is due to the lower charge rate on this day, as shown in the grey curve in the same graph. This is the charge rate curve; showing the amount of energy charged every hour to the storage by the PV. In the first average operation days, the charge rate reached the full charge designed capacity of 236 GW (when the grey curve hits the green line of maximum charge rate). On the critical point day, the charge rate was significantly lower than on other regular operation days; it is lower in both the **peak** and **width** of the graph compared to other days, indicating a lower power input sent from the PV, as shown later. The second difference in the critical point day is that the Kingdom's electricity demand was higher than other regular operation days. This is noticed in the higher width discharge curve (yellow curve) compared to other days in the week. Additionally, the increased electricity demand is evident not only in the discharge curve but also in the storage capacity curve.

The storage capacity curve at that day reached to a lowest value at 609 GW than the first regular days at 815 GW. This indicates that the amount of energy consumed from the storage that day was higher than the amount consumed from the storage on other regular days. The lack of sufficient solar energy, coupled with an increased demand, resulted in the storage capacity reaching zero after effectively meeting the grid demand during the night, before the storage began to recover in the subsequent days. If the storage designed capacity was less than 2,039 GWh, say 1,631 GWh, then from the same graph, the first three days' storage capacities will have lower peaks at 1,631 GW instead of 2039 GW; this will have a cumulative effect on all other days. This implies that the effects from one day will carry over to the next: day one will impact day two, day two will affect day three, and so on, until this cumulative effect reaches the critical point day. On this day, the storage capacity curve (as shown in the graph) will drop below zero (into the negative x-axis), resulting in an inability to meet grid demand and causing a shortage, which contradicts the primary objective of the system.

From Figures 50, 51, 52, and 53, it can be concluded that in the PV+Battery system for Saudi Arabia in 2050, the battery energy capacity of 2,039 GWh is confirmed to be the lowest designed storage capacity required to fulfil the demand each hour of the year with no shortage, including normal operation days and days with critical points such as the days highlighted in green circles and most critical blue circle point in Figure 50. The battery discharged energy for the nighttime grid demand from Figure 51 is shown in numbers in Figure 52. Figure 53 shows the PV supply during the most critical point day in the same week.

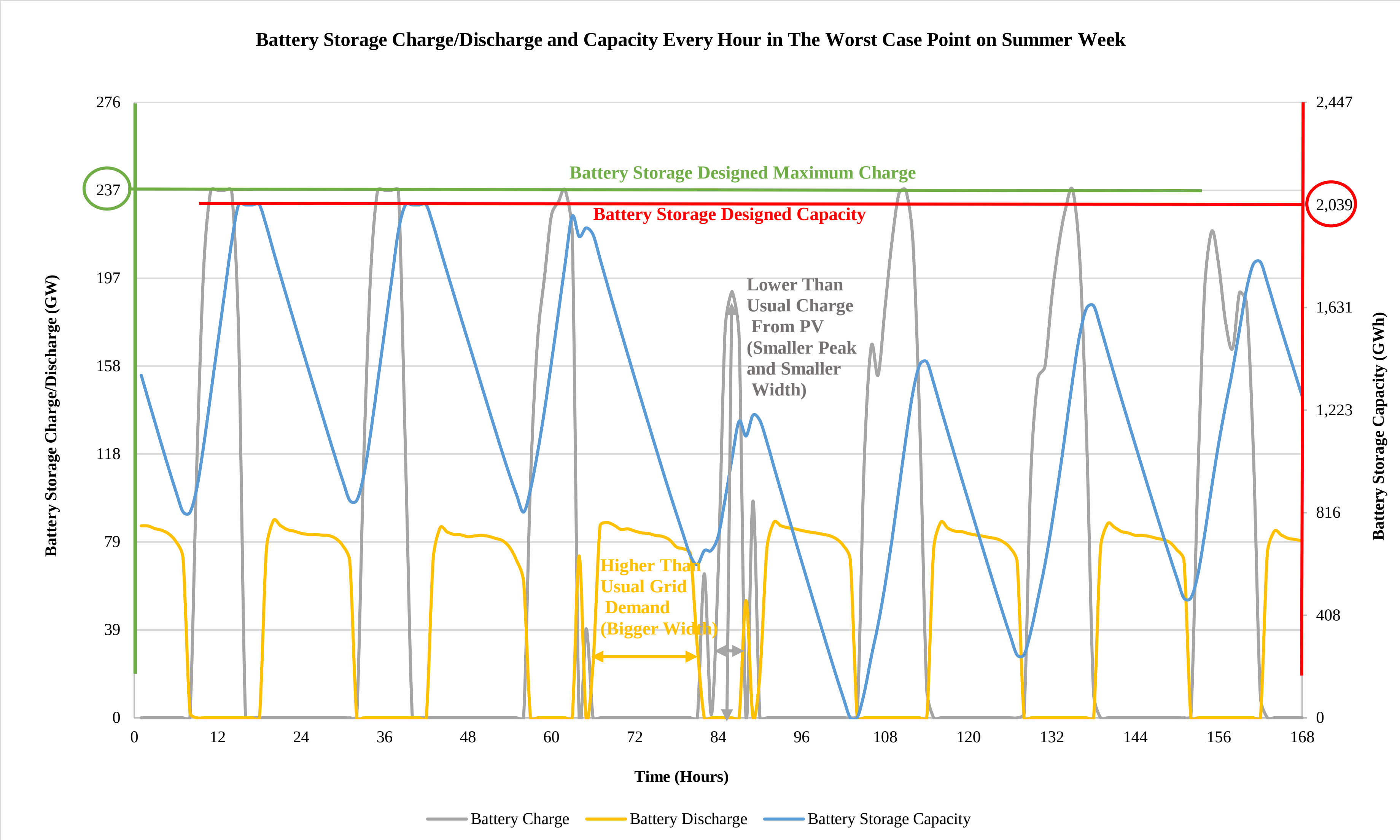

Figure 51 Battery Storage charge/discharge and capacity every hour in the worst-case point on summer week [Author: constructed from simulations].

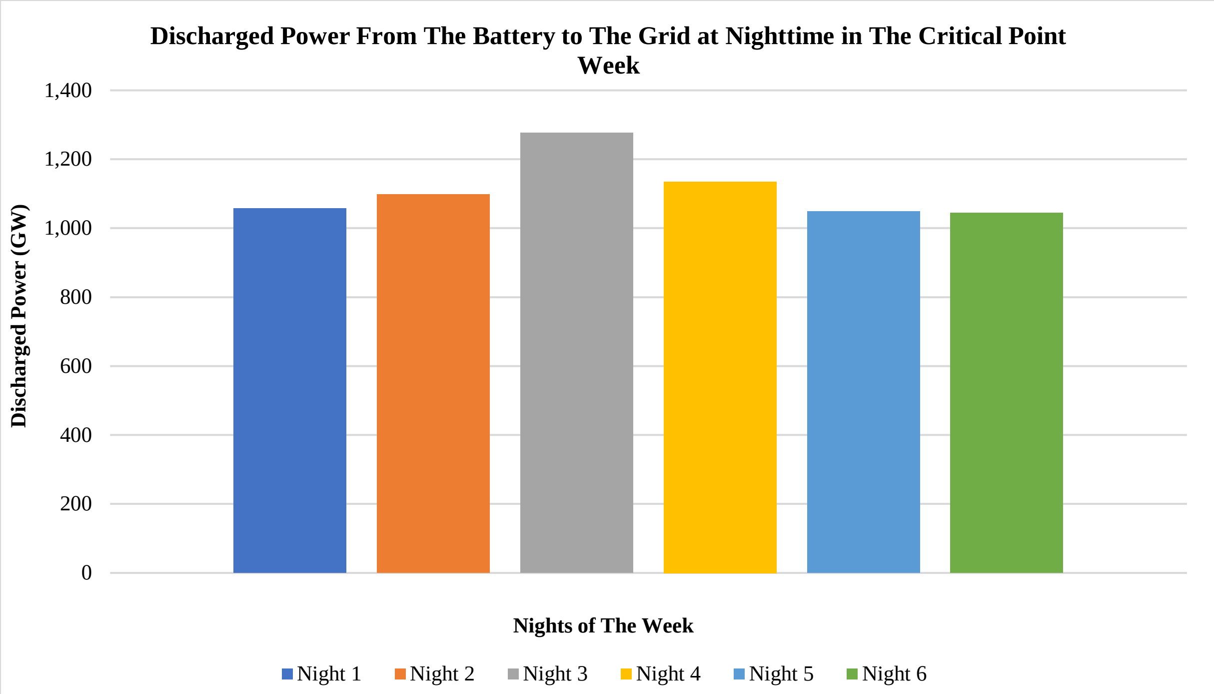

Figure 52 Discharged power from battery to the gid at nighttime in the critical point week [Author: constructed from simulations].

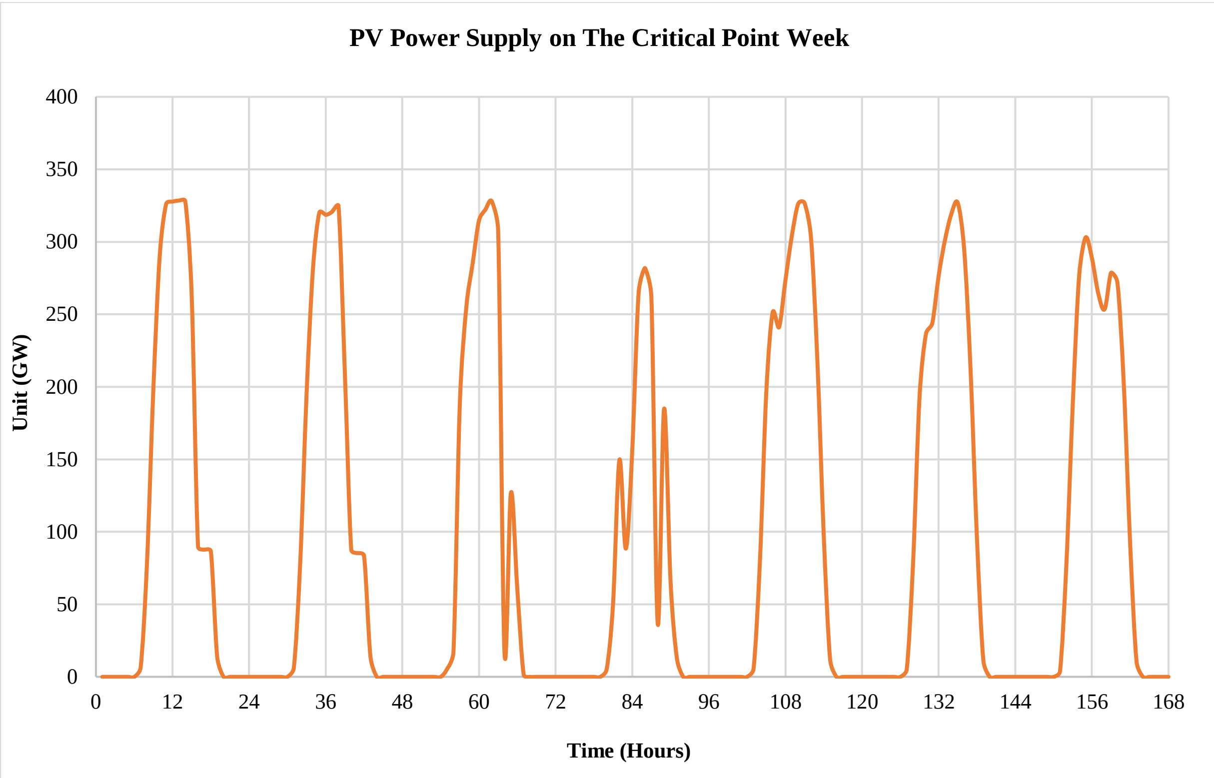

Figure 53 PV Power supply on the critical point week [Author: constructed from simulations].

Figure 52 quantitatively illustrates the discharged energy levels at night, corresponding to the yellow curve in Figure 51. Notably, on the third night, the evening prior to the point at which storage capacity reached zero, demand was significantly higher than on typical operational days. This suggests that storage energy had been substantially depleted the night before this critical event. Furthermore, the following morning on day 4, PV generation was noticeably lower compared to standard operational days, showing a reduced peak and a narrower production period, as shown in Figure 53.

Table 18 Simulations results of RES solutions

	PV	PV + Battery	Wind	Wind+ Battery	Wind+PV	PV+Wind+ Battery	PV+Wind+ Battery Optimized
Installed Capacity (GW)	577.1	577	1,662	262	Wind 600 PV 115.403	Wind 132.109 PV 195.405	Wind 150.398 PV 195.405
Storage							
Storage Type	None	Battery	None	Battery	None	Battery	Battery
Storage Capacity (GWh)	0	2,039	0	639.6	0	639.6	400
Storage Charge/ Discharge Efficiency (%)	0	85/90	0	85% / 90%	0	85% / 90%	85% / 90%
Storage Charge/ Discharge Capacity (GW)	0	236 / 91	0	65/ 64	0	40/ 57	42/ 52
Annual Average Charge/ Discharge (GW)	0	45/ 34	0	3.54 / 2.70	0	3.23 / 2.47	2 / 1.5
Annual Maximum Charge/ Discharge (GW)	0	236 / 91	0	65 / 64	0	40 / 57	42 / 52

Annual Minimum Charge/	0 / 0	0 / 0	0	0 / 0	0	0/0	0/0
Energy (TWh)							
Total Energy Produced by Renewable	251	652	558	565	Wind 383 PV 174	Wind 334 PV 230	Wind 337 PV 225
Total Energy Charged to Storage	0	401	0	31.10	0	28.41	18.14
Total Energy Discharged by Storage	0	307	0	23.79	0	21.73	13.88
Surplus Energy	0	0	0	0	0	0	0
KPI's							
System Ability to avoid shortage hour by hour all year (%) (Energy security)	41%	100%	100%	100%	100%	100%	100%
Total Electricity Import (TWh)	307	0	0	0	0	0	0
RES share of Electricity Production (%)	45 %	116.9%	100%	101.3%	100%	101.2 %	100.8%
Total Power Generated (Without Stopping Surplus)	1,052	1,052	6,754	1065.27 TWh	Wind 2,438 PV 210	Wind 536 PV 356	Wind 611 PV 356

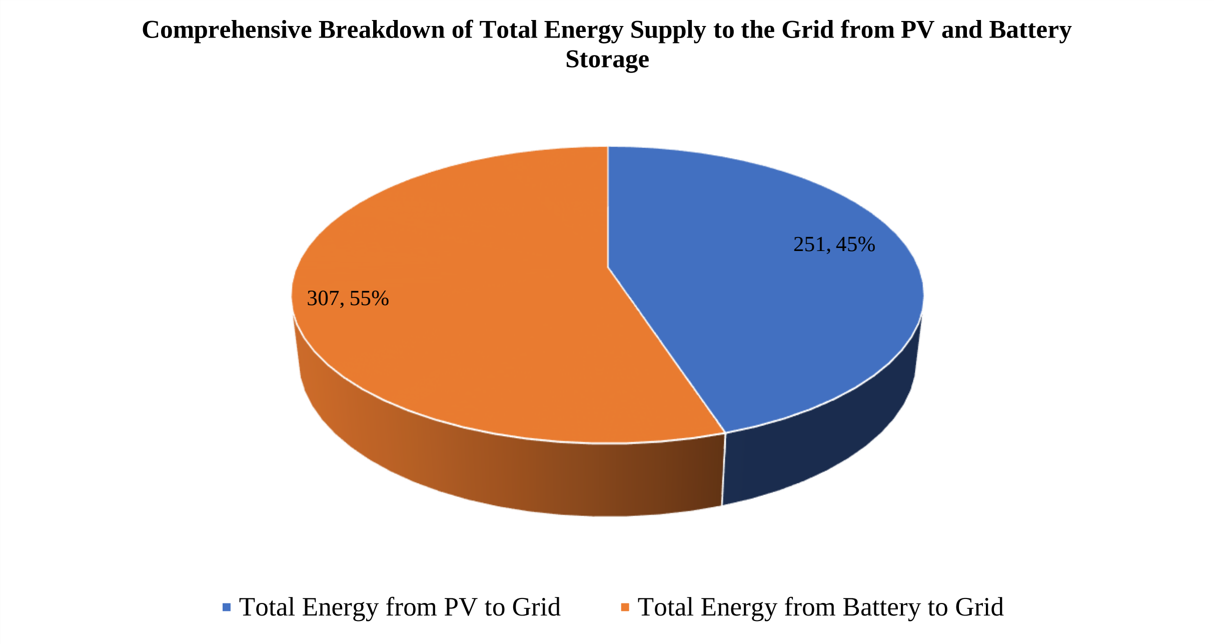

Figure 54 The breakdown of the total energy supplied to grid from PV+Battery RES [Author: constructed from results].

Figure 54 illustrates the total energy delivered to the grid, with PV supplying energy during the daytime and battery storage providing power during nighttime and early morning hours. During the day, PV contributed 251 TWh, which constitutes approximately 45% of Saudi Arabia's projected electricity demand in 2050. At night and during certain early morning periods, battery storage provided 307 TWh, accounting for around 55% of the Kingdom's total electricity demand.

4.3.2 Wind / Wind+Battery Storage

4.3.2.1 Wind Farm Potential Location and Data

Wind has proven to be an excellent renewable energy resource by many research papers in Saudi Arabia. Research has demonstrated the viability of utilizing wind power in northern Saudi Arabia, particularly in areas like Tabuk and Alwajh. These locations, along with the newly developing futuristic city of NEOM, offer optimal wind speeds and significant power potential. Studies, including those referenced in [217], have assessed the feasibility of Saudi Arabia's first large utility-scale wind farm, the 400 MW Dumat Aljandal Wind Farm Project. Located in the northern region of Dumat Aljandal, this is the largest wind farm in the area, and evaluations using SAM have confirmed its viability for large-scale utility use. This project is a part of the Saudi Arabian government's plan to diversify its energy mix to reach 50% of the electricity supply from RES by 2030. Another study [218] identified the best locations for siting wind farms over Saudi Arabia in summer with low-risk wind turbine disruption with wind speeds exceed 9 m/s for at least half of the time in summer, and the risk of disruption of wind turbine operations is lower than 1% probability using Bayesian Spatial extremes. These locations were on the western coast of Saudi Arabia, with the majority in the northwest part of Saudi Arabia near and in the futuristic NEOM city. Paper [219] provided analytical assessment of the feasibility of wind energy in Saudi Arabia's NEOM city. In this paper, the researchers found the wind speeds pattern in the city by the method of minimising the mean squared error of the difference between the Weibull distribution and the empirical distribution and concluded that wind farms are viable both technically and financially in NEOM city for commercial use.

A significant limitation noted in wind studies and in this thesis is the absence of actual measured production data from wind turbines in these high-potential wind areas. Saudi Arabia has started to develop RES projects for large-scale use only recently, such as the 400 MW wind farm, that was connected to the grid in 2022. This wind power plant still does not have readily available hourly data for researchers and engineers. In addition to the discussed studies, Figure 55 shows the mean power density from the Global Wind Atlas with the latest 2023 update.

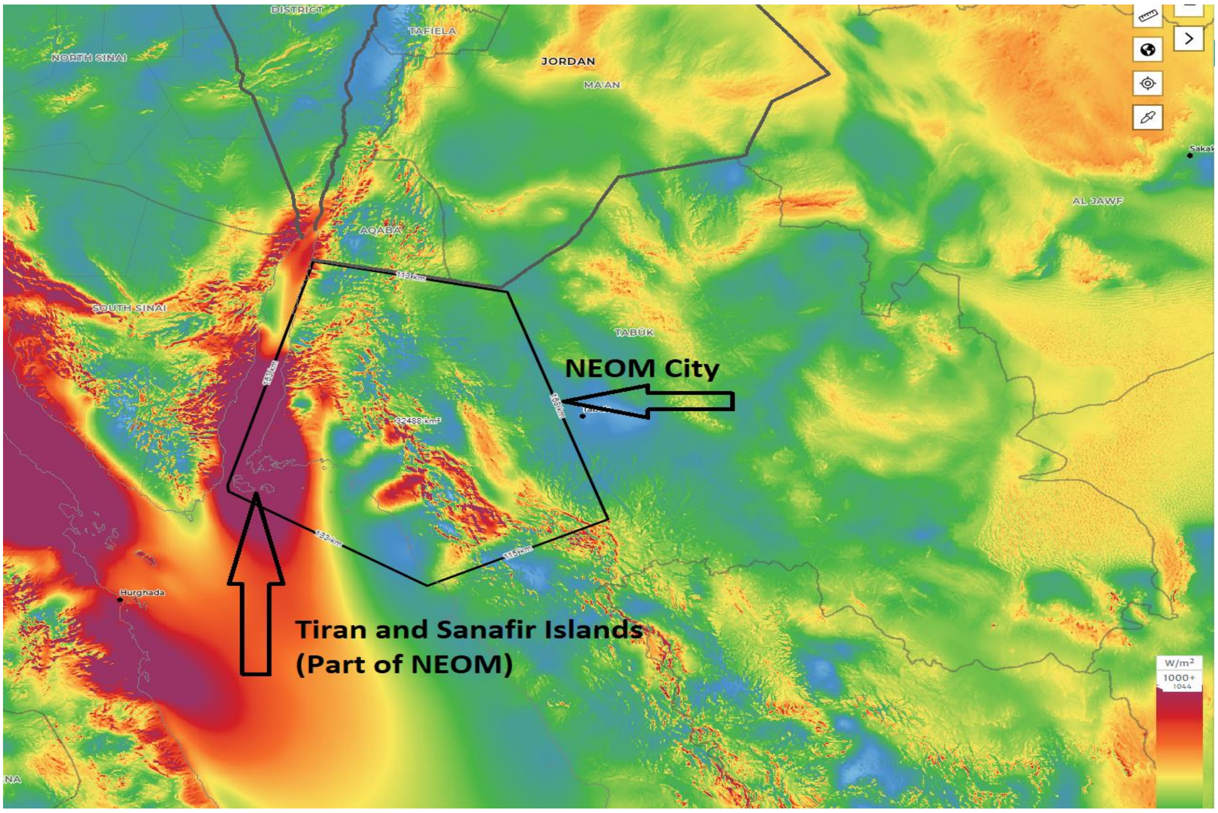

Figure 55 Mean wind power density for NEOM city in Saudi Arabia [Global Wind Atlas 2023].

Based on the results from the earlier research papers and the mean power density from the Global Wind Atlas in Figure 55, NEOM city was considered as the location of the wind power plants in this study.

4.3.2.2 Simulation Methodology and Results

For the data of the distribution file in EnergyPLAN, there are still no historical wind power data in this area from large-scale wind power plants. This is because Saudi Arabia is still new to the RES field and only recently started to build large-scale RES such as the 400 MW wind farm, connected to the grid only last year. Thus, the required distribution file data was taken from the model of Staffell & Pfenninger [220]. Staffell & Pfenninger have developed a model for simulating the hourly output from wind farms anywhere in the world and validated it across 23 countries. This model utilizes the MERRA and MERRA-2 reanalysis datasets developed by NASA, with adjustments made to correct wind speed biases. These biases previously resulted in significant errors in average wind capacity factor estimates, ranging from underestimations of 30% in countries like Portugal and Romania to overestimations of 60% in regions such as Germany and Denmark. They developed mathematical equations to correct this bias, which depends on the region's historical and simulated capacity factors. After their correction was applied in this model, the simulated capacity factors can replicate historic data with exceptional accuracy.

Reanalysis - the output from global atmospheric simulations- is the process whereby an unchanging data assimilation system is used to consistently reprocess meteorological observations, typically spanning an extended segment of the historical data record. The process relies on an underlying forecast model to combine disparate observations in a physically consistent manner, enabling the production of gridded data sets for a broad range of variables, including ones that are sparsely or not directly observed. As such, and with appropriate consideration of the inherent uncertainties, reanalysis products have not only become a staple of the atmospheric research community but are used increasingly for climate monitoring as well as for business applications in, for example, energy and agriculture [221]. Reanalysis models are rapidly gaining popularity for simulating wind power output due to their convenience and global coverage [220]. The wind farm parameters considered in the distribution file data are shown in Table 19.

Table 19 Initial wind farm parameters used to generate the hourly power output for EnergyPLAN distribution file.

Data set	MERRA-2
Data set Year	2017 to 2022 Average
Wind Farm Location Coordinates	NEOM, Saudi Arabia (Lat 28.56, Lon 34.9)
Wind Farm Initial Capacity (GW)	20
Wind Farm Hub Height (M)	80
Turbine Model	GE 3.2 130
Capacity Factor	45.5 %
Turbine Cut in Speed (m/s)	2 m/s
Turbine Cut Out Speed (m/s)	25 m/s
Turbine Power Capacity (MW)	3.2 MW

The hourly generated wind power data was calculated based on the average of the historical (from 2017 to 2022) weather data. The generated data for the EnergyPLAN distribution file from the model of Staffel and Pfenninger has been validated in the Saudi Arabia location in terms of the capacity factor by comparing the model output to the wind farm output from the research paper in NEOM [219]. In this study, the capacity factor of the GE 3.2-130 turbine at an 80-meter hub height in 2017, located at coordinates Latitude 28.15 and Longitude 34.75, was approximately 42.5%. In comparison, the Staffel and Pfenninger model, using the same turbine specifications, hub height, location, and year, yielded a capacity factor of 45.6%. The difference of 6.7% between the two values demonstrates that the Staffel and Pfenninger model provides a reliable framework for simulating wind power output in Saudi Arabia

For this study, the location coordinates, wind farm initial capacity, hub height and turbine model were selected, as shown in Table 19. Starting with the location coordinates. It was found that in the same NEOM city if the location coordinates are slightly changed, it would give more optimal wind energy power output than the location of [219] in NEOM. The initial design capacity of wind energy is required as an initial input to calculate the hourly power output. This value can be adjusted later within the EnergyPLAN model after incorporating the distribution file and integrating it with the rest of the system. Adjustments are made following the completion of simulations to ensure alignment with overall system requirements. Hub height must also be selected, as the hub height of the wind turbine usually differs from the height at which meteorological stations take the wind measurements. Hub height was selected at 80 meters as [219]. Turbine model GE 3.2 130 was selected as the optimal turbine with the highest capacity factor in all years in the same paper when compared with 4 other turbines in the same location.

It is crucial to emphasize the significance of location selection in wind power projects. To illustrate this, the same turbine model and hub height, as outlined in Table 19, were analysed for the government's 400 MW wind power plant project in Dumat Al-Jandal, Saudi Arabia (coordinates: Lat 29.56, Lon 40.12), referenced in paper [217]. At this location, the capacity factor was calculated to be 35.6%. In contrast, the capacity factor at NEOM's location under identical parameters is 45.6%. This substantial difference highlights the critical impact of selecting an optimal site for wind energy development.

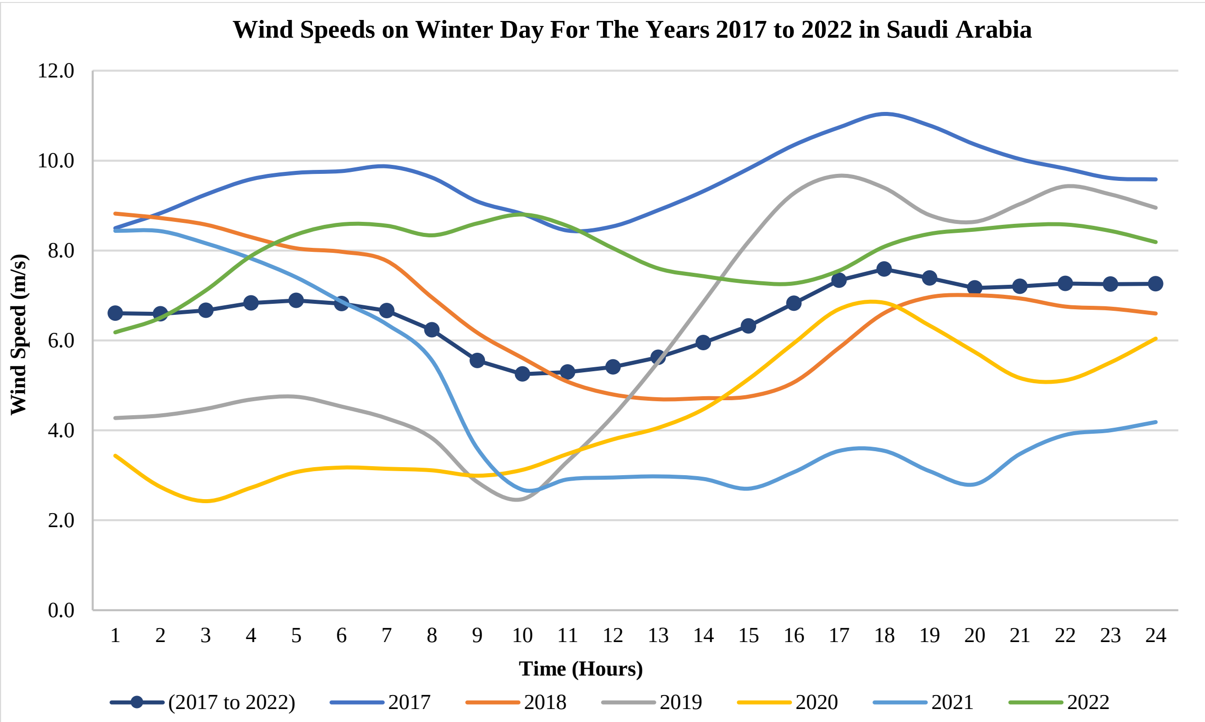

Figure 56 Wind speeds for a winter day in six years (from 2017 to 2022) in Saudi Arabia [Author: excel file constructed from [220] energy model].

Figure 56 shows the hourly wind speeds for one day in a six-year period in Saudi Arabia. The annual wind speed variations necessitate using this project's average wind speed data. Figure 57 shows the average monthly wind speeds for one year. The author manually calculated the wind speeds monthly average based on the hourly values each month. In Figure 57, the wind speeds vary between 6.2 m/s, which occurred in winter, to approximately 8 m/s, the highest wind speed during the year. The lowest wind speeds occur in Saudi Arabia in winter, especially in January, February, November, and December. While the highest wind speeds during the year occur from the spring in March to October, with the summer months have the maximum wind speed peaks. Figure 58 illustrates hourly wind speeds for a winter day and a summer day, showing that wind speeds are notably higher in summer, particularly during nighttime. Winter wind speed is slightly higher in some areas during the day. Notably, wind speeds are higher at night than during the day in both summer and winter. This pattern is advantageous, as in the PV+Battery power plant, most of battery storage demand is at night when PV generation is unavailable. This suggests a strong potential benefit from the addition of wind turbines to the PV+Battery RES to reduce the battery size.

The hourly estimates of wind speeds effectively address the inherent variability of wind through a combination of statistical methods and data processing techniques. Central to this approach is time averaging, which involves calculating the average wind speed for each hour based on second-to-second variations rather than capturing every fluctuation. Additionally, statistical models, such as the Weibull distribution, are employed to estimate wind speed characteristics over time, representing the likelihood of various wind speeds while smoothing out variability.

When continuous data is available, the interpolation method is used to generate hourly estimates by aggregating multiple observations from the same hour. Furthermore, meteorological reanalysis datasets contribute gridded wind speed data at different temporal resolutions, utilising historical weather data that encompasses short-term variations to yield hourly estimates that reflect longer-term trends and patterns. Although wind speed is subject to constant change, the hourly data provides a broader trend useful for energy planning and resource assessment applications.

By integrating these methodologies, these data offer a representative and practical approximation of wind speed that balances accuracy with the need for usability in data analysis.

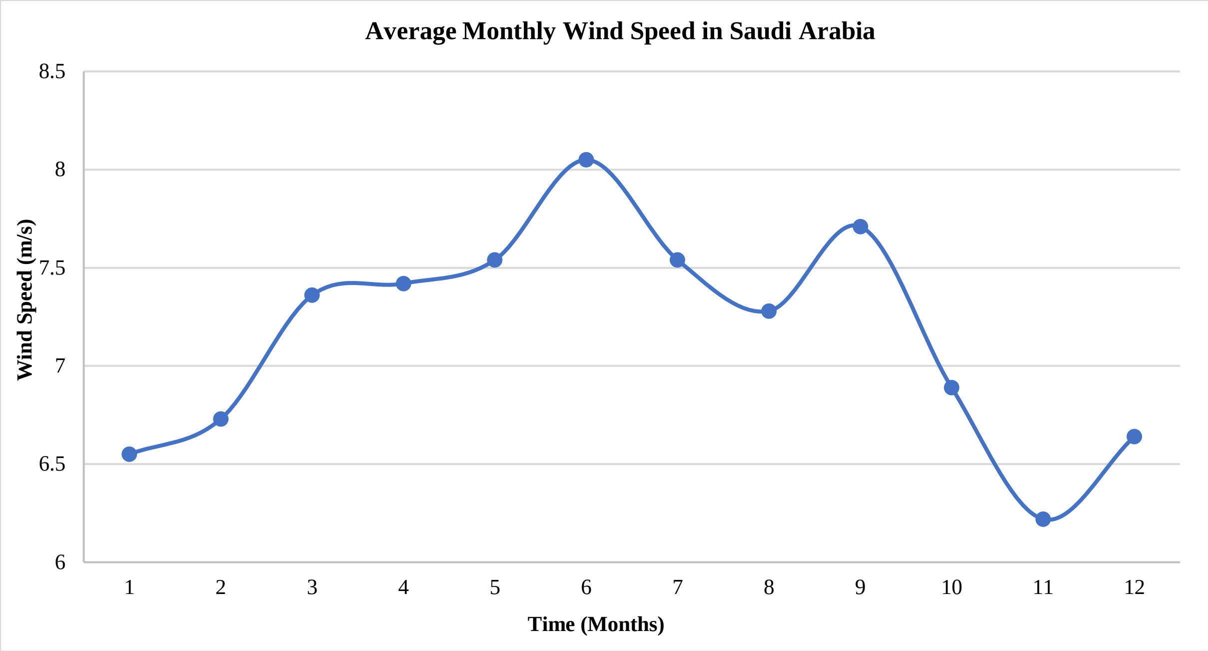

Figure 57 Average monthly wind speed in Saudi Arabia [Author: constructed from [220] energy model].

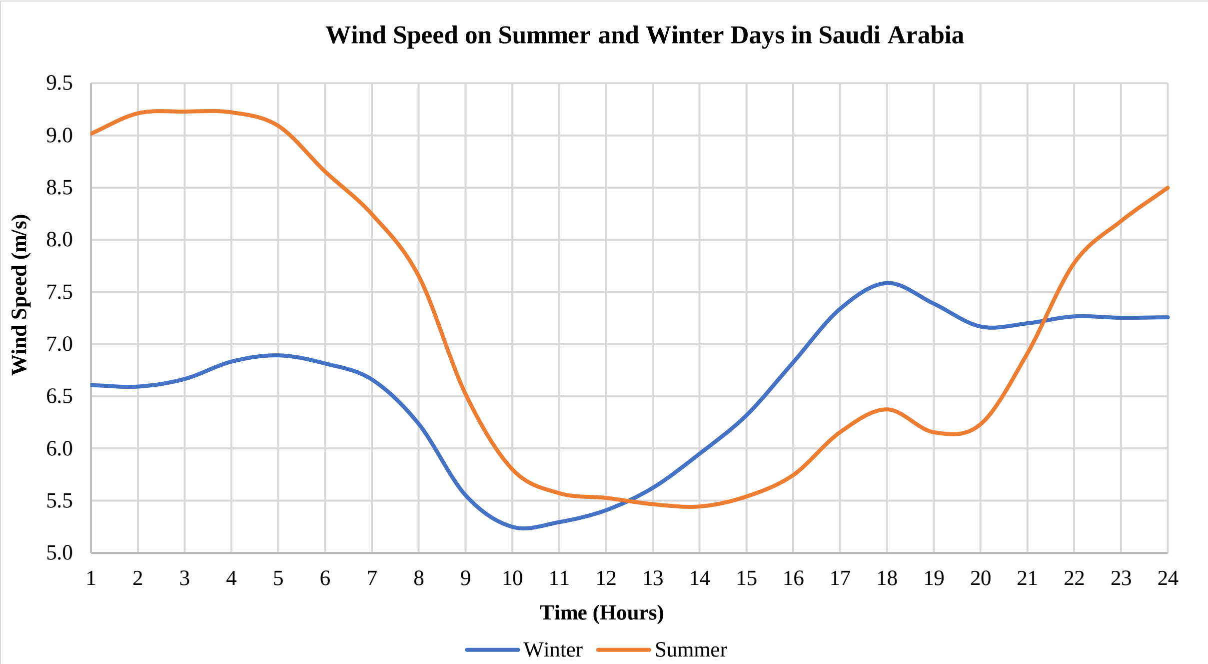

Figure 58 Wind speed on summer and winter days [Author: excel file constructed from [220] energy model].

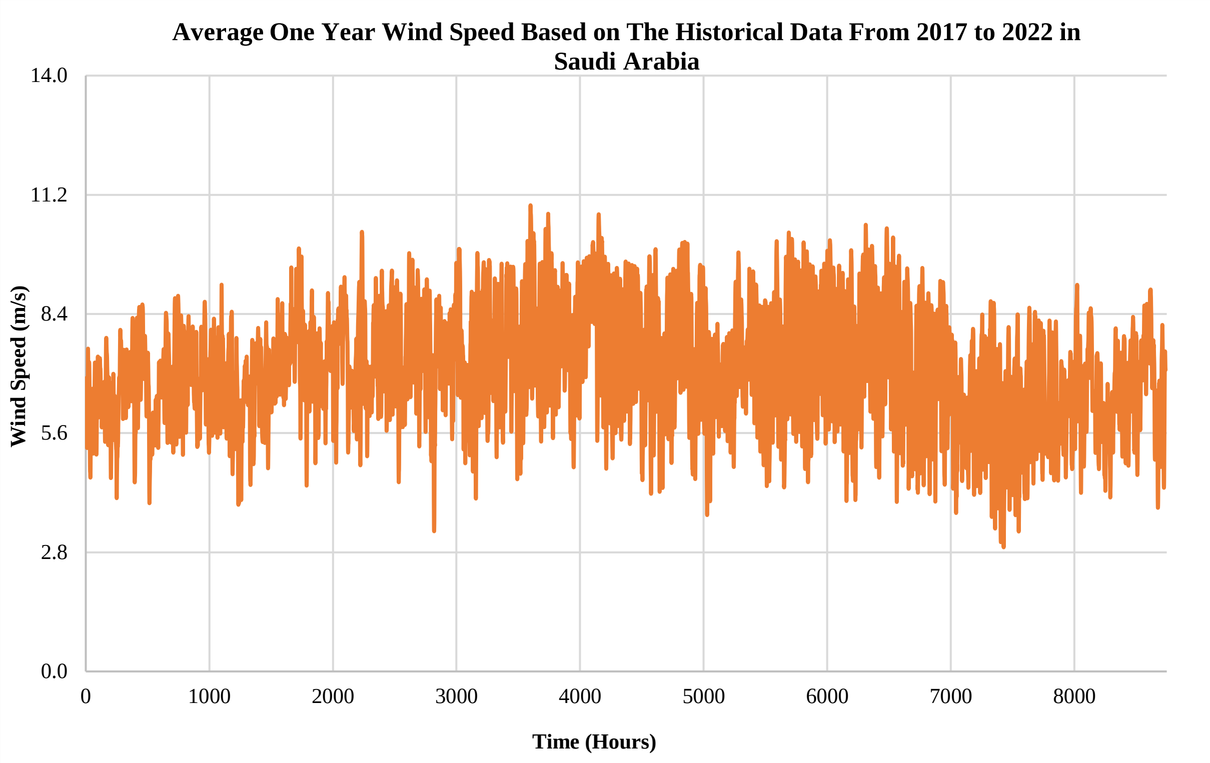

Figure 59 Average wind speeds based on historical data from 2017 to 2022 [Author: excel file constructed from [220]].

Figure 59 shows the average wind speeds for one year based on the last six years' historical weather data in the selected location of NEOM city. The minimum wind speed is 2.8 m/s, while the maximum is 11 m/s.

The distribution file was inserted into the energy model, and the simulation started. First, the wind power plant was deployed solely in the simulation to assess its ability to supply the grid demand. A parametric analysis was executed, and the wind power plant was increased by 2 MW steps in a series of iteral processes. The main goal was to 100% supply the grid demand without any shortage at any hour in the year. The results are shown in Table 18 above. In this table, it was concluded that the wind turbines power plant can be theoretically deployed solely to supply the grid's demand 24 hours all year round. The minimum capacity required to achieve this goal is 1,662 GW. Thus, the Kingdom's demand was 100% supplied by wind RES, day and night without shortage at any hour in the year.

The next step was to observe the effect of battery storage addition to the solo wind power plant on the system. In fact, in the Wind+Battery system, the goal of battery storage addition is not primarily technical as in the PV+Battery, i.e., to cover the nighttime demand at worst case hour. Solo wind power plant can supply the grid demand for the Kingdom, day and night 24 hours regardless of enormous wind turbine resources. However, storage will be used in this situation to reduce the large wind power plant capacity (reducing deployed wind turbine resources). Suppose the wind plant capacity is reduced, shortages would occur during specific limited hours of the day, while the energy demand for the remainder of the day would still be fully met. To understand this impact, the standalone wind power plant must have a minimum capacity of 1,662.129 GW to consistently meet grid demand over a 24-hour period, as outlined in Table 18, thereby guaranteeing no shortages occur at any hour throughout the year. However, if the capacity of the deployed wind turbines is reduced by even 1 MW, shortages will occur during certain hours. As capacity decreases further, the frequency and extent of shortages increase, both in the number of hours affected and the amount of energy shortage during each hour. The shortage will initially emerge during the year's most critical periods when wind production cannot meet the demand.

The capacity of the wind power plant was reduced by 26 GW decreasing to 1,636.129 GW, with the Kingdom's demand and the wind power plant supply are shown in Figure 60 below.

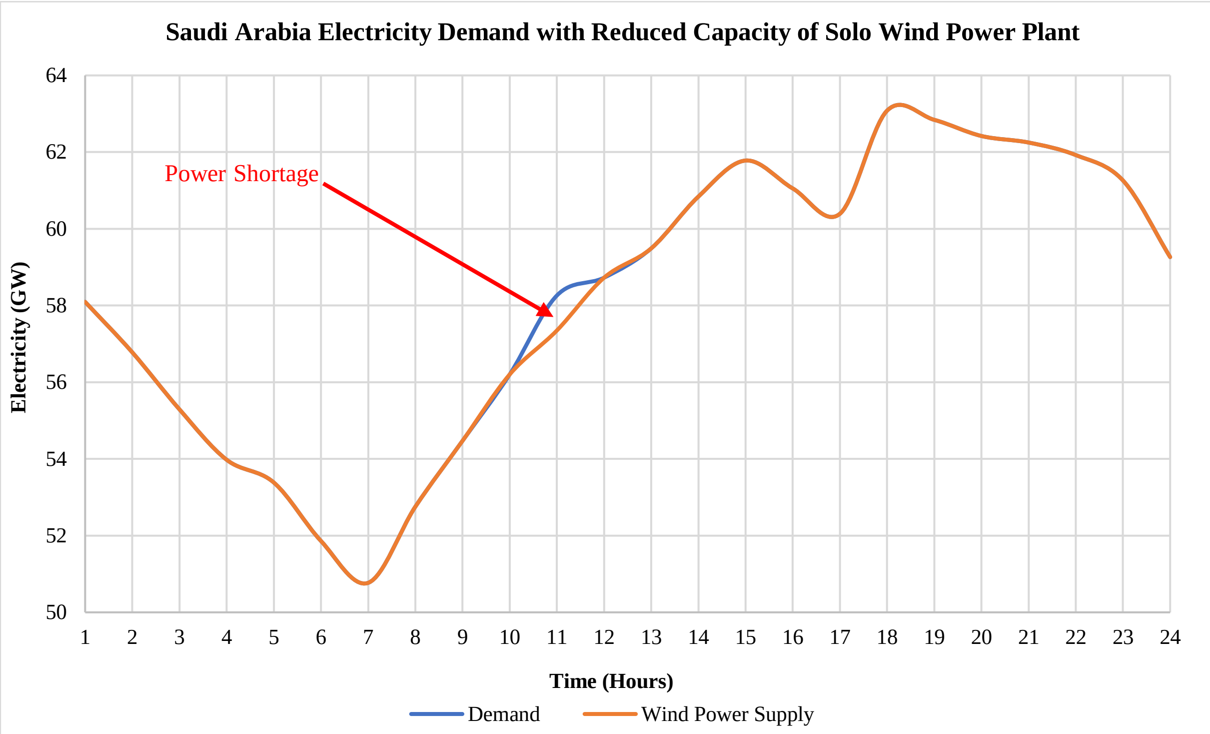

Figure 60 Saudi Arabia's electricity demand with the reduced wind power plant capacity [Author: constructed from simulations].

Figure 60 shows the Kingdom's electricity demand with the wind turbine power plant generation on a summer day, when the capacity of the wind power plant was reduced by 26 GW decreased to 1636.129 GW. A power shortage was observed between 10:00 AM and approximately 12:00 noon across the country, attributed to the inability of wind power plants to produce adequate electricity due to decreased wind speeds during this timeframe. This is the first critical point of the year where a shortage occurred, and as the capacity of the wind power plant is further reduced, additional shortages will arise, starting from the most critical points and extending to the less critical ones.

There are two solutions to address this shortage problem. The first solution is by increasing the capacity of the wind power plant to cover the current shortage. On the other hand, the second solution is adding a battery storage with sufficient size to cover this temporal power shortage. The issue with the first solution is that, upon closely examining the wind power supply curve, it becomes evident that the wind power plant is already supplying the grid demand efficiently for most of the day. However, there is only a small temporal shortage time for approximately 2 hours with 911 MW shortage in power that are not supplied by the wind turbines.

Increasing the total wind turbine capacity means increasing the entire wind power plant supply curve (orange curve) upwards in the graph. From a graphical perspective, it is not an ideal solution to increase the entire curve (with the same pattern) solely to address a minor power shortage during a limited time period. Increasing the entire curve for every hour means increasing the entire wind resources deployment only to cover a minor, limited shortage gap.

To confirm the conclusion found from the graph, the wind power plant capacity was increased back to 1662.129 GW, which is sufficient to eliminate the power shortage of 911 MW. The total system capacity was increased by **26 GW.** In terms of the second solution, the system capacity was reduced again by 26 GW, which resulted in a power shortage of 911 MW. This time, a lithium-ion battery storage system was added with sufficient minimum capacity to eliminate the power shortage of 911 MW. The required battery storage capacity to eliminate the same shortage amount of 911 MW was **1.013 GWh**. The two solutions summary is shown in Table 20 below.

Table 20 The two possible solutions to eliminate power shortage with required capacity addition.

	Solution 1 (Wind Only)	Solution 2 (Wind+Battery)
System Ability to Eliminate Power Shortage (%)	100%	100%
Required Capacity Addition (GW/GWh)	26 GW of wind	1.013 GWh of battery

In Table 20, both solutions can achieve the technical goal of the system stability by eliminating the power shortage of 911 MW. However, the difference in resources deployment is enormous, and thus, the costs will be higher, as shown in detail in Chapter 5. If solution 1 is considered, which involves increasing the total capacity of the wind power plant to scale up the supply and cover the shortage, this would require an addition of 26 GW of wind turbines. However, if the battery storage is considered instead, this will result in an addition of 1.013 GW (1,013 MW). The simulation results comply with the conclusion found in Figure 60.

In conclusion, the addition of the battery storage system is significantly more effective than the addition of more wind turbines to supply the minor temporal power shortage in Saudi Arabia. The results of battery addition can also be seen in Figure 61.

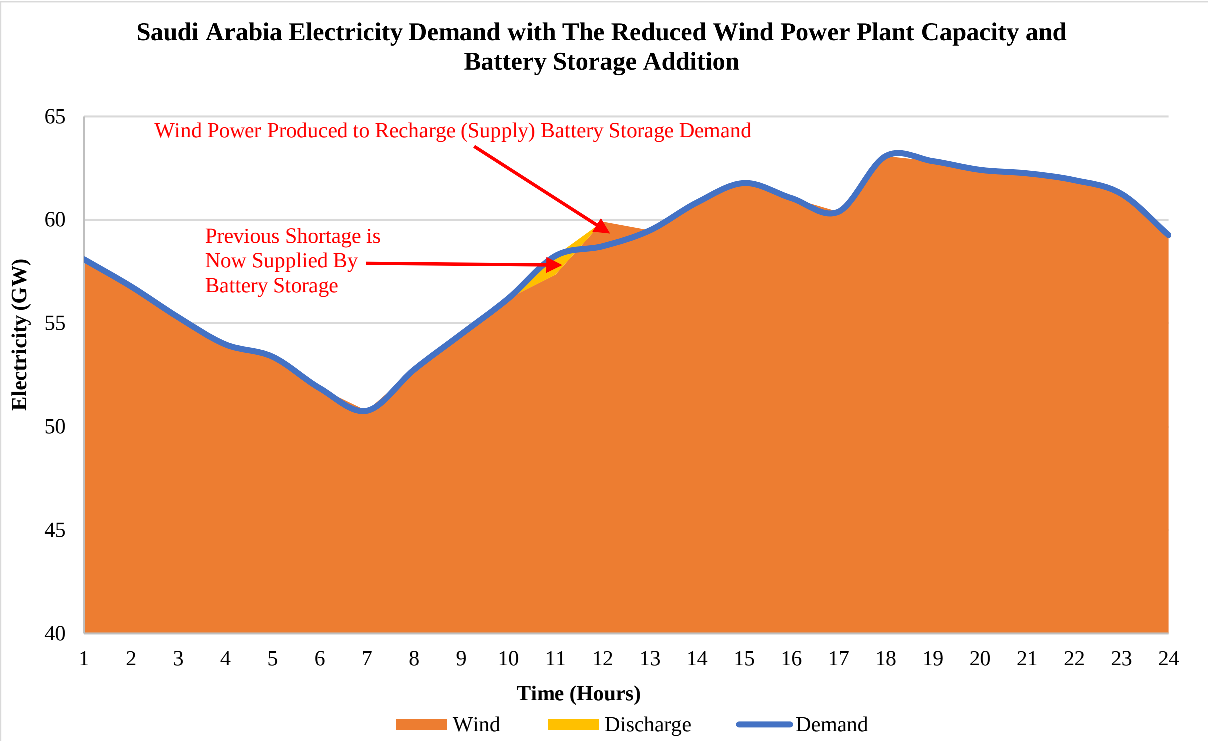

Figure 61 Saudi Arabia electricity demand with the reduced wind power plant capacity and added battery storage [Author: constructed from simulations].

Figure 61 shows the same graph as in Figure 60 with the addition of 1.013 GWh of battery storage to supply the minor shortage. The total grid demand was supplied by Wind+Battery storage system for the entire day without any shortage. The small wind production peak after the shortage hour was to supply/charge the required battery storage demand. From a numbers point of view, the previous shortage power in Figure 60 was 911 MWh. The required storage size to supply this power shortage was 1,013 MWh, including the losses, 1,013 MWh × 0.9 = 911.7 MWh. The required charge power (battery storage demand) from the wind turbines that day is 1,192 MW, including the charge process losses = 1,192 MW × 0.85 = 1,013 MWh = 1.013 GWh, the designed capacity.

In conclusion, battery storage proved to be significantly more effective than wind turbines in addressing minor temporal shortages in the energy system. Therefore, battery storage was integrated with wind power plants to manage critical shortages, such as those illustrated in Figure 60 for the entire year. The methodology previously applied for a single critical day (as seen in Figure 60 and Table 18) is now extended to cover the entire year. This approach allows for the identification of optimal design points for wind power and battery storage that can achieve the system's technical goal of 100% supply stability without any shortages throughout the year. Both system configurations, solutions 1 and 2, have been simulated for the entire year to ensure supply stability. A detailed economic comparison of these two solutions is presented in Chapter 5, highlighting the cost implications of each approach. The final hourly supply for Wind+Battery system, along with an analysis of its ability to meet the Kingdom's energy demand, are presented in Figures 62 and 63 for both winter and summer scenarios. This analysis highlights the effectiveness of the Wind+Battery system in maintaining consistent and reliable energy supply across varying seasonal demands.

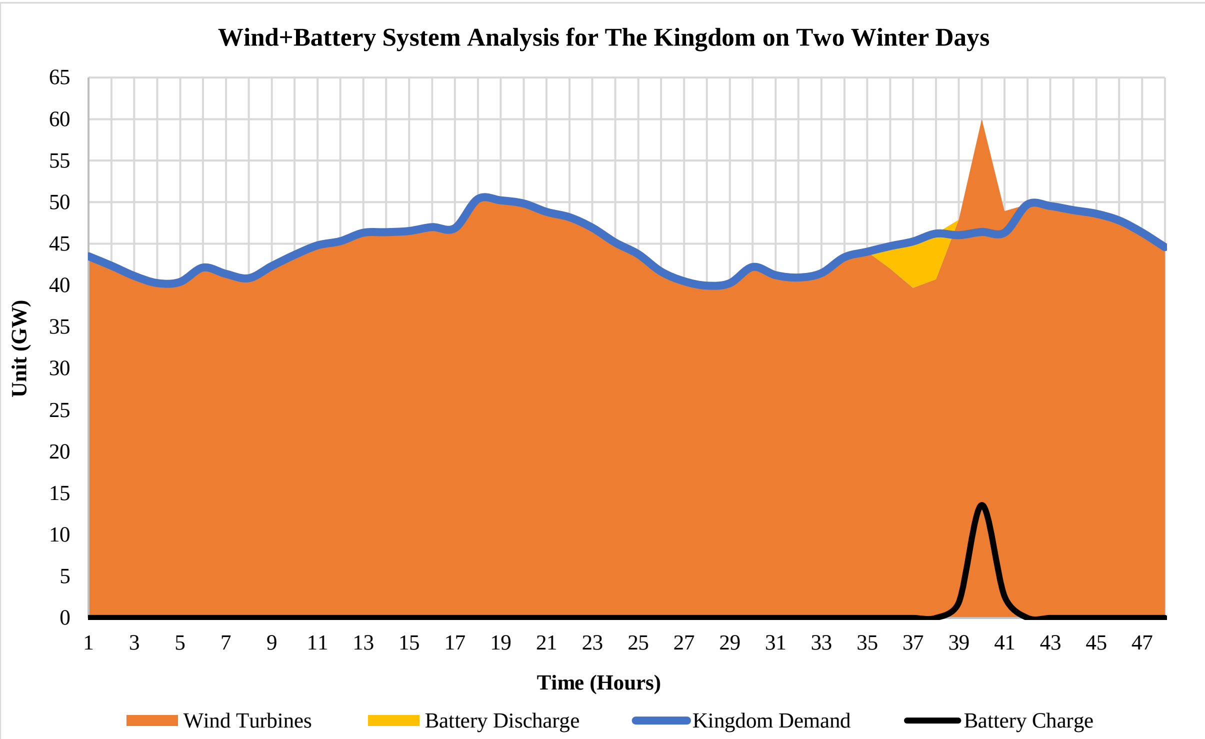

Figure 62 Wind+Battery with the Kingdom's electrical demand analysis on two winter days [Author: constructed from simulations].

Figure 62 shows the final designed Wind+Battery RES generation with the electrical demand of Saudi Arabia in two winter days. The demand in the first day was fluctuating between 40 GW and 50 GW in winter, which was successfully supplied by wind turbines solely, day and night, without any need for storage. However, in the next day, a shortage occurred and lasted for 3 hours, and the wind power plants could not generate sufficient power to meet the demand. This shortage was successfully supplied by the battery storage system as shown in the Figure. In the next hour, right after the battery discharge, wind turbines supplied the required power to charge the battery demand at this hour.

From a numerical perspective, the shortage amount supplied by battery discharge was 2,722 MW, 5,570 MW, and 5,497 MW for hours 36, 37, and 38, respectively. The battery storage had an initial total capacity of 639,600 MWh before discharge, which was reduced to 624,278 MWh after the discharge. This reduction, representing the discharged power amount plus losses, can be calculated as follows: 639,600 MWh - 624,278 MWh = 15,322 MWh. Accounting for the 10% discharge losses, the effective discharged power is 15,322 MWh × 0.9 = 13,789 MWh. This value corresponds to the total discharged power over the three hours, with the sum of the individual discharges being 2,722 MWh + 5,570 MWh + 5,497 MWh = 13,789 MWh.

Figure 63 below illustrates the analysis of the Wind+Battery system power plant's performance in relation to the country's electrical demand over two summer days. As shown in the figure, wind turbines are capable of supplying the majority of the grid's demand during the day, with only minor power shortages occurring for short periods. On both days, the battery storage system effectively supplied the grid during these shortage periods. The battery was subsequently recharged by the wind turbines, such as during hours 14-15 on Day 1 and hour 37 on Day 2, ensuring a continuous supply to meet the grid's demand.

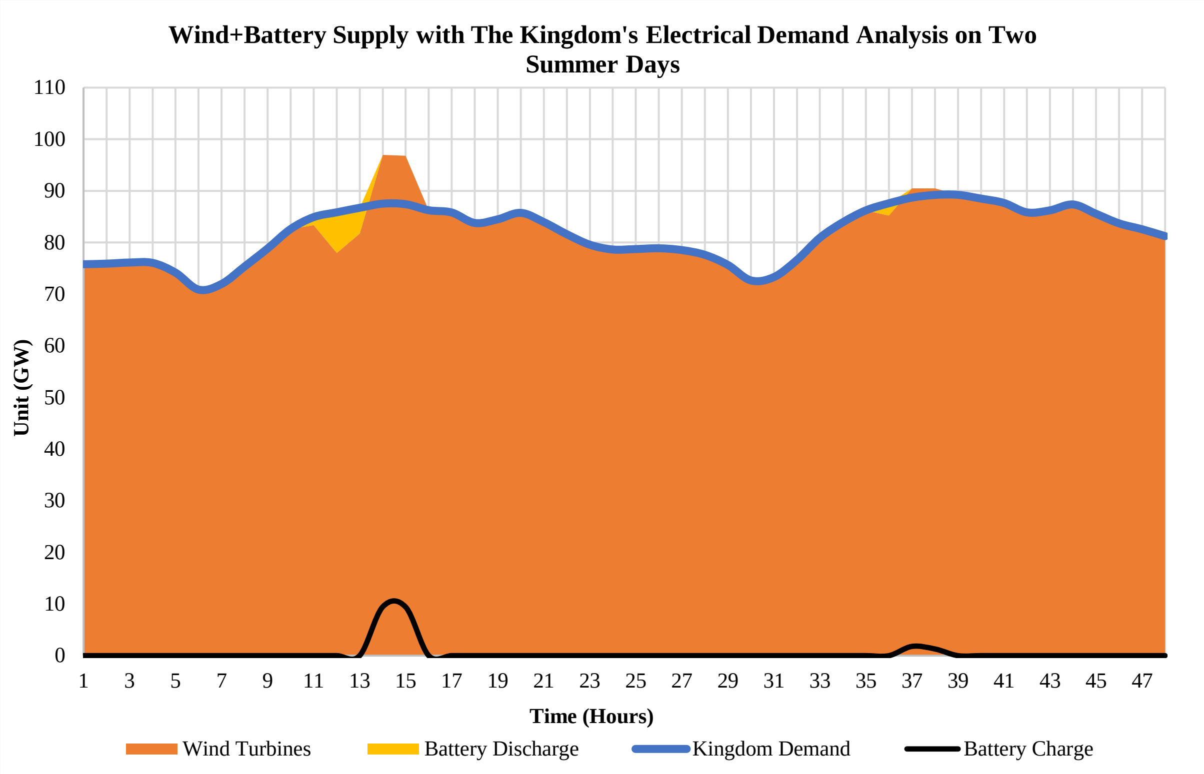

Figure 63 Wind+Battery with the Kingdom's electrical demand analysis on two summer days [Author: constructed from simulations].

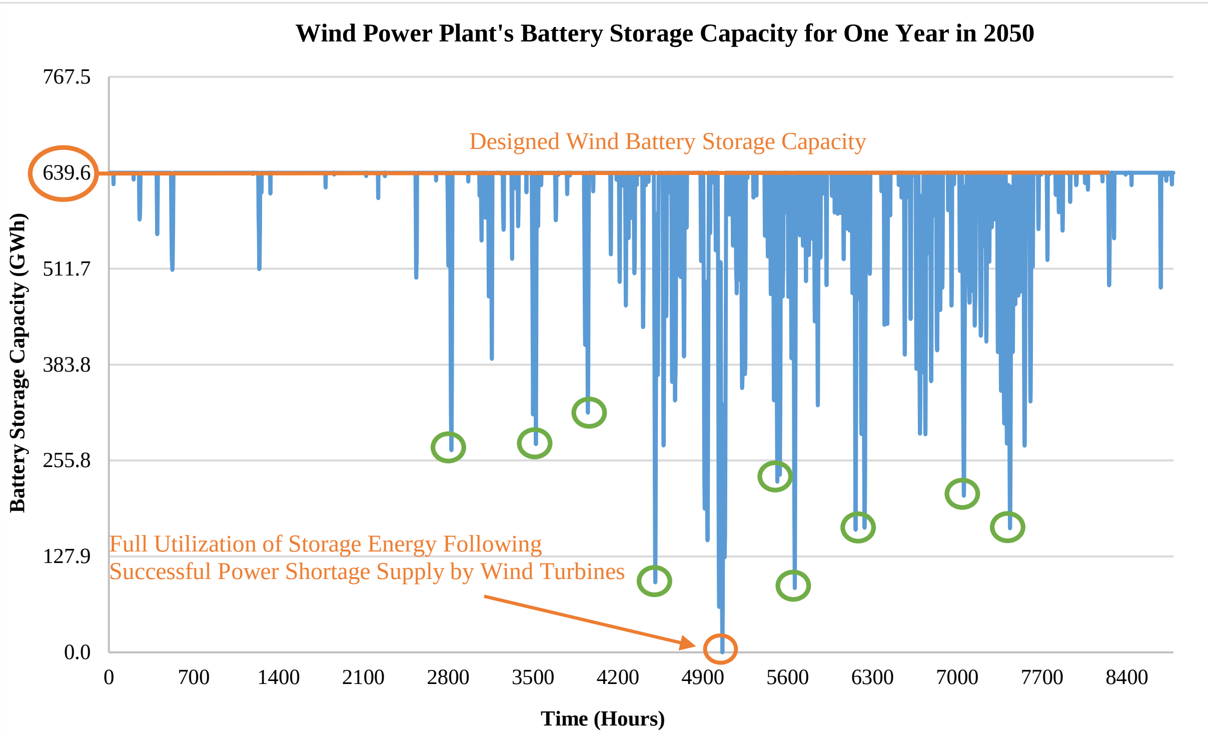

Figure 64 Wind battery storage hourly capacity in 2050 [Author: constructed from simulations].

Figure 64 shows the battery storage capacity of the wind power plant each hour throughout the entire year. The battery storage system was designed to accommodate the minimum required capacity needed to supply the power shortage during the year, as indicated by the orange point in the figure. At the orange point, the wind turbines did not generate sufficient power to meet the grid demand, resulting in the maximum power shortage in the year supplied by the battery storage.

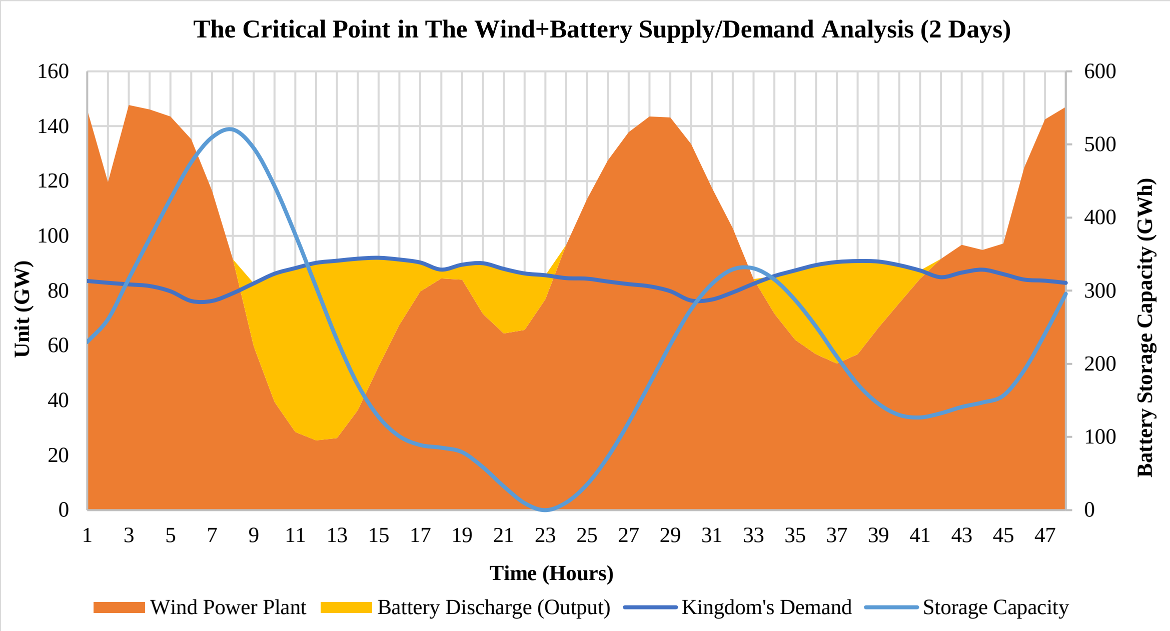

Figure 65 Worst case Wind+Battery supply/demand analysis (2 days) [Author: constructed from simulations].

Figure 65 illustrates the worst-case day (marked by the orange point in Figure 64), where the battery storage was fully utilized to cover the limited hours of power shortage over two days. The power shortage during these days was higher than usual due to less power produced from wind power plants. The wind power generation peaks in the curve above the demand line represent the required power for battery storage charging, which will later be discharged during power shortages.

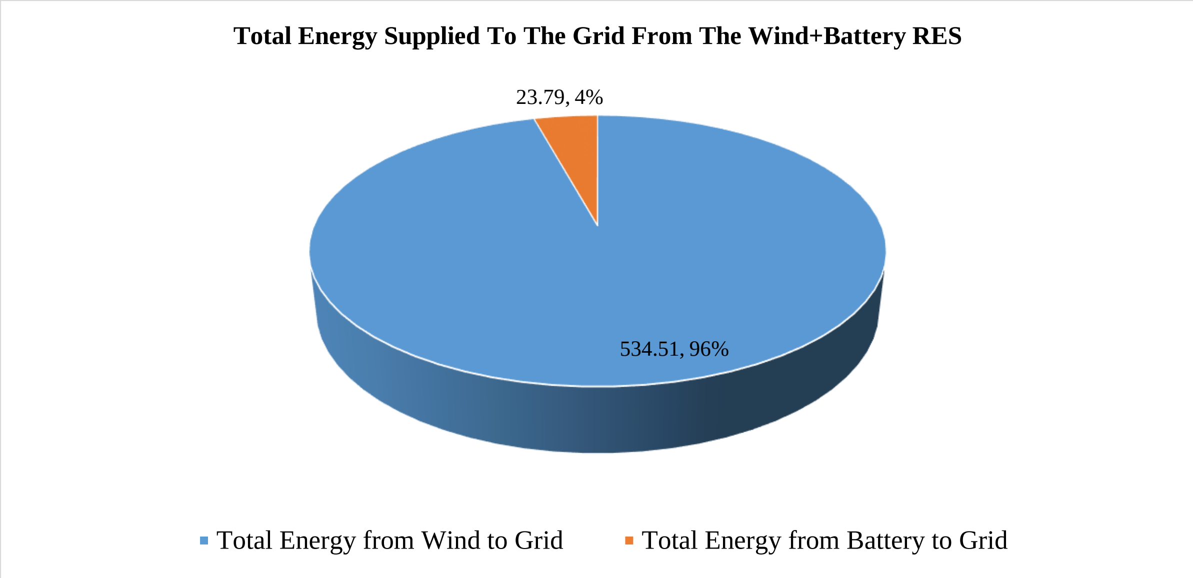

Figure 66 Total energy supplied to grid from Wind+Battery RES breakdown [Author: constructed from simulations results].

Figure 66 illustrates the energy supplied to the grid by the Wind+Battery storage RES. The total grid demand was 558.3 TWh, with wind turbines meeting 96% of this demand, while the remaining 4% was provided by the battery storage system. In contrast, the PV+Battery storage system saw PV generating 45% of the total grid demand, with the remaining 55% supplied by battery storage. This difference is due to the fact that PV can only generate power during the daytime, whereas wind power is capable of being generated both day and night, providing a more consistent energy supply throughout the day and night.

4.3.3 PV+Wind+Battery

4.3.3.1 PV+Wind (No Storage)

The process of designing the RES capacities significantly depends on the grid demand, demand pattern, RES generation, and generation pattern in the entire year. For example, suppose the same demand curve of Saudi Arabia is considered with only wind power plant supply at a specific capacity. The wind power plant will supply the demand; for example, for most of the day, some hours have a shortage because the wind will not generate sufficient power at this time, like at 8 AM for example. In this case, the addition PV power plants will not have any benefit. No benefit will occur even with the increase in capacity and power plant size. On the contrary, this will be a waste of resources and costs. Whatever size of PV plant is added, it will not eliminate the shortage occurred by wind at the hours when the PV cannot generate power due to the absence of the sun or with very low PV generation due to insufficient sun radiation like in early morning hours.

For a PV+Wind system without a battery storage component, the sizing of the PV and wind capacities depends on the generation and demand patterns, as previously discussed. For instance, any changes to the wind power plant capacity, whether an increase or decrease, would require an analysis of the demand and supply patterns. After adjustments are made, the hourly results must be re-evaluated to assess the impact, and this iterative process continues. This approach is time-consuming, requiring constant recalibration to ensure that the system meets the demand effectively. With any change in the PV or wind capacity, even by 1 MW, the 8,784 hourly values need to be checked one by one, and thus, a tremendous amount of time will be required. Thus, the best method to find the required PV/wind capacities is by parametric analysis in EnergyPLAN, first to get the result, then to check the hourly profiles of the demand/supply and justify the results. First, the capacities of both wind and PV power plants were increased to high levels, ensuring that they could provide 100% supply without any shortage at any time of the year. Secondly, a parametric analysis was conducted to evaluate the system's performance under varying conditions and assess the impact of different parameters on the energy supply. The first parametric analysis was executed by decreasing the PV power plant capacity while at constant wind capacity until the minimum required capacities are achieved before the shortage occurs. The second parametric analysis used constant PV capacity while wind power plant capacity was reduced gradually until the minimum required capacity was achieved before the shortage occurs. The simulation results are shown in Tables 18 and 21. Table 21 shows the two solutions that achieve the technical goal and stability of the system with the Kingdom’s demand.

Table 21 Two RES solutions of PV+ Wind power supply

	Solution 1	Solution 2
Capacity PV/Wind (GW)	115.403 / 600	600 / 570.7
System Stability (100%)	100%	100%

Solution 1 represents the configuration with the minimal deployment of power plant resources. In contrast, Solution 2 requires an increase in PV plant capacity by 485 GW, offset by only a 30 GW reduction in wind plant capacity, to meet the same objective as Solution 1. Therefore, Solution 1 was considered, technically explained, and justified below, with the comprehensive economic analysis provided in Chapter 5.

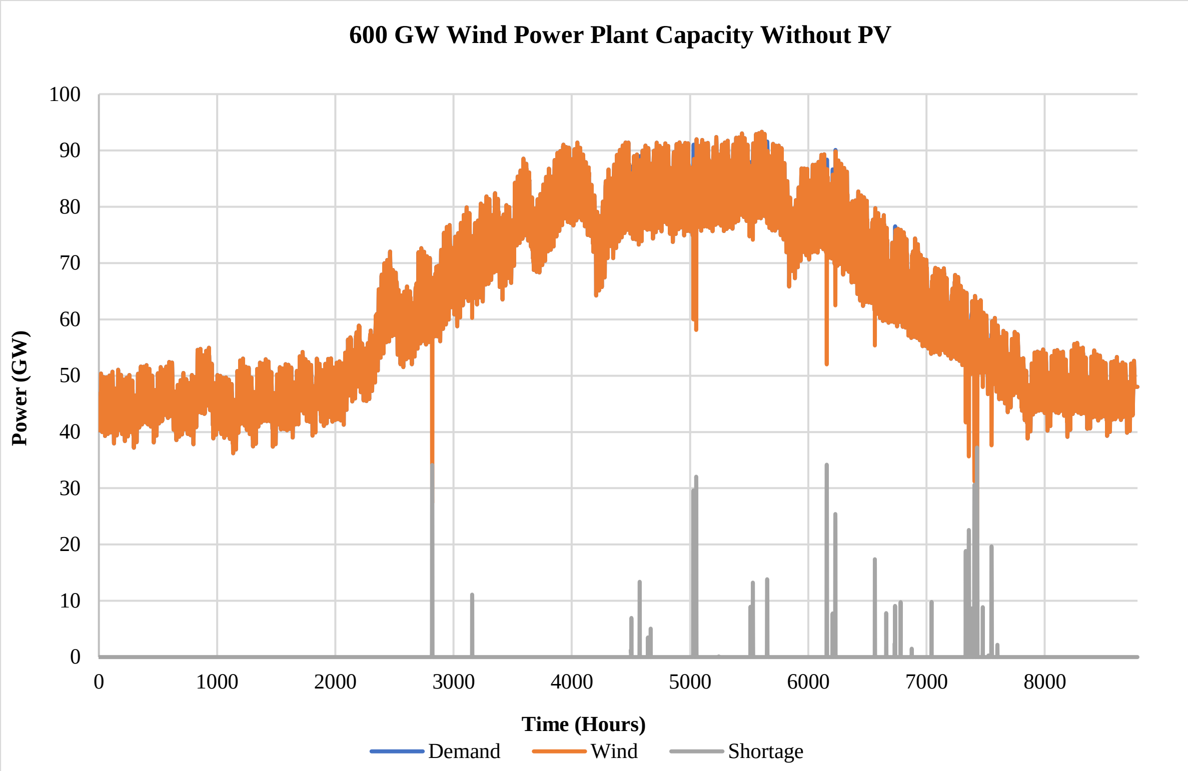

Figure 67 600 GW wind power plant without PV [Author: constructed from simulations].

With 600 GW of wind turbines and zero PV, the annual shortage amount is 1.33 TWh, with a maximum peak of 37,230 MW. Conversely, with 600 GW of PV and zero wind, the yearly shortage amount is 306.54 TWh, and the maximum is 91,439 MW.

Looking at Figure 67, the 600 GW system of wind power plants without PV or storage results in a total power shortage of 1.33 TWh in a few hours of the year, as the wind could not supply the total demand despite the high capacity. The power shortage is also shown for the entire year in grey curve. All the 1.33 TWh power shortages occurred between 9:00 AM and 16:00 on all days of the year when shortage existed. Thus, all these power shortages could be 100% supplied by PV since it occurred at the same time as the PV generation hours. Examining the hourly values of the power shortage of 1.33 TWh for the entire year and compare that with wind supply and PV supply, reveals that the PV capacity was designed based on the worst-case point of the four variables, which are wind/PV/demand/shortage. This worst point is not the maximum power shortage. Before the gradual deployment of PV, the solo wind case experienced several significant shortages, such as the 37,230 MW power shortage at hour 7,427 (11:00 AM), the largest shortage of the year, as illustrated in Figure 67. However, PV was able to offset this peak shortage with a capacity lower than the designed one of 115,403 MW (Table 18). This raises the question: if the year's highest shortage could be addressed with a smaller PV capacity than the designed one of 115,403 MW, why was this specific capacity chosen as the minimum to avoid shortages? To explore this, in Solution 1, the designed PV capacity was reduced by 15,403 MW decreasing to 100,000 MW. Under this adjustment, shortages would reappear at various times throughout the year. Notably, the **first** instance of shortage, where it initially fails to meet demand, becomes the critical point, **not necessarily the moment of maximum shortage**. The results are presented in Figure 68.

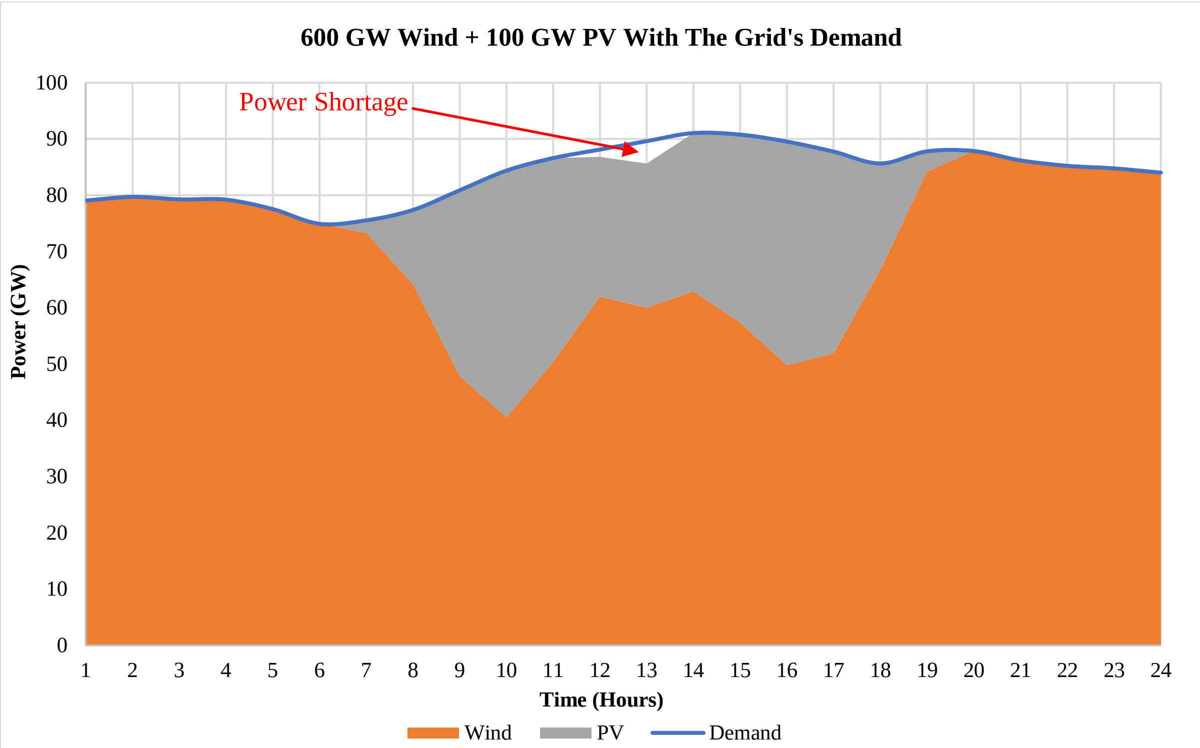

Figure 68 600 GW wind + 100 GW PV with the demand [Author: constructed from simulations]

Looking at Figure 68, when the PV capacity was reduced below the minimum design of 115,403 MW, the first and only shortage occurred at hours 12 and 13 afternoon (5,028 and 5,029 in Figure 67). Before the PV addition, in the solo wind power plant scenario, the shortage at these two hours was 26,118 MW and 29,617 MW, respectively, while the maximum shortage was 37,230 MW at hour number 7,427. However, when PV was added to the designed capacity and then reduced, the first failure (shortage) occurred in hours 5,028 and 5,029, respectively, which had lower peak shortage curve, not in hour 7,427, with the highest peak in the shortage curve. To understand this, we must go a few steps backwards with the solo wind of 600 GW. In the 600 GW solo wind plant, the power shortage at hours 5028, 5029, and 7427 was 26,118 MW, 29,617 MW and 37,230 MW, respectively, as shown in Table 22 below.

Table 22 Shortage on the most critical hours in the 600 GW solo wind power plant.

Hour Number	Demand (MW)	Wind Supplied (MW)	Shortage (MW)
5,028	88,122	62,004	26,118
5,029	89,613	59,996	29,617
7,427	58,261	21,031	37,230

In Table 22, the highest peak power shortage was 37,230 MW. One might think that the PV should be designed based on this peak of shortage, which is the maximum. However, the answer is no, because the design capacity of the PV, in this case, if added to the already existing wind, will depend 100% on the PV generation pattern in the year for every hour. This was the maximum shortage point **before** PV was added in the solo wind, as shown in Figure 67. However, with the addition of PV, the new critical point will not be the same at hour 7,427. **It will now be the point in which the PV performs worse.** For example, in the 600 GW solo wind, with the gradual addition of PV, starting from zero. As the PV capacity was increased, the maximum shortage at hour 7,427 was fully supplied, with no shortage occurring at all. However, the shortages at hours 5,028 and 5,029, which had a smaller shortage compared to hour 7,427 in the solo wind power plant, still persisted. The reason for the full supply of the largest shortage at hour 7,427, despite it being a higher shortage hour than the shortages at 5,028 and 5,029, lies in the PV generation pattern.

Suppose a PV capacity of 115,303 MW is added to the system, the combined PV and solo wind generation at specific hours—hours 5,028, 5,029, and 7,427—reveals a notable decrease in PV performance at hours 5,028 and 5,029, compared to its output at hour 7,427, as seen in Table 23. At these critical points, the performance of PV is significantly lower at hours 5,028 and 5,029. This lower performance, however, does not automatically lead to a shortage in power supply, as it depends on multiple factors such as demand and wind conditions at the same time. Specifically:

1. Demand: If the demand is low during the hours with poor PV generation (like hours 5,028 and 5,029), the system may still meet the grid's requirements even if PV generation is insufficient, as wind energy could compensate for the shortage.
2. Wind Conditions: If wind power generation is high during these hours, it can offset the reduced PV generation, thus preventing a shortage. Wind generation, which is less

dependent on time of day, can provide a more consistent supply, especially during periods of low or no solar generation (like at night or cloudy conditions).

Therefore, the most critical points are not simply those with poor PV performance but those where all three factors—wind, demand, and PV—align in a way that causes a shortage. If either wind generation or demand is favourable, the system may still avoid a shortage despite low PV performance at specific hours. The key takeaway is that PV performance alone is not always the determining factor in whether a shortage occurs; it's the combined influence of wind, demand, and PV generation that dictates whether the system can meet demand without shortages.

Table 23 Critical points comparison before and after the addition of the PV.

	Hour 5,029				Hour 7,427			
	Demand (MW)	Wind (MW)	PV (MW)	Shortage (MW)	Demand (MW)	Wind (MW)	PV (MW)	Shortage (MW)
Solo 600 GW Wind	89,613	59,996	0	29,617	58,261	21,031	0	37,230
Wind 600 GW, PV 115.303 GW	89,613	59,996	29,591	26	58,261	0	58,261	0

As shown in Table 23, the solo wind power plant experienced its highest shortage at hour 7,427, amounting to 37,230 MW, while at hour 5,029, the shortage was comparatively lower, at 29,617 MW. This demonstrates that the shortage at hour 5,029 was less than the peak shortage observed at hour 7,427. When the PV was added (at less capacity than the designed one, so shortage can be observed) of 115,303 MW, the earlier highest peak shortage at hour 7,427 was completely eliminated, and the demand was 100% supplied. While at hour 5,029 (the earlier less shortage hour), the shortage still existed. The higher shortage at 7,427 was supplied before the less shortage at 5,029. As mentioned earlier, the reason is related to the PV generation pattern, as the Table shows.

When PV was integrated into the solo wind power plant, it generated substantially more power during the highest shortage hour at hour 7,427 compared to the power output during the lowest shortage hour at hour 5,029. PV generated 58,261 MW at hour 7,427 while only generated 29,591 MW at hour 5,029. The PV generation in the highest shortage hour was, in fact, sufficiently excellent to stop the wind and supply the entire demand with PV only, as shown in the Table. Both hours 5,029 and 7,427 occurred during the daytime, with hour 5,029 at 1:00 PM and hour 7,427 at 11:00 AM, eliminating the shortage reason of non-sufficient PV production due to times with less solar radiation like in times before sunset or early morning hours. Since the shortage in both hours occurred in the noon time which is the peak PV generation time. This indicates that reduced PV generation at hour 5,029 was primarily due to cloud cover. On that day, the presence of clouds at hour 5,029 resulted in noticeably lower PV output.

To confirm this conclusion, the next day's PV generation was checked at the same hour at 13:00. The PV generation in the next day at the same time of 13:00 (hour 5,053) was 64,306 MW, and the day after, at the same time at 13:00 (hour 5,077) PV generation was 71,789 MW. This clearly indicated that PV generation at these days was excellent except the day when the shortage occurred because of temporary less PV generation due to passing clouds. Therefore, the minimum PV generation capacity needed should be determined by its ability to meet the demand at the critical point of hour 5,029, rather than the peak shortage in solo wind generation observed at hour 7,427. This is because PV output at the same capacity was substantially lower at hour 5,029 than at hour 7,427. The designed value had to be increased until the **minimum PV production** could supply the first critical point at 5,029. Otherwise, failure will occur in hours with shortage and less PV production, one by one from the lowest PV generation hours to the highest. In addition, this also depends on the amount of shortage, demand, and wind.

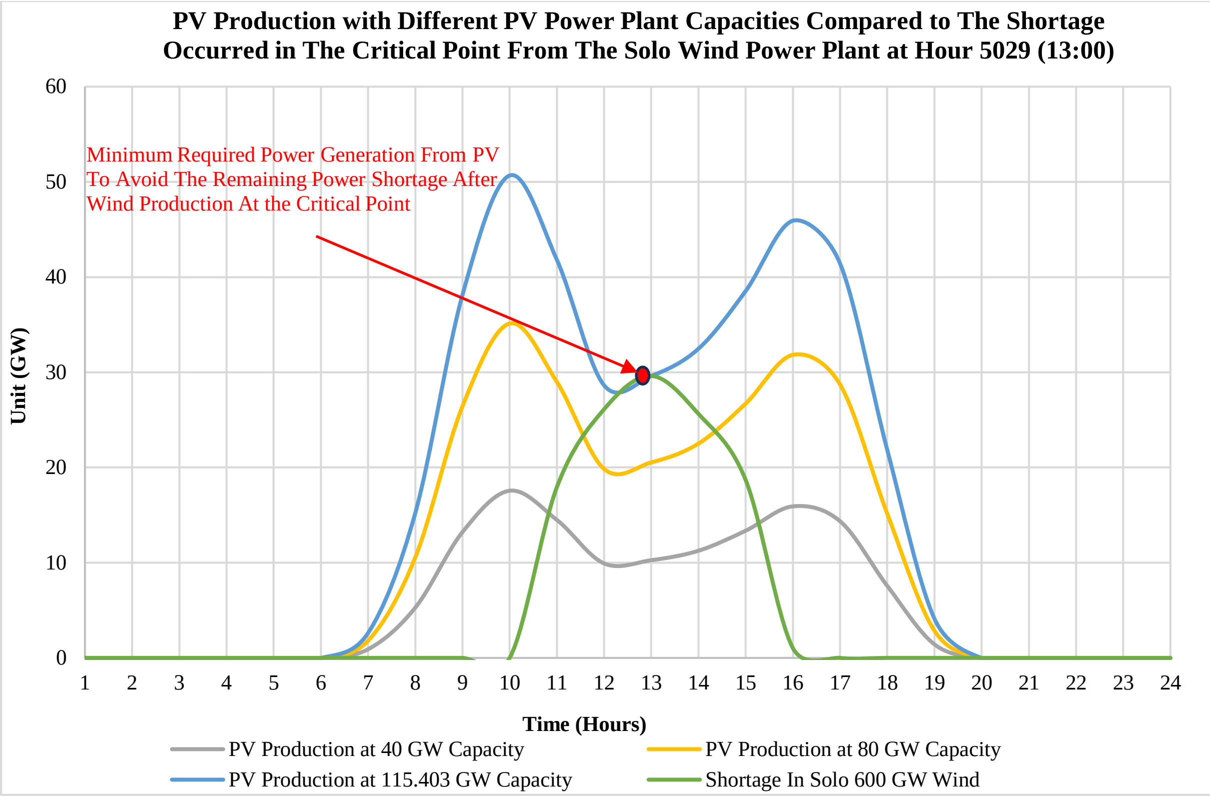

Figure 69 PV generation with different PV power plant capacities compared to the shortage that occurred in the critical point resulted from the solo wind power plant at hour 5029 (13:00) [Author: constructed from simulations].

Figure 69 shows the power shortage that occurred at the solo wind power plant. This shortage is the same shortage at hour 5,029 in Table 22, which occurred after the wind supplied its maximum power at 59,996 MW, yet a shortage remained that could not be fully addressed by wind alone. Figure 69 also confirms what was shown in Table 23 and discussed earlier that this is the minimum required power from the PV to compensate for the shortage from the solo wind when the wind could not supply the total demand at this hour. The blue curve is the generation of PV from the designed capacity of 115.403 GW, which shows that this was the minimum capacity required to cover the critical point shortage at 13:00. Suppose the designed capacity is decreased, whether by 40 GW, 80 GW, or even as small as 1 MW, this adjustment would cause the PV supply curve to drop below the shortage threshold, resulting in a system failure, as illustrated in the referenced figure.

This is one of the disadvantages of relying exclusively on PV and wind without storage as there is a need for overdesigning capacity to account for critical shortages, as illustrated in Figure 69. While PV may produce sufficient power throughout the day, occasional shortages occur when PV or wind generation falls short. Consequently, the power plant capacity must be expanded to ensure that the lowest output from the RES can supply the resulting shortage during these periods. This approach incurs additional resource usage, increased costs, and potentially significant excess electricity generation beyond grid requirements, potentially leading to system instability if not effectively managed or curtailed.

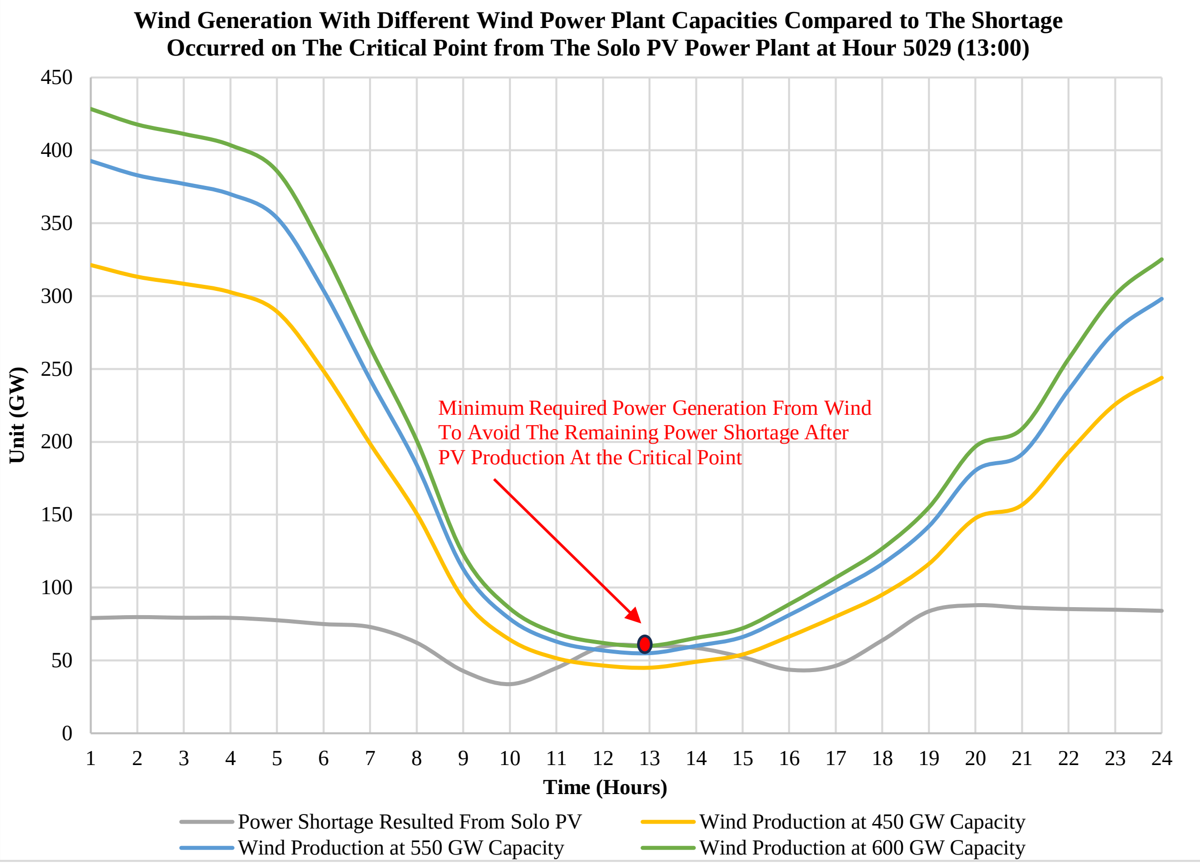

Figure 70 Wind generation with different wind power plant capacities compared with the shortage occurred in the critical point from the solo PV power plant at hour 5029 (13:00) [Author: constructed from simulations].

Figure 70 represents the wind power generation at different wind capacities with the designed PV capacity of 115,403 MW. When the wind power plant was reduced, power shortages occurred at the same critical hour of the year as when PV was reduced at constant wind capacity. This occurred because, although wind generation was lower than usual during this hour, it was not the sole factor; PV generation was also reduced during the same period. This indicates that this system is designed at the minimum capacities of wind turbines and PV to avoid the shortage in most critical points of the year, which simultaneously have the least PV and wind generation. It can also be noticed that significant amount of power was generated above the shortage requirements (above the demand line), such as in the early morning hours and later night hours, where the wind generation was significantly larger than the demand (shortage curve here represents the remainder of the country's demand after the PV has supplied its power at its design capacity) which resulted in critical excess energy production beyond the grid ability if not stopped or controlled. This also indicates that increasing the total capacities of the system such that the minimum production of these systems must meet the shortage occurs at these points is, from a technical perspective, correct (if only PV and wind are to be used). However, this also indicates that there are better solutions, such as using battery storage system which that can supply minor, limited shortages without increasing the RES capacity to higher levels as shown in the next section.

As solution 1 was considered, explained and justified. A question that might come to the mind is if this system could be optimised, for example, by reducing the substantial wind capacity and increasing the PV to decrease deployed resources and thus costs. The answer is no; wind capacity can't be reduced below the designed capacity and replaced with PV. There are times during the year when the production of PV is almost near zero, like at 18:00, as shown in the Figure below. At this sunset hour, the production of PV is negligible (near zero). At this time, wind generation was sufficient to meet the demand, as it operated at its designed capacity without causing any shortages. However, PV generation was insufficient due to it coinciding with the period of lowest solar radiation, specifically during the final hour before sunset. Even if the PV is increased to a significantly higher capacity than its designed one and significantly higher than the wind capacity, it will still be insufficient to supply the shortage. This scenario repeats multiple times throughout the year. One example, illustrated in the figure below, shows a reduction in wind capacity from 600 GW to 500 GW while PV capacity is simultaneously increased from 115.403 GW to 900 GW.

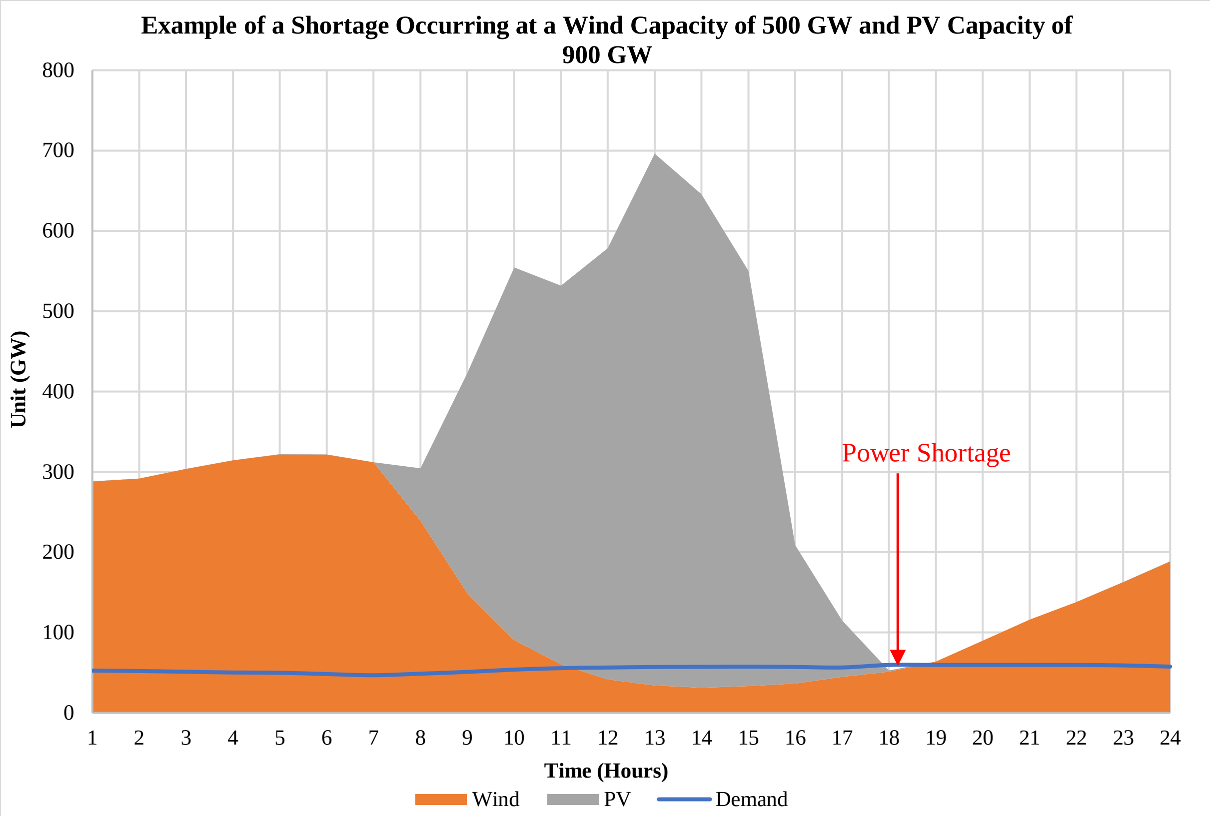

Figure 71 Example of a shortage occurring at a wind capacity of 500 GW and PV capacity of 900 GW [Author: constructed from simulations].

Figure 71 shows a scenario in which a substantial increase in PV capacity, coupled with a reduction in wind capacity, resulted in a power shortage occurring at sunset (18:00). Specifically, the wind capacity was reduced from 600 GW to 500 GW, while PV capacity was increased dramatically from 115.403 GW to 900 GW. Despite this substantial increase in PV capacity, the power shortage at sunset could not be resolved.

This outcome further reinforces the conclusion discussed earlier: Solution 1, which utilized only wind and PV without storage, was technically better in terms of ability for grid supply. However, this solution comes with a significant drawback, although it successfully provides the grid demand, it requires considerably more RES capacity than in systems with battery storage, and thus leading to higher costs as shown later in Chapter 5. The increased costs are driven by the need for overdesigning the PV and wind power plants to address supply shortages during periods of low generation without the support of energy storage, as previously illustrated in Figures 69 and 70. Consequently, while technically feasible, this system is less cost-effective compared to PV+Battery or Wind+Battery configurations, as detailed in Chapter 5. In addition, this system will not be reliable in terms of the grid stability concerns as PV and wind turbines are fluctuating and intermeeting RES technologies. Based on these findings, the next section explores the integration of battery storage with the current PV and wind system to optimize both technical performance, reliability, stability and reduce the deployed RES resources.

4.3.3.2 PV+Wind+Battery Storage

The previous section outlined and demonstrated the drawbacks of utilizing RES without storage. This section discusses the advantages of incorporating storage into the RES configuration. The subsequent step involves taking the Wind+Battery system, which has been theoretically identified as the most optimal thus far and optimizing it further by integrating PV generation and reducing wind capacity while adding battery storage. The optimisation process was essential for two main reasons. The first reason is that even though the Wind+Battery system was the winner on paper. **However**, if the system is applied practically on the ground, it will not perform as good as on paper. This is because excellent wind resource locations in the Kingdom are limited. The Wind+Battery system was designed based on the best location for high wind power potential in the Kingdom, NEOM city north. The problem is that the area of 263 GW wind turbines will be insufficient in the city.

The city will have several projects, such as hydrogen stations, PVs, residential areas, resorts, hotels, etc. Even when considering second best locations with high wind potential within the Kingdom, these sites are largely confined to limited areas along the west coast. A wind capacity and power potential sufficient to meet the Kingdom’s demand by 2050 cannot be replicated in other regions, such as in the north at locations like Dumat Al Jandal, as certain studies indicate. The capacity factor and power potential are considerably lower in other locations compared to the selected site in NEOM. Some studies have reported that the capacity factor in these alternative locations ranges from 20% to 28%, whereas NEOM exhibits a much higher capacity factor of 45.5%. Theoretically, this system appears optimal; however, given the limited high wind power potential areas identified in the ATLAS and supporting research, its practical implementation is challenging, highlighting a critical need for further optimization.

The addition of PV with the reduction of wind turbines resources has a very high potential application on the practical side. This system can be applied practically on the ground since the optimal PV power potential areas in Saudi Arabia are the entire northern region with a vast unoccupied land mass. Although PV can also be deployed in central, east, and west regions with high PV power output. However, the northern part was found to be the optimal because of the high solar radiation and the lower climate temperature, an essential factor for PV power production. Other regions have high solar radiation but with higher climate temperatures, which lowers PV generation.

A significant advantage of utilizing PV technology in the Kingdom lies in its versatility; it can be deployed across any location within the Kingdom, given the vast solar potential and extensive land areas available, including the northern region. Moreover, PV generated power generally has lower costs than wind energy, as will be demonstrated in subsequent sections. Thus, based on these conclusions, the Wind+Battery system was taken and then optimised so that the final supply system would include PV+Wind+Battery power plant system. The same methodology of the previous RES technologies with and without storage was applied. The results are shown in Figure 72.

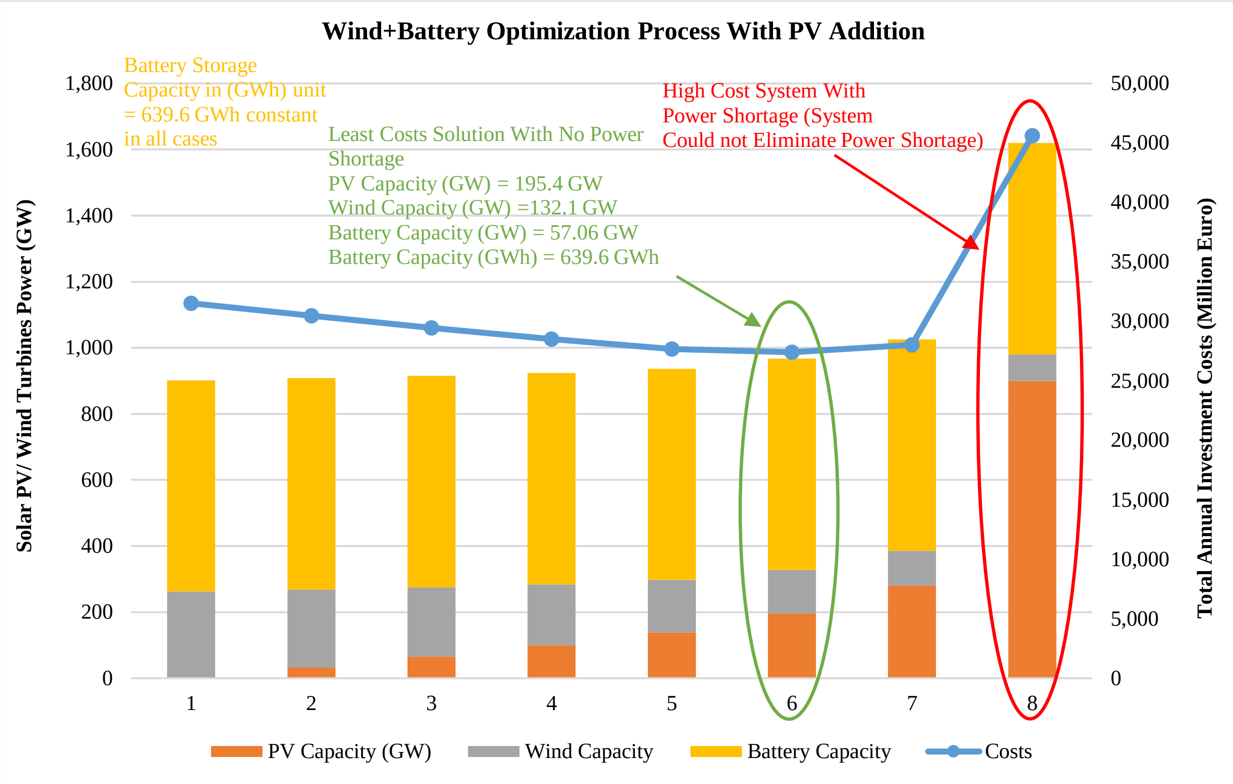

Figure 72 Wind+Battery optimisation process with PV addition [Author: constructed from simulations].

Figure 74 shows the Wind+Battery power plant at point one, with showcasing a gradual reduction in wind power capacity alongside an incremental increase in PV power capacity. With each step, wind power was reduced by 26,004 MW and the PV capacity was increased by the minimum required capacity to eliminate the resulting power shortage. This optimization process was carried forward until the combined costs reached their minimum at point 6. At this optimal point, the technical objective of completely eliminating power shortages was achieved, ensuring a 100% supply to the grid throughout the year while deploying only the minimum required RES resources. After point 6, the system costs started to increase gradually as the PV power increased and the wind power decreased, as discussed in detail in Chapter 5. Finally, at point 8, the system resources increased by a considerable amount with 900 GW of PV and 80 GW of wind with the same battery capacity, which resulted in significantly higher costs and failure in achieving 100% system stability, as shortage existed with an amount of 390 GWh during the entire year. The main factor in this case is the economic factor, which has a higher effect on the optimisation process. It is further explained in detail in Chapter 5.

Table 18 shows the Wind+Battery system compared to the optimised system with added PV and reduced wind turbines resources. Wind combined with PV and battery system specifications are shown in Table 18. In the original Wind+Battery system, the wind capacity was 262,129 MW, with no PV. Through the parametric analysis, which involved reducing wind capacity and increasing PV capacity while maintaining constant battery storage, the final system design parameters were established as 132,109 MW of wind turbines, 195,405 MW of PV, and 639.6 GWh of battery storage, as detailed in Table 18.

The reduction in wind power capacity between the first and second systems amounts to a total of 130,020 MW. This reduction results in an annual shortage of 63.22 TWh, with a peak shortage of 77,686 MW, in the absence of PV capacity. To mitigate this shortage, a minimum PV power capacity of 195,405 MW is required. By decreasing the installed wind power capacity by 130,020 MW and replacing it with 195,405 MW of PV capacity, the system meets the necessary conditions to eliminate all shortages, ensuring 100% stability throughout the year.

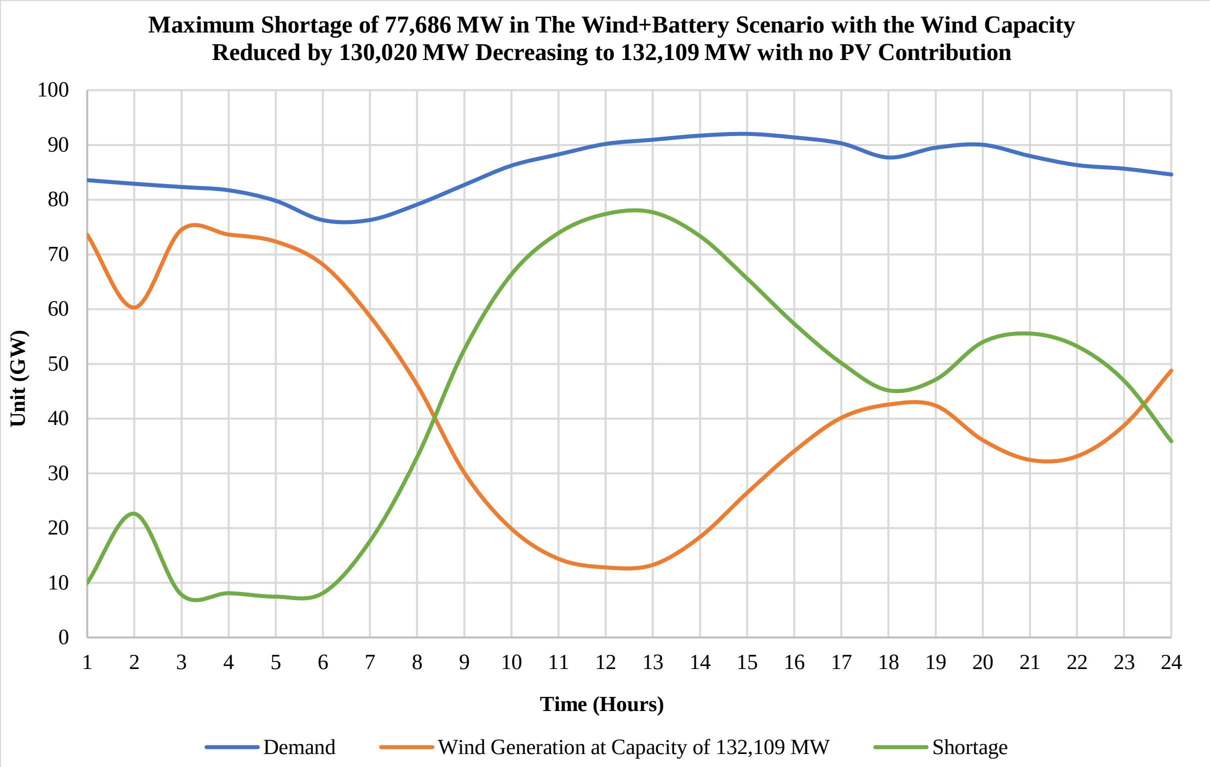

Figure 73 Maximum shortage of 77,686 MW in the Wind+Battery scenario with the wind capacity reduced by 130,020 MW dropping to the final capacity of 132,109 MW with no PV contribution [Author: constructed from simulations].

Figure 73 illustrates that the maximum power shortage of 77,686 MW occurred when wind capacity was reduced by 130,020 MW prior being offset with PV. At this reduced capacity, wind generation was insufficient to satisfy demand, particularly as it coincided with lower-than average wind speeds and high demand levels, while the battery storage was depleted. Notably, this peak shortage occurred during morning and afternoon hours, suggesting a strong potential for PV integration. Figure 74 further shows that restoring wind capacity to the design value of 262,129 MW in the Wind+Battery configuration could address this deficiency.

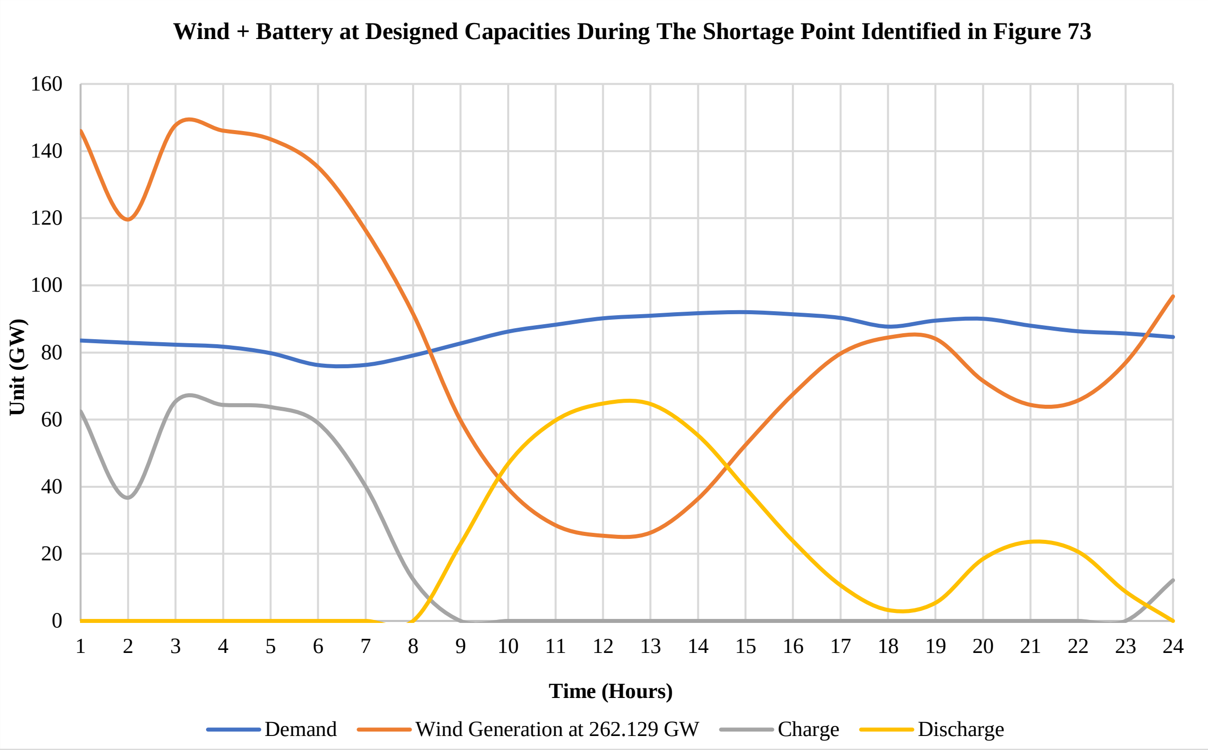

Figure 74 Wind + Battery system at designed capacities during the shortage point identified in Figure 73[Author: constructed from simulations].

Figure 74 shows the same Figure 73 but with the increased wind capacity at the designed Wind+Battery capacity of 262.129 GW for wind with 639.6 GWh for battery storage. If Figure 73 is compared to Figure 74, this is the minimum power generation required from wind to supply the shortage in Figure 73. The wind power capacity was increased to supply the battery storage with the minimum energy required to discharge at the shortage point. The wind generation curve still falls below the demand curve at the shortage point. However, storage was already installed in both cases in Figure 73 and Figure 74. The wind power generation curve was not raised above the demand curve; instead, it was adjusted to supply the battery with the minimum charge power required to meet the minimum discharge demand of the pre-installed battery at the point of shortage. In Figure 73, the storage existed with the same capacity. However, there was insufficient wind power to charge the battery for later discharge at the shortage point. Not only this shortage point, but all other ones during the year.

Suppose the designed wind capacity at 262,129 MW with the same battery capacity was slightly reduced by 1,000 MW decreasing to 261,129. In that case, the first power shortage will occur at the same critical point in Figures 64 and 65, which was hour number 5,063; when the total storage energy capacity was utilized (critical point). However, the critical point shifted when the wind capacity was reduced by 130,020 MW. When the wind capacity was reduced to

132,109 MW with no PV and the same installed storage capacity, not only did a shortage arise due to the reduced wind supply, but also a shortage occurred due to insufficient battery storage capacity. The reduction in wind power capacity has led to additional shortages, as the battery supply became insufficient due to reduced charging before the shortage hours. This was caused by the decreased surplus power generated by the lower wind power plant capacity, which in turn limited the ability of the battery storage to charge adequately and meet demand during the shortage periods. When the storage was depleted, the critical point shifted. In the initial case, where the wind capacity was reduced by only 1,000 MW, the critical point occurred at hour 5,063, which marked the first and only hour experiencing a power shortage.

On the other hand, when the wind power capacity was reduced by 130,020 MW, the critical point was hour number 5,053 (equivalent to hour 23:00). In this scenario, the critical point is defined as the moment when the maximum gap between demand and wind generation occurs while storage capacity is zero.

As illustrated in the subsequent figures, storage depletion resulted from significantly reduced charging power due to a lower surplus from wind generation, attributable to decreased wind capacity. Here, "surplus" refers specifically to the power generated from RES after meeting the grid demand, with any remaining energy directed fully toward battery storage, and not the critical excess energy that exceeds both grid and battery demand.

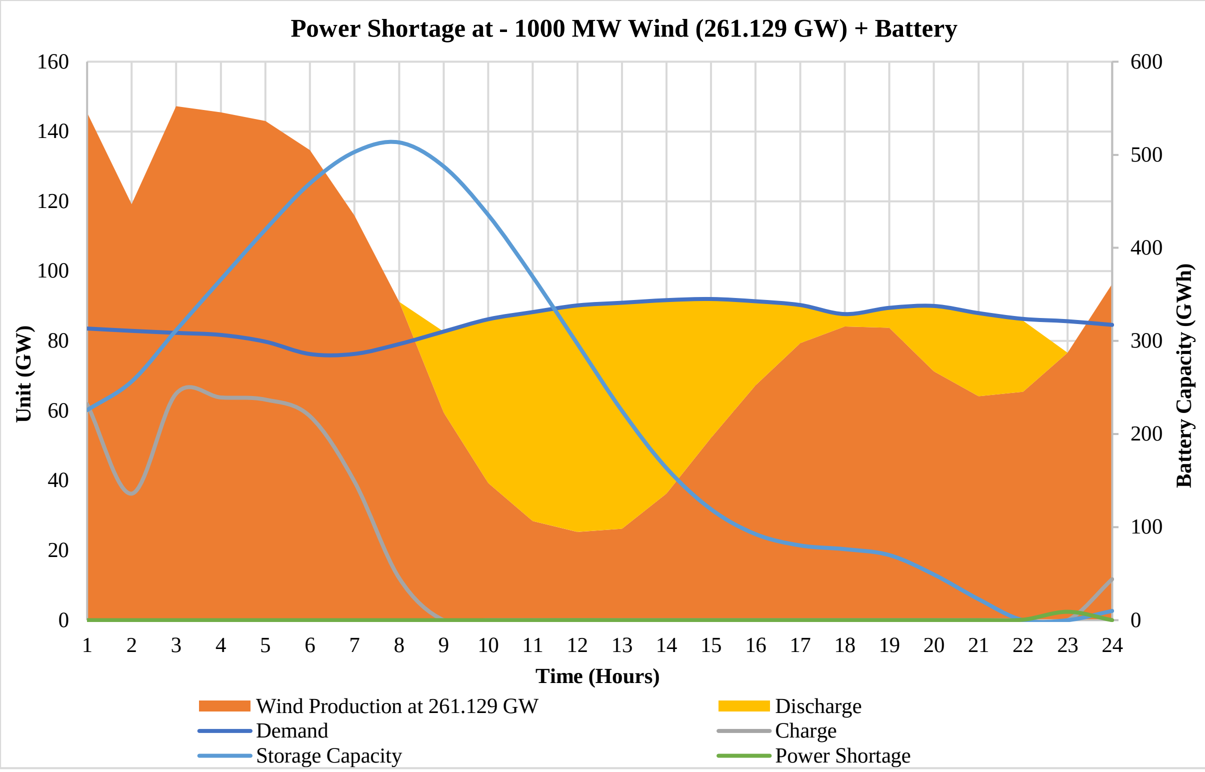

Figure 75 Power shortage at - 1000 MW wind (261.129 GW) + battery [Author: constructed from simulations].

A comparison of Figures 75 and 76 reveals that when the wind capacity was reduced by 1,000 MW with battery storage in place, a shortage only occurred at the first critical point, hour 23:00 (or hour 5,063), corresponding to the minimum storage capacity designed. At this hour, storage was fully utilized to meet demand before being depleted. The reduction in wind capacity resulted in decreased battery charge, consequently limiting discharge and causing a power shortage, as shown in Figure 75. Conversely, in Figure 76, the critical point shifted to hour 13:00 (or hour 5,053), representing the peak shortage of 77,686 MW. At this point, the storage was entirely depleted, with neither charge nor discharge occurring throughout the day. Due to insufficient wind generation, all wind-generated power remained below the demand curve, indicating an inadequate wind supply to meet demand with no surplus to charge the battery for later discharge. Therefore, the critical point in Figure 76 was marked by the maximum gap (shortage) between demand and wind generation at hour 13:00.

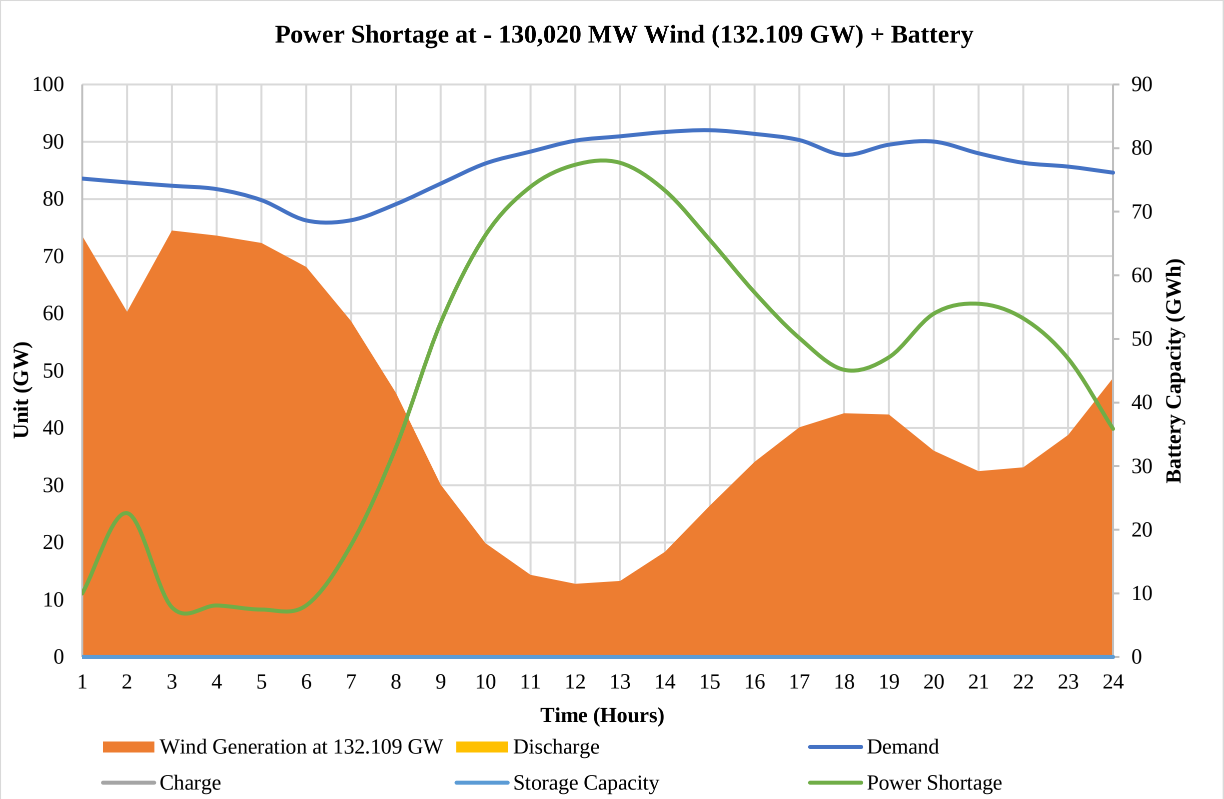

Figure 76 Power shortage at - 130,020 MW wind (132.109 GW) + battery [Author: constructed from simulations].

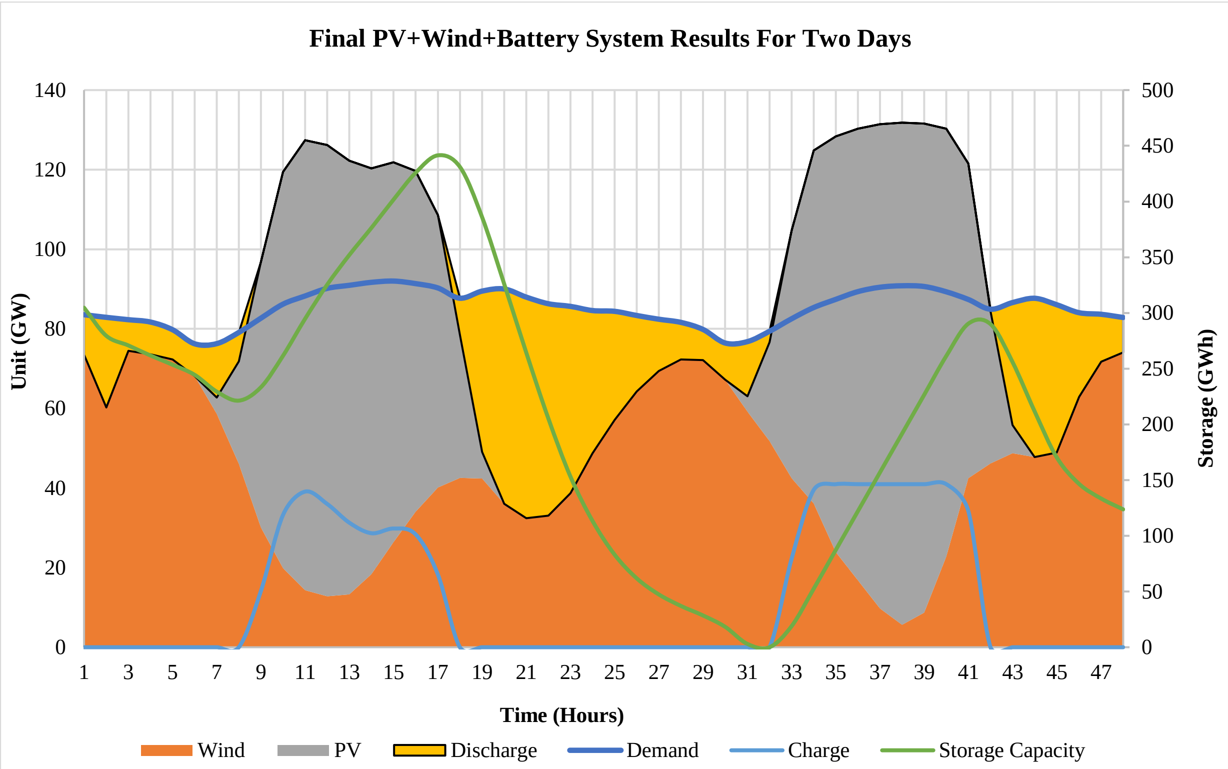

Figure 77 Final PV+Wind+Battery system results for two days [Author: constructed from simulations].

Figure 77 shows the final PV+Wind+Battery system results for two days. At the designed wind capacity of 132,109 MW, PV of 195,405 MW, with the battery storage capacity of 639.6 GWh.

The first day is the same as the day in Figures 73,74,75,76, and the second day is the day after. Figure 77 shows the harmony of power supply between the RES components. During night hours, such as from 1:00 AM to 7:00 AM after midnight, wind turbines did not produce sufficient energy to cover the entire demand despite sufficient capacity of 132.109 GW, where the peak demand did not exceed 83.558 GW at 1:00 AM. However, despite sufficient maximum wind capacity, the wind did not generate sufficient power at that time due to lower wind speeds on those hours. Wind supplied the grid's demand by all the produced wind energy, while the remaining demand, was supplied by the battery storage discharge, which was charged earlier days from the surplus generated by PV. In the morning hours, PV started to generate at 7:00 AM with its lowest value of 4.043 GW. The PV generation has reduced the required discharge power from the battery to save it for later use in the same day.

At 7:00 AM, the analysis was as follows: the country's electricity demand was 76,286 MW, wind supplied a maximum of 58,559 MW with remaining shortage of 17,727 MW. PV supplied a maximum of 4,043 MW only because it is still early morning with insufficient sun radiation. The remaining shortage was then equals to 13,684 MW, supplied by the battery storage, as shown in the Figure. At later hours, from 9 AM to 17:00, PV supplied the remainder of the demand after the wind supplied its full power without the need of battery storage.

PV surplus was utilized to charge the battery storage for later discharge use. This indicates that reducing the wind and increasing the PV was a less costly solution because the PV performs better than the wind if the shortage hours are within the PV power generation timeframe. When the sun's radiation started to disappear as the sunset approached, PV and wind generations were lower. Thus, storage was needed. For example, at hour 19:00, the electricity demand was 89,482 MW, while the wind's maximum generated power was 42,371 MW, with the PV's generation at its lowest value of 6,682 MW due to lower solar radiation as the sunset approaches. This has resulted in a shortage of 40,429 MW, which was supplied by the battery storage. In addition, the battery storage was completely depleted after supplying the required discharge energy from hours 18:00 to 32:00, when the wind generation was insufficient, and the PV generation was unavailable from hours 20:00 to 30:00.

This indicates that the storage design of 639.6 GWh is the minimum required to prevent shortage at the critical points in addition with the PV and wind generation mix as shown in the Figure. In addition, if the PV is reduced below its minimum designed value, the shortage will occur in the early morning hours, since the PV generation will be at its lowest levels at that time and with insufficient wind power. On the other hand, shortages will occur during hours when storage is needed, such as at 21:00 or 23:00, due to the insufficient charging of the battery in earlier hours and days. This lack of prior charging will prevent the storage from providing the necessary discharge energy during these critical periods.

Suppose the wind is reduced at constant PV and storage. In that case, a shortage will occur in the hours when PV is not generating, in one of the critical hours such as at hour 32. During this period, the required discharge power from battery storage will become greater while the charge in earlier days and hours is constant. This will result in a larger output rate at a constant input rate in the storage, leading to supply failure (shortage). Even if the storage capacity increases with significantly higher capacity while the PV is constant, this will not prevent the shortage.

- **Final PV+Wind+Battery RES Optimisation**

Upon examining the final system design shown in Figure 77, the segments where only wind and storage contribute to the supply (indicated in yellow and orange zones) demonstrate that it is possible to reduce battery storage up to a certain threshold, while simultaneously increasing wind power capacity to lower costs by minimizing the need for storage. Beyond this limit, the wind increase, and storage decrease will stop the benefit as significantly higher wind capacity will be required to supply the shortage, which can be supplied by less storage capacity addition and thus, less battery resources deployed.

Storage has a benefit limit, which depends on the amount of shortage and the generation pattern of the wind. For example, if the storage capacity was decreased by 300 GWh, and the resulting shortage was supplied by wind at times when the wind was at its lowest generation due to lower wind speeds. Then, the wind turbines will be required to increase to a significantly higher capacity to supply minor, limited shortages at the bottom of the wind generation curve, as shown in the earlier results. This minor, limited shortage could be supplied by less resources using battery storage. Therefore, an optimization of the final RES solution was necessary. A parametric analysis was conducted through simulations in EnergyPLAN, where battery storage was reduced in increments of 100 GWh. The resulting shortage was then compensated by increasing the wind power capacity, continuing this process until the minimum required RES resources were achieved. Beyond this point, further increases in wind capacity and reductions in storage would no longer provide additional benefits, as they would lead to an overall increase in RES resources and, consequently, higher costs. The results are shown in Tables 18, 24 and Figure 78. Table 24 shows the reduced battery storage size, which is the most expensive component in the RES. Even with the increase in wind power plant capacity, the optimised solution achieved lower RES resources, especially in the system's most expensive component, as shown later in the economic analysis and details in Chapter 6.

Table 24 Final RES solution compared to the optimised one (PV+Wind+Battery) system design

	Final PV+Wind+Battery System	Optimisation of Final PV+Wind+Battery System
PV Capacity (MW)	195,405	195,405
Wind Capacity (MW)	132,109	150,398
Battery Storage Capacity (GWh)	639.6	400
Battery Duration (hr)	12	8

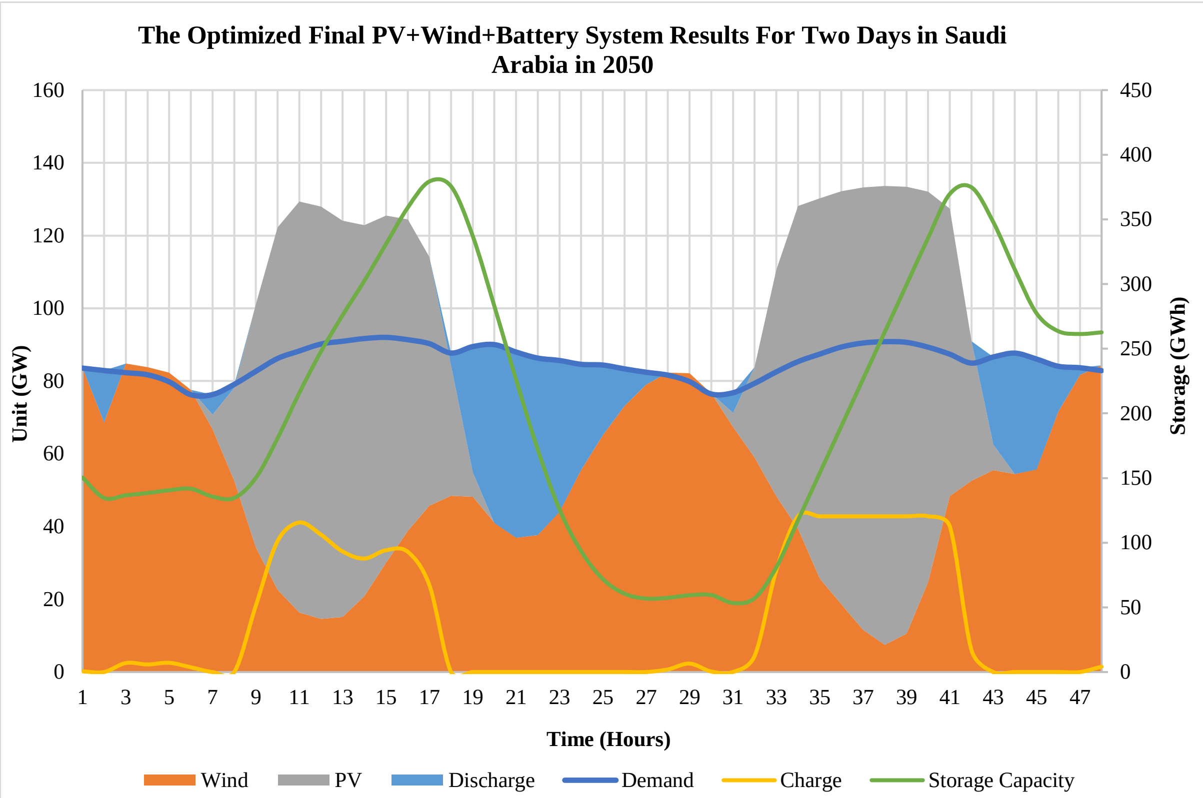

Figure 78 Optimised final PV+Wind+Battery system results for two days [Author: constructed from simulations].

Figure 78 shows the optimized PV+Wind+Battery RES for the same two-day period shown earlier in Figure 77. Through the optimization process, battery storage capacity and duration were minimized, effectively reducing system costs, a result substantiated in Chapter 5.

Upon closely examining Figure 78, the optimized PV+Wind+Battery system demonstrates a carefully managed response to the Kingdom's energy demand over two days, reflecting precise shifts in generation and storage dynamics. During nighttime hours, from around midnight to approximately 7:00 AM, demand remains steady at around 80 - 82 GW. At this time, with no solar contribution, the grid relies on wind generation, which delivers a consistent output. The shortage of about 10 GW is met by the battery storage system, which discharges steadily to cover this gap.

As dawn breaks around 7:00 AM, PV generation begins to increase. By 10:00 AM, combined PV and wind output reached approximately 125 GW successfully supplied the grid. This PV generation not only meets part of the ongoing demand but also provides surplus energy that is immediately directed towards recharging the battery. By late morning, around 11:00 AM, PV generation increases significantly, reaching around 110 GW, and peaks at midday. During this midday period, the system enters a surplus generation phase, when PV and wind combined generation of approximately 125 GW exceed grid demand. The battery storage leverages this surplus by accumulating charge to prepare for evening and night demands.

Throughout the afternoon, as sunlight gradually decreases, PV generation begins to taper off around 3:00 PM, descending from its peak towards lower levels. By 5:00 PM, PV output drops significantly and continues to decline until sunset, leaving wind generation and battery storage to sustain the grid as PV generation becomes negligible. As evening approaches, around 6:00 PM, the battery enters discharge mode once again, drawing on the stored energy that was accumulated during the day and earlier days. This discharge process continues through the night, with wind power maintaining a base generation level of 40 GW, while battery storage fills the gap to consistently meet the 83 GW demand.

In sum, Figure 78 illustrates a well-optimized harmony between PV, wind, and battery storage over a complete day-night cycle. PV generation during daylight hours supports both immediate demand and battery recharging, allowing stored energy to be efficiently conserved for overnight supply. The variations in battery storage capacity throughout the day align directly with the generation patterns of PV and wind, highlighting an optimized strategy that balances generation, storage, and demand, ensuring stable power supply and cost-effective operation across the entire day.

4.4 Green Hydrogen Backup Power Plant

4.4.1 Introduction

In this section, the green hydrogen backup power plant was introduced as a backup power with the optimized final RES (PV, wind, and battery storage) from Table 18 in case of potential unusual events in 2050. The primary function of this backup system is to support grid demand when any unexpected shortages arise from the RES due to unusual events or irregularities in the future. Importantly, this backup plant does not serve as an additional regular supply source alongside the RES; it operates solely as a standby facility, activated only during RES shortage. These shortages could occur in 2050 as a result of unusual conditions, such as unusual weather patterns, unexpected demand spikes, or sudden shutdowns in parts of the RES, perhaps due to extreme weather, like winds exceeding turbine safety limits or extended absence of sunlight impacting parts of the PV system. Such shortages underscore the inherent unpredictability associated with a 100% RES-dependent grid in 2050. This unpredictability extends to both weather fluctuations and potential shifts in future demand patterns, which may arise from policy adjustments, climate factors, or significant international and local events that could influence energy use and grid requirements.

The backup system in this study utilises green hydrogen entirely generated from the surplus energy from the existing RES using electrolysers. Hydrogen power plants could help the RES by capturing excess energy, with electrolysis, when they produce surplus power and fill the gaps with that energy when they aren't producing as much [222]. The current optimised RES supplies the grid entirely without a shortage and, at the same time, produces surplus energy that the grid does not need. The surplus energy was taken to produce the green hydrogen using electrolysers, which is then supplied to the combined cycle power plant, as shown in the following sections. The backup power plant is then set to standby mode when any shortage between the current RES and the demand is detected due to the earlier-mentioned reasons. In this thesis, it was assumed that RES could curtail or remain non-operational for up to a maximum of 20% of the system's total capacity. Once the shortage is detected, the backup power plant will operate, using green hydrogen as the primary fuel to supply the required power.

Due to the no generation of CO2 emissions from the green hydrogen power plant, the hydrogen power plant was first tested as a contributing system to the current RES with reduced RES capacity. The battery storage capacity (GWh) was reduced, and the resulting shortage compensated by energy supplied from the green hydrogen power plant. The costs of both systems involved comprehensive evaluation and discussion in Chapter 5. The results indicated that replacing part of the battery storage with the hydrogen power plant resulted in higher costs due to the added costs of the hydrogen power plant, electrolysers, and hydrogen storage. Thus, the green hydrogen power plant was only employed as a standby backup power system.

4.4.2 Why hydrogen as a fuel for gas turbines and not natural gas?

For the last few decades, the focus on reducing carbon emissions in the energy sector has been on the development of RES generation using mainly wind and solar energy. Although free from carbon emissions, RES sources exhibit significant intermittency caused by fluctuations in meteorological conditions and variations in sun irradiation and wind. This frequently occurs in conjunction with differences between the demand and supply of energy. Although demand side management is essential for addressing these imbalances, supply management is also necessary. This includes curtailing RES generation during periods of excess supply, implementing energy storage solutions, and utilising dispatchable and flexible conventional power plants for backup power. Recently, there has been a proliferation of storage solutions that enable both short term storage during the day and long-term storage spanning entire seasons. Although batteries are effective in facilitating the daily shift of energy demand from mid-day to night, chemical energy storage is the sole practical option for storing energy over extended periods and for seasonal storage.

Among the traditional methods of generating thermal fuel, combined cycle power plants are the optimal choice in terms of efficiency and environmental cleanliness. Replacing coal power stations with natural gas-fuelled open-cycle gas turbines can significantly reduce CO2 emissions, ranging from 25% to 50%. Deploying combined cycle power plants can result in additional reductions of CO2 emissions, ranging from 20% to 23%. When compared to the separate production of electricity in a combined cycle plant and heat in a fossil-fuel-powered boiler, the co-generation of heat and power in combined heat and power plants results in even lower specific CO2 emissions. Modern gas turbines with cogeneration can have a total energy efficiency above 90%.

The pursuit of carbon neutrality is increasingly becoming a crucial objective for countries and institutions in the long run. The European Union (EU) has demonstrated leadership by setting a target to achieve this objective by the year 2050. Nevertheless, transitioning from coal to natural gas for electricity generation and enhancing efficiency can only serve as the initial phase towards achieving it. As the next step, substituting natural gas fuel with sustainable hydrogen is a feasible method to facilitate carbon-neutral operation of power plants, as hydrogen combustion does not generate any CO2. In addition, the combination of natural gas and hydrogen can significantly reduce carbon emissions and achieve a consistent reduction in emissions as the proportion of hydrogen in the fuel is gradually increased over time [223].

4.4.3 Hydrogen Sources

The production of hydrogen requires energy. The classification of hydrogen as grey, blue, or green depends on both its energy source and the synthesis process employed. Hydrogen can be derived from natural gas, coal, or biomass, but greenhouse gas emissions come with these energy sources. Hydrogen can be produced using electrolysis, a technique that involves splitting water into oxygen and hydrogen.

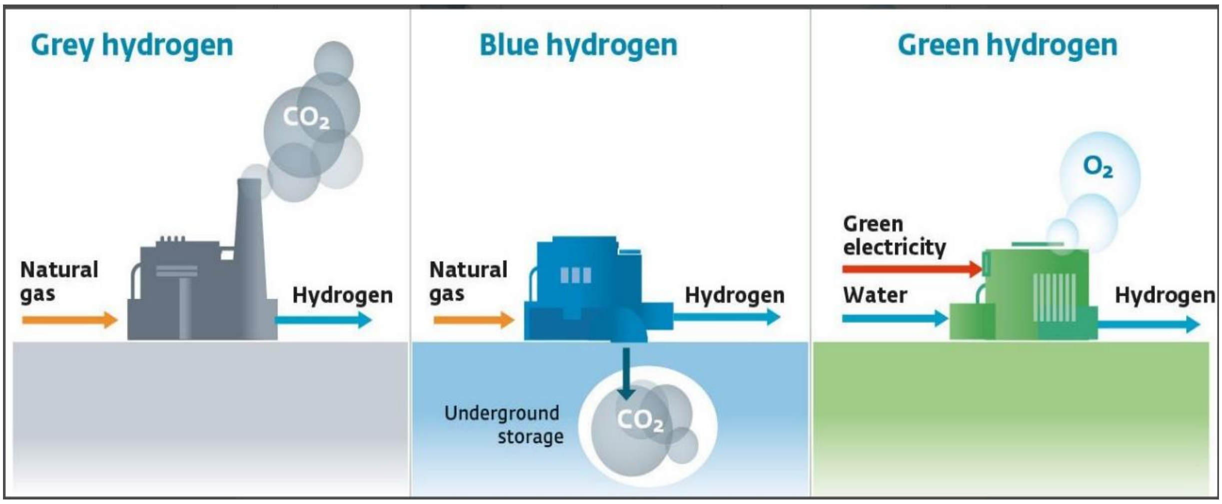

Figure 79 Illustration of grey, blue, and green hydrogen production.

- Grey Hydrogen

Grey hydrogen refers to hydrogen generated by using fossil fuels, such as natural gas or coal. Approximately 95% of the hydrogen produced globally at present is derived from grey hydrogen. Steam methane reforming and coal gasification are the primary production techniques. Both processes release CO2 into the atmosphere, and when this occurs during hydrogen production, the resulting hydrogen is classified as grey hydrogen. Grey hydrogen does not meet the criteria of being classified as a low-carbon fuel.

- Blue Hydrogen

Hydrogen produced from natural gas using carbon capture and storage is commonly referred to as blue hydrogen. Blue hydrogen closely looks like grey hydrogen, with the key distinction being that a significant portion of the CO_2 emissions are captured and stored underground through carbon capture and storage (CCS) technology. The process of capturing and isolating CO_2 instead of emitting it into the atmosphere enables blue hydrogen to function as a low-carbon fuel. The primary techniques for production include steam methane reforming and coal gasification, both of which include carbon capture and storage. Blue hydrogen is a more environmentally friendly option compared to grey hydrogen; however, its cost is high due to the utilisation of carbon capture technology.

- Green Hydrogen

Hydrogen produced by electrolysis using RES sources, such as wind or solar power, results in a clean and sustainable form of energy known as green hydrogen. Green hydrogen refers to hydrogen generated by using power derived from environmentally friendly energy sources. Green hydrogen is classified as a low or zero-emission form of hydrogen because it uses energy sources like wind and solar, which do not emit greenhouse gases during power production. Green hydrogen is produced through the process of electrolysis, which involves the separation of water (H_2O) into its constituent elements: hydrogen (H_2) and oxygen (O_2). Water splitting, sometimes referred to as electrolysis, requires an energy input. The procedure of providing energy to split water is costly, although significantly more eco-friendly than the manufacturing of grey hydrogen. In this thesis, green hydrogen is generated from the surplus energy of the final RES using electrolysers.

- Other Colours

Within the energy sector, other colours may be employed to distinguish between various hydrogen categories. While grey, blue, and green are the most prevalent colours, molecular hydrogen can also exhibit black, brown, red, pink, yellow, turquoise, and white colours.

4.4.4 Simulation Methodology and Results

In this study, the green hydrogen power plant was designed as a backup system to address potential shortages that may arise in 2050 from unusual events, as previously outlined. The green hydrogen plant, characterized by its zero CO2 emissions, was initially tested as a power supply contributor to the existing RES. This integration involved a strategic reduction in the capacity of certain RES components, notably the battery storage capacity (measured in GWh). The green hydrogen plant was subsequently introduced to compensate for the resulting energy shortage, thereby optimizing the overall system's costs by minimizing the most expensive components in the RES, the battery storage. Comparative cost analyses for both systems are presented in Chapter 5, while in this chapter, the focus remains on the technical aspects. Findings in Chapter 5 indicate that, despite its environmental benefits, integrating the hydrogen power plant as a regular power contributor to the RES is not feasible due to increased overall costs.

To simulate the hydrogen power plant in conjunction with the RES, data on total investment costs, fixed operation and maintenance costs, and variable operation and maintenance costs are required. However, a challenge arises due to the limited application of 100% hydrogen-fuelled CCGT power plants, leaving cost information largely unavailable.

Siemens has the required costs, and it's the leader in this technology with its advanced hydrogen combined cycle power plant and advanced hydrogen gas turbines, which vary in model according to the level of hydrogen integration. Some models support mixing with natural gas at 80% gas, 20% hydrogen, 40% hydrogen and 60% natural gas by volume. Siemens also aim to have gas turbines capable of operating on 100% hydrogen fuel by 2030 in their 100% hydrogen gas turbine roadmap. One of the Siemens power plants is the demonstration plant at their gas turbine manufacturing facility in Finspång, Sweden, to show how hydrogen and gas turbines, RES production and energy storage work together in a future flexible and sustainable energy system. Excess energy from gas turbine tests and electricity from solar panels are used to produce hydrogen in an electrolyser. The hydrogen is stored and used later as a fuel for gas turbine testing. It will be possible to optimise energy use through storage, such as hydrogen and batteries, in the local microgrid created. Hydrogen produced in the plant will also enable continued research and development to optimise the use of hydrogen in gas turbines and reach Siemens energy ‘s goal to run gas turbines on 100% hydrogen.

While Siemens does possess the costs data for a 100% hydrogen-fuelled CCGT power plant, the company declined to share this information with the author of this thesis, citing that such data is restricted to large-scale, implemented projects. Consequently, an alternative approach was needed to estimate the future costs of a 100% hydrogen CCGT power plant in 2050. This method involved using projected costs for CCGT power plants in 2050, along with the additional retrofit costs required to operate on 100% hydrogen without any natural gas blending.

In the coming years, newly constructed gas power plants will primarily operate using natural gas. This is because natural gas substantially reduces greenhouse gas emissions compared to alternative dispatchable fuels, such as coal. Additionally, large quantities of hydrogen as a fuel source are currently limited. Nevertheless, it is quite probable that newly constructed power plants would eventually need to be modified to utilise a mixture of hydrogen, potentially up to 100%, during their operational lifespan. Consequently, it is necessary to incorporate provisions for a cost-effective retrofit to enable hydrogen operation in the future. When evaluating a power-to-hydrogen system, it is essential to consider including current gas turbine assets, as they can be modified to run on hydrogen-based fuels. One benefit of gas turbines is their ability to be modified for use with different fuels, particularly those with higher concentrations of hydrogen.

Switching to a fuel with higher hydrogen content may necessitate modifications to the gas turbine, its accessories, and the balance of the plant. The quantity of hydrogen in the fuel determines the extent of the necessary modifications. If the new fuel consists of a mixture of hydrogen and natural gas, the necessary modifications may involve modest adjustments to the controls and the installation of new fuel nozzles for the combustor. Considering the numerous variations in fuel types, combustor layouts, and other factors, the necessary extent of evaluation must be determined individually for each case [224].

Suppose the conversion is aimed at utilising a fuel with a high hydrogen content. In that case, the project scope may encompass modifications to various gas turbine systems, as shown in Figure 80. This fuel change may necessitate transitioning to a different combustion system, necessitating the installation of new fuel accessory pipework and valves.

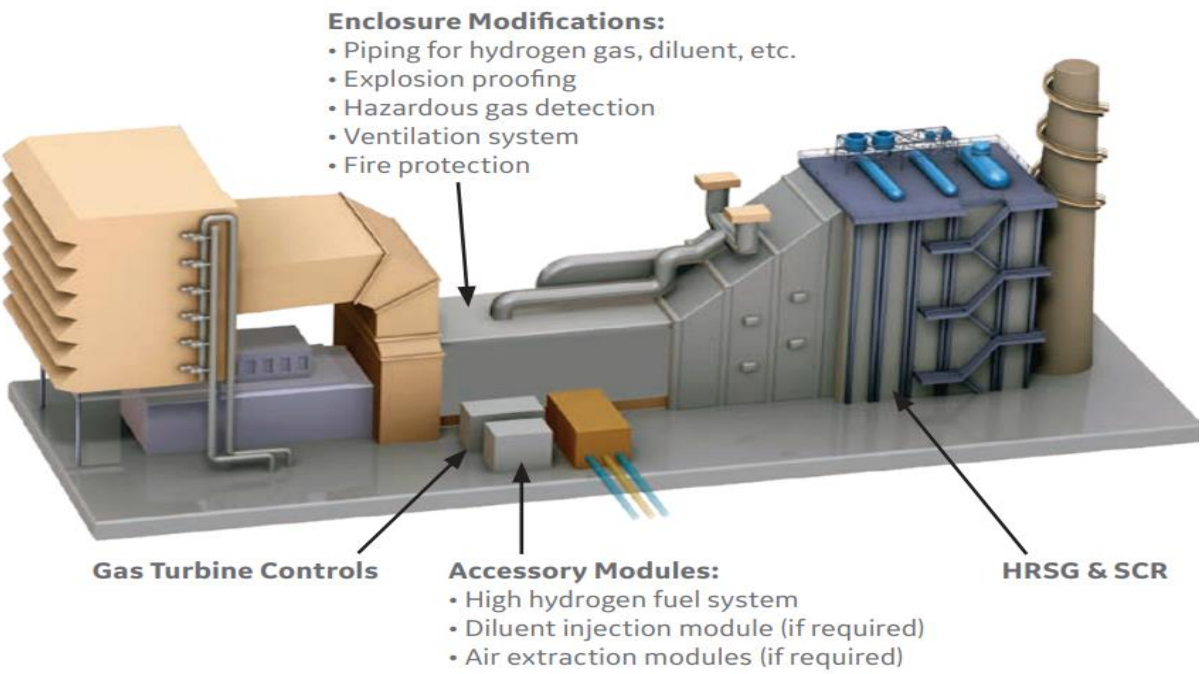

Figure 80 Potential impact of hydrogen fuel conversion on gas turbine systems.

Additionally, it may necessitate the acquisition of new fuel skids and adjustments to the enclosure and ventilation system. Additional modifications required due to the previously emphasised safety issues are the installation of advanced flame detectors capable of detecting hydrogen fires and the replacement of gas sensors with models specifically designed to detect gases with lower quantities of hydrocarbons. In addition to physical alterations, transitioning to a high hydrogen fuel may necessitate modifications to the gas turbine controls, potentially affecting the performance of the gas turbine in terms of both power production and thermal efficiency. Modifications in the fuel can also influence the broader breadth of the plant's balance of plant. Increasing the hydrogen concentration in the fuel can substantially increase NOx emissions. Additionally, there may be a modification in the exhaust energy generated by the gas turbine, which would need a reassessment of the limits of the Heat Recovery Steam Generator (HRSG) [225]. The magnitude of the required changes is a function of the amount of hydrogen in the fuel.

A recent study by ETN Global [226] in 2022 had analysed the retrofit costs of conventional thermal power plants when they are changed to operate on hydrogen and natural gas mix and pure 100% hydrogen. These analyses were applied to different power plant configurations, such as small OCGT, CHP, medium OCGT, large OCGT, and large CCGT. The retrofit costs are also divided as per the amount of hydrogen addition by volume, starting from the original natural gas power plants at 100% natural gas and 0% hydrogen up to pure hydrogen use (0%

natural gas, 100% hydrogen). For example, 70% natural gas and 30% hydrogen, 30% natural gas with 70% hydrogen etc. The retrofit costs considered in this thesis are based on the data from this report, as it was the only available and reliable reference with these detailed data for each power plant configuration with the amount of hydrogen addition. No other references were found as this report with such detailed and available data. Table 25 below shows the assumed CCGT power plant in 2050 with the retrofit changes on efficiency and lifetime to run the power plant 100% on hydrogen. The selected power plant is a large CCGT at approximately 500 MW. Tables 25 and 26 below show the assumed electrolyser and hydrogen storage efficiencies and lifetimes. For the economic side, the retrofit cost assumptions, electrolysers and hydrogen costs are shown and discussed separately in Chapter 5.

Table 25 Assumed CCGT power plant efficiency, and lifetime with retrofit effects required to operate on 100% hydrogen.

	2050 Initial CCGT power plant	Retrofit Effect	Final CCGT power plant Retrofitted
Efficiency (%)	64% [230]	-1.3 (2%) [230]	62.7%
Lifetime (Years)	25 [227]	-	25

Table 26 Assumed electrolyser efficiency and lifetime in 2050.

	Alkaline Electrolyser
Conversion Efficiency (%)	80% [228],[229]
Lifetime (Years)	25 [227]

Table 27 Assumed hydrogen storage lifetime in 2050.

	Hydrogen Storage
Lifetime (Years)	20 [227]

In terms of grid stability, some research papers [231][232] assumed that 30% is the minimum required capacity of production from grid stabilising units such as condensing power plants or hydro running all the time each hour of the year to achieve the minimum 30% production each hour. However, this work could not be carried out in this project as the total RES share of electricity production for the entire year will drop, which contradicts with this thesis's primary goal; the 100% RES electricity demand production. In addition, this study assumes that by 2050, the grid stability will be managed when providing a high share of PV and wind power systems with the current continuous research and new technologies and control systems.

- Green Hydrogen Power Plant as a Standby Backup System.

In this chapter, the hydrogen power plant was considered as a power backup system to address the power shortages that may arise due to the inherent unpredictability of the RES, potential climate uncertainties, and other previously discussed factors. However, in Chapter 5, the hydrogen power plant was tested as an integral, active component of the RES. In this role, it functioned not only as a complementary technology but also as a key contributor to the system's energy generation. This integration allowed for a reduction in battery storage capacity, which was strategically implemented to optimize the overall system design and achieve cost reductions while maintaining energy reliability and sustainability.

The future scenario presents considerable uncertainties, particularly regarding climate impact and the natural unpredictability of the RES. Thus, certain assumptions are necessary. In this thesis, we assumed a possible shortage in RES supply by 2050, potentially due to climate variability, the unpredictability of RES, and fluctuations in demand. Specifically, the assumption was that the possible future shortage may affect up to 20% of the total RES, with a 10% reduction in PV capacity due to factors like lack of sunlight or extreme weather, and a 10% reduction in wind capacity, possibly resulting from wind speeds exceeding turbine cutoff thresholds or falling below operational speeds. In the event of such a shortage, the thermal backup power plant would be activated immediately to compensate the power shortage.

Following the 20% blackout in RES, wind capacity would be adjusted to 135,359 MW, while PV capacity would drop to 175,864 MW in EnergyPLAN. The entire year simulations started with the addition of the green hydrogen power plant. The results indicated that the minimum hydrogen power plant capacity needed to cover the resulting shortage at the critical point was 8,693 MW, as shown in Figure 81.

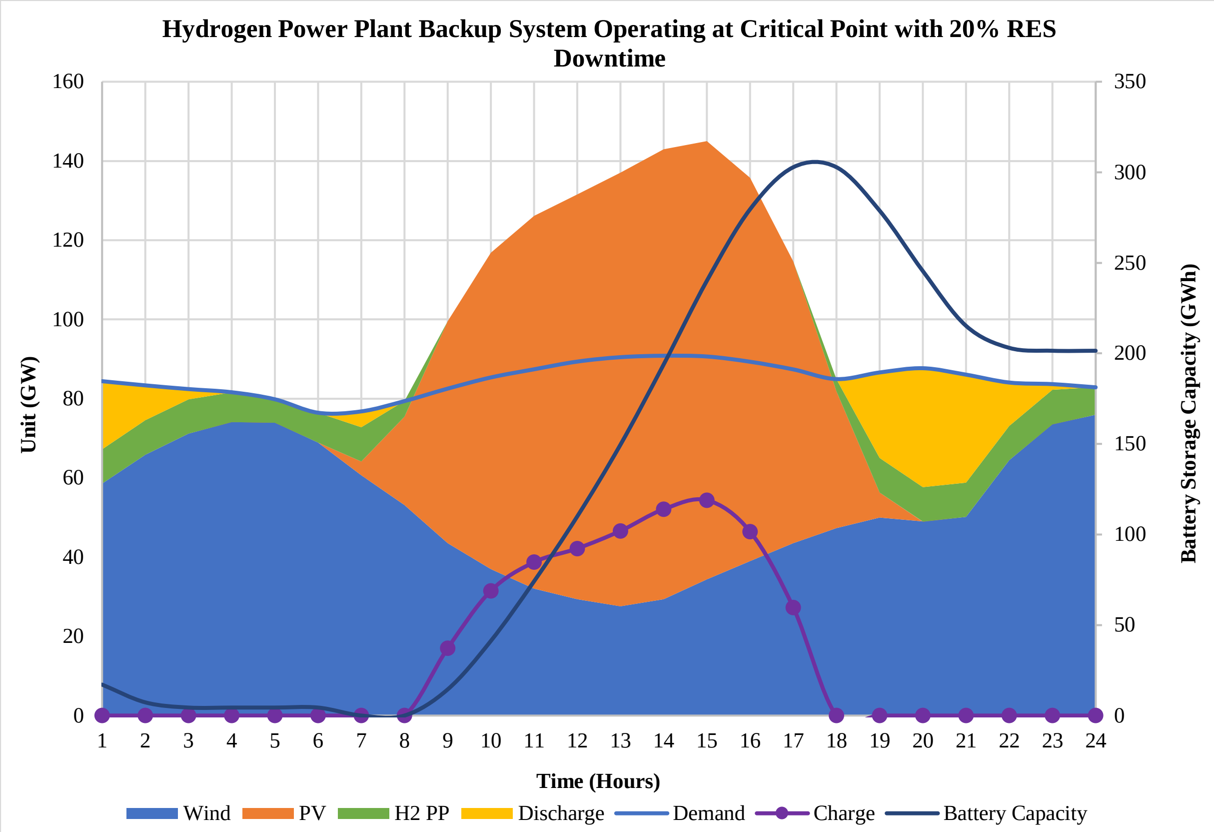

Figure 81 Hydrogen power plant backup system running when 20% RES is off at the critical point [Author: constructed from simulations].

Figure 81 illustrates the performance of the RES system during an emergency downtime caused by factors such as climate change, the inherent unpredictability of the RES, or sudden climate variations, with the hydrogen backup system engaged to cover the resulting shortage. At 7 AM, the battery storage was nearly fully depleted, marking a critical moment when the hydrogen power plant must operate at its minimum required capacity to bridge the shortage. At this point, the Kingdom's demand was 76,787 MW, while wind generation provided 60,664 MW and PV contributed by 3,456 MW of power. The battery storage supplied an output of 3,973 MW, which was entirely depleted shortly after. Consequently, a shortfall of 8,693 MW appeared. The hydrogen power plant maximum capacity was then sized based on the maximum shortage that occurred in the system for the entire year.

Throughout the day, PV generation sufficiently supplied the grid demand and recharged the battery storage. However, the shortage appeared due to RES downtime during dawn and nighttime hours, when wind production was insufficient, and battery storage became essential. To analyse the impact of a reduced hydrogen power plant capacity, the capacity of the power plant was reduced by 300 MW decreasing to 8,393 MW. The results of this adjustment are presented in Figure 82.

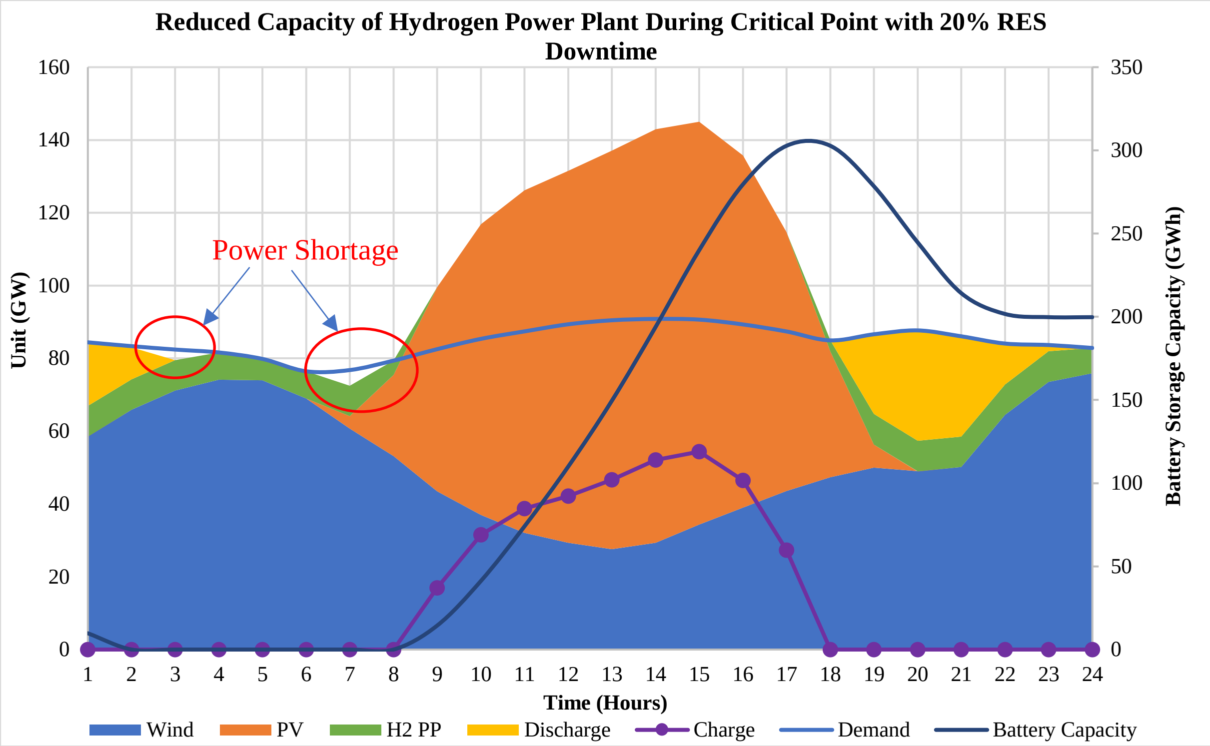

Figure 82 Reduced hydrogen Power plant capacity when 20% RES is off at the critical point [Author: constructed from simulations].

Figure 82 shows the same graph of Figure 81 but with the reduced hydrogen power plant capacity below the minimum required. The shortage occurred at a critical point at 7 AM, when the country electricity demand reached 76,787 MW. At that time, wind energy production contributed 60,664 MW, while PV production provided 3,456 MW. The battery storage, however, was fully depleted, providing no power (0 MW) to the system. The battery storage was depleted not only at the critical point but also at 2 AM (5 hours before the critical point) due to higher total accumulative discharged energy from storage to supply shortage in other hours of the year after the 20% downtime in RES. At the same hour, hydrogen power production provided 8,393 MW: the maximum capacity. Therefore, the total occurred shortage resulted in as follow:

The demand (- 76,787 MW) + wind power (60,664 MW) + PV power (3,456 MW) + hydrogen power plant (8,393 MW) + battery discharge (0 MW) = - 4,273 MW which is the resulting power shortage.

Following the determination and validation of the hydrogen power plant's capacity, it is crucial to calculate the necessary electrolysers and hydrogen storage capacities. To begin, the green hydrogen demand for the backup power plant must be determined, as illustrated in Figure 83.

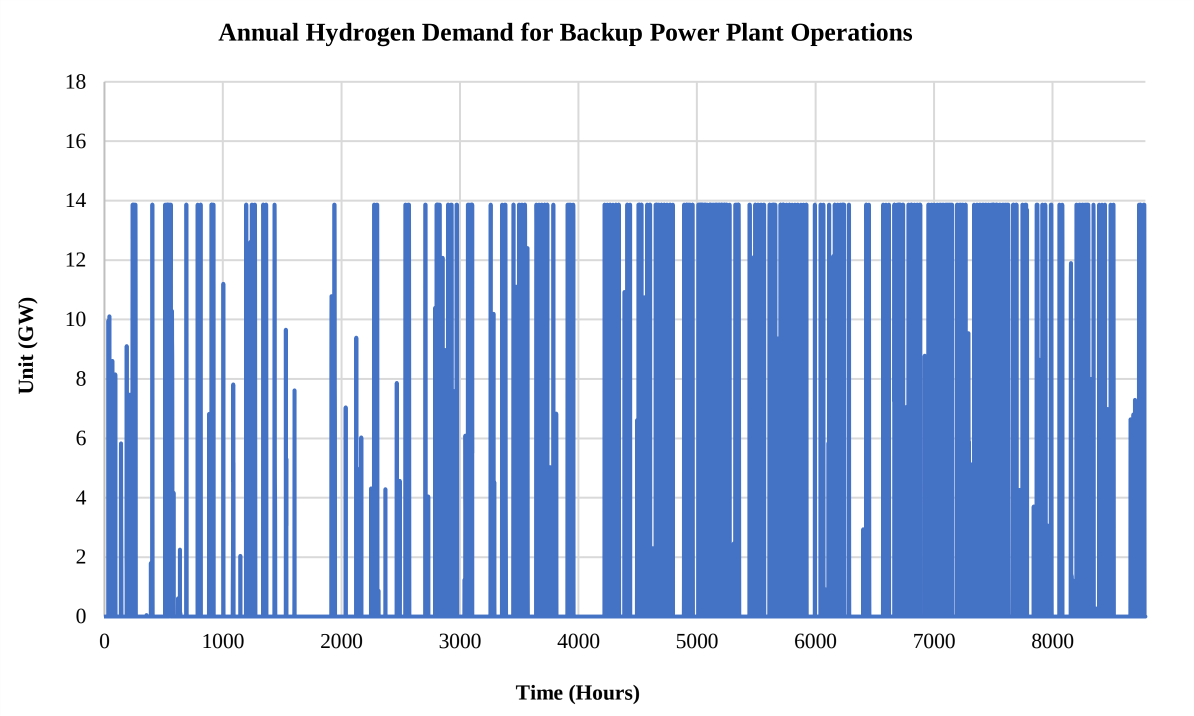

Figure 83 Hydrogen demand for the backup power plant when operating during the entire year [Author: constructed from simulations].

Figure 83 shows the annual hydrogen demand of the backup power plant, under the assumption that the system operates continuously throughout the year (though this is not an accurate operational scenario). The intent is to determine the peak hydrogen demand over the year, which is essential for appropriately sizing the electrolyser and storage capacities. This approach identifies the highest continuous hydrogen discharge required within a single day, forming the basis for storage sizing. As shown, the peak hydrogen demand reaches approximately 14 GW (13,864 MW precisely), with the maximum sustained discharge occurring during the summer months. Figure 84 further examines this by detailing the peak hydrogen requirement over a full day of continuous discharge, enabling analysis of the highest daily demand.

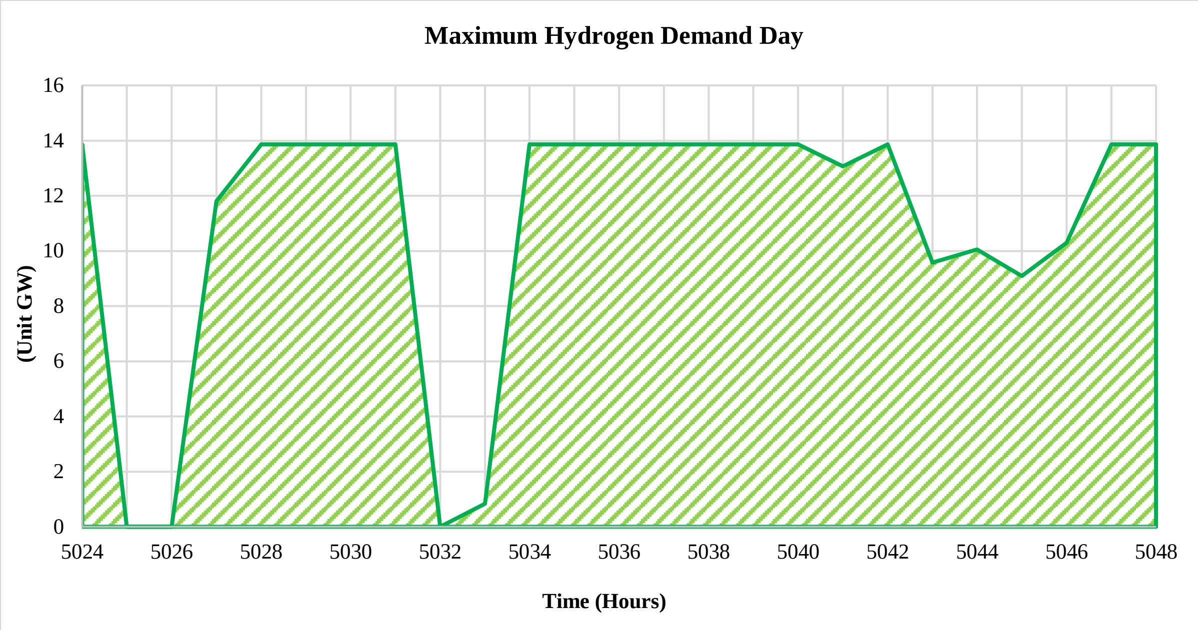

Figure 84 The day with maximum hydrogen demand [Author: constructed from simulations].

Figure 84 shows the day when the maximum hydrogen demand is required. The peak is 13,864 MW. The area under the curve is the amount of hydrogen demand in GWh, representing the minimum required hydrogen storage capacity. As mentioned earlier, the maximum hydrogen demand occurred in summer between hours 5,024 to 5,048, representing 8:00 AM on the first day until up to 8 AM on the second day. Total area under the curve is 272,676 MWh = 272.676 GWh. Although this should be the minimum storage size. However, for safety factors, it was assumed that at the maximum demand day, hydrogen demand operates at a maximum capacity of 13,864 MW for the entire day (24 hours) before running out of hydrogen supposing there is no electrolyser production. It was assumed that the hydrogen storage must cover the maximum hydrogen demand capacity required for 24 hours without any electricity received to the electrolyser (and thus no hydrogen production) as the worst-case scenario. Thus, the required storage and electrolyser capacities are calculated as follows:

$$Minimum\ Electrolyser\ Capacity\ Required = \frac{\text{Max Hydrogen Demand (14,000 MW)}}{\text{Electrolyser Conversion Efficiency (0.8)}} = 17{,}500\ \text{MW}$$

$$Required\ Hydrogen\ Storage\ Assumption = \frac{\text{14,000 MW}*\text{24 hrs}}{1000} = 336\ \text{GWh}$$

- Brief Summary of Hydrogen Backup Power Plant Design and Operation

To summarize, the hydrogen power plant was incorporated as a backup system to mitigate potential shortages stemming from the future unpredictability and uncertainties previously outlined. It was assumed that up to 20% of the projected 2050 RES capacity could experience downtime, leading to a power shortage. This shortage is intended to be addressed by the hydrogen power plant during the RES downtime. The plant's maximum capacity requirement was determined based on a scenario assuming 20% downtime in the RES. This resulted in a design capacity of 8,693 MW, corresponding to the highest annual power shortage that occurred under these conditions. Following this, cost and efficiency evaluations were performed using retrofit expenses associated with existing natural gas CCG power plants, as the hydrogen plant was intended to operate exclusively on 100% hydrogen, necessitating retrofits due to the absence of fully hydrogen-operated plants today. The peak annual hydrogen demand for the plant was then estimated at 14 GW based on the entire year simulations, as shown in Figure 83. Additionally, the maximum one-day hydrogen discharge demand was calculated at 272.676 GWh, as indicated by the green curves in Figure 84, establishing the baseline hydrogen storage requirement.

Despite fluctuations in hourly hydrogen consumption, sometimes dropping to zero demand, the design conservatively assumes a sustained full capacity demand of 14 GW over a day to ensure reliability as a safety factor which resulted in the final required hydrogen storage size for one day of RES downtime supposing no electrolysers production. Moreover, the necessary capacities for electrolysers and hydrogen storage over a 24-hour period were calculated based on these assumptions at 17,500 MW and 336 GWh, respectively, as demonstrated in earlier equations. Importantly, the electricity required for the electrolysers was entirely supplied by surplus RES, eliminating the need for additional power plant installations. This strategy not only leverages excess RES generation to stabilize the grid but also reduces costs linked to building additional backup generation capacity. The Alkaline Electrolyser used operated at an 80% power-to-gas conversion efficiency, as specified in Table 26

4.5 Transport Electrification Scenario

4.5.1 Why is Transport Electrification Required?

The transport sector plays a crucial role when considering a high share of RES for a country like Saudi Arabia, and this importance is grounded in two primary reasons. First, one of the primary goals of this thesis is to significantly reduce or eliminate CO2 emissions within the country’s future energy system, with the transport sector being the largest contributor to CO2 emissions in the Kingdom. Second, and more fundamentally, a high-RES share across various sectors results in considerable surplus energy, which remains unused for grid demand or battery storage, particularly within the electricity sector. This surplus is a natural outcome associated with a high-RES share, as documented in many research and studies. Managing this surplus is essential for maintaining grid stability, particularly in terms of voltage and frequency, which traditionally has been addressed by large power stations. Although this thesis assumes that, by 2050, advancements in technology and control systems will adequately manage these stability issues linked to surplus energy, it remains preferable to minimize surplus generation to promote grid reliability and efficiency.

To do so, one of the highly effective approaches in managing surplus energy is integrating the transport sector into the overall RES energy system. As the share of RES power increases, it becomes increasingly challenging for flexible energy systems to handle excess electricity production, necessitating additional strategies over time. Electrifying the transport sector introduces battery flexibility while simultaneously enhancing fuel efficiency [233]. This integration yields dual benefits: it significantly improves fuel efficiency and reduces CO2 emissions from ICE vehicles while also reducing excess electricity production from RES. In other words, the RES supports the transport sector in becoming greener and more efficient, while the transport sector aids RES by mitigating surplus electricity generation. Additionally, transitioning the transport sector to battery and hydrogen vehicles dramatically reduces fuel consumption, given the relatively low efficiency of combustion engines. In this thesis, the focus is on direct electrification of transport, rather than hydrogen-powered vehicles using RES-derived hydrogen, due to the superior efficiency of battery electric vehicles and the less complexity.

4.5.2 Transport Electrification Scenario's Calculations

To estimate transport demand in 2050, it is essential to determine both the number of passenger vehicles and the total annual mileage. Research by [234] provided an estimation of Saudi Arabia's vehicle fleet size, based on historical data spanning from 1980 to 2020, covering both passenger and non-passenger vehicles currently active on the road. The projected number of active vehicles in 2050 was derived by analysing the historical trends identified in [234]. Initially, the annual growth factor is calculated as follows:

$$Yearly\ Growth\ Factor\ (Vehicle\ fleet\ size) = \left(\frac{100 - 100 * \left(\frac{3\text{ million cars}}{10.5\text{ million cars}} \right)}{20\text{ Years}} \right) = 3.5\ \%$$

Where:
The number of vehicles in 2000 is 3 million cars
The number of vehicles in 2020 is approximately 10.5 million cars.

The annual growth rate is then multiplied by the number of years from 2020 to 2050 as follows:

3.5% × 30 years = 105%

The number of active vehicles on the road in 2050 is then calculated as follows:

10.5 million vehicles × 2.05 (105%) = 21.52 million vehicles

The same paper estimated the total number of passenger cars out of the total active vehicles on the road in 2016 using GaStat's demographic survey data, which provided information of the passenger cards owned by Saudi households and the ownership of passenger cars for foreign households. The results showed that passenger cars comprised around 84% of the total active vehicles on the road in 2016. The same fraction is assumed for 2050; thus, the total number of passenger cars in 2050 is estimated as follows:

21.52 million active road vehicles × 0.84 = 18 million passenger vehicles.

Following the calculations of the future passenger vehicles fleet in 2050, it is crucial to calculate the total annual miles. The total annual miles are calculated as follows:

18 million passenger vehicles × 16,000 annual miles per passenger vehicle in S.A. [234]
= $(2.88) \times (10)^{11}$ miles per year = 463,491,072,000 km per year.

For the electric vehicles, different cars have different efficiencies. Research [235] have consulted various specification sheets and concluded a representative range of high and low efficiency ranges to be from 0.09 kWh/km as the lower range to 0.20 kWh/km as the higher range. In this study, we used the average EV efficiency between the higher and lower range which equals to 0.14 kWh/km. The assumed EV efficiency of 0.14 kWh/km in this thesis falls within the range of values observed in "real-world" data from other markets. However, Saudi Arabia is still in the early stages of adopting electric vehicles. As of 2023, only a limited number of electric vehicles, such as those from Lucid, have entered the Saudi market. Given this nascent stage, obtaining accurate data on the "real-world" efficiency of electric cars in Saudi Arabia is challenging. However, some papers such as [237] indicated that electric car efficiency in Saudi Arabia varies among factors like usage, climate, etc. Still, on average values, the efficiency varies between 0.15 - 0.20 kWh/km, which falls within the range of the assumed value in this thesis. Assuming 100% of the 18 million passenger vehicles are to be replaced by EV's with 16,000 miles per passenger car per year results the total required power by the grid as follows:

463,491,072,000 KM per year × 0.14 kWh/km = 64.88 TWh of electric energy required for EV's by the grid annually.

Now for comparison with the deployment of EV's, if the 18 million cars are to be used as ICE vehicles and not as EV, the amount of energy required is calculated as follows: Assuming passenger ICE vehicles fleet economy is 7.15 km/L [234]. The annual gasoline consumption will result in $(6.48) \times (10)^{10}\ liters\ per\ year,$ which is translated into 576.9 TWh of fuel energy required for passenger ICE vehicles in 2050, as 1 Liter of gasoline contains energy equivalent to 8.9 kWh of electricity [236].

Utilizing EV's technology has resulted in decreased total transport passenger vehicle fleet energy demand from 576.9 TWh to 65 TWh in 2050 as the efficiency of EV's are significantly higher than the low efficiency ICE vehicles fleet. The RES can completely supply the required electricity for transportation sector from the surplus energy in addition to supplying the hydrogen backup system, as shown in the earlier section. Although the deployment of this size of EV's fleet might be more aggressive and practically difficult due to the global uptake levels of annual EV car sales, such as in the scenarios of 3.5%, 7%, and 14% of the annual car sales [235]. However, it was chosen to assess how the high deployment level of EV's would affect the power sector and the CO2 emissions in 2050.

One of the concerns that must be considered is the charging times patterns. Deployment of the high share of EV's will require a systemised approach to charging patterns, such as nighttime charge, which is the most common, off-peak charge, peak charge, or random charge, etc. In this paper, the electrical demand of the passenger vehicles fleet in the transport sector was 100% supplied by surplus power generated from the RES as shown in the earlier sections. The challenge is that surplus power is not 100% predictable; yes, it is predictable to some extent, but not exactly. This means that charging times for the EVs can't be specified for the entire sector in certain hours. For example, assuming a nighttime charge of 50% of the transport electrical demand from 8:00 PM to 12:00 PM, the surplus grid power is varying and might not be able to supply the required demand in specific hours. Thus, in this example, the grid surplus might not be sufficient at these specific hours **even though** the daily surplus **can** supply the entire electrical transport demand. Daily RES surplus can 100% supply the entire transport electrical demand, but the ability of this supply is varying among different hours of the day.

The best method to manage this problem is to have the passenger car transport demand as flexible one-day period demand. A demand can be distributed freely over a specific period, such as a one-day flexible demand. This means that the total accumulated day transport demand can be met by the surplus power generated that day. However, the charging time will be flexible during the 1-day period at any hour within the day. In other words, the charging times should be synced with the surplus generation hours based on the total surplus generated each hour. This will require a method of consumer notification [233]. In the designed RES in the earlier sections, Saudi Arabia will have a daily surplus power of around 926 GWh and annual surplus power of approximately 400 TWh, which is sufficient supply the entire transport's passenger car fleet.

It is essential to mention that this paper only focuses on the link between EVs and Saudi Arabia's energy mix. It does not consider the complete life cycle of the vehicle, the battery, or any of its other components. This paper is not a life cycle assessment (LCA) study. It does not consider the emissions associated with finding, extracting, and transporting the primary fuel [238]. While LCAs are essential and insightful [239], they are beyond the scope of this paper. This paper assumes that charging stations and other infrastructure supporting EV deployment are readily available.

As EVs are deployed, the grid must supply additional energy for battery charging. The additional energy needed depends, among several other factors, on the deployment rate and distances travelled. These two parameters, in particular, deserve a dedicated research undertaking. Arriving at deployment rates and distances travelled should ideally be conducted through tailored studies that consider consumer perceptions of EVs against ICEVs, and consumer driving patterns and habits. However, such an endeavour is beyond the scope of this paper. Instead, we have studied different deployment scenarios and travelled distance scenarios to capture the impact of EV deployment on required grid power.

The 65 TWh energy consumption of the passenger vehicle fleet in Saudi Arabia in 2050 replaced the total gasoline consumption of the transport sector in 2050 in Table 15. This table shows the fuel consumption from all types of vehicles in 2050, including passenger gasoline cars, heavy work diesel trucks, lightweight utility diesel trucks and vehicles, and aviation, which is 1054.51 TWh per year. Gasoline accounts for 55% of the total transport energy demand, as illustrated in Figure 10, since all passenger vehicles are assumed to operate on gasoline. Diesel usage in passenger vehicles is negligible due to its limited share [240]. Thus, 55% of the total estimated transport fuel demand was removed and replaced by 65 TWh of electricity, resulting in a total transport demand of 474.52 TWh, including EVs for passenger cars, diesel for heavy and light utility tucks, kerosene for internal aviation.

CHAPTER 5

Model Economic Analysis, Assumptions and Fuel Prices with RES Scenarios' Economic Evaluation

5.0 Introduction

Following the completion of the technical analysis in Chapter 4, this chapter conducts the economic analysis of the same RES to assess each system and scenario from an economic perspective. The aim is to provide a comprehensive final evaluation that integrates both technical and economic aspects of each scenario. This chapter focuses on the economic analysis and outlines the key assumptions underlying the model and future RES scenarios. The chapter begins by discussing the economic parameters for the reference case model, including the methods used to calculate these parameters and the assumptions made in the process. The economic evaluation first considers the power plants in the reference year model, accounting for factors such as investment costs, fixed and variable O&M costs, plant capacities, lifetime efficiency, and interest rates. Following this, the chapter details the calculations and assumptions related to fuel prices across the entire system model. Lastly, the chapter presents the complete economic analysis for all the RES scenarios, including PV, wind, and battery storage. These scenarios are compared based on the assumptions made, and the results are discussed with reference to reliable sources. This integrated analysis provides a robust comparison of the technical and economic viability of the different RES configurations, supporting the overall conclusions and recommendations of this research as discussed later in Chapter 6

In the economic analysis, assumptions regarding the feasibility of each system design are assessed by calculating the total annual costs, and LCOE under different designs and simulation strategies. To perform these calculations, several key inputs are required, including investment costs, O&M costs, system lifetime, the applicable interest rate and the discount rate. The model then evaluates the socioeconomic impacts of energy production by breaking down the costs into specific categories: 1) fuel costs, 2) variable operational costs, 3) investment costs, 4) fixed operational costs, 5) electricity exchange costs and benefits, 6) potential CO2 emissions payments, and 7) LCOE. The interest rate plays a crucial role in calculating the annualized costs for each system design, allowing for a clear comparison between scenarios. By incorporating these elements, the model offers a comprehensive economic evaluation of each

RES configuration, considering both direct operational expenses and broader socioeconomic factors. This approach ensures that the financial viability of each scenario is fully understood in the context of long-term energy planning.

Interest rate is assumed to at 3% in Saudi Arabia for all the scenarios based on low interest rates of large-scale RES projects and initiatives in the GCC region, including Saudi Arabia, in the IRENA report [241]. IRENA report shows the favourable financing condition in Saudi Arabia, the Gulf region, which enables low prices for large-scale RES projects. These conditions include low interest rates, extended loan duration and high debt-to-equity ratios. Region's loans for large-scale RES projects typically tenure (over 20 years) with low interest rates (120-200) basis points over LIBOR.

O&M cost data for PV and wind systems in Saudi Arabia for the year 2050 are currently unavailable, as large-scale RES projects are still in the development phase and not yet fully operational. Saudi Arabia has only recently begun initiating large-scale RES projects over the past two years, and as a result, no comprehensive technical or economic data are available at this stage. Consequently, for this research, these costs were estimated based on forecasted RES costs for 2050 provided by Aalborg University, as detailed in the cost datasheet [242]. These assumptions allow for a more informed analysis of future scenarios, compensating for the current lack of localized cost data while aligning with international projections for RES costs.

Discount rate was assumed for the LCOE calculations. For the discount rate, the value of 7% was considered for Saudi Arabia for its RES in 2050. The recommendation of a 7% discount rate for Saudi Arabia's RES projects in 2050 is supported by insights from global energy institutions such as the IRENA and IEA, as well as research in the field of RES finance. These organizations analyse global RES financing, and they provide guidelines on appropriate discount rates for various regions, considering the local economic conditions, risk factors, and government policies. IRENA, in its Renewable Power Generation Costs and Global Renewables Outlook reports, indicates that discount rates in the Middle East typically range between 5% and 10% for RES projects. This range reflects the cost of capital, project risk, and the level of government backing. For Saudi Arabia, given its extensive RES plans under Vision 2030 and the Saudi Green Initiative, a 7% discount rate is suitable as it represents a moderate risk profile, where strong government policies and investments reduce uncertainties, but some economic and technical risks still exist. Reports from the IEA, such as the World Energy Investment Outlook, also support the use of discount rates in the 6-8% range for countries like

Saudi Arabia, which benefit from robust government support and a stable economy but still face challenges typical of large-scale RES transitions. Saudi Arabia’s energy transition is expected to be well advanced by 2050, making it more financially stable, yet the capital markets may still factor in moderate risk for renewable energy projects. Studies by the World Bank and the European Investment Bank further corroborate this by highlighting that Middle Eastern countries with strong governmental energy policies, such as Saudi Arabia, benefit from moderate-risk environments where financing costs can be reflected by a 7% discount rate. As Saudi Arabia’s RES sector matures and attracts foreign investment, the cost of capital is expected to stabilize, making 7% an appropriate figure based on both financial and policy projections for 2050 [243-247].

In calculating the LCOE, the lifetime of all RES solutions was assumed at 30 years. The choice of a 30-year project lifetime for RES solutions in Saudi Arabia in 2050, despite the differing lifetimes of individual components (such as PV panels with a 40-year lifetime, battery systems with a 15-year lifetime (needs one time replacement), and wind turbines with a 30-year lifetime), can be explained by several key technical, financial, and operational factors. These factors align with best practices in energy system design and economic optimization, as backed by high-quality research papers and recommendations from reputable energy institutions.

1. Technical Alignment with the Shortest-Lived Major Component

One of the key reasons for adopting a 30-year project lifetime is the desire to align the project with the operational lifespan of the wind turbines, which typically last 30 years. Wind turbines, a significant part of RES in Saudi Arabia, face mechanical degradation, wear and tear, and increased maintenance needs after 30 years, which can lead to significant downtime or expensive overhauls. Research from IRENA [248] indicates that after 30 years, the economic viability of wind turbines diminishes due to increased maintenance costs and declining performance. While PV panels can technically last 40 years, wind turbines often dictate the overall project lifetime in hybrid systems involving both wind and PV. Designing a project around the 30-year operational life of the wind turbines ensures economic balance and minimizes the need for costly replacements beyond that point.

2. Economic and Financial Optimization

A 30-year project lifetime is often chosen because it optimizes the LCOE by balancing the economic lives of different components, including battery systems, which typically require replacement every 15 years. Extending the project to 40 years, just to match the lifetime of PV panels, would require replacing the batteries twice (at year 15 and again at year 30), significantly increasing costs. NREL's research [249] on battery energy storage systems shows that frequent battery replacements introduce both financial risks and operational complexity. By selecting a 30-year project lifetime, the number of battery replacements is reduced to one, minimizing LCOE and capital expenditure. This is important in Saudi Arabia, where future large-scale RES projects are focused on cost-competitiveness as they aim to displace conventional energy sources.

3. Degradation of PV Performance

While PV panels may have a technical lifespan of 40 years, their performance degrades over time, typically at a rate of 0.5% to 0.8% per year [250]. By year 30, the performance of PV systems may have degraded by up to 20%, reducing the energy output and financial returns in the final decade of operation (years 30 to 40). This degradation means that the economic value of extending the project for an additional 10 years may not justify the associated costs of battery replacements and other operational expenses. PhD research conducted at Loughborough University [251] demonstrated that a 30-year project lifetime is often economically optimal for hybrid systems (PV + battery), as the cost of maintaining the PV system in the last 10 years is outweighed by the declining performance and increased operational complexity.

4. Simplifying Financial Management and Risk Reduction

In large-scale RES projects, financial predictability is critical for securing long-term financing and attracting investors. A 30-year project horizon provides a clear, well-defined timeframe for investors and developers, aligning with the lifetime of power purchase agreements (PPAs) and other contractual obligations. Extending the project to 40 years complicates financial modelling because it introduces additional uncertainty in cash flows due to battery replacements and PV performance degradation. In its Operational Guidelines for RES [252], IRENA recommends setting the project lifetime to the shortest-lived major component (often wind or battery systems), as this simplifies financing, operations, and decommissioning plans. Investors and financiers prefer projects where the operational risks and maintenance schedules are aligned over a shorter and predictable timeframe.

5. Practicality of Battery Replacements

In a hybrid system, the battery storage typically lasts only 15 years, requiring at least one replacement within the 30-year project lifetime. However, if the project is extended to 40 years, the batteries would need to be replaced twice (at years 15 and 30). This introduces significant costs, as battery replacement is expensive, and the technology may evolve rapidly, making it difficult to predict future battery costs. Research from NREL [249] suggests that the optimal project length for systems incorporating battery storage is aligned with the second battery replacement cycle (i.e., 30 years), after which the financial returns diminish due to the high cost of the second battery replacement.

6. Industry Best Practices and Standards

Several high-level energy institutions and PhD research papers recommend aligning the project lifetime with the 30-year wind turbine lifespan for hybrid systems in which wind power is a significant component. Extending the project lifetime beyond 30 years introduces operational and financial complexity, particularly due to the need for multiple battery replacements and PV degradation. For example: IRENA [248] suggests that hybrid RES projects involving wind and storage should consider the wind turbine’s operational life as the guiding factor when determining the overall project life. NREL and Fraunhofer ISE both recommend a 30-year project lifetime for similar hybrid energy systems due to the technical limitations of batteries and the degradation of PV systems [249][250].

The cost data presented in this study are projections for 2050, derived from historical and current data on RES projects. These projections are based on several key factors, including the costs of existing power plants, historical cost trends, and expected growth patterns. The data encompass future investment costs for PV and wind power plants, as well as projected O&M costs and estimated system lifetimes. The cost datasheet used in this analysis was developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark.

The forecasted costs for lithium-ion battery storage in 2050 are sourced from the "Cost Projections for Utility-Scale Battery Storage: 2023 Update" report by NREL [150] and calculated using Equation 6. O&M costs for the battery system are estimated based on the performance and costs of current large-scale lithium-ion battery systems used in RES projects. Typically, the fixed O&M costs for these systems range from 1% to 3% of the initial capital investment per year [231][232]. Accurate estimation of O&M factors for PV, wind, and lithium-ion battery storage is critical in calculating the future total annual investment costs of RES. These assumptions provide a foundation for assessing the long-term financial viability of large-scale RES projects, ensuring that the cost models reflect both current technology trends and future projections for energy storage systems.

Carbon cost is assumed to be zero since Saudi Arabia does not have a carbon tax.

The following sections begin with the economic analysis of the 2017 reference year model, which includes the current conventional steam power plants, and then proceed to evaluate the 2050 RES scenarios. These scenarios were assessed individually, covering configurations such as PV, PV+Battery, Wind, Wind+Battery, PV+Wind, PV+Wind+Battery, and the optimized PV+Wind+Battery system. The final RES for the Kingdom was then evaluated by integrating the technical data from Chapter 4 with the economic analysis from Chapter 5. The optimal system, which balances both technical performance and economic efficiency, was selected and presented in Chapter 6. This comprehensive approach ensures that the selected energy system meets the dual criteria of technical reliability and cost-effectiveness for Saudi Arabia's energy future.

5.1 2017 Reference Case Model

In previous sections, the energy model was established using technical parameters sufficient to validate its performance and reliability. This section details the developed energy system scenario for Saudi Arabia, focusing on the key economic parameters and assumptions applied in modelling the country's energy framework. In this chapter, the economic data was integrated into the reference model for 2017, along with foundational assumptions. This data includes fixed and variable O&M costs, annual investment costs, and additional parameters such as power station lifetimes and fuel prices. Certain values were manually calculated and tailored to align with the specific requirements of the model, as the necessary data—such as aggregated capacities, efficiencies, and costs for all power plants—was not readily available in the required format. Additionally, the projections of fuel prices and growth factors were incorporated for 2050, with relevant assumptions outlined in this section.

5.1.1 2017 Costs Assumptions of The Reference Model

Saudi Arabia's energy costs for the reference case in 2017 include the power plants' fixed O&M, fuel costs, and fuel handling costs. Saudi Arabia has different types of power plants depending on the technology used, such as steam turbines, gas turbines, combined cycle power plants, and diesel power plants. These power plants vary in efficiency, fuel used, investment costs, O&M, including fixed and variable costs. These costs are can be found in the EnergyPLAN cost sheet, which provides the costs associated with various power station types, and fuels based on international market prices. However, in the case of Saudi Arabia, the situation is slightly different, since Saudi Arabia is a major oil exporting country with one of the top oil reserves in the world. The prices, in general, are lower than those of other countries and the international market prices, especially for fuel; thus, it was essential to find the costs for Saudi Arabia without sticking to the international market prices with particular attention to fuels.

Saudi Arabia has different power plant technologies, such as steam or gas turbines, with different costs and lifetimes. The challenge is that EnergyPLAN does not consider all these variations among the different power plants. It considers all the power plants in the Kingdom as one aggregate type as ‘’condensing power plants’’ with one efficiency, one investment cost, one O&M cost and one lifetime period. To address this limitation, the weighted average of each value was calculated based on the power plants capacity in Saudi Arabia in 2017 by type, as shown in the Table 28 below. The 2017 statistical report published by WERA, provides a detailed overview of various power plant types and their aggregate capacities. This information, presented in Table 28, is accompanied by data on key parameters, including system lifetimes, investment costs, fixed and variable O&M costs, as referenced in [242].

Table 28 Power plants by technology type with lifetimes and costs in Saudi Arabia 2017

Power Plant Type	Aggregate Capacity (MW) [253]	Aggregate Capacity (%) [253]	Lifetime (Years) [254]	Investment Cost (U$/MWe) [254]	Fixed O&M Costs (% of Investment) [254]	Variable O& M Costs (U$/MWh) [254]
Steam Turbine	36,100	40.7 %	40	1,680,000	2.17 %	1.6
Gas Turbine	35,000	39.4 %	30	1,180,000	0.94 %	4
Combined Cycle	17,200	19.4 %	35	1,010,000	1.97%	3.3
Diesel	400	0.5 %	20	755,000	4.5 %	13.7

Table 28 highlights the diverse range of power plant types in the Kingdom, each characterized by varying capacities, lifetimes, and associated costs. Within the EnergyPLAN model, a single aggregate value is utilized for each parameter column. The calculation of the weighted average investment costs is detailed in Equations 1 and 2.

Aggregate investment costs weighted average (U$):

$$\left(36{,}100\ MW\ Steam \times\ 1{,}680{,}000\ \frac{\text{U\$}}{\text{MW}}\right) + \left(35{,}000\ MW\ Gas \times\ 1{,}180{,}000\ \frac{\text{U\$}}{\text{MW}}\right) + \left(17{,}200\ \ MW\ Combined\ Cylce \times\ 1{,}010{,}000 \frac{\text{U\$}}{\text{MW}}\right) + \left(400\ MW\ Diesel \times\ 755\ \frac{\text{U\$}}{\text{MW}}\right) = 1.193 \times\ 10\text{^}11\ \text{U\$}$$

Equation 1

$$Investment\ Cost\ \left(\frac{\text{U\$}}{\text{MW}}\right) = \frac{\text{Total Investment Cost (U\$)}}{\text{Total Capacity (MWe)}} = \frac{1.1932 \times 10\text{^}11\ \ (\text{U\$})}{88{,}700\ (\text{MWe})} = 1.3452\ million\ \frac{\text{U\$}}{\text{MW}}$$

Equation 2

Aggregate lifetime weighted average (years): $(0.47 \times\ 40\ years\ Steam) + (0.394 \times\ 30\ years\ Gas) + (0.194 \times\ 35\ years\ Combined\ Cycle) + (0.005 \times\ 20\ years\ Diesel)$

$= 38\ years$

Equation 3

Aggregate fixed operation & maintenance cost weighted average (% of investment costs) : $(0.47 \times\ 0.0217\ Steam) + (0.394 \times\ 0.0094\ Gas) + (0.194 \times\ 0.0197\ Combined\ Cycle) + (0.005 \times\ 0.045\ Diesel) = 1.79\ \%$

Equation 4

To determine the variable O&M costs, expressed in USD/MWh, it is essential to quantify the annual energy generation from each power plant type. This includes the total energy produced by all steam turbine plants, all gas turbine plants, and other categories combined.

Unfortunately, this data is not available. Therefore, it was assumed that the generated energy's contribution from power plants is proportional to the aggregate capacity by each plant type.

This means that most of the energy generated was from steam turbines which contributes to 40.7% of the total capacities followed by gas turbines (39.4%), combined cycle (19.4%), and diesel (0.5%) respectively as shown in Equation 5.

Aggregate variable operation & maintenance cost weighted average ($\frac{\text{U\$}}{\text{MWh}}$):

$$\left(0.47 \times 1.6\ \frac{\text{U\$}}{\text{MWh}}\ Steam\right) + \left(0.394 \times 4\ \frac{\text{U\$}}{\text{MWh}}\ Gas\right) + \left(0.194 \times 3.3\ \frac{\text{U\$}}{\text{MWh}} Combined\ Cycle\right) + \left(0.005 \times 13.7\ \frac{\text{U\$}}{\text{MWh}} Diesel\right) = 3.03\ \frac{\text{U\$}}{\text{MWh}}$$

Equation 5

The consideration of fuel pricing is a critical factor, particularly in Saudi Arabia, where domestic fuel prices are substantially lower than those in the international market, including the fuel supplied to electricity providers. To illustrate the disparity between domestic and global oil prices, in 2017, the international price for Arab Light crude oil was $40.96 per barrel, while the domestic price within the Kingdom was only $6.35 per barrel. This domestic price, despite being increased following the initial energy price reform in 2016, remained substantially lower than global market rates [255]. While fuel prices were drawn from 2017 data, it is important to note that these prices are consistent with those reported in 2016 according to the source cited by the author. For modelling purposes, the fuel prices were converted to a per-gigajoule (GJ) basis, as detailed below. It is also relevant that EnergyPLAN only allows for one value per fuel type. In the context of Saudi Arabia, two types of petrol are available: Petrol 91 and Petrol 95, with the latter having a higher price. Petrol 95 was considered for the analysis in EnergyPLAN. Additionally, there are two different diesel prices: one lower rate is offered to electricity providers and industries, while a slightly higher rate is applied to the transport sector. For this study, the higher transport sector diesel price was utilized, in line with EnergyPLAN's requirement to input a single price per fuel type.

Fuel Oil Price: $3.80\ \frac{\text{U\$}}{\text{Barrel}}$ [134] = $\frac{3.80\ \text{U\$}}{(0.1571\ \text{Barrel})} = 24.20\ \frac{\text{U\$}}{\text{Tonne}} = \frac{24.20\ \text{U\$}}{(1\ \text{Tonne} \times 41.57)} = 0.582\ \frac{\text{U\$}}{\text{Gj}}$

Diesel price: $19.93\ \frac{\text{U\$}}{\text{Barrel}}$ [134] = $\frac{19.93\ \text{U\$}}{(0.134\times1\ \text{Barrel})} = 148.73\ \frac{\text{U\$}}{\text{Tonne}} = \frac{148.73\ \text{U\$}}{(1\ \text{Tonne}\times43.38)} = 3.42\ \frac{\text{U\$}}{\text{Gj}}$

Petrol price (95): $38.16\ \frac{\text{U\$}}{\text{Barrel}}$ [134] = $\frac{38.16\ \text{U\$}}{(0.120\times1\ \text{Barrel})} = 318\ \frac{\text{U\$}}{\text{Tonne}} = \frac{318\ \text{U\$}}{(1\ \text{Tonne}\times44.75)} = 7.1\ \frac{\text{U\$}}{\text{Gj}}$

Jet Fuel price: $25.70\ \frac{\text{U\$}}{\text{Barrel}}$ [134] = $\frac{25.70\ \text{U\$}}{(0.127\times1\ \text{Barrel})} = 202.36\ \frac{\text{U\$}}{\text{Tonne}} = \frac{202.36\ \text{U\$}}{(1\ \text{Tonne}\times43.92)} = 4.6\ \frac{\text{U\$}}{\text{Gj}}$

Natural Gas Price: 1.25 $\frac{\text{U\$}}{\text{MMBTU}}$ [134] = $\frac{1.25\ \text{U\$}}{(1.055055\times 1\ \text{MMBTU})} = 1.18\ \frac{\text{U\$}}{\text{Gj}}$

The conversion factors used in this analysis were sourced from BP's Approximate Conversion Factors [256]. A comprehensive summary of the calculated costs and price values derived from EnergyPLAN is presented in Table 29, while a detailed summary of fuel prices can be found in Table 30.

Table 29 Aggregate power plants calculated costs and lifetime.

Aggregate Power Plants Description	
Investment Cost ($\frac{\text{Million U\$}}{\text{MWe}}$)	1.3452
Lifetime (Years)	38
O&M Costs (% of Investment)	1.79 %
Variable O&M costs ($\frac{\text{U\$}}{\text{MWh}}$)	3.03

Converting costs to euro currency as the input for EnergyPLAN results in an investment cost of **1.24** ($\frac{\text{Million EUR}}{\text{MWe}}$) and variable O&M costs of **2.79** ($\frac{\text{EUR}}{\text{MWh}}$).

Table 30 Fuel prices in 2017 after currency conversion.

Fuel Type	Fuel Price ($\frac{\text{U\$}}{\text{Gj}}$)	Fuel Price ($\frac{EUR}{\text{Gj}}$)
Fuel Oil	0.58	**0.55**
Diesel	3.42	**3.23**
Petrol	7.10	**6.70**
Jet Fuel	4.60	**4.34**
Natural Gas	1.18	**1.11**

5.1.2 Projected Fuel Prices' Growth Assumptions for 2030 and 2050

Forecasting future fuel and electricity prices in Saudi Arabia presents significant challenges, as these prices are not necessarily tied to historical growth trends. For decades, Saudi Arabia has maintained substantially lower fuel prices compared to international markets. However, in recent years, the government has implemented two major energy price reforms aimed at gradually aligning domestic prices with global market levels, ensuring long-term economic stability and sustainability. No existing studies or research have been able to predict future fuel prices, particularly in terms of whether additional energy price reforms will occur before 2030 or 2050, as such decisions rest with the government.

For the purposes of this research, a similar assumption to that in [257] was adopted, but for fuel, assuming that post-2018 energy reform fuel prices will remain constant until 2030. From 2030 to 2050, it was assumed that further price reforms will occur, progressively aligning Saudi fuel prices with international market rates by 2050. The projected fuel prices for 2050 were sourced from the EnergyPLAN cost sheet, which reflects expected global market prices by that year, as noted in [246]. The forecasted fuel costs are detailed in Table 31, with currency conversions from USD to EUR applied for the use in EnergyPLAN inputs. The same BP's conversion factors previously referenced [256] were used to calculate fuel prices, as shown below.

Table 31 Fuel price assumptions and forecasts for 2030 and 2050.

Fuel Price ($\frac{U\$}{Gj}$)			
Fuel Type	Post-EPR 2018	2030	2050
Fuel Oil	0.61	0.61	17.16
Diesel	3.42	3.42	20.89
Petrol	16.10	16.10	21.00
Jet Fuel	4.86	4.86	21.96
Natural Gas	1.18	1.18	13.00
Fuel Price ($\frac{EUR}{Gj}$)			
Fuel Type	Post-EPR 2018	2030	2050 [242]
Fuel Oil	**0.58**	**0.58**	**16.1**
Diesel	**3.23**	**3.23**	**19.6**
Petrol	**15.20**	**15.20**	**19.7**
Jet Fuel	**4.59**	**4.59**	**20.6**
Natural Gas	**1.10**	**1.10**	**12.2**

Fuel Oil Price: $3.99\ \frac{U\$}{\text{Barrel}}$ [255] $= \frac{3.99\ U\$}{(0.157\times 1\ \text{Barrel})} = 25.41\ \frac{U\$}{\text{Tonne}} = \frac{25.41\ U\$}{(1\ \text{Tonne}\times 41.57)} = 0.61\ \frac{U\$}{Gj}$

Diesel price: $19.93\ \frac{U\$}{\text{Barrel}}$ [255] $= \frac{19.93\ U\$}{(0.134\times 1\ \text{Barrel})} = 148.73\ \frac{U\$}{\text{Tonne}} = \frac{148.73\ U\$}{(1\ \text{Tonne}\times 43.38)} = 3.42\ \frac{U\$}{Gj}$

Petrol price (95): 86.49 $\frac{\text{U\$}}{\text{Barrel}}$ [255] = $\frac{86.49\ \text{U\$}}{(0.120\times 1\ \text{Barrel})} = 720.75\ \frac{\text{U\$}}{\text{Tonne}} = \frac{720.75\ \text{U\$}}{(1\ \text{Tonne}\times 44.75)} = 16.10\ \frac{\text{U\$}}{\text{Gj}}$

Jet Fuel price: 27.13 $\frac{\text{U\$}}{\text{Barrel}}$ [255] = $\frac{27.13\ \text{U\$}}{(0.127\times 1\ \text{Barrel})} = 213.62\ \frac{\text{U\$}}{\text{Tonne}} = \frac{213.62\ \text{U\$}}{(1\ \text{Tonne}\times 43.92)} = 4.86\ \frac{\text{U\$}}{\text{Gj}}$

LPG Price: 31.80 $\frac{\text{U\$}}{\text{Barrel}}$ [255] = $\frac{31.80\ \text{U\$}}{(0.086\times 1\ \text{Barrel})} = 369.76\ \frac{\text{U\$}}{\text{Tonne}} = \frac{369.76\ \text{U\$}}{(1\ \text{Tonne}\times 46.15)} = 8.01\ \frac{\text{U\$}}{\text{Gj}}$

Natural Gas Price: 1.25 $\frac{\text{U\$}}{\text{MMBTU}}$ [255] = $\frac{1.25\ \text{U\$}}{(1.055055\times 1\ \text{MMBTU})} = 1.18\ \frac{\text{U\$}}{\text{Gj}}$

5.2 2050 RES Scenario: PV/PV+Battery Storage

In this section, the PV and PV+Battery storage RES for 2050, as outlined in Chapter 4, are analysed and evaluated and from an economic perspective. The first part of the analysis focuses on assessing the economic viability, advantages, and constraints of utilizing PV power as the primary energy source for the entire Kingdom of Saudi Arabia by 2050. In the second part, the analysis extends to examine the combined system of PV coupled with battery storage. The assumed costs for the PV system, presented in Table 32, are derived from version 4 of the cost datasheet [227]. Due to the inherent difficulties in accurately forecasting economic parameters for 2050, the cost projections for PV power plants are based on credible references, extrapolating from current and historical cost trends. These projections consider factors such as future investment costs, projected operational expenditure, and estimated system lifetimes. The cost data were compiled by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. For the PV+Battery storage system, the projected costs of lithium-ion battery storage in 2050 are sourced from [258], as previously discussed and validated in earlier sections. These detailed cost assessments enable a comprehensive evaluation of both systems, facilitating a deeper understanding of their economic viability within Saudi Arabia's future energy landscape.

Table 32 PV and battery storage assumed system costs in 2050

PV Power Plant Costs Assumptions in 2050	
Investment Costs (Million Euro / MWe)	0.56
Fixed Operation and Maintenance Costs (% of Investment)	1.32 %
Lifetime (Years)	40
Lithium-Ion Battery Storage Costs Assumptions in 2050	
Investment Costs (Million Euro / MWe)	151.5
Fixed Operation and Maintenance Costs (% of Investment)	2%
Lifetime (Years)	15

The cost assumptions for PV and battery storage, as outlined in Table 32, serve as the basis for estimating the economic aspects of the system. Accurately predicting the costs of PV components such as panels, inverters, and ancillary equipment in the future specifically in 2050, poses considerable challenges. These prices are not dictated by a single company or brand; instead, they fluctuate annually due to various factors including market dynamics, RES policies, supply and demand, economic conditions, political environments, and global trends. Given the prominence of the RES sector, prices for PV power plants in this study were expressed per unit of MWe for 2050 to account for these uncertainties.

For lithium-ion battery storage, a report from NREL [258] provided the projected utility-scale battery storage prices for future years, including estimates for 2030 and 2050, based on analyses from recent studies conducted in 2023. These publications show a wide range of potential cost reductions for battery storage over time. The NREL report utilized a baseline of 4-hour battery storage for their projections and developed low, mid, and high-cost scenarios. However, the battery storage duration in this project differs significantly, with approximately 2,039 GW of total capacity and 91 GW of maximum discharge, resulting in an estimated duration of 22 hours. Consequently, the cost of battery storage is calculated using Equation 6, which separates energy and power costs, allowing for the estimation of capital costs for battery storage systems of varying durations.

$$Total\ Capital\ Cost\ \left(\frac{\$}{\mathrm{kWh}}\right) = Energy\ Cost\ \left(\frac{\$}{\mathrm{kWh}}\right) + \frac{Power\ Cost\ \left(\frac{\$}{\mathrm{kW}}\right)}{Duration\ (hr)} \quad [258]$$

Equation 6

Once the costs of the energy and power components are determined, the price of a lithium-ion battery for any specified duration can be accurately calculated. These component costs are sourced from [258], where the "MID" cost projection was adopted. By 2050, the mid-projected cost for energy components is estimated at \$150/kWh, while the mid-projected cost for power components is approximately \$280/kW. For a battery with a duration of 22 hours, substituting these values into Equation 6 yields a calculated capital cost of \$162.7/kWh, as demonstrated in the equation.

$$Total\ Capital\ Cost\ \left(\frac{\$}{\mathrm{kWh}}\right) = 150\ \left(\frac{\$}{\mathrm{kWh}}\right) + \frac{280\ \left(\frac{\$}{\mathrm{kW}}\right)}{22\ (hr)} = 162.7\ \frac{\$}{\mathrm{kWh}}$$

The equation was validated by applying it to a 6-hour battery storage system and comparing the results with the 6-hour battery cost curve provided by NREL. This comparison confirmed consistency, yielding an estimated cost of approximately \$200/kWh for 6-hour battery storage in 2050. For use in EnergyPLAN, this cost must be converted to units of million euros per GWh, as demonstrated below. Fixed O&M costs are assumed to be 2% of the capital cost, with the system having a lifetime of 15 years.

$$162.7\ \frac{\$}{\mathrm{kWh}} = 151.5\ \frac{€}{\mathrm{kWh}} = \frac{151.5\ €}{\frac{1}{1{,}000{,}000}GWh} = \frac{151{,}500{,}000\ €}{\mathrm{GWh}} = \textbf{151.5 million euro/GWh}$$

The primary objective of this study is to evaluate and compare the technical and economic performance of RES in meeting Saudi Arabia's annual energy demand on an hourly basis. The analysis ensures that energy demand is met without shortages or the need for imports at any hour, day, or season throughout the year, while simultaneously minimizing system capacities and total costs. Consequently, all RES solutions were designed to achieve this objective at the lowest possible cost. To comprehensively assess the economic feasibility of the proposed systems, the LCOE is calculated using Equation 9, as outlined below.

$$LCOE = \frac{Total\ Discounted\ Costs}{Total\ Usefull\ Energy\ to\ the\ Grid}$$

Equation 9

To ensure accurate LCOE calculations, the key inputs for the RES are summarized in Table 33. The interest rate is set at 3%, which is used to determine the annual loan repayment for the initial investment. The discount rate is established at 7%, reflecting the present value of annual payments over the system's lifetime. Furthermore, all RES solutions are designed with a lifetime of 30 years, as previously discussed and justified. These parameters serve as the foundation for the LCOE calculation, enabling a thorough evaluation of the systems' economic viability.

Table 33 PV+Battery RES inputs summary

	Total Inv. Costs (m €)	Annual Inv. Costs (m €)	Annual O&M Costs (m €)	Annual Energy Generated (TWh)	Lifetime (Years)	Energy Discharged to The Grid (TWh/Year)	Energy Charged from PV to Battery (TWh/Year)
PV	323,181	13,982	4,266	652.63	40	251.21	401.42
Battery	308,908	25,876	6,178	0	15	307.08	401.42

1. Total Annual Investment Costs (Investment + O&M)

PV System= 13,982+4,266= 18,248 (m € /year)

Battery System=25,876 + 6,178= 32,054 (m € /year)

2. Discounting the Annual Costs (Using the 7% Discount Rate)

Present Value= Annual Cost $\times \frac{1-(1+r)^{-T}}{r}$ Where:

r = discount rate 7% (0.07)

T= system lifetime

Present Value for PV= 18,248 $\times \frac{1-(1+0.07)^{-30}}{0.07}$ =18,248 × 12.409 = 226,439 m €

For the battery system, the replacement cost must be accounted after the 15 years lifetime. The present value of the replacement cost and the annual costs over 15 years are calculated below.

Battery replacement cost= $\frac{F}{(1+r)^{T}}$ Where:

F is the future value (in this case, the cost of the battery replacement) (Total Investment Costs in EnergyPLAN).

r is the discount rate (7%)

T is the time in years until the replacement (in this case, 15 years)

Battery replacement cost= $\frac{308{,}908}{(1+0.07)^{15}} = \frac{308{,}908}{2.759} = 111{,}931$ m €

The present value of the annual costs over 15 years is calculated and then the replacement cost is added.

Present Value for Battery= $32{,}054 \times \frac{1-(1+0.07)^{-15}}{0.07} + 111{,}931 = 32{,}054 \times 9.107 + 111{,}931 =$ 403,878 m €

3. Total Discounted Costs

   Total Discounted Costs= 226,439 (PV) + 403,878 (Battery)= 630,317 m €

4. Useful Energy Delivered to the Grid

   We calculate the useful energy delivered to the grid, accounting for the energy used to charge the battery and energy discharged from the battery.

   Useful Energy from PV to Grid= Total PV Generated Energy – Energy Charged to Battery Storage

   = 652.63 - 401.42 = 251.21 TWh/year

   Adding the energy discharged from the battery storage to the grid = 251.21 + 307.08= 558.29 TWh

   Total Useful Energy over 30 Years = 558.29 ×30= 16,748 TWh

5. LCOE = $\frac{Total\ Discounted\ Costs}{Total\ Usefull\ Energy\ to\ the\ Grid} = \frac{630{,}317\ \text{m €}}{16{,}748\ TWh} = 37.63$ €/MWh

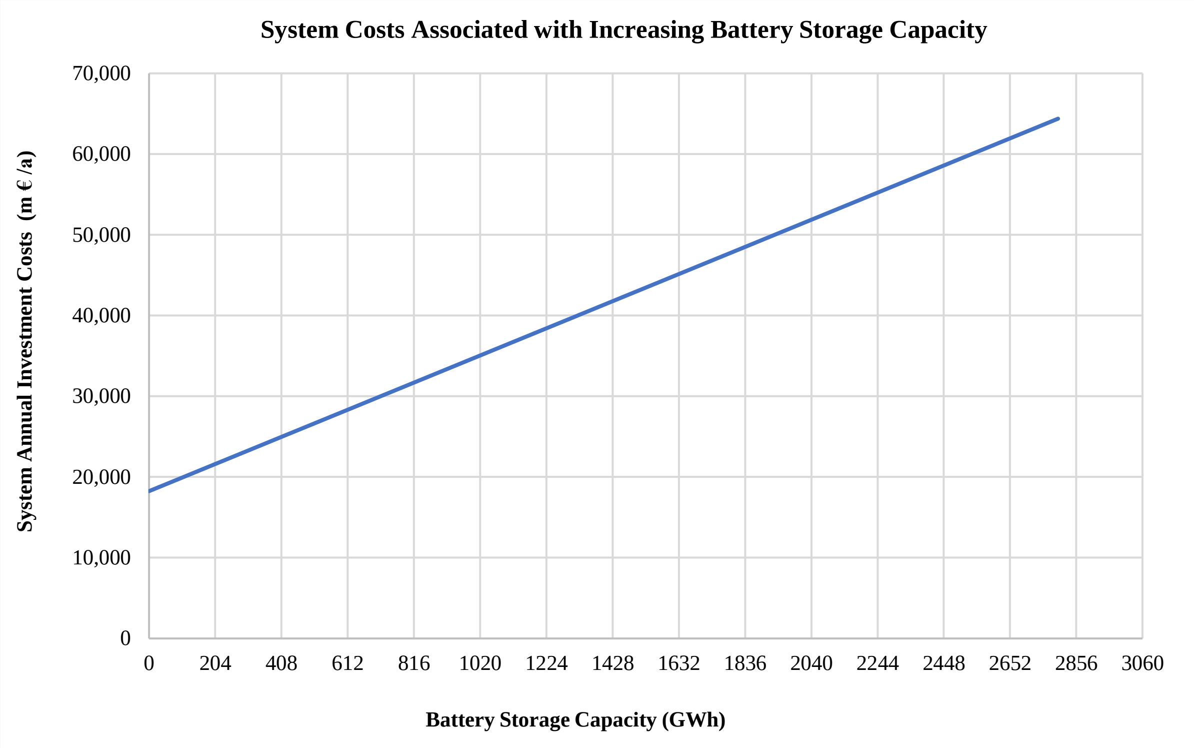

Figure 85 PV+Battery system costs associated with increasing battery storage capacity [Author: constructed from simulations].

Figure 85 illustrates the relationship between the total annual investment costs and the increase in battery storage capacity for the PV+Battery system. As anticipated, the total annual cost of the PV+Battery system exhibits a linear increase as the battery storage capacity expands. At the designed battery storage capacity of 2,039 GWh, the total system cost amounts to 50,302 million euros annually, as detailed in Table 34.

Table 34 PV/PV+Battery storage total systems costs

	Costs (m € /a)	
RES	PV	PV+Battery
Total Variable Costs	0	0
Fixed Operation and Maintenance Costs	0	10,444
Annual Investment Costs	0	39,858
Total Annual Costs	**0**	**50,302**
LCOE (Euro/MWh)	**0**	**37.63 Euro /MWh**

Table 34 illustrates that the technical objective established in Chapter 4 for the PV+Battery system was successfully attained. In contrast, the standalone PV system failed to satisfy the Kingdom's energy requirements during nighttime, making it technically inadequate and resulting in its associated costs being reduced to zero. The integration of a battery storage system proved crucial in meeting the first technical goal, enabling the PV+Battery system to supply 100% RES to the Kingdom without any shortages throughout the entire year. The costs for the designed RES are detailed in Table 34, with the minimum costs calculated as follows: 10,444 million euros per annum for fixed O&M, 39,858 million euros per annum for annual investment, and a total annual cost of 50,302 million euros for the PV+Battery RES, with a LCOE of 37.63 Euro /MWh.

5.3 2050 RES Scenario: Wind/Wind+Battery Storage

In this section, the economic analysis of future Wind/Wind+Battery storage power systems in 2050 from Chapter 4 are discussed and evaluated. The analysis begins by examining the economic feasibility and benefits of a standalone wind power plant. Subsequently, the same evaluation and simulations are extended to the combined Wind+Battery system. Finally, both systems are compared against the PV+Battery system to provide a comprehensive economic assessment. The assumed costs for the wind power system are outlined in Table 35, with the data sourced from version 4 of the cost datasheet [227].

Table 35 wind power plant + battery costs assumptions

Wind Power Plant Costs Assumptions in 2050	
Investment Costs (Million Euro/MWe)	0.93 [227]
Fixed O&M Costs (% of Investment)	3.4 % [227]
Lifetime (Years)	30 [227]
Interest (%)	3%
Lithium-Ion Battery Storage Costs Assumptions in 2050	
Investment Costs (Million Euro/MWe)	162.48 [258]
Fixed O&M Costs (% of Investment)	2 %
Lifetime (Years)	15
Interest (%)	3%

$$Battery\ Total\ Capital\ Cost\ \left(\frac{\$}{\mathrm{kWh}}\right) = 150\ \left(\frac{\$}{\mathrm{kWh}}\right) + \frac{280\ \left(\frac{\$}{\mathrm{kW}}\right)}{10\ (hr)} = 178\ \frac{\$}{\mathrm{kWh}}$$

$$178\ \frac{\$}{\text{kWh}} = 162.48\ \frac{€}{\text{kWh}} = \frac{162.48\ €}{\frac{1}{1{,}000{,}000}GWh} = \frac{162{,}480{,}000\ €}{\text{GWh}} = \text{ 162.48 million euro/GWh}$$

The battery cost was adjusted to reflect the change in battery duration, which decreased from approximately 22 hours in the PV+Battery system to 10 hours in the Wind+Battery system.

Accurately estimating the cost of wind turbines and other ancillary equipment 26 years into the future, such as in 2050, is challenging. These costs are not determined by a single brand or company but fluctuate annually based on various factors such as market conditions, RES policies, supply and demand, economic and political circumstances, future policies, and global trends, particularly in the rapidly evolving RES market. For this study, wind turbine plant costs are calculated per unit of MWe for 2050, as outlined in version 4 of the cost datasheet. The LCOE for the Wind+Battery system is calculated using the same method previously applied for the PV+Battery system, employing Equation 9.

Table 36 Wind/Wind+Battery storage total systems costs

	Costs (m € /a)	
RES	Wind	Wind+Battery
Total Variable Costs	0	0
Fixed O&M Costs	52,557	10,367
Annual Investment Costs	78,865	21,143
Total Annual Costs	**131,421**	**31,510**
LCOE (Euro/MWh)	**97.39 Euro/MWh**	**23.50 Euro/MWh**

Table 36 presents the two final systems that achieved the technical objective of supplying 100% RES to the Kingdom throughout the entire year, as demonstrated in Chapter 4. However, a significant cost difference exists between the systems, largely due to the greater capacity required for the wind turbine power plant. The costs associated with the solo wind system are substantially higher compared to both the Wind+Battery and the PV+Battery Systems, signalling economic inefficiency.

While utilizing only wind turbines can meet the Kingdom's energy demand both day and night year-round, doing so would require an enormous number of turbines to achieve a higher total wind power plant capacity, as explored in detail in Chapter 4, Section 4.3.2.2. This leads to significantly higher costs, driven by the need for additional turbines to address temporary energy shortages that occur throughout the year, as shown earlier in Figure 60. Solely relying on wind energy to cover these shortages is not cost-effective because the required increase in wind capacity to cover these minor temporal shortages would involve expanding the entire wind turbine fleet, thus increasing costs.

Introducing a battery storage system has proven to be a highly effective solution, significantly reducing the overall capacity of the wind power plant. The primary advantage of battery storage is its ability to store excess power during periods of high wind production and lower demand, enabling flexible energy supply during the minor temporary shortages that wind turbines alone cannot meet. This results in a lower required wind power capacity to meet the technical goal of providing 100% RES supply for the Kingdom in 2050, without shortages or the need for power imports.

To confirm the findings in Chapter 4, Section 4.3.2.2, the wind power plant capacity was reduced by 26 GW decreasing to 1,636.129 GW, which led to a 911 MW shortage between 10:00 AM and 12:00 AM. Two potential solutions were identified: first, increasing the wind turbine capacity to eliminate the shortage; and second, adding battery storage to the current wind system to address the shortage.

In the first solution, the wind capacity was increased back to 1,662.129 GW, sufficient to eliminate the 911 MW shortage. However, this expansion raised the total annual system costs by 2,055 million euros (from 129,366 million euros to 131,421 million euros), driven by increased investment in wind turbines as well as higher O&M costs.

In the second solution, the system capacity was again reduced by 26 GW, resulting in the same 911 MW shortage. This time, a lithium-ion battery storage system with a capacity of 1.013 GWh was added, sufficient to eliminate the shortage. The total system costs increased by only 15 million euros (from 129,366 million euros to 129,381 million euros), including both annual investment and O&M costs. A comparison of these two solutions is summarized in Table 37, highlighting the cost efficiency and practicality of integrating battery storage with the wind power system.

Table 37 The two possible solutions to eliminate power shortage with the required capacity and cost addition.

	Solution 1 (Wind Only)	Solution 2 (Wind+Battery)
System Ability to Eliminate Power Shortage (%)	100%	100%
Required Capacity Addition (GW/GWh)	26 GW of wind	1.013 GWh of battery
Increased Fixed O&M Costs	823 million Euro	3 million Euro
Increased Annual Investment Costs	1,234 million Euro	12 million Euro
Added Annual Investment Costs	2,055 (m € /a)	15 (m € /a)

In Table 37, both proposed solutions successfully achieve the technical goal of system stability by eliminating the 911 MW power shortage. However, the cost difference between the two solutions is substantial. In Solution 1, increasing the total capacity of the wind power plant would result in the same supply curve pattern as shown in Figure 60, but scaled upward to meet the demand and cover the shortage. This would require the addition of 26 GW of wind turbines, leading to an increase in total annual costs by 2,055 million euros.

In contrast, Solution 2, which involves adding a battery storage system, would only require an additional 1.013 GWh (1,013 MW) of storage capacity, with a minimal increase in total annual costs of only 15 million euros. The simulation results align with the conclusions drawn in Figure 60. In summary, incorporating a battery storage system proves to be a far more cost-effective solution than adding more wind turbines to address minor temporal power shortages in Saudi Arabia. The technical benefits of adding battery storage are further illustrated in Figure 61 of Chapter 4.

In conclusion, battery storage proves to be significantly more effective than additional wind turbines for addressing minor temporal power shortages. Consequently, battery systems are integrated with wind power plants to resolve critical points, such as those illustrated in Figure 60, throughout the entire year. The same methodology previously applied to a single day, as shown in Figure 60 and Table 18, has now been extended to include the entire year. This approach enables the identification of the optimal design points for wind and battery storage that achieve the technical objective of 100% system stability without any shortages for the full year. Both solutions 1 and 2 have been evaluated for the entire year, and the results are presented in Figure 86 below.

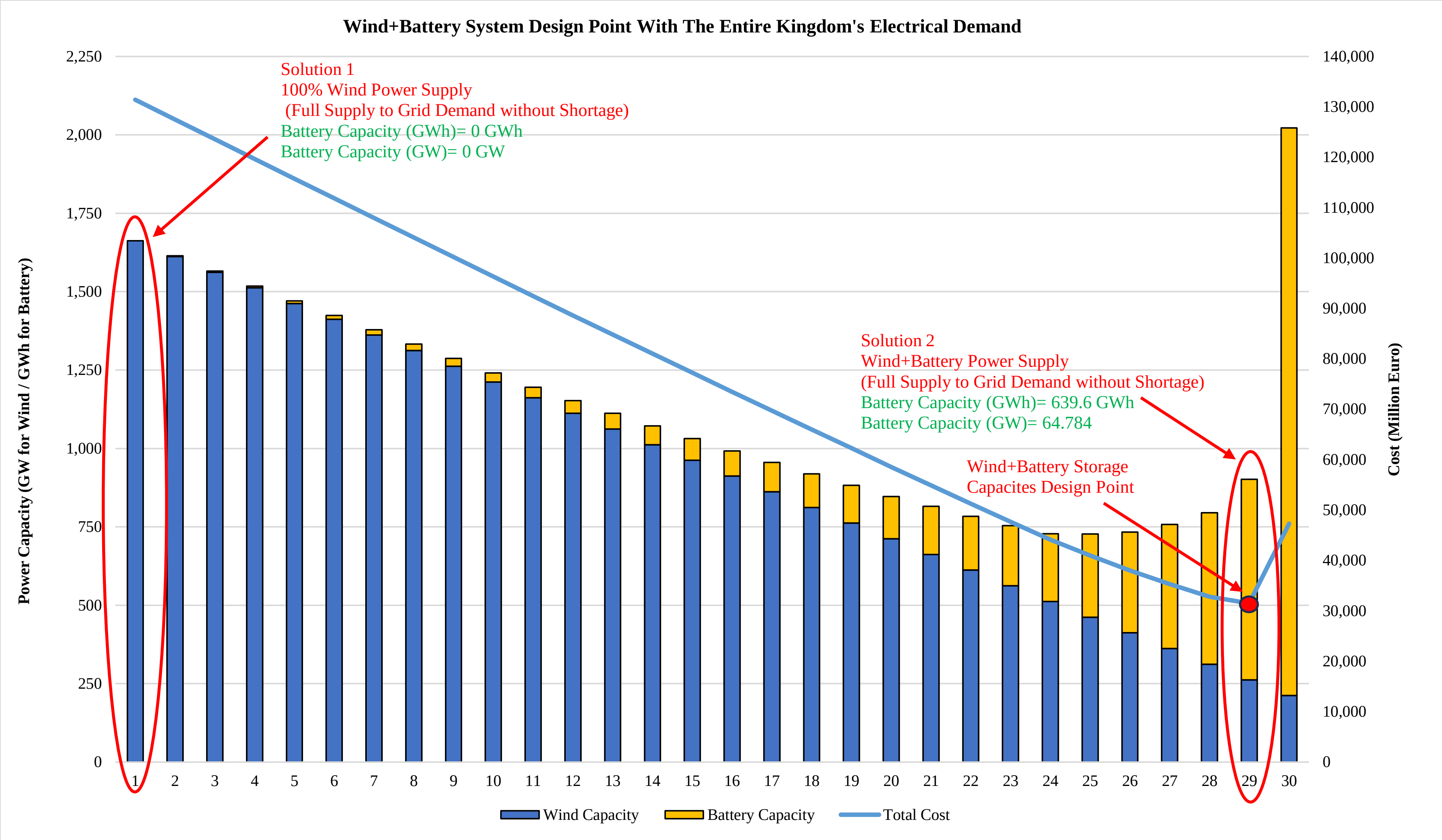

Figure 86 Wind+Battery system design point with the entire Kingdom's electrical demand [Author: constructed from simulations].

Figure 86 illustrates point 1, which represents the wind turbine power plant capacity required to meet the grid's demand for the entire year, both day and night, without any power shortages, as previously outlined in Table 18. While the wind power plant is technically capable of supplying the Kingdom's total grid demand around the clock theoretically, it fails from an economic standpoint, as explained earlier. The analysis of wind power supply in relation to demand aimed to identify the optimal solution, as presented in Figures 60, 61, and Table 18. In Figure 86, the total demand of the Kingdom is incorporated and analysed with the RES supply, via the same methodology applied to the single-day graphs but for the entire year. Point 1 in the figure represents the minimum design capacity required for wind power plants to fully supply the grid demand. From point 2 to point 30, the wind power plant capacity is progressively reduced by 50 GW at each step. With each reduction, battery storage is incrementally added, beginning at 1 GWh. At every stage, the battery storage system is sized based on the minimum required capacity to stop the shortage caused by the reduction in wind turbine capacity. This results in a specific energy shortage at particular times, which increases as the wind power plant’s capacity decreases. Consequently, the addition of battery storage ensures the elimination of the shortage and enhances system stability.

As the capacity of the wind power plant was reduced and the battery storage system capacity increased, total costs were subsequently reduced. This outcome aligns with the reasoning presented in the single-day analysis shown in Figure 60 and Table 18, where a reduction in wind turbine capacity led to the gradual increase in battery storage to address the shortages occurring at critical points throughout the year starting from the most critical points to the least critical ones. The year is not including only one or two critical points; rather, there are numerous ones, sometimes lasting only one or two hours, where the standalone wind power plant cannot meet grid demand, leading to small, temporary shortages. In these cases, the battery storage system gradually supplies the required power to cover these minor shortages. Meanwhile, the overall system costs continue to decrease until a threshold is reached, at which point costs begin to rise, as shown in Figure 86. The figure identifies the optimal design point for the wind and battery storage system, where costs are minimized just before they begin to increase. This approach enables the identification of the most cost-effective solution that ensures 100% grid supply year-round with the lowest costs.

It is also evident that the costs increase sharply after the optimal design point, which is attributed to the substantial increase in the required battery storage size, as shown in the figure. This significant increase in storage requirements occurs because the battery storage system has already addressed the shortages at critical points throughout the year. At this stage, it begins to supply the primary, high demand. From a graphical perspective, the battery has already covered the critical points below the main wind supply curve and is now supplementing the main demand curve, as illustrated in Figure 60. In other words, the added benefit of battery storage has diminished, as it has already reliably addressed the small shortages at critical points (where it outperformed the standalone wind system). Any further increase in storage capacity would shift the battery's role to predominantly supplying the main demand, thus reducing the contribution of the wind power plant. The optimal design specifications for the Wind+Battery system is summarized in Table 18.

In summary, the integration of battery storage with wind turbines was driven more by economic optimization than technical necessity. While wind turbines alone are capable of meeting Saudi Arabia's grid demand theoretically, particularly in areas with high wind potential like the west coast, this approach comes with prohibitively high investment, operational, and maintenance costs. It was observed that reducing the capacity of a standalone wind power plant results in occasional, short-duration power shortages, although the majority of the grid demand is still met without issue. To mitigate these minor shortages, two potential solutions were identified: increasing the wind power plant's capacity by adding more turbines in Solution 1 or incorporating a battery storage system alongside the wind turbines in Solution 2.

These power shortages occur intermittently throughout the year, typically lasting for only a few hours on certain days (e.g., 2 hours per day). The first solution—expanding wind turbine capacity—proved economically inefficient, as it involves shifting the entire supply curve upward to cover a small, temporary demand, wasting considerable resources. As seen in Figure 60, increasing wind turbine capacity to eliminate such shortages results in an unnecessarily large supply curve, leading to high costs.

In contrast, the second solution—utilizing battery storage—allows for the flexible management of these minor shortages. Battery systems can provide the precise amount of power needed during these shortage periods, without the need to increase the overall capacity of the wind power plant. This approach increases the supply curve only where needed, preventing resource waste and resulting in a more cost-effective solution.

The total annual investment cost for a standalone wind power plant, including both investment and O&M costs, amounts to €131,421 million per year. By integrating a battery storage system with the wind turbines, these costs were reduced by 76%, bringing the total to €31,510 million per year for the combined Wind+Battery system. This demonstrates the economic efficiency and enhanced reliability of the integrated approach.

5.4 2050 RES Scenario: PV+Wind

In this section, the combined PV+Wind RES, which was technically simulated and analysed in Chapter 4, is evaluated from an economic perspective. The primary rationale for incorporating PV into the wind power plant, despite the Wind+Battery system appearing excellent on paper as demonstrated earlier, is rooted in practical considerations. While the Wind+Battery system showed favourable results in theory, its real-world application presents significant challenges due to the limited availability of high-wind resource areas in Saudi Arabia.

The design of the Wind+Battery system was based on the region with the highest wind power potential in the Kingdom, NEOM city in the north. However, the space available in NEOM for the installation of 263 GW of wind turbines is insufficient due to competing projects such as hydrogen production facilities, PV installations, residential zones, resorts, and hotels. Even when considering the second-best wind resource locations along the west coast, these areas are also geographically limited and incapable of supporting the necessary wind power capacity to meet the Kingdom's total demand.

Moreover, attempting to implement such a system in other areas with lower wind potential, such as Dowmat Al Jandal in the north, would be inefficient. Research shows that the capacity factor in these alternative locations ranges between 20% and 28%, compared to 45.5% in NEOM. While the Wind+Battery system may be the optimal solution on paper, the lack of high-wind potential areas makes it impractical for large-scale deployment, highlighting the need for optimization.

Integrating PV into the system, while reducing reliance on wind turbines, presents a highly viable practical solution. This combined system is more feasible because Saudi Arabia has abundant areas with excellent solar potential, particularly in the northern region, which offers vast, unoccupied land. Additionally, PV installations can be effectively implemented in other regions such as the central, eastern, and western parts of the Kingdom, all of which have strong solar output. The northern region, however, stands out due to its high solar radiation and cooler temperatures, critical factors that enhance PV efficiency and power production. Thus, combining PV with wind power addresses both the technical limitations and land use constraints, making it a more practical and economically viable solution for achieving 100%

RES supply in Saudi Arabia. In Chapter 4, from section 4.4.3.1, the optimal PV+Wind RES solutions are shown in Table 38 with the costs of each system.

Table 38 The two possible solutions of PV+ Wind power supply

	Solution 1	Solution 2
Capacity PV / Wind (GW)	115.403 / 600	600 / 570.7
System Stability (%)	100%	100%
Total Annual Investment Costs (Million Euro)	51,090	65,095

In conclusion, as discussed and justified earlier in Chapter 4, Solution 1 emerged as the better technical option. The total annual investment costs for both solutions are outlined in Table 38, demonstrating that Solution 1 not only proves to be the better technical solution but also the more favourable economic choice. Solution 1, with a total annual investment cost of €51,090 million, compares favourably to Solution 2, which has a total annual investment cost of €65,095 million. This makes Solution 1 the clear winner from an economic perspective, particularly when only wind and PV are utilized without any storage.

Although Solution 1 theoretically supplies the grid successfully, it comes with the drawback of higher costs compared to the PV+Battery and the Wind+Battery system. This cost increase is due to the required overdesign of PV and wind power plants to ensure all shortage points are covered during periods of low generation in the absence of storage, as shown earlier in Figures 69 and 70. To address this limitation, the addition of battery storage to the current PV+Wind system was explored from a technical perspective in Chapter 4. In the following section, this solution is evaluated from an economic perspective.

5.5 2050 RES Scenario: PV+Wind+Battery Storage

In Chapter 4, the disadvantages of relying solely on RES without storage were demonstrated. This was further corroborated in Chapter 5 through the economic analysis presented in the earlier sections. This section now explores the benefits of incorporating storage into the RES mix and provides an economic rationale for doing so. Referring to Table 18, the most optimal solution, both technically and economically on paper, was the Wind+Battery system. This combination was able to meet the Kingdom's total grid demand without shortages and at the lowest cost compared to other scenarios.

The subsequent phase entailed the integration of PV technology into the Wind+Battery system. As detailed and substantiated in Chapter 4, this configuration emerged as the most optimal RES solution for Saudi Arabia. The addition of battery storage has demonstrated significant advantages, particularly in addressing small, temporary demand fluctuations using far fewer resources. Battery storage was thus proven to be the optimal solution when combined with PV and wind RES technologies to supply the Kingdom's entire energy demand.

In this section, the system was evaluated economically to validate the conclusions drawn in Chapter 4. The Wind+Battery system was optimized further to form the final supply system, comprising PV, wind, and battery. The same methodology employed in the previous analyses of RES, both with and without storage, was utilized in this section. The corresponding results are illustrated in Figure 87. Equation 6 was utilized to calculate battery storage costs under the same assumptions outlined previously. However, the battery costs were adjusted to account for the increased storage duration, which rose from 10 hours in the original Wind+Battery system to 12 hours in this combined system.

$$Total\ Capital\ Cost\ \left(\frac{\$}{\mathrm{kWh}}\right) = 150\ \left(\frac{\$}{\mathrm{kWh}}\right) + \frac{280\ \left(\frac{\$}{\mathrm{kW}}\right)}{12\ (hr)} = 173.33\ \frac{\$}{\mathrm{kWh}}$$

$$173.33\ \frac{\$}{\mathrm{kWh}} = 158.22\ \frac{€}{\mathrm{kWh}} = \frac{158.22\ €}{\frac{1}{1{,}000{,}000}GWh} = \frac{158{,}220{,}000\ €}{\mathrm{GWh}} = \text{€158.22 million /GWh}$$

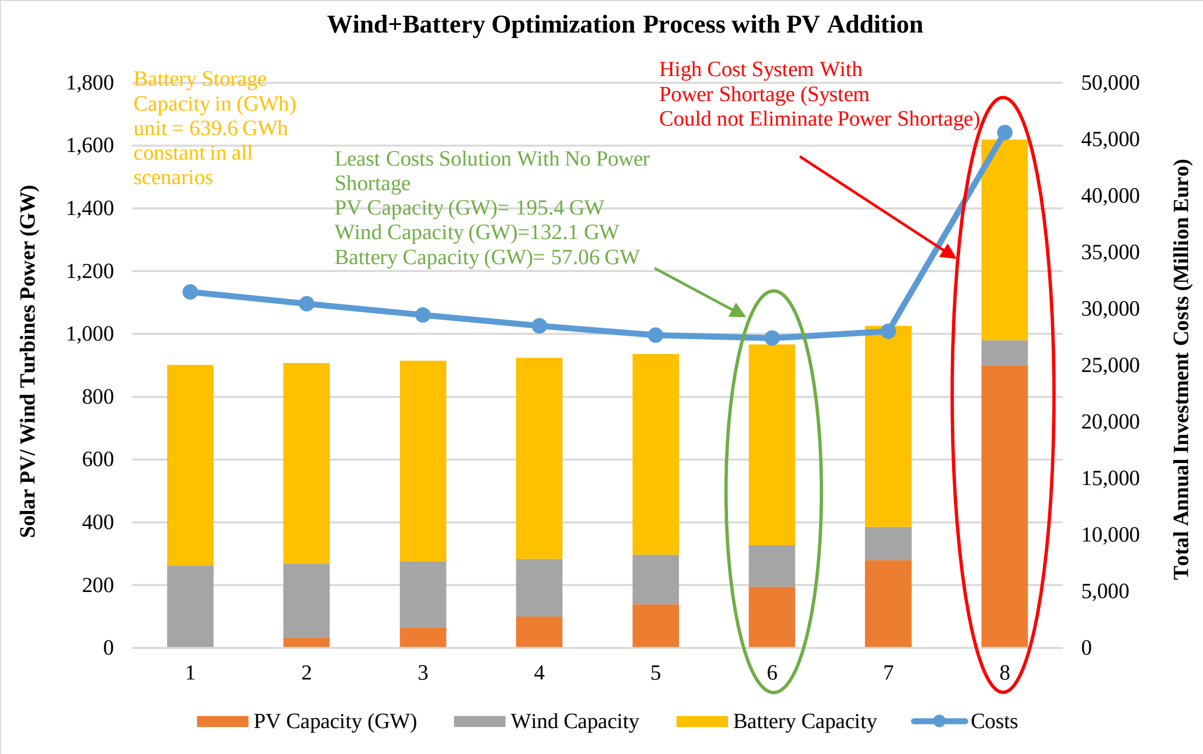

Figure 87 Wind+Battery optimisation process with PV [Author: constructed from simulations]

Figure 87 illustrates the original Wind+Battery power plant at point number 1, alongside the gradual reduction in wind power capacity as PV power capacity increases. With each step, wind power was reduced by 26,004 MW and the PV capacity was increased by the minimum required to eliminate the resulting power shortage. The process continued until the combined costs reached their minimum at point 6, representing the optimal solution that both fulfilled the technical goal of eliminating power shortages and ensuring 100% grid supply throughout the year, as well as the economic goal of being the least-cost solution compared to other systems. After point 6, the system costs gradually increased as the PV power increased, and the wind power decreased. Finally, at point 8, the system capacity was significantly increased with 900 GW of PV and 80 GW of wind, while maintaining the same battery capacity. This led to higher costs and a failure to achieve 100% system stability, resulting in a shortage of 390 GWh over the course of the entire year.

Table 18 shows the original Wind+Battery system compared to the optimised system with added PV and reduced wind turbines deployment. Wind combined with PV and battery system specifications are shown in Table 18. In the Wind+Battery system, the wind capacity was 262,129 MW of wind with 0 PV. With the parametric analysis of wind capacity reduction and increased PV capacity at constant battery storage, the final system design was 132,109 MW wind, 195,405 MW PV and 639.6 GWh of battery storage, as shown in Table 18. The difference in wind power capacities between the first and second cases is a total reduction of 130,020 MW of wind turbines. This has resulted in a shortage of 63.22 TWh annually, with a peak of 77,686 MW without adding PV. The minimum required PV power capacity to avoid this shortage was 195,405 MW. Reducing 130,020 MW from the wind power plant and replacement with 195,405 MW is the minimum required capacity by PV to eliminate all the shortage and achieve 100% system stability. This has also resulted in less total investment and O&M costs, as shown in Tables 39 and 40 below.

Table 39 Wind+Battery RES costs compared to the Wind+PV+Battery scenario.

	Wind + Battery			Wind + PV + Battery		
	Total Investment Costs (m €)	Annual Investment Costs (m €)	Fixed O&M Costs (m €)	Total Investment Costs (m €)	Annual Investment Costs (m €)	Fixed O&M Costs (m €)
Wind	243,790	12,437	8,289	122,861	6,268	4,177
PV	0	0	0	109,427	4,734	1,444
Battery	103,922	8,705	2,078	101,198	8,477	2,024
Sum	347,702	21,142	10,367	333,486	19,479	7,646
Total Annual Investment Costs (m €)	31,510			27,125		

Table 40 Wind+Battery/Wind+PV+Battery total systems costs

	Costs (m € /a)	
RES	Wind+Battery	Wind+PV+Battery
Total Variable Costs	0	0
Fixed O&M Costs	10,367	7,646
Annual Investment Costs	21,142	19,479
Total Annual Costs	**31,510**	**27,125**
LCOE (Euro/MWh)	**23.50 Euro/MWh**	**20.16 Euro/MWh**

Tables 39 and 40 confirm the findings presented in Chapter 4, demonstrating that the addition of PV to the current RES provides better both technical and economic benefits. Both systems are technically capable of meeting the entire Kingdom's demand. However, there is a noticeable cost difference. In the first system, where PV is not utilized, the total annual cost amounted to 31,510 million euros. In contrast, the addition of PV resulted in a 14% reduction in total annual investment costs. Additionally, the LCOE decreased from 23.50 Euro/MWh in the Wind+Battery system to 20.16 Euro/MWh in the Wind+PV+Battery system. The inclusion of PV led to a reduction of 130 GW in the wind turbine power plant capacity, requiring fewer wind turbine resources. This addition also resulted in lower total investment and reduced O&M costs for the RES, as shown in Tables 39 and 40.

In Chapter 4, the optimal Wind+PV+Battery RES solution, as shown in Figure 77 and Tables 18 and 39, was further optimised. In Figure 77, the regions where power was solely supplied by wind and storage (shown in yellow and orange) demonstrate that battery storage can be reduced to a certain threshold while simultaneously increasing wind power capacity. This strategy results in a reduction of overall costs, attributable to the decreased need for storage capacity. However, beyond this limit, further increases in wind capacity and reductions in storage capacity would stop the benefits, as a significantly larger wind capacity would be needed to meet the shortage, which could otherwise be covered by a smaller increase in storage capacity (and at lower costs). Battery storage has a benefit threshold, which depends on both the magnitude of the shortage and the wind generation pattern. For instance, if the battery storage was reduced by 300 GWh, and the resulting shortage was to be supplied by wind during periods of low wind generation (due to lower wind speeds), the wind capacity would need to increase substantially to compensate for the small, limited shortage at the low end of the wind generation curve, as previously observed. This small shortage could be more cost-effectively addressed by using battery storage. Therefore, the final RES solution should be optimized.

A parametric analysis with simulations was conducted in EnergyPLAN by progressively reducing battery storage in 100 GWh increments, compensating for the resulting shortage by increasing wind power capacity until the minimum costs were achieved. If the analysis continued beyond this point, the benefits of increasing wind capacity and reducing storage would diminish, leading to a rise in costs. The results of this optimization are presented in Table 18 (from a technical perspective) in Chapter 4 and in Table 41 below (from an economic perspective). The cost of battery storage was changed because the duration changed, using Equation 6 with the same assumptions and adjusted battery storage duration.

$$Total\ Capital\ Cost \left(\frac{\$}{\text{kWh}}\right) = 150 \left(\frac{\$}{\text{kWh}}\right) + \frac{280 \left(\frac{\$}{\text{kW}}\right)}{8\ (hr)} = 185\ \frac{\$}{\text{kWh}}$$

$$185\ \frac{\$}{\text{kWh}} = 168.67\ \frac{€}{\text{kWh}} = \frac{168.67\ €}{\frac{1}{1{,}000{,}000}GWh} = \frac{168{,}670{,}000\ €}{\text{GWh}} = \text{ 168.67 million Euro/GWh}$$

Table 41 The Final RES and optimised final RES (PV+Wind+Battery) systems design with costs.

RES	Final PV+Wind+Battery System	Optimisation of Final PV+Wind+Battery System
PV Capacity (MW)	195,405	195,405
Wind Capacity (MW)	132,109	150,398
Battery Storage Capacity (GWh)	639.6	400
Battery Duration (hr)	12	8
Total Investment Costs (m €)	333,186	316,764
Annual Investment Costs (m € /a)	19,479	17,522
Fixed O&M Costs (m € /a)	7,646	7,549
Total Annual Costs (m € /a)	**27,125**	**25,071**
LCOE (Euro/MWh)	**20.16 Euro/MWh**	**18.65 Euro/MWh**

In Table 41, the optimization process led to a 7.5% reduction in annual investment costs. This decrease is primarily attributed to the reduction in battery storage capacity from 649.6 GWh to 400 GWh (from 12 hours to 8 hours). These results confirm the findings in Chapter 4, demonstrating that, through optimization, this system represents the optimal RES solution for the Kingdom of Saudi Arabia in 2050. It reliably supplies the grid demand without shortages and power imports while incurring the least costs compared to all other RES solutions.

5.6 Hydrogen Backup Power Plant

5.6.1 Introduction

In this section, the economic evaluation of the green hydrogen backup power plant is conducted, a system that was first introduced in Chapter 4. The primary purpose of the backup system is to address potential shortages in the RES due to unexpected circumstances, unusual events and unpredictability of RES in the future. These shortages could arise from various factors, including the natural uncertainties of a 100% RES-based system by 2050, unpredictable weather conditions, or unexpected changes in future energy demand. Factors such as future policy shifts, weather fluctuations, and international or local events may lead to increased or altered energy demand patterns in 2050.

The first part of the evaluation, conducted in section 5.6.2, tests and analyses the economic performance of the green hydrogen power plant as a power supply contributor with reduced RES size to cover the grid demand. This entails determining whether integrating the green hydrogen power plant with reduced RES size can meet the Kingdom's full energy demand, potentially reducing reliance on the most expensive component of the RES, battery storage, and thus lowering overall costs. The primary goal of this analysis is economic optimization. If reducing the 100% RES share to, for example, 95%, with 5% supplied by the hydrogen power plant, proves more cost-effective, then this modified system would be considered the new optimal solution.

However, if the integration of the green hydrogen power plant does not result in any significant economic benefits, the hydrogen plant would serve as a backup power source for the 100% RES solution. This would be operated in the event of unusual circumstances or unpredictable factors related to RES performance or weather conditions, as discussed in section 5.6.3.

5.6.2 Demonstrating the High Costs of the Current Optimized RES and the Potential for Cost Reduction Through the Integration of Hydrogen Power Plant as a Power Supplier with RES.

In this study, as previously outlined, the green hydrogen power plant is proposed as a backup system to address potential shortage in 2050 resulting from unexpected and usual events. However, due to its zero CO_2 emissions, it was initially tested as a power supply contributing system to the existing 100% RES with a reduced RES capacity. The battery storage capacity (in GWh) was decreased, and the resulting shortage was compensated by the green hydrogen power plant. The extent of the battery overdesign in the optimized final 100% RES is illustrated in Figure 88 below.

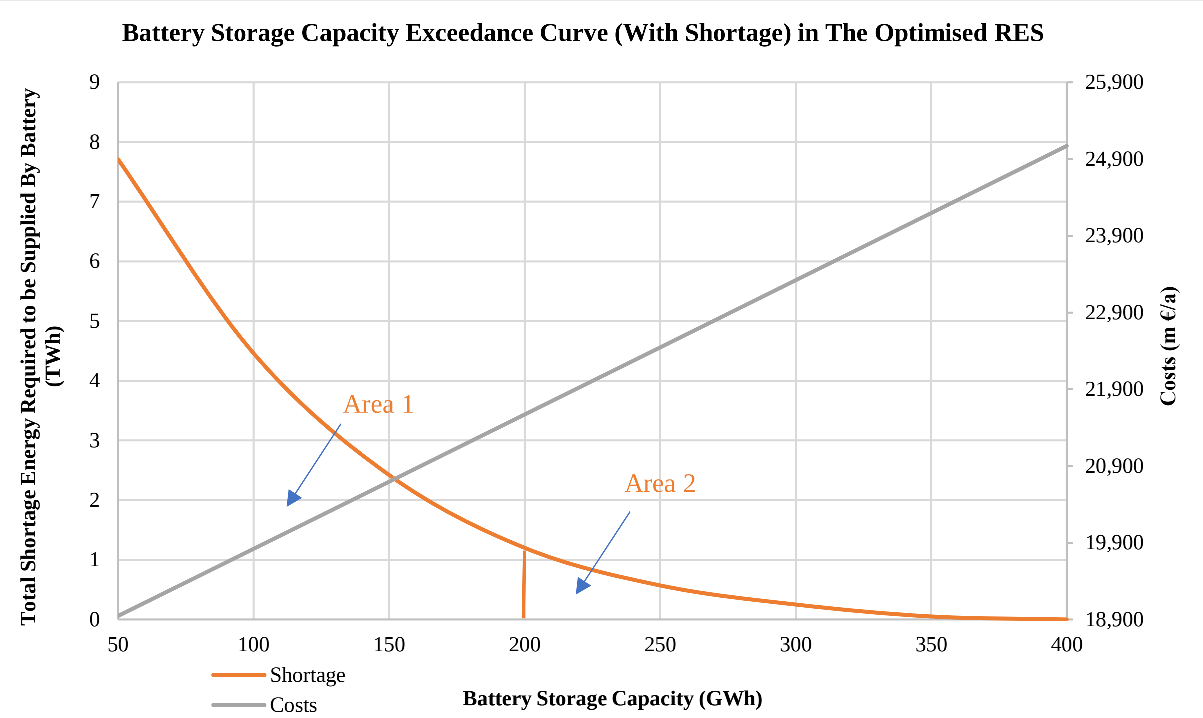

Figure 88 Battery storage capacity exceedance curve (with shortage) [Author: constructed from simulations].

Figure 88 illustrates the varying sizes of the battery storage system and their impact on energy requirements and costs. The designed system's battery storage capacity was set at 400 GWh, which represents the minimum capacity necessary to prevent shortages at any hour in the Kingdom, even during the most critical conditions, as discussed in earlier sections. For instance, with a battery capacity of 350 GWh, a shortage of 0.05 TWh occurred. To address this minor shortage, an additional 50 GWh of battery capacity was needed, resulting in an increase in costs of 867 million €/a to supply only 0.05 TWh of energy.

By comparison, at a storage capacity of 50 GWh, the total power shortage is substantial, reaching 7.72 TWh annually, necessitating a significant increase in capacity. Between 50 GWh and 200 GWh, the total energy supplied (or avoided shortage) is 6.51 TWh (calculated as 7.71 TWh - 1.2 TWh). However, from 200 GWh to 400 GWh, the additional energy supplied to avoid shortages is only 1.2 TWh (calculated as 1.2 TWh - 0 TWh). This demonstrates that as storage capacity increases, the cost-benefit diminishes significantly.

Cost areas 1 and 2 were defined as indicators of the cost-benefit analysis in two scenarios: the first case involves increasing storage from 50 GWh to 200 GWh, while the second case considers increasing storage from 200 GWh to 400 GWh, as follows:

Δ Energy Supplied (50 GWh – 200 GWh) = 6.51 TWh.

Δ Costs (50 GWh – 200 GWh) = 2,625 m €/a

Δ Energy Supplied (200 GWh – 400 GWh) = 1.2 TWh.

Δ Costs (200 GWh – 400 GWh) = 3,500 m €/a

$$\text{Costs } Area\ 1 = \frac{\Delta \text{ Costs (50 GWh – 200 GWh)}}{\Delta \text{ Energy Supplied (50 GWh – 200 GWh)}} = \frac{2{,}625 \text{ m €/a}}{6.51\ TWh} = 403 \text{ m}\frac{€}{\text{a}}/\text{TWh}$$

$$\text{Costs } Area\ 2 = \frac{\Delta \text{ Costs (200 GWh – 400 GWh)}}{\Delta \text{ Energy Supplied (200 GWh – 400 GWh)}} = \frac{3{,}500 \text{ m €/a}}{1.2\ \ TWh} = 2{,}916 \text{ m}\frac{€}{\text{a}}/\text{TWh}$$

This high-cost difference between Areas 1 and 2 indicates that the system is over-designed. The cost is lower in ‘’Area 1 costs’’ because the numerator is lower, and the denominator is higher than in ‘’Area 2 costs’’. In simpler words, the increased capacity from 50 GWh to 200 GWh resulted in lower costs due to lower increased capacity (150 GWh total increase) and higher supplied energy (larger avoided shortage) than in the second case (200 GWh – 400 GWh) where the total cost is higher due to larger capacity increase (200 GWh total increase) and less avoided shortage. This is because, in the second case, the storage capacity was increased to 400 GWh not only to eliminate the total shortage but also to meet the critical point demand during the year. At this critical point, the storage system required sufficient capacity to supply the remaining demand after the PV and wind systems had already delivered their maximum output, as detailed in earlier sections. Figure 89, along with the previous analysis, demonstrates that the battery storage system is overdesigned, as indicated by the number of days shown in Figure 89.

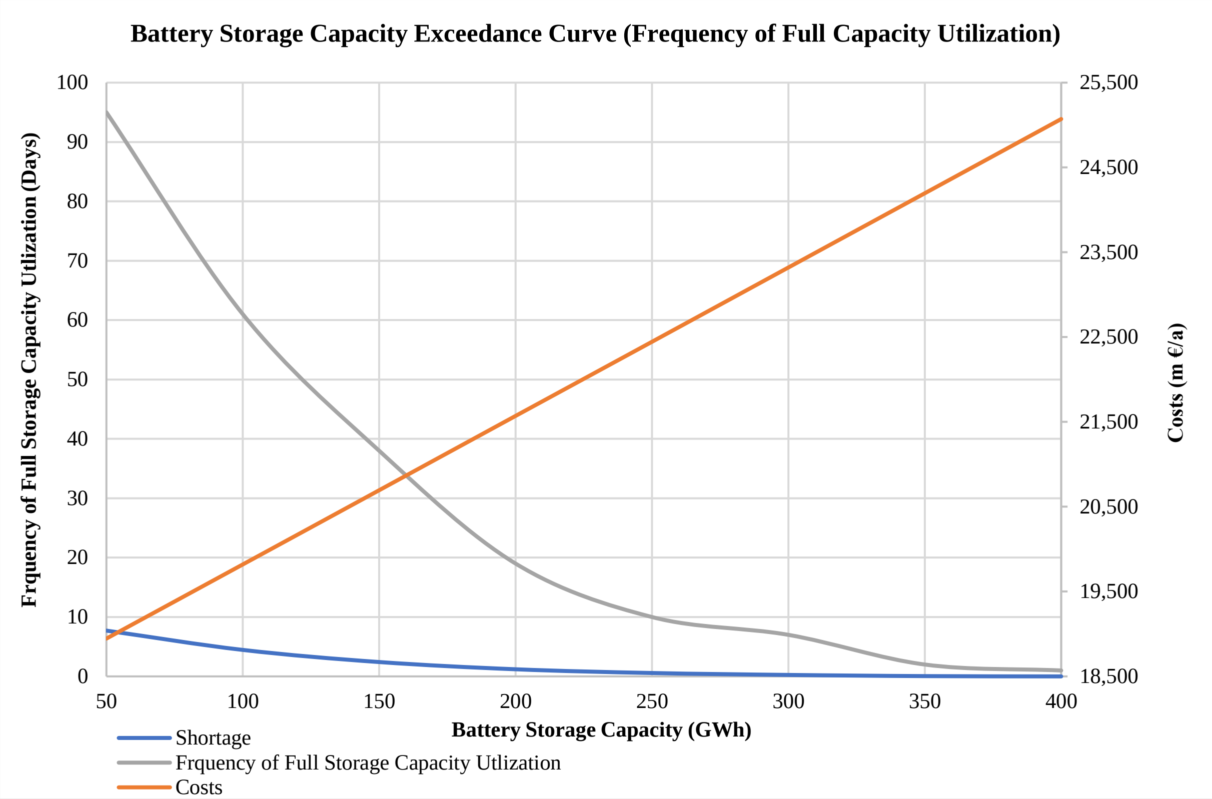

Figure 89 Battery storage capacity exceedance curve with frequency of total storage capacity utilisation [Author: constructed from simulations].

Although the overdesign could be represented better by the shortage amount and energy supplied, as in Figure 88, the same results were conducted but with the frequency of full capacity utilisation during the year (in days), as shown in Figure 89, providing an extra indication of the higher storage capacity. Figure 89 shows the number of days when the battery storage was fully utilised to supply the remaining shortage after the PV and wind produced their maximum daily power. At a storage capacity of 50 GWh, the system operated at full capacity on 95 days of the year. In contrast, a storage capacity of 400 GWh was utilized at full capacity on only a single day throughout the year, during the most critical period when both PV and wind generation experienced minimal output, as previously discussed. For example, the storage capacity was increased from 350 GWh to 400 GWh to address the worst-case scenario, adding coverage for just one additional critical day in the year. While this adjustment successfully prevented shortages and ensured system stability throughout the year, it resulted in a substantial cost increase of €875 million per annum. This suggests that storage capacity can be reduced by avoiding the need for higher capacities to cover critical points when PV and wind production are at their lowest. Instead, these critical demands can be met more cost-effectively by utilizing a conventional condensing power plant, rather than relying solely on battery storage.

5.6.3 The Hydrogen Power Plant with Retrofit Costs and Its Potential as a Contributor to Power Supply with Reduced RES.

The green hydrogen power plant was first tested as an integral component of the RES, with the RES capacity reduced, and then the costs of both systems, the optimized 100% RES and the hydrogen power plant combined with a reduced RES, were compared. The goal of incorporating the hydrogen power plant into the current RES was to assess whether this could lower the total costs of Saudi Arabia's energy supply system, as the current 100% RES solution involves overdesign, particularly in the battery storage component. Suppose hydrogen is used in conventional thermal power plants by taking the surplus power from RES. In that case, the costs of the hydrogen power plants in addition to the electrolysers and hydrogen storage must be included, as shown in this section below. The challenge is that the new 100% pure hydrogen CCGT power plant costs are still unavailable because of the limited applications. Siemens is the leader in this technology with its advanced hydrogen combined cycle power plant and advanced hydrogen gas turbines, which vary in the models according to the level of hydrogen integration. Some models support mixing with natural gas at 80% gas, 20% hydrogen, 40% hydrogen and 60% natural gas by volume. Siemens also aims to have gas turbines capable of operating on 100% hydrogen fuel by 2030 in their 100% hydrogen gas turbine roadmap [259].

Although Siemens possesses data on the costs associated with a 100% hydrogen-fuelled CCGT power plant, the company declined to disclose this information to the author of this thesis despite repeated attempts to establish contact. Siemens indicated that such data is exclusively available for large-scale, on-the-ground projects. Consequently, an alternative method was employed to estimate the costs of a 100% hydrogen CCGT power plant for 2050. This approach involved using the projected costs of future CCGT power plants for 2050 and adding the retrofit costs required to convert these plants to operate entirely on hydrogen (without blending with natural gas). Chapter 4 provided a detailed explanation of the technical retrofit process and the conversion of natural gas CCGTs to 100% hydrogen-fuelled CCGTs. This section, however, focuses on the associated retrofit costs and the final costs of operating the hydrogen power plant.

A recent study conducted by ETN Global (2022) [226] examined the retrofit costs associated with converting conventional thermal power plants to operate on hydrogen-natural gas blends and 100% hydrogen. The analysis encompassed various power plant configurations, including small OCGTs, CHP systems, medium OCGTs, large OCGTs, and large CCGTs. Retrofit costs were assessed based on the proportion of hydrogen introduced by volume, starting from the baseline of 100% natural gas (0% hydrogen) to full hydrogen operation (0% natural gas, 100% hydrogen). Intermediate blends, such as 70% natural gas with 30% hydrogen and 30% natural gas with 70% hydrogen, were also evaluated. The retrofit costs analysed in this thesis were derived from the ETN Global report, as it represents the only reliable source providing detailed data on retrofit costs for various power plant configurations and corresponding levels of hydrogen integration. No other references were identified that offered comparable detail or accessibility for this specific analysis. Table 42 below shows the assumed CCGT power plant costs in 2050 with the retrofit costs to operate the plant 100% on hydrogen. The selected power plant is a large CCGT at approximately 500 MW.

Table 42 Assumed CCGT plant costs, efficiency, and lifetime with retrofit costs required to operate on 100% hydrogen.

	2050 Initial CCGT Power Plant	Retrofit Effect	Final CCGT power Plant Retrofitted
Investment Costs (m €/MW)	0.80 [227]	+25% [230]	1
Efficiency (%)	64% [230]	-1.3 (2%) [230]	62.7%
Lifetime (Years)	25 [227]	-	25
Fixed O&M Costs (% of Investment)	3.25% [227]	+50% [230]	4.8%
Variable O&M Costs (m €/MWh)	2.654 [227]	-	2.654

Although the assumed retrofit costs are well-developed for low levels of hydrogen integration, higher hydrogen blending or 100% hydrogen usage retrofit costs are based on assumptions outlined in the same report. This is due to the limited current applications, as the report states: "*The GT upgrade and fixed maintenance costs, the GT derating factor, and GT efficiency, which vary as a function of hydrogen blending level, have been developed through extensive internal consultation and review with ETN member organizations, including GT OEMs and GT users. The values are currently well-developed for low levels of hydrogen blending, but for higher hydrogen blending, retrofit applications are currently limited, and therefore, assumptions were made on these values*" [226]. As a result, the outcomes of these analyses are heavily reliant on the author's assumptions and the data provided in the report. Tables 43 and 44 below present the assumed electrolyser and hydrogen storage costs and their lifetimes.

Table 43 Assumed electrolyser costs, efficiency, and lifetime in 2050.

	Alkaline Electrolyser
Investment Costs (m €/MW)	0.5 [227]
Conversion Efficiency (%)	80% [228],[229]
Lifetime (Years)	25 [227]
Fixed O&M Costs (% of Investment)	5% [227]

Table 44 Assumed hydrogen storage costs, efficiency, and lifetime in 2050.

	Hydrogen Storage
Investment Costs (m €/GWh)	6.40 [227]
Lifetime (Years)	20 [227]
Fixed O&M Costs (% of Investment)	2.03 [227]

For grid stability, some studies [231][232] suggest that a minimum of 30% production capacity from stabilizing units, such as condensing power plants or hydropower, is required to operate continuously every hour of the year to ensure stability. However, this approach cannot be implemented in this project because it would reduce the total annual RES share of electricity production, contradicting the primary objective of this thesis: achieving 100% RES electricity supply. Additionally, this study assumes that by 2050, grid stability will be effectively managed with a high share of PV and wind power systems, supported by advancements in research, technologies, and control systems.

The cost-saving potential of partially substituting RES with a thermal power plant operating on hydrogen and/or natural gas—particularly when the backup system also contributes to the existing RES in power generation—is analysed and presented in Figure 90 below.

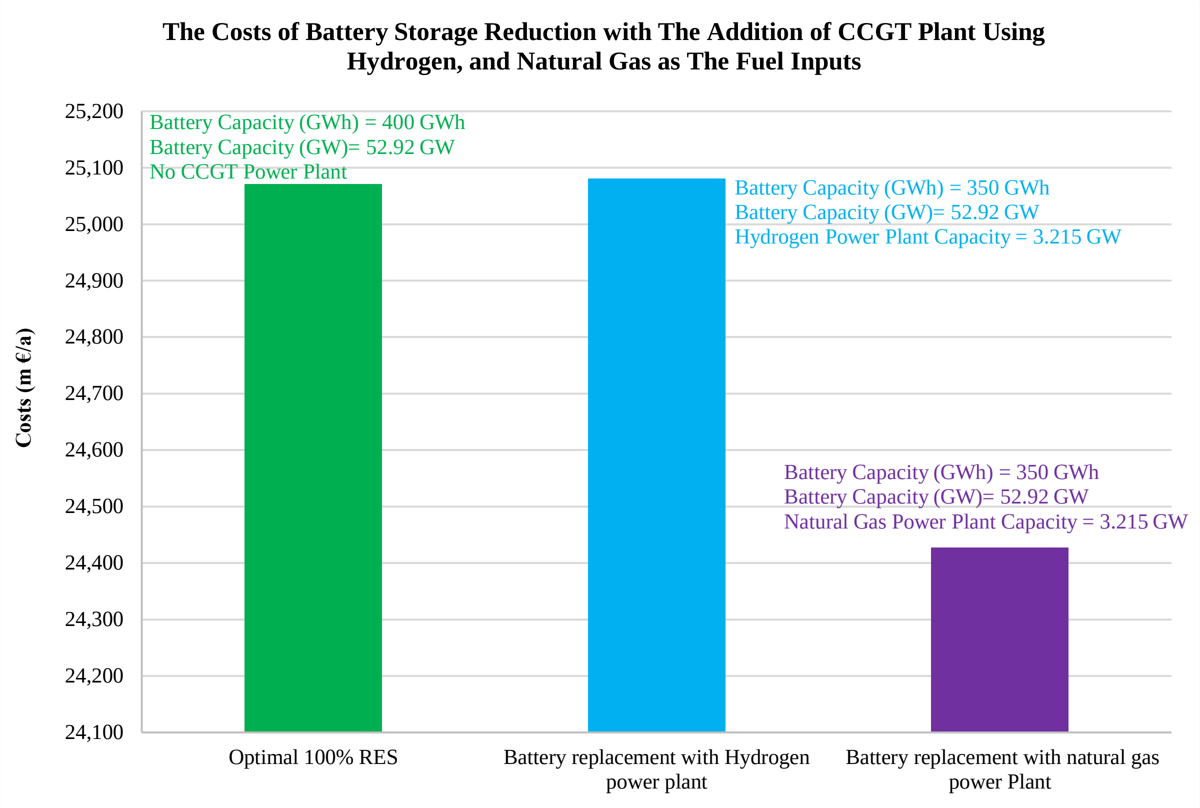

Figure 90 The effect of 50 GWh battery replacement with hydrogen and natural gas power plants [Author: constructed from simulations].

Figure 90 illustrates the impact of substituting 50 GWh of battery storage from the 100% RES optimized configuration with hydrogen and natural gas power plants. This change involved removing 50 GWh of battery capacity and adding each type of power plant at the minimum capacity needed to prevent a supply shortage due to the battery reduction. Replacing the battery storage with a hydrogen power plant led to slightly higher costs compared to the original optimized 100% RES setup with a 400 GWh battery system. While hydrogen power plants did not emit CO2, they did release other emissions, such as NOx.

As shown in the same figure, utilizing a natural gas power plant instead could cover the supply gap at a significantly lower cost than the hydrogen power plant but would generate CO2 emissions of 0.89 Mt annually. Natural gas power plants thus present a viable solution for reducing the overdesign of RES systems. However, as this thesis aims to eliminate fossil fuel use by 2050, this approach is not sustainable in the long term. The increased costs associated with the hydrogen power plant arise from the need to the retrofit process for 100% hydrogen use and from the additional expenses of electrolysers and hydrogen storage. Consequently, employing a hydrogen power plant as a cost-saving measure to reduce the 100% RES reliance is not economically viable. Table 45 below provides the parameters used for both power plants.

Table 45 Hydrogen and natural gas power plants performance parameters

	Hydrogen power plant	Natural gas power plant
PP Capacity (MW)	3,215	3,215
PP Power Production (TWh)	2.77	2.77
PP Gas Consumption (TWh)	4.4	4.3
Electrolyser Capacity (MW)	9,301	0
Hydrogen Storage (GWh)	72	0
Electrolyser Input Power Taken From surplus energy of RES (TWh)	5.51	0

The results in Figure 90 indicate that utilizing a hydrogen power plant as an additional power source for the current RES, with a reduced battery storage capacity, is not economically viable. This is primarily due to the high costs associated with the hydrogen power plant, particularly the retrofitting required for 100% hydrogen compatibility, along with the added expenses of electrolysers and hydrogen storage.

5.6.4 Hydrogen Power Plant as a Backup Power Solution.

In section 5.6.2, green hydrogen was found to be economically unviable as a contributor to total power generation within the current RES, primarily due to its higher costs. The existing RES, with its original specifications, proved more cost-effective than a system with reduced RES capacity supported by a hydrogen power plant. This cost difference is attributed to the high expenses associated with hydrogen power plants, particularly retrofitting, as well as the costs of electrolysers and hydrogen storage. The use of natural gas power plants is also impractical, given the CO2 emissions generated and the need to eliminate fossil fuels. Therefore, the hydrogen power plant was proposed only as a backup solution for potential future shortages arising from RES variability, climate uncertainties, and other previously mentioned factors.

The future holds numerous uncertainties, especially concerning climate impacts and the variability of RES performance. In light of this, certain assumptions are necessary. It was assumed that by 2050, a shortage in RES supply could occur due to climate changes, RES unpredictability, and demand fluctuations. As detailed in Chapter 4, this assumption includes a potential downtime affecting 20% of the total RES, 10% of the total PV capacity due to lack of sunlight or extreme weather, and 10% of total wind capacity due to conditions like wind speeds outside the turbine's operational range and general unpredictability.

In the event of a shortage, the thermal backup power plant would immediately activate to bridge the gap. Chapter 4 offered detailed technical data and assumptions regarding RES capacities during downtimes, the operation of the hydrogen power plant during RES downtime, backup power plant hydrogen requirements, required electrolyser capacities, and hydrogen storage requirements. Table 46 below summarizes the total costs of the final system configuration for a 100% RES setup including a hydrogen standby backup power plant.

Table 46 The final optimised 100% RES with hydrogen power plant backup system costs compared to the original optimised 100% RES without a backup system.

	The Final Optimised 100% RES			The Final Optimised 100% RES with the Addition of Hydrogen Backup Power Plant		
	Total Investment Costs	Annual Investment Costs	Fixed O & M Costs	Total Investment Costs	Annual Investment Costs	Fixed O&M Costs
Wind	139,870	7,136	4,756	139,870	7,136	4,756
PV	109,427	4,734	1,444	109,427	4,734	1,444
Battery	67,468	5,652	1,394	67,468	5,652	1,394
Electrolyser	0	0	0	8,750	502	438
Hydrogen Storage	0	0	0	2,150	145	44
Hydrogen CCGT PP	0	0	0	8,693	499	417
Sum	316,765	17,522	7,549	336,358	18,668	8,448
Annual Fixed O&M Costs (m €)	7,549			8,448		
Annual Investment Costs (m €/a)	17,522			18,668		
Total Annual Costs (m €/a)	25,071			27,116		

Table 46 shows the costs of the optimised 100% RES combined with the standby green hydrogen backup power plant. Total costs increased by 7.5% due to the addition of the standby backup power plant with all the required electrolysers and hydrogen storage. This configuration represents the optimal 100% RES system with a backup solution tailored for Saudi Arabia in 2050.

It is important to note that the 100% RES system currently relies on grid-stabilizing services provided by conventional fossil fuel power plants, an issue that must be addressed in the future—specifically by 2050—with non-fossil fuel solutions. This paper assumes that by 2050, ongoing research will yield non-fossil fuel systems and controls capable of delivering these grid stability services. However, the development of such future grid-stabilizing solutions lies beyond the scope of this paper.

In the next chapter, the final optimal 100% RES configuration with a standby power plant is presented in detail, alongside a comparison with other RES configurations, summarizing all relevant technical and economic parameters.

Chapter 6

The100 % RES Solutions with Green Hydrogen Backup Power Plant Results Summary, Thesis Discussion, Key Contributions, Limitations, and Future Work

6.1 RES Solutions Summary

6.1.1 All The 100% RES Solutions Summary

This section summarises all the RES solutions simulated in this thesis with all the KPIs, technical and economic parameters, and the optimal 100% RES solution for the Kingdom in 2050 with the hydrogen backup power plant. The summary is shown in details with each RES solution separately in Table 47 below.

Table 47 RES solutions summary

	PV	PV + Battery	Wind	Wind+ Battery	Wind+ PV	PV+Wind+ Battery	PV+Wind+ Battery Optimized
Installed Capacity (GW)	577	577	1,662	262	Wind 600 PV 115	Wind 132 PV 195	Wind 150 PV 195
Storage							
Storage Type	None	Battery	None	Battery	None	Battery	Battery
Storage Capacity (GWh)	0	2,039	0	639.6	0	639.6	400
Storage Charge/ Discharge Efficiency (%)	0	85 / 90	0	85 / 90	0	85 / 90	85 / 90
Storage Charge/ Discharge Capacity (GW)	0	236 / 91	0	65 / 64	0	40 / 57	42 / 52

Annual Average Charge/ Discharge	0	45 / 34	0	3.5 / 2.7	0	3.2 / 2.4	2.06 / 1.58
Annual Maximum Charge/ Discharge (GW)	0	236 / 91	0	65 / 64	0	40/ 57	42 / 52
Annual Minimum Charge/ Discharge	0 / 0	0 / 0	0	0 / 0	0	0/0	0/0
Energy (TWh)							
Total Energy Produced by Renewable	0	652.63	558.30	565.61	Wind 383.33 PV 174.97	Wind 334.71 PV 230.26	Wind 337.24 PV 225.32
Total Energy Charged to Storage	0	401.42	0	31.10	0	28.41	18.14
Total Energy Discharged by Storage	0	307.08	0	23.79	0	21.73	13.88
Surplus Energy (Export)	0	0	0	0	0	0	0
Costs (m € /a)							
Total Variable Costs	0	0	0	0	0	0	0
Fixed O&M Costs	0	10,444	52,557	10,367	19,825	7,646	7,549
Annual Investment Costs	0	39,858	78,865	21,143	31,265	19,479	17,522
Total Annual Costs	0	50,302	131,42	31,510	51,090	27,125	25,071
LCOE (Euro/MWh)	0	37.63	97.37	23.50	37.85	20.16	18.65

KPI's							
System's Ability to Prevent Hourly Shortages Throughout the Year (%) (Energy Security)	41%	100%	100%	100%	100%	100%	100%
Total Electricity Import (TWh)	0	0	0	0	0	0	0
RES share of Electricity Production (Equation 7) (%)	0	116.9%	100%	101.3%	100%	101.2 %	100.8%
Total Power Generated (Without Stopping Surplus) (TWh)	0	1052	6,754	1,065	Wind 2438.36 PV 210.45	Wind 536.88 PV 356.35	Wind 611.21 PV 356.34
Critical Excess Electricity Production (CEEP) (TWh)	0	0	0	0	0	0	0
Total Annual System Costs (Million Euro)	0	50,302	131,42	31,510	51,090	27,125	25,071

The KPIs are, first, the ability of the system to provide 100% hourly electricity supply for the grid's year demand on an hourly basis without the need for import and without shortage at any time. The system's ability to avoid shortage and import is defined in equation 8. Secondly, the economic analysis of the system includes fixed O&M costs, variable O&M costs, investment or capital costs, total annual costs, and LCOE. The final KPI used is the technical KPI in Equation 7. All systems performance parameters, including the RES plant, storage, energy parameters, costs, and KPI, are shown in Table 47.

$$\frac{\textit{Net annual energy produced by system}}{\text{Annual energy demand}} \times 100\%$$

Equation 7

$$\frac{\textit{Number of hours with no shortage and import}}{8784} \times 100\%$$

Equation 8

Table 47 summarizes all the 100% RES configurations developed in this thesis, detailing each system's technical and economic KPIs. Each system met the Kingdom's energy demands with 100% RES power, except for the standalone PV plant, which could not supply power during nighttime. The RES optimization process began with standalone PV, followed sequentially through PV+Battery, Wind, Wind+Battery, and other RES solutions, all aiming to meet specific technical and economic objectives.

The primary technical objective was to ensure that the RES could fully meet the Kingdom's demand, providing a continuous supply of energy without shortages or the need for imports from neighbouring countries, both during the day and at night, throughout the entire year. Upon meeting this goal, the focus shifted to achieving the lowest possible cost among RES options. Notably, factors beyond technical and economic goals, such as system reliability, also influenced these optimization efforts for a sustainable RES solution for the Kingdom by 2050. For instance, while a PV+Wind system, without storage, could theoretically meet the Kingdom's annual demand, it would be impractical due to RES variability and generation fluctuations. Similarly, a Wind+Battery system could meet demand at a lower cost than earlier options, yet it faced limitations in practical implementation. This limitation arose from the restricted area of optimal wind resources and the substantial space required for a large number of wind turbines, particularly in NEOM city, which does not have enough available land to support such an extensive installation.

6.1.2 Optimal 100% RES for Saudi Arabia in 2050 Spatial Layout and Land Use Analysis

The final optimal 100% RES solution, which can reliably supply the power for Saudi Arabia in 2050 with the minimum costs, is highlighted in grey colour in Table 46. This system uses a combination of PV, wind turbines, and lithium-ion battery storage. The system achieves the first technical goal followed by the second economic goal with the optimal reliability among other systems. Below are the calculations for the number of PV panels, wind turbines, battery units, and required land areas. The PV panel module is the Miasole FLEX-03 500W, shown earlier in Table 10, while the wind turbine model is GE 3.2 130, also shown in Table 19.

PV Panels total land area is calculated as follows:

PV area per panel = $3.34\ m^2$ [260]

$$\text{Number of Panels} = \frac{Total\ Installed\ PV\ Capacity}{Power\ per\ Panel} = \frac{195{,}405{,}000\ kW}{0.501072\ kW/Panel} = 389.87\ million\ panels$$

$$\text{Total Area of Panels} = Number\ of\ panels \times Area\ per\ panel$$

$$= \ 398.87\ million \times \ 3.34\ m^2 = 1{,}303{,}423{,}016\ m^2$$

Land Coverage Efficiency = Assuming 40% [261].

Land Coverage Efficiency, known as the ground coverage ratio for solar PV installations, is widely used in the industry to account for space between rows of solar panels, access paths, and the need to prevent shading between panels. This value can vary based on the specific project layout, but 40% is a common estimate for large-scale solar installations [261].

$$\text{Total Land Area} = \frac{1{,}303{,}423{,}016\ m^2}{0.4} = \frac{3{,}258{,}557{,}540\ m^2}{1000} = 3{,}258\ \ km^2$$

Now, the wind turbines total land area is calculated as follows:

$$\text{Number of Turbines} = \frac{Total\ Installed\ Wind\ Capacity}{Power\ per\ Turbine} = \frac{150{,}398\ MW}{3.2\frac{MW}{Turbine}} = 47{,}000\ Turbines$$

First, spacing requirements are needed to calculate the land area for the turbines. Wind turbines are spaced apart to reduce wake effects, which occur when the airflow around one turbine disturbs the airflow for nearby turbines, reducing their efficiency. The standard industry guideline recommends spacing wind turbines a specific number of rotor diameters apart. This required spacing is determined by the rotor diameter of the turbine being used. For the selected wind turbine GE 3.2-130, the rotor diameter is 130 meters. Based on standard guidelines, we calculate the necessary spacing as follows:

A) Spacing in the Wind Direction (7 Rotor Diameters). Wind turbines are spaced more widely in the wind direction because the turbines upstream create turbulence that can reduce the efficiency of turbines placed too closely behind them.

$$Spacing\ (wind) = 7\ \times Rotor\ Diameter = 7\ \times 130\ m = 910\ m.$$

This means that each turbine is placed **910 meters apart** from the next in the direction of the prevailing wind [262].

B) Spacing Perpendicular to the Wind (3 Rotor Diameters). Less spacing is required perpendicular to the wind direction because the turbulence created by a turbine affects turbines less when placed side-by-side.

$$Spacing\ (Crosswind) = 3\ \times Rotor\ Diameter = 3\ \times 130\ m = 390\ m.$$

This means that each turbine is placed **390 meters apart** from the next turbine in a direction perpendicular to the wind [262].

Area per Turbine = $Spacing\ (Wind) \times Spacing(Crosswind) = 910\ m\ \ \times 390\ m = 354{,}900\ m^2.$

This calculation shows that each turbine requires **354,900** m^2 (or 0.3549 km^2) of land to operate effectively.

Total Land Area for All Turbines= $Number\ of\ Turbines \times Area\ per\ Turbine =$

$$47{,}000\ turbines\ \times 354{,}00\ m^2\ per\ turbine = \frac{16{,}690{,}300{,}000\ m^2}{1000{,}000} = 16{,}690\ \ km^2$$

The seven rotor diameters in the wind direction and three rotor diameters perpendicular are based on industry-standard guidelines. These are designed to minimise the loss of efficiency caused by wake effects (turbulence created by the turbine blades) and ensure that each turbine receives as much uninterrupted wind as possible. Wake effects can reduce the efficiency of downstream turbines by as much as 10-20%, so proper spacing is critical to maximising the overall energy production of a wind farm. These values are widely accepted in the wind energy industry for large, utility-scale wind farms [262].

Now, for the lithium-ion battery units, total land area is calculated as follows:

Total Battery Storage Capacity = 4,000 MWh

Capacity per Battery Unit: 1 MWh per unit.

For large-scale lithium-ion battery installations, the land area required per MWh typically varies depending on the system configuration, cooling requirements, control systems, and safety spacing. A commonly used estimate by industry for the area needed per MWh of battery capacity is 10 m^2 per MWh. This includes space for physical battery racks, cooling systems, inverters and power electronics, ancillary infrastructure, fire suppression systems and access space for maintenance [263].

$$\text{Total Battery Land Area} = 4{,}000\ MWh \times \frac{10\ m^2}{MWh} = \frac{40{,}000\ m^2}{1000{,}000} = 0.04\ km^2$$

Table 48 below summarises all PV, wind and battery storage capacities, quantities and required land areas.

Table 48 Final Optimal 100% RES solution for Saudi Arabia in in 2050 system performance and spatial planning summary

System Component	Total Capacity	Quantity	Land Area Required	Units
PV	195.405 GW	389,873,000 Panels	3,258.56 km^2	Capacity: GW Panels: Units Land Area: km^2
Wind Turbines	150.398 GW	47,000 Turbines	16,690.30 km^2	Capacity: GW Turbines: Units Land Area: km^2
Battery Storage	4,000 MWh	4,000 Units	0.04 km^2	Capacity: MWh Battery: Units Land Area: km^2

The sensitivity analysis presented in Table 49 below highlights the effects of total investment costs, O&M costs, and interest rates on the overall economics of the optimized 100% RES, specifically focusing on their impact on the levelized cost of energy.

Table 49 Sensitivity analysis for the optimal 100% RES solution

Scenario	Total Investment Costs Sensitivity	O&M Costs Sensitivity	Interest Rate Sensitivity
	LCOE (€/MWh)		
Base Case	18.65	18.65	18.65
20% increase	19.98	19.72	19.56
40% increase	23.31	20.79	20.49
60% increase	26.65	21.85	21.46

The sensitivity analysis conducted on the LCOE highlights the impact of changes in interest rates, O&M costs, and total investment costs, each of which plays a crucial role in the economics of the project. The base case LCOE is €18.65/MWh, but as each factor increases by 20%, 40%, and 60%, the LCOE responds accordingly. Total investment cost changes show the largest impact on LCOE, with a 60% increase pushing the LCOE to €26.65/MWh, indicating that the total investment cost is the most significant driver of cost fluctuations in the project. In contrast, a 60% increase in interest rates and O&M costs results in LCOEs of €21.46/MWh and €21.85/MWh, respectively.

This suggests that while financing and operational expenditures are important, total investment cost has a more substantial effect on long-term economic performance. Given the capital-intensive nature of RES projects, strategies to optimize the total investment cost, such as efficient procurement, technology advancements, and economies of scale, can lead to more significant improvements in economic viability. In comparison, O&M optimizations and securing favourable financing terms remain important but secondary considerations. This analysis emphasizes the need to prioritize upfront investment cost management to achieve the most economically viable energy systems, aligning with industry standards and high-quality academic practices.

6.2 Primary Energy Supply & CO_2 Emissions

In the power sector, a comparison between the 2017 reference scenario and the projected 2050 scenario reveals a significant shift in energy sources. In 2017, power generation was primarily dependent on oil, oil products, and natural gas through conventional condensing power plants. By 2050, however, all conventional power plants are fully replaced by RES, as shown in Figure 91. Despite the increase in power demand, fuel requirements, and population growth by 2050, CO_2 emissions from burning oil, oil products, and natural gas for power generation are eliminated through the implementation of RES, as illustrated in Figure 92.

Figure 92 also highlights Saudi Arabia's prior dependence on oil products and natural gas for power generation via conventional condensing power plants across the Kingdom in 2017. The RES system has effectively addressed this, fully replacing these plants with a combination of PV, wind, and battery storage, supported by a green hydrogen backup power plant. This new system meets 100% of the Kingdom's energy demand in 2050, achieving zero CO_2 emissions from the power sector and passenger vehicles fleet in the transport sector, as illustrated in Figures 91 and 92.

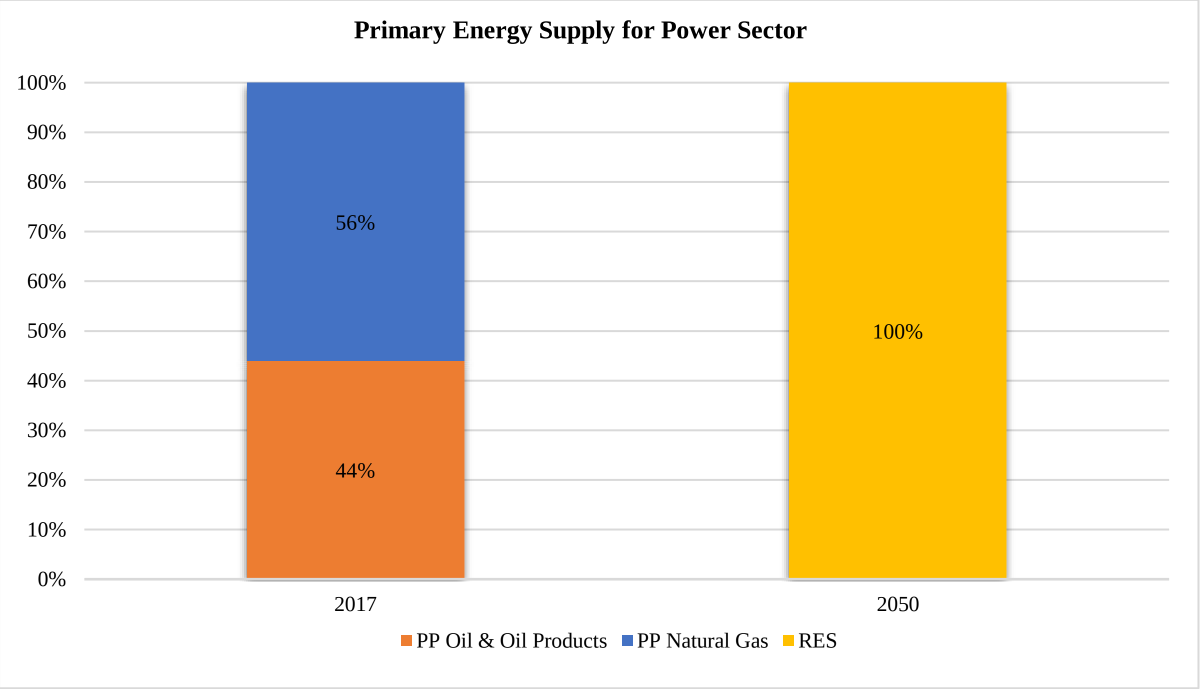

Figure 91 Primary energy supply for power sector [Author: constructed from simulations and IEA].

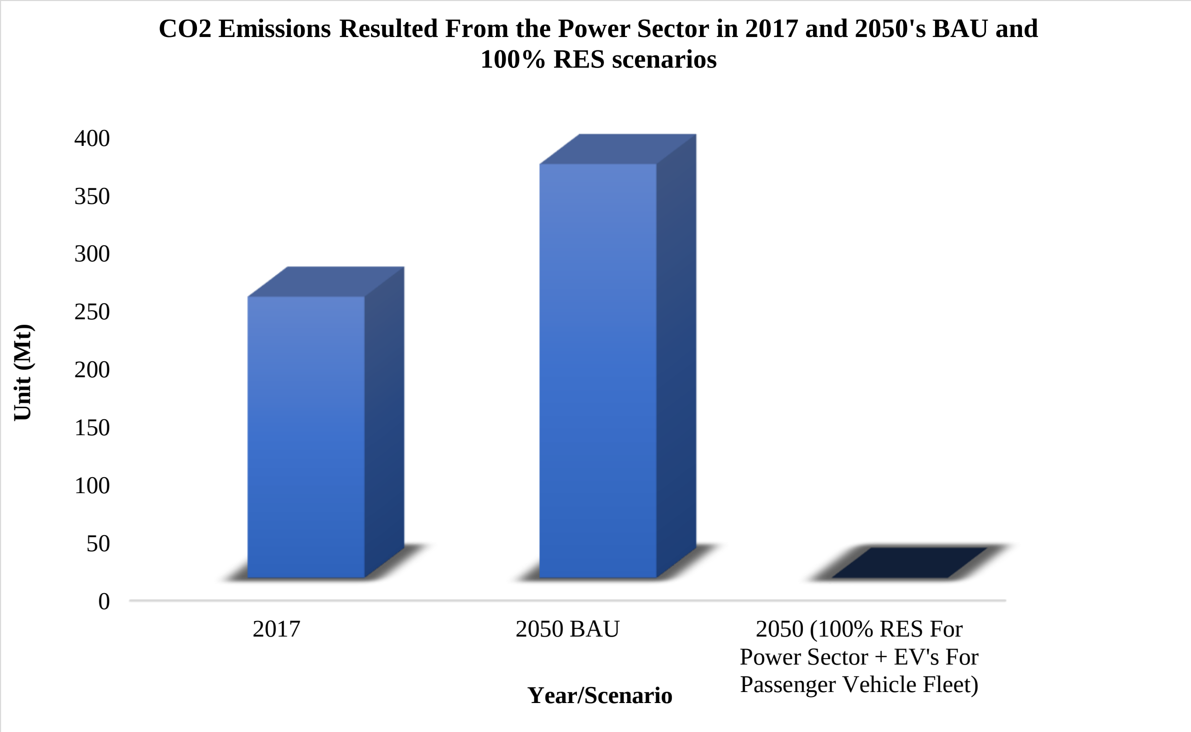

Figure 92 CO2 emissions resulted from the power sector in 2017 and 2050's BAU and 100% RES scenarios [Author: constructed from simulations and IEA].

By 2050, conventional condensing power plants in Saudi Arabia's power sector will have been entirely replaced by RES, achieving a 100% RES electricity supply and eliminating CO2 emissions from the power sector. It is important to note that this study is not a lifecycle analysis; CO2 emissions may still occur from the production, manufacturing, transportation, and transfer of various RES components. The CO2 elimination discussed in this research specifically refers to the reduction in emissions from the direct combustion of fossil fuels, such as when fossil fuels are used as input energy in condensing steam or gas power plants for electricity generation.

Although the Kingdom's power sector will be fully decarbonized by 2050, with passenger ICE vehicles replaced by EVs, this transition does not render the entire energy system emissions-free. Other sources of CO2 emissions will remain, particularly from sectors within the broader transport category, such as light and heavy ICE trucks and airplanes, which were not addressed in this study. Additionally, emissions from the industrial sector, including factories, remain a significant challenge. Future work will need to address these emissions, potentially through the use of synthetic gases produced from RES, such as hydrogen and CO2 hydrogenation.

The figures below compare the Kingdom's energy sectors and CO2 emissions across three scenarios: the 2017 baseline, and two 2050 scenarios. The first 2050 scenario, a business-as-usual (BAU) case, projects CO2 emissions across the Kingdom if no RES solutions are implemented, allowing for the natural growth of all demands as detailed in Table 15 and assuming continued use of conventional power plants at existing efficiency and fuel distributions. The second 2050 scenario integrates 100% RES to meet power demand and utilises surplus power to support passenger vehicle electrification through the RES.

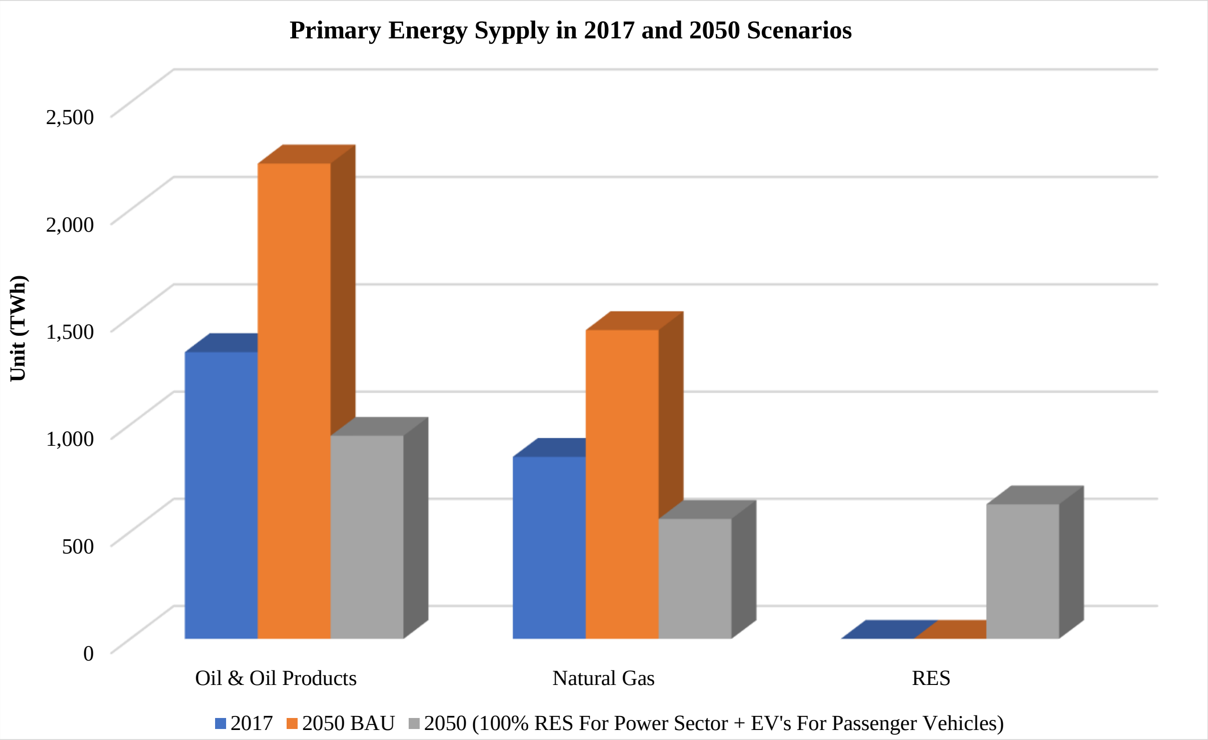

Figure 93 Primary energy supply and CO2 emissions in 2017 & 2050 scenarios [Author: constructed from simulations and IEA].

Figure 93 presents the primary energy supply for the entire Kingdom, covering all sectors, including power, transport, and industry. Despite a considerable increase in energy demand and fuel supply across all categories from 2017 to 2050, a notable decline in fossil fuel consumption was observed. A comparison of the two 2050 scenarios reveals that the incorporation of RES in the second scenario led to a 58% reduction in the consumption of oil and oil products, alongside a 62% decrease in natural gas consumption.

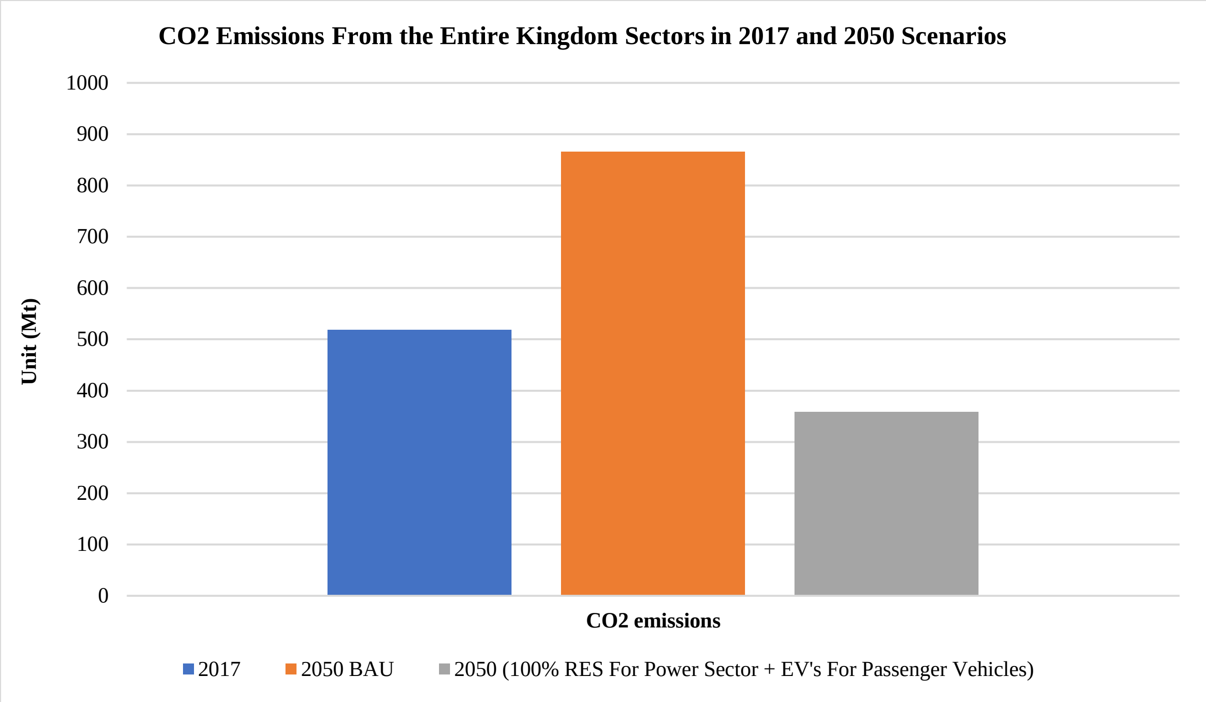

Figure 94 CO2 emissions of the entire Kingdom's sectors in 2017 and 2050 scenarios [Author: constructed from simulations and IEA].

Figure 94 presents CO2 emissions across all sectors in Saudi Arabia for 2017 and the projected 2050 scenarios, covering the power sector, industry, transport, and other unspecified areas. If the Kingdom maintains its current growth trajectory with conventional power plants supplying electricity and ongoing gasoline use for passenger vehicles, CO2 emissions are projected to reach a concerning 865.25 Mt by 2050. However, the solutions outlined in this thesis—including a 100% RES for all sectoral power demands and complete electrification of the passenger vehicle fleet, resulted in a significant CO2 reduction, achieving an overall emissions decrease of 60%.

6.3 Discussion

Saudi Arabia is a global leader in oil production, having one of the world's most extensive oil reserves, estimated to account for roughly one-third of global oil resources. This substantial oil resources, coupled with supportive government policies, has driven a decades-long reliance on fossil fuels across nearly all sectors. Conventional power plants, primarily fuelled by oil, oil products, and natural gas, generate the country's electricity, while energy-intensive desalination facilities, transportation systems, and industrial sectors are almost entirely dependent on oil products. This extensive dependence on fossil fuels has placed Saudi Arabia among the highest greenhouse gas emitters globally.

In the current era, however, the sustainability of this fossil fuel reliance has become increasingly untenable. Escalating levels of CO2 and other greenhouse gases are intensifying global warming, a critical global issue with far-reaching impacts. In response, countries worldwide are taking active measures to address this challenge, including policy interventions, awareness initiatives, international conferences, global agreements, and a strategic shift toward renewable and cleaner energy sources.

As part of these international efforts, Saudi Arabia joined the Paris Agreement during COP 21, committing to a unified objective of limiting global warming to well below 2°C, with aspirations of achieving a 1.5°C target compared to pre-industrial levels. Saudi Arabia's participation implies its recognition of the urgent need for global climate action and its commitment to contributing to a sustainable, low-carbon future.

In addition to global warming, countries are confronted with another critical challenge: the non-renewable nature of fossil fuel resources. These conventional energy sources, despite their abundance in some regions like Saudi Arabia, are finite and will eventually be depleted. Recognizing this limitation, countries worldwide have begun transitioning toward renewable and cleaner energy alternatives. This shift has gained extensive contributions from researchers, scholars, scientists, engineers, government entities, regulators, industry stakeholders, and innovators. Among the foundational steps in this transition are strategic planning and policymaking, which serve as essential building blocks for transforming existing energy systems into more sustainable ones.

The path to RES adoption is complex and demands intensive research, substantial policy development, and long-term planning, often spanning decades, as in the case of targets set for

2050. A critical methodological approach in this process is energy systems modelling, which supports future-oriented planning and policy-making by enabling comprehensive analysis of energy system structures. Energy modelling involves constructing computer-based models of energy systems to facilitate decision-making, policy formulation, and the exploration of future scenarios. These models can be applied to buildings, specific systems, or entire national or regional energy infrastructures. Whole-system modelling, in particular, is vital for understanding the complex interactions among various energy sources, such as electricity, gas, oil, and their derivatives, across sectors like power, transport, industry, desalination and agriculture. This approach allows for a holistic view of future energy supply, management, and consumption at national, regional, and local scales.

By adopting a whole-system perspective, policymakers, regulators, and investors can create a collaborative environment that accelerates innovation, enabling low-carbon technologies to move swiftly from prototype to marketplace. This collaborative approach not only promotes low-carbon economic growth but also allows decision-makers to make informed choices with reduced risk. Consequently, energy modelling is pivotal in developing optimal plans, avoiding costly mistakes, and conserving both energy and financial resources.

With these objectives, this research explores potential future energy scenarios, including the feasibility of a 100% RES for Saudi Arabia, by employing energy modelling approach. Through accurate data collection, validation, and simulations, the study addresses the research questions outlined in Section 1.3, assessing pathways for RES adoption in Saudi Arabia. It investigates various scenarios involving energy mix optimization, RES resource potential, and the technical and economic considerations necessary for the transition.

The primary goal of this research is to analyse the feasibility of achieving a fully renewable power sector by 2050, alongside electrification of the transportation sector, by conducting a comprehensive technical and economic analysis. It provides recommendations for policy development, while also highlighting the limitations and challenges inherent in this transition.

This research contributes to knowledge by constructing a detailed model of Saudi Arabia’s energy system, incorporating demand and supply across all sectors within the Kingdom and accounting for the complex interdependencies among these sectors. This model offers a valuable foundation for evaluating future energy system configurations, supporting planning, analysis, and policy-making processes. Setting 2050 as a target year, this study presents technically and economically viable scenarios that reduce dependence on fossil fuels while meeting anticipated growth in energy demands, paving the way for a sustainable energy future for Saudi Arabia.

The Kingdom of Saudi Arabia has recently begun developing RES projects and progressively integrating these resources into the national grid. These initiatives, however, are relatively new, emerging only within the past few years as part of the strategic objectives outlined in Vision 2030. Prior to this vision, there was limited motivation to explore RES in a country with such a significant reliance on oil. This trend is common among oil-dependent economies like Saudi Arabia, which historically exhibit less urgency in pursuing alternative energy sources. While RES activities have been explored in Saudi Arabia since the 1970s, few studies have comprehensively addressed future national-scale energy planning that considers all energy sectors and examines the complexities of integration between supply and demand across these sectors.

This research addresses this gap by developing a national model that includes the power from all energy sectors in addition to transport sector electrification and other sectors fuel demands, examining the intricate interconnections among them, and analysing the dynamic relationships on both the supply and demand sides. To the best of our knowledge, there is no comprehensive research modelling Saudi Arabia’s energy system holistically for long-term planning and policy-making, including considerations for sectoral interdependencies, power from all sectors, transport sector electrification from RES surplus energy, RES intermittency, storage, and the limitations and recommendations for large-scale RES integration from a technical, economic and environmental perspectives for a target year in 2050. Additionally, this model is designed to be adaptable for other researchers interested in conducting their own analyses, studies, or modifications.

Furthermore, the investigation of Saudi Arabia's energy system is particularly relevant because such studies remain few in the Middle East, where future energy plans are less common compared to regions like Europe and the UK. In contrast, nearly every European nation has detailed energy transition plans with specific targets for 2030 or 2050. This research thus contributes valuable insights to an area with limited regional focus, advancing the understanding of RES planning under the unique conditions of Saudi Arabia.

In this research, an extensive review of Saudi Arabia's energy system was conducted as a foundational step. This review analysed the energy system by supply and demand sectors, focusing on the reference year 2017. The review was essential for two primary reasons. First, there was a limited clarity surrounding the structure and details of Saudi Arabia’s energy system. In several areas, data was either unavailable, classified, or inconsistent. Qualitative and quantitative information was sparse, and inconsistencies were evident between various sources, such as significant differences between data from WERA and IEA in some parts. As such, data needed to be accurately gathered and validated from multiple sources to ensure accuracy. In certain instances, essential figures and tables had to be constructed from scratch, synthesizing data from various resources to create a solid and reliable dataset. A comprehensive review was necessary to consolidate accurate information, identify gaps, and address missing data.

The second reason for this review was to establish a primary input source for the energy model. The year 2017 was chosen as the reference due to the availability of the most complete dataset at the start of this research. Where feasible, additional data up to 2024 was also incorporated. The next phase involved building the energy system model for Saudi Arabia using the EnergyPLAN and SAM modelling tools. Through scenario analysis, the model examined various assumptions, policies, and the technical and economic feasibility of different energy pathways. Once developed, the model undertook validation against actual data from sources such as the IEA, the Saudi Ministry of Energy, WERA (formerly ECRA), and the Saudi General Authority of Statistics. This validation confirmed that the model accurately represents the energy system of Saudi Arabia.

The third phase of this research involved simulating, analysing, and assessing various RES scenarios for Saudi Arabia’s future. Each scenario was evaluated in terms of technical and economic analysis, with a comprehensive discussion on the recommendations, limitations, and the potential integration challenges across sectors such as power, oil, gas, transport, and industry. The potential of RES and recommendations for future work were also discussed.

The final phase of this research consisted of an overarching discussion, offering a clear overview of the thesis's purpose, methodology, and findings. Additionally, the limitations of this research were outlined, along with recommendations for future work to guide subsequent studies and developments in Saudi Arabia’s RES landscape.

Furthermore, in the third phase of this research, the model was initially developed for 2017 as the reference year, after which the future energy system for 2050 was simulated, analysed, and discussed from both technical and economic perspectives. The primary objective for achieving a 100% electricity supply to meet Saudi Arabia's demand in 2050 was to identify the optimal RES solution. The methodology aimed at finding the most effective RES configuration by addressing two key objectives. The first objective was to ensure that the system could supply 100% of the grid's demand using RES, operating continuously day and night throughout the year, without any power losses, shortages or imports in this closed system. Once this was achieved, the second objective focused on identifying the least-cost solution that would still satisfy the first objective. The analysis began by evaluating each RES technology independently, without a storage.

The **first solution** involved utilizing PV as the primary RES to meet the grid demand as a standalone system. However, this solution failed to achieve the primary objective, as it was unable to supply the total grid demand throughout the entire year. This limitation arose from the obvious fact that PV power plants are unable to generate electricity at night due to the absence of sunlight.

The **second solution** involved analysing the impact of adding battery storage to the PV power plant for Saudi Arabia in 2050. Simulations in EnergyPLAN were conducted by initially increasing the PV capacity to a level sufficient to meet daytime grid demand while assuming zero battery storage. Nighttime demand was then identified and the hourly generation and demand patterns analysed on hourly basis for the entire year. The battery storage was then progressively increased in increments until power shortages were eliminated throughout the year, thereby identifying the minimum storage required to supply the nighttime demands and the low RES generation times while preventing any power shortages through the entire year. Once the minimum battery capacity was determined, the PV capacity was gradually decreased to the lowest level that could still meet demand, charge the battery storage with the minimum capacity. The process continued and the final design parameters were established.

The reduction of PV capacity, in this case, was aimed at minimizing costs until the minimum required PV capacity was reached, at which point any further reduction would lead to a shortage. The shortage occurred when the PV capacity was reduced further, as it coincided with the lowest power generation from the PV system at 7:00 AM (hour 5743), when solar radiation had just begun to increase in the early morning hours. Thus, a shortage occurred because, with the reduction of PV capacity, additional storage was required at a point when it was already fully utilized. Increasing storage would allow for more charge energy to be supplied from surplus generation, thereby providing more discharge energy to address the shortage. However, the minimum required battery storage had already been determined, and further increasing storage to supply the shortage was not beneficial, as the cost of additional storage far exceeded that of the PV system. The hourly simulation results were then analysed and discussed, as presented in the earlier sections.

The simulations work by analysing the hourly inputs of the RES technologies with the demand, storage, RES power plant capacities, efficiencies, conventional power plants, hydrogen power plants, electrolysers, and all other parameters hour by hour for the entire year.

For example, after inputting the annual PV generation and hourly demand and supply patterns into the tool, these are analysed and calculated on an hourly basis. This analysis identifies power generation, any shortages between demand and supply, surpluses, and the battery demand required (if included) to prevent shortages. Additionally, it determines the hourly charge needed to adequately fill the battery for subsequent discharge during periods when shortages are identified, based on the design capacities and RES generation patterns in comparison to demand.

Once the simulations are completed, key metrics such as any shortages, surpluses, total energy generated, peak and minimum generation levels, CO2 emissions (if fossil fuels are present), and detailed hourly analysis results become available. These outputs include shortage locations and magnitudes, stability concerns, CEEP, grid supply dynamics, generation and demand patterns, and resource demands for natural gas, hydrogen, synthetic gas, oil, and oil products (if applicable). Additionally, all variable, fixed, and annual costs, alongside other relevant parameters, are provided for each hour throughout the year.

The user must then examine all 8,784 hourly values in the system to identify any shortages, understand their causes, and determine subsequent actions within the methodological framework. For example, if PV capacity was adjusted to a specific value during simulation, this may result in a quantified power shortage (in TWh for the year) peaking at certain times, seasons, hours, or days. The user would then analyse the entire system over 8,785 hours to determine when and why these shortages occurred. For example, a shortage could arise from factors such as lower-than-expected PV generation due to cloud cover, even if the installed capacity exceeds peak demand. Additionally, the shortage could also arise from many other factors which require deep analysis, specially when the system is complex including many components and parameters such as PV, wind, battery, natural gas and hydrogen conventional power plants, electrolysers, hydrogen storage, transport, industry, fuels and grid balance. The entire system model must be analysed and studied carefully to assure the dynamics and relationship between the entire system components and parameters.

The user must decide the optimal solution within the established framework, aiming to meet objectives like cost minimization and full reliable power supply or shortage prevention. For instance, the user may incrementally increase PV capacity, repeating simulations and reviewing hourly outcomes until identifying the minimum capacity that fulfils demand without shortages. This approach allows for comparing solutions, such as maintaining PV capacity while adding battery storage, hydro, or other options like wind power if it has higher potential during critical demand periods. The choice of solution will depend on generation and demand patterns as well as associated costs across different hours and the dynamics between all complex system components.

The PV+Battery system was then designed and justified as shown earlier, with all its parameters shown in Table 18 and the tables and figures in Section 4.3.1. The **third solution** involved exploring the use of a standalone wind power plant for Saudi Arabia in 2050, which successfully achieved the first goal without the need for storage. However, this solution required an enormous capacity, resulting in high costs, making it the least economically viable option when compared to other solutions. Furthermore, it was practically unfeasible. While theoretically, standalone wind turbines could generate power continuously, day and night, due to their large capacity, the impracticality stemmed from the unpredictability and unreliability of using standalone RES for grid power supply without a storage system. Additionally, the substantial wind resources required for such a setup could not be fully utilized due to the limited excellent wind resources geographical area available in Saudi Arabia to accommodate the enormous wind turbines.

The fourth solution involved integrating battery storage with wind turbines to address the limitations identified in the third solution. First, the reasons behind the substantial capacity requirements in the third solution were analysed. These issues resulted from the generation pattern of wind power and its alignment with demand, as explained in detail in Section 4.3.2. Despite high installed capacity, wind power generation was significantly lower during certain hours due to reduced wind speeds. To cover these small, limited shortage periods, the capacity of the wind power plant needed to be increased substantially, leading to inefficiency.

To address these challenges, battery storage was incorporated into the solution. The wind power capacity was progressively reduced in 50,000 MW increments, while the battery storage capacity was increased to the minimum level required to eliminate shortages resulting from the reduction in wind power generation. Following each adjustment, simulations were performed, and the 8,784 hourly values for the entire year were analysed. Both technical and economic metrics were recalculated to ensure optimal system performance. The analysis proceeded until further cost reductions stopped.

The findings revealed that reducing wind power capacity and compensating for shortages using battery storage significantly lowered costs. This is detailed in Section 4.3.2, which demonstrates that the addition of battery storage effectively addressed small, limited shortage periods occurring during times of low wind generation. Designing the storage system with the minimum required capacity to handle these critical periods proved far more economical than relying solely on wind power. Utilizing wind power alone theoretically would have required a substantial increase in wind capacity to address the lowest points of the wind generation curve, leading to excessive resource use and higher surplus generation during other periods.

In summary, the Wind + Battery system was designed and evaluated in Section 4.3.2.2. The integration of battery storage demonstrated greater economic efficiency than expanding wind turbine resources to address small, limited shortage periods.

Despite the fact that the Wind+Battery system was the optimal solution on paper compared to other systems in terms of technical and economic results. However, the main challenge with this system was again the impracticability on the ground. This is due to the limited area and insufficient land mass available at the selected wind location in NEOM city, which, despite being considered the best in the Kingdom, will be occupied by various other projects, including green hydrogen generation, RES, as well as commercial and residential developments. The other optimal wind resource locations are limited in the Kingdom which necessitated the need for wind turbines resources reduction with the addition of another reliable on the ground technology such as PV. Therefore, the fifth solution was introduced.

The fifth solution included the investigation of the PV+Wind as a standalone system without storage as the first step, which was investigated and analysed in detail in section 4.3.3.1. The system performed well on paper and could supply the grid demand entirely, day and night. However, the system has resulted in significantly higher costs than those of other previous systems due to the PV and wind overdesign. This overdesign occurred because of the absence of battery storage, as in this case, wind and PV resources had to be increased to a higher level to meet the grid demand in the areas where they perform worse, i.e. clouds in the PV and less wind speeds in the wind turbines. As previously discussed, when comparing the power generation curve with the demand, it becomes evident that there are instances when both PV and wind generation are insufficient, leading to power shortages despite the higher capacity of RES. This issue arises because these shortages occur during periods of low generation (at the bottoms of the RES generation curve), necessitating an upward shift of the entire generation curve (by increasing the overall capacity and resources of the power plants) to address small, temporary shortages, an approach that proved to be both ineffective and inefficient. Furthermore, this system faces reliability challenges due to the inherent intermittency and unpredictability of relying solely on RES without storage. As a result, the sixth solution was introduced.

The sixth solution was then investigated, which involved the use of PV+Wind+Battery. This system was an optimisation of the theoretically best solution system, the Wind+Battery system. This optimisation process was important for two main reasons: first, as mentioned earlier, the Wind+Battery solution could not be applied practically on the ground. Although theoretically, it was the winner so far. This is due to the limited available areas with high wind power potential, such as in NEOM city, where the power plant is located. NEOM city and some areas of the West Coast have the best wind power potential. The issue stemmed from the limited available area; the designed Wind + Battery system was based on the high wind potential resources in NEOM. This solution required the installation of 262 GW of wind turbines, in addition to the necessary battery storage system. Each wind turbine has a capacity of 3.2 MW, requiring a total of 81,875 turbines. However, this number exceeds the available area with favourable wind speeds in NEOM city, making it unfeasible to accommodate all the turbines within the optimal locations. Other locations within the Kingdom did not provide sufficient wind potential to meet the entire national demand. As previously highlighted in the simulations and various studies, wind power plants in these areas had capacity factors ranging between 22% and 31%, which are significantly lower than the capacity factor achievable in NEOM city. Conversely, PV systems benefit from a vast expanse of available land across the Kingdom, as nearly the entire region holds substantial PV potential, with the northern part offering the highest efficiency. If the PV systems are situated in the northern region, as proposed in this project, the extensive unoccupied land can easily accommodate all the required PV panels along with the associated plant infrastructure. Additionally, PV is more cost-effective than wind for covering daytime power demand, as demonstrated in earlier analyses.

The initial Wind+Battery power plant was simulated and optimized by progressively reducing the wind power capacity by 26,004 MW. To address the resulting power shortage, PV capacity was incrementally increased by the minimum required capacity. Each simulation required a detailed analysis of the system's 8,784 hourly values, along with a review of technical and economic metrics. Costs decreased with each step as wind power capacity was reduced and PV capacity increased, while storage remained constant, up to a certain threshold. Beyond this point, further adjustments led to higher costs and persistent power shortages.

This cost increase beyond the lowest cost point was linked to the PV-to-wind power ratio, which is influenced by generation patterns and demand. At the design point of the PV+Wind+Battery system (wind: 132,109 MW, PV: 195,405 MW, battery: 639.6 GWh), as shown in Figure 87, costs decreased to the left side of the design point when wind capacity was reduced, and PV capacity increased. However, on the right side of the design, costs began to rise, as reducing wind capacity further required disproportionately larger PV capacity to compensate for the shortages, as illustrated in Figure 95.

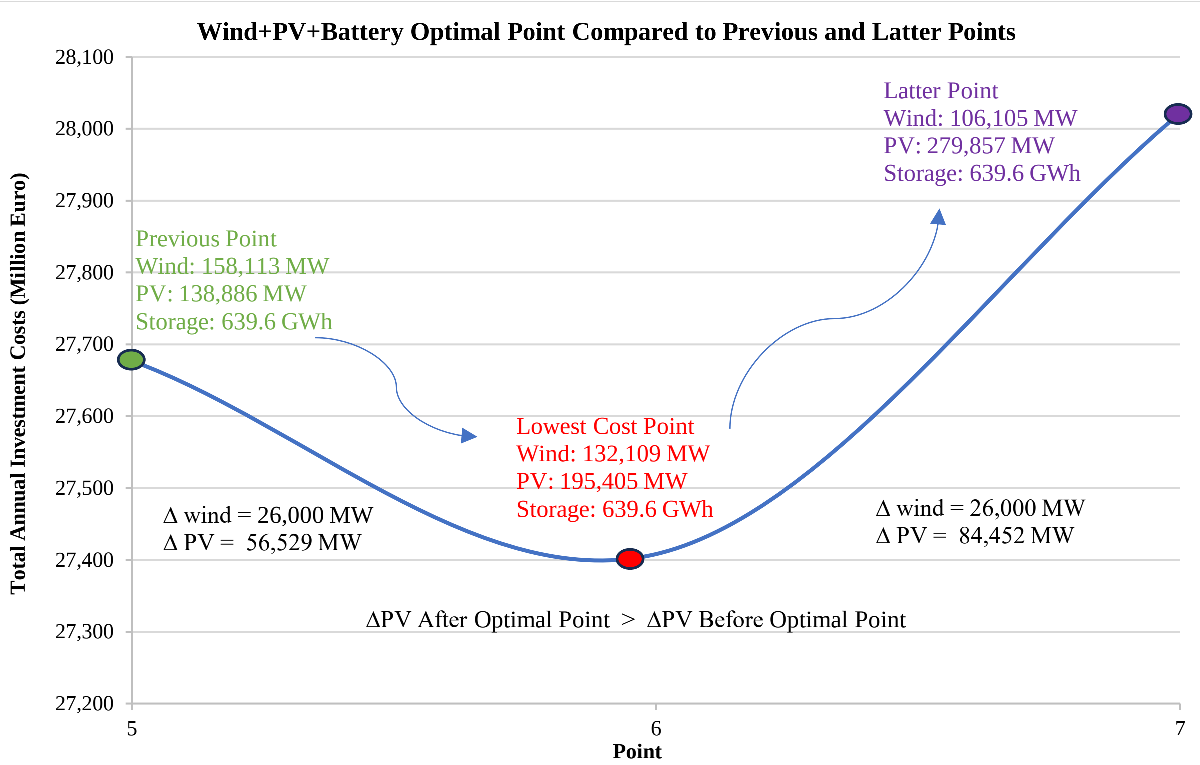

Figure 95 PV and wind power plants capacities before and after the lowest cost point with the difference.

Figure 95 demonstrates that the required increase in PV capacity (delta PV) becomes greater after the lowest cost point for the same reduction in wind capacity (delta wind). Conversely, before reaching the lowest cost point, the delta PV is smaller for the same delta wind. This indicates that the cost-benefit has reached its limit. As previously explained, the increase in delta PV after the lowest cost point is due to the differing generation patterns of PV and wind. If a shortage coincides with the PV system's lowest generation period, a significantly larger PV capacity would be needed to address the shortage. Therefore, reducing wind capacity and replacing it with PV in such cases becomes inefficient, as it not only fails to provide economic benefits but actually worsens the overall cost-effectiveness.

Further reductions in wind capacity, when combined with increases in PV capacity, would still result in substantial shortages, even if the PV capacity was expanded to 900 GW. This outcome arises from the fact that a reduction in wind capacity would impact the system's ability to meet nighttime demand, a challenge that cannot be resolved solely by increasing PV capacity, particularly when the storage capacity remains constant. Thus, the optimal design point for the PV+Wind+Battery system was determined, as it effectively fulfils both primary objectives. This RES solution demonstrated the lowest costs across all economic parameters, including O&M expenses, annual investment costs, total annual costs, and LCOE. Among all evaluated systems, the PV+Wind+Battery configuration achieved the best results in fulfilling both goals.

As illustrated in Figure 77, which presents the final optimal system, the wind and battery supplies (indicated by the orange and yellow zones) highlight the potential to reduce battery capacity by offsetting it with an increase in wind power generation. During specific hours throughout the year, the demand is fully met by wind and battery sources. As a result, an additional optimization via simulations was implemented on the final system design, reducing the storage capacity to 400 GWh and increasing the minimum wind capacity to 150,396 MW. This change led to a 7.6% cost reduction. The final optimized RES configuration for Saudi Arabia in 2050 is detailed in Tables 18, 24, 40 and 47 with an in-depth hourly analysis presented in Figure 78.

Although the optimal 100% RES for Saudi Arabia effectively meets both technical and economic objectives, these results remain theoretical at present. If this system is implemented in a real-world context, its performance may differ from the theoretical outcomes due to several factors, as discussed below.

1. This system was designed based on the forecasted hourly electricity demand for 2050, using historical demand trends and the assumptions such as those detailed in Table 13. However, the actual demand pattern may deviate from the forecast, potentially increasing or decreasing due to global or local events, regulations, and policy changes. Therefore, the system must include a reliable backup to accommodate these uncertainties.
2. The system design relies on historical weather data for solar and wind resources. For PV, the TMY file was used, representing averaged historical weather data over multiple years, while

wind data was based on average wind speeds from the past six years. By 2050, however, actual weather conditions may diverge from historical patterns due to factors such as global events, policy shifts, climate change, unusual events, and geopolitical issues. Consequently, the system must incorporate a reliable backup to address potential variations in weather conditions.

3. The unpredictability factor of 100% RES supply.
4. Saudi Arabia currently lacks actual data on large-scale RES generation, as its engagement in this field is recent. Large-scale projects, such as the 400 MW wind farm in Dumat Al Jandal, were only connected to the grid recently in the last few years, and public data on their performance is not yet available. Therefore, all data used in this project are based on simulations of RES generation. While simulation data are accurate and validated by numerous research studies and projects, real-world data remains preferable for the most reliable assessment.

In addition, there are limitations to the 100% RES supply in this thesis, which are:

5. The 100% RES system for Saudi Arabia was designed with inherent oversizing. For example, storage capacity was sized to cover the maximum shortage periods when PV and wind generation are insufficient. However, the full 400 GWh storage capacity may only be utilised for a few days or hours throughout the year to address worst-case scenarios, leading to additional costs. A practical solution to mitigate these costs could be integrating a small share of natural gas power plants to replace the excess battery storage capacity. As previously shown, reducing battery storage and replacing it with natural gas plants could significantly improve cost efficiency. However, this study specifically aims for a system that eliminates CO2 emissions, thus excluding natural gas power plants from the 2050 model due to their associated CO2 emissions.
6. This point is related to the previous point. Suppose that the oversized battery storage was replaced with a hydrogen power plant instead of a natural gas plant (as discussed previously), it would avoid CO2 emissions and could reliably supply the remaining power. However, this option has been shown to be more costly than battery storage. Even with a higher capacity, battery storage requires lower costs than hydrogen power, primarily due to the higher costs associated with hydrogen power plants compared to natural gas plants, including retrofitting expenses. Additionally, the costs for electrolysers and hydrogen storage add further financial burdens to hydrogen power generation. Consequently, for Saudi Arabia's 2050 energy model, battery storage remains a more cost-effective solution than hydrogen power plants and a more environmentally cleaner that natural gas power plants.

7. Surplus energy remains substantial, as 100% RES for Saudi Arabia consistently generate excess energy beyond grid and storage needs. This surplus is undesirable for the grid due to the instability it can cause. In this study, any energy surplus beyond grid and storage demand was controlled and stopped in the simulations. For real-world application, however, control systems would be needed to continuously monitor and analyse signals from each RES source against demand, adjusting production during surplus periods. For instance, in PV systems, this could involve controlling the inverters to reduce the DC voltage reference to the PV panels, thereby curtailing excess generation.

   Therefore, due to the reasons and limitations outlined above, this study's optimal 100% RES was further optimised by incorporating a green hydrogen CCGT power plant, as shown in Section 4.4. The green hydrogen power plant serves as a reliable backup to accommodate potential future fluctuations in weather, demand, or RES generation, ensuring grid stability during any power shortages in case of unusual events. Additionally, it reduces surplus energy generated by the RES system, as hydrogen was produced entirely from excess energy using electrolysers. A dedicated green hydrogen backup system was therefore designed to operate in response to hourly power shortages throughout the year. This backup system operates solely on surplus energy from the RES, producing green hydrogen that is subsequently utilized in a combined cycle power plant, as detailed in previous sections.

   Prior to utilizing the green hydrogen backup power plant as a backup system for the 100% RES, it was tested as a power supply contributor with a reduced RES capacity in an effort to minimize the overdesign of the 100% RES and thus reduce associated costs, as outlined in point 6 and in section 5.6.3. In this analysis, 50 GWh of battery storage from the 100% RES was removed and replaced with both green hydrogen and natural gas power plants separately. In the scenario with the green hydrogen power plant, the total system costs for the combined RES with the green hydrogen plant were higher than those of the original 100% RES solution without the green hydrogen power plant. Conversely, in the second scenario involving the natural gas power plant, the total system costs were significantly reduced compared to the original 100% RES. The increase in costs with the green hydrogen power plant was primarily due to higher retrofitting, electrolyser, and hydrogen storage costs, making it less cost-effective as a power supply contributor when compared to the battery, despite its high capacity. In the second scenario, while the combination of RES and natural gas power plant resulted in lower costs, the natural gas plant generated CO2 emissions, which contradicted the primary objective of this thesis to fully decarbonize the power from all sectors and transport sector by 2050.

To further advance the decarbonization of the Kingdom's energy sectors, the transportation sector's passenger vehicle fleet was comprehensively electrified by leveraging surplus energy produced by RES. The utilization of surplus RES energy played a pivotal role in supporting both the backup energy system and the transportation sector, thereby delivering a dual benefit. First, using this surplus energy in the backup and transport applications reduces the amount of surplus energy generated by the RES, thereby mitigating potential grid instability issues that might occur in 2050. The second benefit is a significant reduction in CO2 emissions, both from the backup power generation and the transport sector. This double benefit means that while the transport sector helps manage surplus energy from the RES, the RES aids the transport sector in decarbonization, given the higher efficiency of electric vehicles compared to internal combustion engines. Electrifying the passenger vehicle fleet resulted in reduced total energy consumption by 88% and complete elimination of CO2 emissions from passenger ICE vehicles fleet by 2050.

In the economic analysis in this thesis, assumptions regarding the feasibility of each system design were assessed by calculating the total annual costs under different designs and simulation strategies. To perform these calculations, several key inputs were required, including total investment costs, O&M costs, systems lifetimes, and the applicable interest rate. The model then evaluated the socioeconomic impacts of energy production by breaking down the costs into specific categories: 1) fuel costs, 2) variable O&M, 3) investment costs, 4) fixed O&M costs, 5) electricity exchange costs and benefits, 6) potential CO2 emissions payments, and 7) LCOE. The interest rate plays a crucial role in calculating the annualized costs for each system design, allowing for a clear comparison between scenarios. By incorporating these elements, the model offered a comprehensive economic evaluation of each RES configuration, considering both direct operational expenses and broader socioeconomic factors. This approach ensured that the financial viability of each scenario is fully understood in the context of long-term energy planning.

Interest rate was assumed at 3% for all the scenarios based on low interest rates of large-scale renewable energy projects and initiatives in the GCC region, including Saudi Arabia, in the IRENA report [241]. IRENA report shows the favourable financing condition in Saudi Arabia, the Gulf region, which enables low prices for large-scale RES projects. These conditions include low interest rates, extended loan duration and high debt-to-equity ratios. Region’s loans for large-scale RES projects typically tenure (over 20 years) with low interest rates (120-200) basis points over LIBOR.

O&M cost data for PV and wind systems in Saudi Arabia for the year 2050 are currently unavailable, as large-scale RES projects are still in the development phase and not yet fully operational. Saudi Arabia has only recently begun initiating large-scale RES projects over the past two years, and as a result, no comprehensive technical or economic data are available at this stage. Consequently, for this research, these costs were estimated based on forecasted RES costs for 2050 provided by Aalborg University, as detailed in the cost datasheet [242]. These assumptions allow for a more informed analysis of future scenarios, compensating for the current lack of localized cost data while aligning with international projections for RES costs.

In terms of calculating the LCOE, discount rate assumption was required. For the discount rate, the value of 7% was chosen for Saudi Arabia for its RES in 2050. The recommendation of a 7% discount rate for Saudi Arabia's RES projects in 2050 is supported by insights from global energy institutions such as the IRENA and IEA, as well as research in the field of RES finance. These organizations analyse global RES financing, and they provide guidelines on appropriate discount rates for various regions, considering the local economic conditions, risk factors, and government policies. IRENA, in its Renewable Power Generation Costs and Global Renewables Outlook reports, indicates that discount rates in the Middle East typically range between 5% and 10% for RES projects. This range reflects the cost of capital, project risk, and the level of government backing. For Saudi Arabia, given its extensive RES plans under Vision 2030 and the Saudi Green Initiative, a 7% discount rate is optimal as it represents a moderate risk profile, where strong government policies and investments reduce uncertainties, but some economic and technical risks still exist. Reports from the IEA, such as the World Energy Investment Outlook, also support the use of discount rates in the 6-8% range for countries like Saudi Arabia, which benefit from robust government support and a stable economy but still face challenges typical of large-scale RES transitions. Saudi Arabia's energy transition is expected to be well advanced by 2050, making it more financially stable, yet the capital markets may still factor in moderate risk for RES projects. Studies by the World Bank and the European Investment Bank further corroborate this by highlighting that Middle Eastern countries with strong governmental energy policies, such as Saudi Arabia, benefit from moderate-risk environments where financing costs can be reflected by a 7% discount rate. As Saudi Arabia's RES sector matures and attracts foreign investment, the cost of capital is expected to stabilize, making 7% an appropriate figure based on both financial and policy projections for 2050 [243-247].

In terms of calculating the LCOE, the lifetime of all RES solutions was assumed at 30 years. The choice of a 30-year project lifetime for RES solutions in Saudi Arabia in 2050, despite the differing lifetimes of individual components (such as PV panels with a 40-year lifetime, battery systems with a 15-year lifetime, and wind turbines with a 30-year lifetime), can be explained by several key technical, financial, and operational factors. These factors align with best practices in energy system design and economic optimization, as backed by high-quality research papers and recommendations from reputable energy institutions.

1. Technical Alignment with the Shortest-Lived Major Component

One of the key reasons for adopting a 30-year project lifetime is the desire to align the project with the operational lifespan of the wind turbines, which typically last 30 years. Wind turbines, a significant part of RES in Saudi Arabia, face mechanical degradation, wear and tear, and increased maintenance needs after 30 years, which can lead to significant downtime or expensive overhauls. Research from IRENA [248] indicates that after 30 years, the economic viability of wind turbines diminishes due to increased maintenance costs and declining performance. While PV panels can technically last 40 years, wind turbines often dictate the overall project lifetime in hybrid systems involving both wind and PV. Designing a project around the 30-year operational life of the wind turbines ensures economic balance and minimizes the need for costly replacements beyond that point.

2. Economic and Financial Optimization

A 30-year project lifetime is often chosen because it optimizes the LCOE by balancing the economic lives of different components, including battery systems, which typically require replacement every 15 years. Extending the project to 40 years, just to match the lifetime of PV panels, would require replacing the batteries twice (at year 15 and again at year 30), significantly increasing costs. NREL's research [249] on battery energy storage systems shows that frequent battery replacements introduce both financial risks and operational complexity. By selecting a 30-year project lifetime, the number of battery replacements is reduced to one, minimizing LCOE and capital expenditure. This is important in Saudi Arabia, where future large-scale RES projects are focused on cost-competitiveness as they aim to displace conventional energy sources.

3. Degradation of PV Performance

While PV panels may have a technical lifespan of 40 years, their performance degrades over time, typically at a rate of 0.5% to 0.8% per year [250]. By year 30, the performance of PV systems may have degraded by up to 20%, reducing the energy output and financial returns in the final decade of operation (years 30 to 40). This degradation means that the economic value of extending the project for an additional 10 years may not justify the associated costs of battery replacements and other operational expenses. PhD research conducted at Loughborough University [251] demonstrated that a 30-year project lifetime is often economically optimal for hybrid systems (PV + Battery), as the cost of maintaining the PV system in the last 10 years is outweighed by the declining performance and increased operational complexity.

4. Simplifying Financial Management and Risk Reduction

In large-scale RES projects, financial predictability is critical for securing long-term financing and attracting investors. A 30-year project horizon provides a clear, well-defined timeframe for investors and developers, aligning with the lifetime of power purchase agreements (PPAs) and other contractual obligations. Extending the project to 40 years complicates financial modelling because it introduces additional uncertainty in cash flows due to battery replacements and PV performance degradation. In its Operational Guidelines for RES [252], IRENA recommends setting the project lifetime to the shortest-lived major component (often wind or battery systems), as this simplifies financing, operations, and decommissioning plans. Investors and financiers prefer projects where the operational risks and maintenance schedules are aligned over a shorter and predictable timeframe.

5. Practicality of Battery Replacements

In a hybrid system, the battery storage typically lasts only 15 years, requiring at least one replacement within the 30-year project lifetime. However, if the project lifetime was extended to 40 years, the batteries would need to be replaced twice (at years 15 and 30). This introduces significant costs, as battery replacement is expensive, and the technology may evolve rapidly, making it difficult to predict future battery costs. Research from NREL [249] suggests that the optimal project length for systems incorporating battery storage is aligned with the second battery replacement cycle (i.e., 30 years), after which the financial returns diminish due to the high cost of the second battery replacement.

6. Industry Best Practices and Standards

Several high-level energy institutions and PhD research papers recommend aligning the project lifetime with the 30-year wind turbine lifespan for hybrid systems in which wind power is a significant component. Extending the project lifetime beyond 30 years introduces operational and financial complexity, particularly due to the need for multiple battery replacements and PV degradation. For example: IRENA [248] suggests that hybrid RES projects involving wind and storage should consider the wind turbine's operational life as the guiding factor when determining the overall project life. NREL and Fraunhofer ISE both recommend a 30-year project lifetime for similar hybrid energy systems due to the technical limitations of batteries and the degradation of PV systems [249][250].

The cost data presented in this study are projections for 2050, derived from historical and current data on RES projects. These projections are based on several key factors, including the costs of existing power plants, historical cost trends, and expected growth patterns. The data encompass future investment costs for PV and wind power plants, as well as projected operation and maintenance costs and estimated system lifetimes. The cost datasheet used in this analysis was developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. This comprehensive database compiles information from a variety of reliable sources, providing a robust foundation for the cost assumptions used in the 2050 scenarios.

The forecasted costs for lithium-ion battery storage in 2050 were sourced from the "Cost Projections for Utility-Scale Battery Storage: 2023 Update" report by NREL [150] and were calculated using Equation 6. O&M cost for the battery systems was estimated based on the performance and costs of current large-scale lithium-ion battery systems used in RES projects. Typically, the fixed O&M costs for these systems range from 1% to 3% of the initial capital investment per year [231][232].

Accurate estimation of O&M factors for PV, wind, and lithium-ion battery storage is critical in calculating the future total annual investment costs of the RES. These assumptions provide a foundation for assessing the long-term financial viability of large-scale RES projects, ensuring that the cost models reflect both current technology trends and future projections for energy storage systems.

Earlier sections in Chapter 5 began with the economic analysis of the 2017 reference year model, which involved the current conventional steam power plants, and then proceeded to evaluate the 2050 RES scenarios. These scenarios were assessed individually, covering configurations such as PV, PV+Battery, Wind, Wind+Battery, PV+Wind, PV+Wind+Battery, and an optimized PV+Wind+Battery system. The final RES for the Kingdom was then evaluated by integrating the technical data from Chapter 4 with the economic analysis from Chapter 5. The optimal system, which balances both technical performance and economic efficiency, was determined and presented in Chapter 6. This comprehensive approach ensured that the selected energy system meets the dual criteria of technical reliability and cost-effectiveness for Saudi Arabia's energy future.

In terms of the RES technology selection, CSP RES was not considered and out of this study's scope for several reasons. One of the most important reasons is CSP’s less technological maturity than PV worldwide and in Saudi Arabia. While there have been notable advancements in CSP technology in recent years, it remains comparatively less developed than solar PV or wind power. Consequently, there may be a perception of elevated risks associated with CSP, resulting in slower rates of adoption and constrained investment. In addition to the first reason, is the substantial spread of PV over CSP globally. It is one of the fastest-growing RES technologies and plays an increasingly important role in the global energy transformation. By the end of 2020, the global installed capacity of PV systems had reached 710 GW, significantly surpassing the global installed capacity of CSP, which was nearing 7 GW. Approximately 125 GW of new solar PV capacity was added in 2020, the largest capacity addition of any RES [134]. In 2022, with the latest IREAN data, the total installed PV capacity was 1,055 GW compared to 6.6 GW for CSP worldwide [134].

In terms of investments and costs, CSP systems are usually more costly to build and operate compared to other RES options like PV. This is because CSP setups require more intricate designs, specialised parts, and additional systems for storing heat, all of which drive up the initial expenses. As a result, many projects find CSP less attractive financially. PV power plants have lower investment costs than CSP power plants, which has caught the attention of investors. Especially the massive reduction of PV prices in the last decade, which dropped by 82% from 2010 to 2019, compared to a drop of 47% for CSP in the same period. The vast global investment is seen in the global annual financial commitment to RES by IRENA [134], which shows that is 298.21 billion USD is for PV in 2022 (around 60%). This is the highest annual financial commitment to a RES in the entire globe. The second highest annual financial commitment was for wind, with 140.70 billion USD (28%), while for CSP, it did not exceed 9.3 billion USD (2%)

CSP plants, along with their thermofluids and heat transfer fluids, as well as thermal energy storage systems, face a range of technological and economic challenges. Economically, these challenges involve high initial capital expenses, unpredictable pricing, financing difficulties, limited scalability, fluctuating material prices, availability concerns, and ongoing operational costs. On the technological front, issues include the variability of solar resources, grid integration complexities, corrosion risks, thermal stability concerns, and the intricate nature of system setups. These difficulties emphasise the need for continuous innovation and investment in CSP technology to enhance cost-effectiveness and efficiency. Moreover, addressing these challenges is crucial for facilitating large-scale deployment involving technological advancements and economic considerations. Additionally, governmental support and regulatory frameworks are essential to foster the development of concentrated solar power technology and expedite the transition towards a future powered by clean energy sources [136].

The variability of solar resources caused by meteorological conditions, like clouds and dust, can hinder the efficiency of CSP facilities. Similarly, thermal energy storage technologies within CSP plants may suffer from thermal losses and system complexity, posing challenges to their effectiveness. Integrating CSP plants into the grid can be challenging due to their inherent unpredictability, requiring regular maintenance to maintain efficiency. Furthermore, the high construction costs, uncertain electricity prices, and financing difficulties faced by CSP plants, coupled with the lack of economies of scale in the early stages of the industry, contribute to the comparatively higher cost of CSP-generated power when compared to other RES [136][138][139].

In terms of water consumption, numerous CSP technologies utilise steam cycles or alternative heat transfer fluids to produce electricity. These configurations necessitate substantial quantities of water for cooling and steam generation purposes. In arid locales, water scarcity presents a potential constraint to the viability of CSP facilities, as they may encounter competition with essential water demands or difficulties in ensuring sufficient water availability, such as in Saudi Arabia, as shown earlier in section 2.2.4. This poses a serious problem as most CSP plants are set up in hot, dry regions with limited water resources. CSP plants diverge from traditional gas or coal-fired power stations by utilising mirrors to concentrate solar energy and heating water to generate steam, which then powers turbines for electricity production. Following steam utilisation, cooling is necessary to condense it back into water for the cycle to restart. This cooling phase is responsible for most water consumption in CSP plants, involving evaporation and what's known as drift and blow-down losses. Consequently, CSP plants can consume up to 3,500 Liters of water/MWh of electricity generated, in contrast to approximately 1,000 Liters/MWh for contemporary natural gas-fired power plants. Although cooling represents CSP plants' primary water consumption process, it is not the only one. The routine cleaning of concentrator mirrors also necessitates significant water volumes, particularly in arid, dusty regions [140].

For the grid stability, as mentioned in the earlier sections and the scope of this thesis, the system of 100% RES currently requires grid stabilising services, which currently come from conventional fossil fuels power plants and will have to be addressed in the future, e.g. 2050, with non-fossil fuel systems. This paper assumes that in 2050, with continued research, there will be non-fossil fuel systems and controls that can provide grid stability services for 100% RES. However, the future non-fossil fuels grid stabilising systems and controls are out of the scope of this paper.

6.2 Key Contributions

This study's key contributions are, first, it provides a comprehensive and detailed review of the energy sectors across the Kingdom of Saudi Arabia, accompanied by a robust dataset. The objective of this review and dataset is to address the existing gaps and ambiguities in the Saudi energy system data, as highlighted in previous sections. Secondly, the review and dataset serve a dual purpose: they contribute to expanding knowledge and act as critical inputs for building the energy model of Saudi Arabia. This allows the assessment of future scenarios for 2050 from both technical and economic perspectives.

The detailed energy system review is presented in Chapter 2. Furthermore, the dataset has enabled the development of the energy balance block diagram for the Kingdom. This diagram comprehensively covers all sectors and energy resources, including various fuel types and electricity. Figure 2 illustrates this diagram, with a high-resolution version included in the appendix.

Second, significant contribution of this study is the research itself, which addresses a critical gap in existing literature. There is a notable lack of studies focusing on future RES scenarios within a closed system, where no power is imported or exported between countries, specifically for Saudi Arabia including demands from all sectors, fuels, power from all sectors with transport electrification from the 100% RES surplus power. This study uniquely employs computer modelling to analyse the entire power from all sectors alongside the integrated transport sector. Identifying this gap was one of the key motivations for undertaking this thesis.

The third key contribution is the development of an energy computer model for Saudi Arabia's energy system. This model accurately represents the existing energy infrastructure and offers substantial flexibility to evaluate and implement energy policies both presently and for future scenarios, such as those projected for 2050. This model was developed based on the collected, calculated, and analyzed data for the year 2017 as the reference year, which was then validated with actual data from reliable sources such as the IEA, WERA, KAPRSARC, and IRENA. Then, it was utilized to investigate the future pathways of 100% RES in Saudi Arabia in 2050. This model is made accessible for public use, such as via GitHub, enabling researchers and engineers to explore and modify energy policies and conduct various investigations. For instance, users can analyse the effects of transitioning from a 100% RES to a 90% RES supplemented by a 10% natural gas steam power plant. They can also examine scenarios like reducing PV or wind power plants while increasing battery storage based on 2050 demands, evaluating costs, CO_2 emissions, and supply-demand balance, as well as identifying and addressing potential shortages. Additionally, the model can explore the economic feasibility of hydrogen power plants playing a role in battery storage by reducing battery capacity and integrating hydrogen plants with electrolysis and hydrogen storage. It can also be used to compare technologies like hydrogen power plants versus natural gas steam power plants combined with renewables, assessing their cost-effectiveness, technical viability, and impact on CO_2 emissions for Saudi Arabia in 2050. These are just a few examples of the extensive capabilities of the model, which are significantly broader and more adaptable for various analyses and policy simulations. In conclusion, this model can be used to investigate different current and future energy systems for Saudi Arabia with different policies and pathways technically, economically, and environmentally on an hourly, weekly, monthly, and yearly basis.

The final key contribution encompasses the analysis of 100% RES scenarios for Saudi Arabia by 2050, highlighting their advantages and limitations, offering recommendations for future policies, and identifying existing gaps. In addition, the backup hydrogen power plant and transport electrification results, analysis and discussion will help shape and reform the future policies for energy systems in Saudi Arabia in 2050. In addition, the recommendations and the limitations are discussed.

6.3 Limitations of This Study

'' Nothing is perfect, flaws are interesting''. This thesis has a few limitations, discussed below.

- This thesis required making several assumptions, including technical and economic calculations as well as general projections about potential future policies that may impact decision-making. These assumptions were essential due to the unavailability, confidentiality, or lack of access to specific data in the required format for accurate calculations. For instance, the EnergyPLAN model tool does not provide a detailed power plant module to specify individual plants by capacity, fuel type, efficiency, and other technical and economic parameters; instead, it treats all conventional plants as a single aggregate unit. Consequently, power plant data had to be estimated using alternative methods and certain assumptions to align with the energy model tool, as discussed in previous sections.
- Additional assumptions were incorporated regarding future policies, including growth factors, fuel prices, energy efficiency initiatives, and government decisions, acknowledging the inherent unpredictability of these elements. The results presented in this thesis are directly influenced by these assumptions, and any modification to them would yield different outcomes based on the type and degree of variation. However, all assumptions were carefully aligned as closely as possible with realistic expectations, drawing on other reliable research references and high-quality published papers and available data related to each specific assumption.
- The PV and wind power generation data utilized in this study are based on simulations rather than actual operational data from existing systems. Unlike European countries, where extensive real-world data from RES is publicly accessible, Saudi Arabia's large-scale RES projects have only begun to emerge in recent years. Consequently, comprehensive data from these newly developed power plants remain limited and inaccessible. As a result, simulation data was employed to conduct the analysis. SAM uses its simulation data for power generation for PV based on actual weather and location data in the Kingdom. It has shown exceptional accuracy and was validated and used by many researchers. In addition, in [220], wind simulation data have been validated in more than 23 countries and shown

exceptional accuracy compared to accurate historical data. However, actual data of on the ground systems is always preferred. Other data, such as all the demands of Saudi Arabia, are actual data, such as the hourly electrical demand of the entire Kingdom for one year, sourced from different reliable sources.

- The 100% RES system presently relies on grid-stabilizing services provided by conventional fossil fuel power plants, which will need to be replaced by non-fossil fuel systems by 2050. This thesis assumes that, with ongoing research, non-fossil fuel technologies and control systems capable of ensuring grid stability will be available by 2050. However, the exploration of future non-fossil fuel grid-stabilizing systems falls outside the scope of this study.
- Another limitation of this work is that the hourly energy balance model simulations carried out in this paper are for concept scoping in this study and not carried out for more detailed grid models such as PyPSA, etc.

6.4 Future Work

Future work based on this thesis can proceed in several directions. One approach is to replicate the 2050 analysis for a mid-year between now and 2050, such as 2030, as an initial step towards achieving a 100% RES supply. For instance, a similar analysis could be conducted for 2030 with a 50% RES and 50% conventional power supply mix, recognizing the need for a gradual transition from fossil fuels to RES in Saudi Arabia. The transport sector could follow a similar gradual approach, with a partial integration of EVs by 2030 as a foundational step toward full electrification by 2050. This staged transition would provide valuable insights, experience, and policy guidance for 2050.

Another promising path for future work is expanding the scope to include additional sectors beyond power and transport, such as the industrial and desalination sectors. This would explore the feasibility of decarbonizing these sectors through RES, thereby reducing their dependence on fossil fuels. For example, surplus energy from RES, as identified in this thesis, could be utilized to generate synthetic gas as a substitute for natural gas in industrial and desalination applications. While CO2 emissions have been fully eliminated from the power sector and significantly reduced in the transport sector, emissions persist in other fossil-fuel-dependent sectors, as shown in Figure 94.

6.5 Conclusion

Saudi Arabia's significant reliance on fossil fuels, particularly oil and natural gas, has made it one of the world's leading contributors to CO_2 emissions, which reached 491.7 million metric tons in 2018. This thesis set out to explore the pathways towards a 100% RES supply by 2050, addressing both the power from all sectors and the electrification of the transport sector using the surplus power generated from the 100% RES. It identified and addressed three critical gaps: the lack of comprehensive data on Saudi Arabia's energy system, the absence of a validated hourly model, and the need for a detailed study examining 100% RES scenarios for the power from all sectors in the Kingdom with integrated transport sector electrification for a future target year in 2050 with technical, economic and environmental analysis on hourly basis for the entire year.

The research followed a systematic approach, starting with the development of a robust, validated model of Saudi Arabia's energy system in 2017. The model, developed using EnergyPLAN and SAM, provided the basis for evaluating future energy scenarios in 2050. The study meticulously gathered and analysed comprehensive data across all energy sectors, providing a complete picture of the Kingdom's energy system. This detailed data set was used to inform the model and validate its results, ensuring accuracy and reliability.

Through extensive simulation and analysis, the study concluded that the optimal RES solution for Saudi Arabia by 2050 comprises a combination of PV located in the Tabuk region, wind energy in NEOM and west coast areas, and lithium-ion battery storage. Specifically, the system includes 150.39 GW of wind capacity, 195.4 GW of PV capacity, and 400 GWh of battery storage. This configuration was able to meet 100% of Saudi Arabia's energy demand in 2050, ensuring complete energy independence without reliance on external power imports with the lowest costs. Moreover, it generated sufficient surplus power to fully electrify the personal vehicle fleet in the transport sector, contributing to an 88% reduction in energy consumption and eliminating CO_2 emissions from passenger vehicles fleet.

Crucially, this system was able to reduce CO_2 emissions from the entire Kingdom by 60% in 2050 compared to the BAU scenario, demonstrating its significant environmental benefits.

Economically, the total annual costs for this system were calculated at 25,071 million euros, with a LCOE of 18.65 €/MWh, making it the most cost-effective among all the scenarios analysed. In addition, a green hydrogen combined cycle power plant was proposed as a backup system to enhance the reliability of the RES supply. The hydrogen for this plant would be produced entirely from surplus RES through electrolysis, ensuring that the backup system aligns with Saudi Arabia's 2050 RES goals. While conventional natural gas plants could offer cost savings, their CO2 emissions conflict with the objective of complete decarbonization. Hydrogen power plants, though more costly, offer a CO2 free backup solution that ensures system stability in the event of unusual weather fluctuations, unpredictable events, and uncertainties that may arise due to the inherent challenges of a 100% RES in 2050.

One of the key contributions of this research is the development of a comprehensive 100% RES energy model for Saudi Arabia in 2050. This model can be applied to assess and evaluate different future scenarios from technical, economic and environmental perspectives, providing valuable insights for policymakers, researchers, and energy planners. The model will be made publicly available via platforms like GitHub, enabling other researchers to build upon this work and further explore RES scenarios for Saudi Arabia.

This research also contributes to the broader academic and policy debate on the global energy transition by demonstrating that a 100% RES for Saudi Arabia is both technically and economically feasible. The findings show that Saudi Arabia, with its vast renewable energy potential, can lead by example in the transition away from fossil fuels. The study also highlights the strategic importance of surplus RES energy for applications beyond electricity generation, such as green hydrogen production and electrification of the transport sector.

The limitations of this study, such as the exclusion of certain non-power sectors like desalination and industrial applications, point to potential paths for future research. Future work could focus on sector-specific strategies for RES integration or explore emerging technologies like grid-stabilizing services for 100% RES Additionally, further research could investigate the optimal use of surplus RES power for industrial processes and large-scale hydrogen production.

In conclusion, this study provides a comprehensive and practical roadmap for Saudi Arabia's transition to a fully RES by 2050. It demonstrates that a 100% RES is not only technically viable but also economically competitive. The results offer significant contributions to the understanding of Saudi Arabia's energy future and provide valuable tools for accelerating the Kingdom's transition towards sustainability, energy resilience, and global climate leadership.

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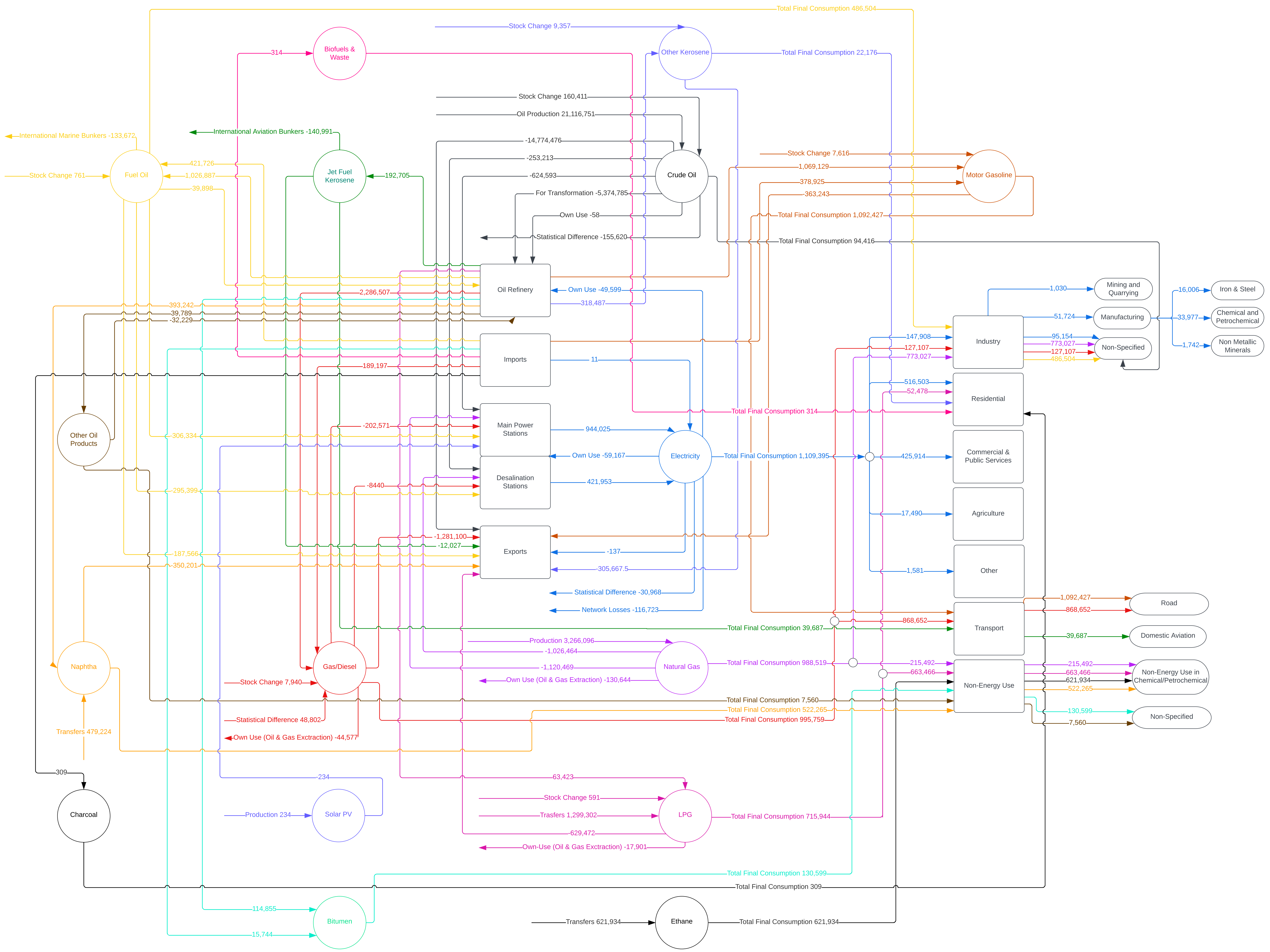
APPENDIX



Total Final Consumption 486,504
Stock Change 9,357
314
Biofuels & Waste
Other Kerosene
Total Final Consumption 22,176
Stock Change 160,411
Oil Production 21,116,751
International Marine Bunkers -133,672
International Aviation Bunkers -140,991
-14,774,476
-253,213
-624,593
For Transformation -5,374,785
Own Use -58
Statistical Difference -155,620
Crude Oil
Stock Change 7,616
1,069,129
378,925
-363,243
Motor Gasoline
Total Final Consumption 1,092,427
Total Final Consumption 94,416
Stock Change 761
Fuel Oil
421,726
1,026,887
39,898
Jet Fuel Kerosene
192,705
Oil Refinery
Own Use -49,599
318,487
2,286,507
393,242
39,789
-32,229
Imports
189,197
11
Mining and Quarrying
Manufacturing
Iron & Steel
Chemical and Petrochemical
Non Metallic Minerals
Non-Specified
1,030
51,724
16,006
33,977
1,742
Industry
147,908
127,107
773,027
95,154
773,027
127,107
486,504
516,503
52,478
Residential
Total Final Consumption 314
Other Oil Products
306,334
-202,571
Main Power Stations
944,025
Own Use -59,167
Electricity
Total Final Consumption 1,109,395
425,914
Commercial & Public Services
295,399
-8440
Desalination Stations
421,953
17,490
Agriculture
-1,281,100
-12,027
-187,566
-350,201
Exports
-137
305,667.5
1,581
Other
Statistical Difference -30,968
Network Losses -116,723
1,092,427
868,652
Road
868,652
Transport
Total Final Consumption 39,687
39,687
Domestic Aviation
Naphtha
Production 3,266,096
-1,026,464
Gas/Diesel
-1,120,469
Natural Gas
Own Use (Oil & Gas Extraction) -130,644
Total Final Consumption 988,519
215,492
663,466
Non-Energy Use
215,492
663,466
621,934
522,265
Non-Energy Use in Chemical/Petrochemical
Stock Change 7,940
Total Final Consumption 7,560
Total Final Consumption 522,265
Statistical Difference 48,802
Total Final Consumption 995,759
130,599
7,560
Non-Specified
Transfers 479,224
Own Use (Oil & Gas Exctraction) -44,577
309
234
63,423
Stock Change 591
Charcoal
Production 234
Solar PV
Trasfers 1,299,302
LPG
Total Final Consumption 715,944
-629,472
Own-Use (Oil & Gas Exctraction) -17,901
Total Final Consumption 130,599
Total Final Consumption 309
114,855
15,744
Bitumen
Transfers 621,934
Ethane
Total Final Consumption 621,934