QATAR UNIVERSITY

COLLEGE OF ENGINEERING

LONG-TERM PLANNING OF ELECTRIC POWER INFRASTRUCTURES CONSIDERING RENEWABLE ENERGY SUPPLY IN QATAR

BY

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ABSTRACT

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Greenhouse Gas (GHG) emissions have been a major contributor to the global warming that the world has been suffering from for many years. It is a challenging matter that, although is clear in its effects, faces obstacles due to the continuous developments witnessed in the world, which hinders the immediate action towards mitigating their effects. Major efforts are taking place to address this matter globally. In Qatar, remarkable goals and actions have been set and taken in this regard. This project investigates a Mixed-Integer Linear Programming (MILP) model that enables optimal strategic planning, over a long-term horizon of 30 years, of the electric power infrastructure. The objective is to minimize the investment and operating costs while meeting specific reduced targets of carbon dioxide, fulfilling the expected electricity demand, and accommodating technical operating constraints along with the specific variability and intermittency characteristics of renewable energy sources. Solar PV power plants were favored due to their reduced costs compared to other renewable plants. Other renewable technologies are expected to witness continuous improvement in cost reductions and technology efficiencies by the time they are required to be integrated into the system.

DEDICATION

To my family; my forever supportive parents, and my beloved siblings.

To my dear grandmother who eagerly waited for this moment and passed away just a month before it came.

Your love and guidance will remain ever-present in my heart. I hope I can make you proud.

ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

The World Health Organization (WHO) estimates that about 99% of the world's population breathe air that contains high levels of pollutants due to the increased worldwide levels of burning fossil fuels resulted from the economic development and increased urbanization, which deteriorated the air quality [1]. As a result, nine out of ten people now breathe polluted air, both ambient air and household exposure to smoke, which kills about 8 million people every year and causes about 7 million premature deaths from stroke, lung cancer and heart disease [2]. Moreover, most countries and economies are expecting large development in the future, especially developing countries. However, the attainment of high development necessitates huge levels of energy consumption [3]. The high energy consumption levels denote high emissions of greenhouse gases (GHGs) into the atmosphere, which are related to the anthropogenic climate change. Dulling the negative effects of CO2 and unburned hydrocarbon emissions requires more penetration of alternative clean energy sources, such as wind and solar energy, in the design of new electric energy production systems. In addition to the climate change burden caused by fossil fuels, their predicted depletion is a second challenge to consider. In fact, these two problems are interrelated as it is predicted that with decreased levels of available fossil fuel, the human-induced climate change would be reduced [4].

Human activities are the main driver of climate change, primarily through the release of greenhouse gases (GHGs). Astonishingly, just 10 countries are responsible for about 60% of global GHG emissions, while the 100 countries with the lowest emissions contribute less than 3%. The energy sector is the largest contributor, accounting for nearly three-quarters of emissions, with electricity and heat generation being the largest sub-sector, followed by transportation and manufacturing. Agriculture also adds a significant share. Land use, land-use change, and forestry (LULUCF) play a dual role, acting as both a source and a sink for emissions, and are crucial for achieving net-zero emissions. Understanding these sectors' contributions is essential for targeted climate action [5].

The fossil fuel depletion challenge and their effect on climate change mandate new planning efforts for the integrated energy resources i.e., renewable energy sources, to increase access to electrical energy and to facilitate the social, environmental, and economic growth. In fact, in the past few years, several countries and governments have endorsed programs and policies to stimulate the integration of renewable energy sources to produce energy in response to the goals of the United Nations' Sustainable Development Agenda [6], [7]. Shifting to these renewable energy sources (RES) has become a strategic goal for many countries in order to boost electricity production whose demand keeps increasing because of the huge development in different domains and reduce the impact of air pollution on public health. Accordingly, creating a balance between the future energy supply and demand is indispensable.

Environmental development is the fourth pillar in Qatar's 2030 National Vision, which is the country's roadmap for future development. The outcomes of this pillar, which aims for "A Balance Between Development Needs and Protecting the Environment", include establishing a comprehensive legal system that is agile to protect all environmental elements including air[8]. In addition to establishing environmental institutions that motivate public awareness about using environmental-friendly technologies to protect the environment through planning tools, campaigns, and environmental research. The assessment of climate change and its negative effects and mitigating them in the region is also an outcome of this pillar, along with establishing sustainable policies considering urban expansion. Qatar has implemented several programs and projects to control CO_2 emissions and air pollution, and to increase the renewable energy sources integration. All these efforts are being made to transform Qatar into an advanced country by the year 2030. In the 2018 Environmental Performance Index, Qatar was the first ranking GCC country by its positive performance in performing measures of sustainable development and environmental protection [9]. Qatar has been showing advancements in the sustainability and environment protection through several actions. Through the installation of solar-powered stadiums and pioneering technologies of cooling and lighting, the FIFA World Cup in 2022 that will be hosted by Qatar is the first carbon neutral World Cup ever. In fact, this is an intermediate stage into achieving Qatar's goal of installing 2 to 4 GW (Giga Watts) of solar power across the country by 2030 to reduce the CO_2 emissions by 5 Mtpa (million tonnes per annum). Kahramaa, the country's national utility company, is developing many projects in response to these efforts, including an 800 MW (Mega Watt) large scale solar power plant, the Al Kharsaah power plant, that was planned to be used in the 2022 World Cup, which correspond to the tenth of the country's peak energy demand. In 2022, the goal is to have 100% electric busses across the country with 400 charging stations distributed across the country. In 2030, 10% of the vehicles in Qatar are expected to be Electric Vehicles. The efforts of Qatar in the sustainable development are not limited to the country. Qatar provided $2 billion to developing countries to assess them in improving their sustainability efforts [9].

Qatar Petroleum (QP) launched a new Sustainability Strategy in 2021 which included several targets to be met in accordance with the Paris Agreement, an international legally binding agreement on climate change to reduce global warming [10]. The targets of QP's strategy aim to reduce the greenhouse gases emissions and mandates the establishment of Carbon Capture and Storage (CCS) facilities that are susceptible to capture more than 7 Mtpa of the country's CO2 emissions [9].

One of the remarkable initiatives towards shifting to renewables as energy sources is that QatarEnergy is consolidating its position in the renewables business and is delivering a mid-term target of generating 5GW of solar power by 2035 as part of its Sustainability Strategy [11]. In fact, Qatar announced its sustainability and climate change goals through several official channels and strategic frameworks, as stated below.

- National Climate Change Plan

In September 2021, the Cabinet of Qatar approved the National Climate Change Plan. The plan outlines specific targets and measures to tackle climate change, including emissions reduction and sustainable practices [12].

- Qatar National Environment and Climate Change Strategy (QNE)

Launched in October 2021, the Qatar National Environment and Climate Change Strategy (QNE) provides a robust policy framework. It aims to safeguard Qatar's environment for future generations across various pillars, including greenhouse gas emissions reduction, air quality, biodiversity, water, circular economy, waste management, and land use [13].

- Ministry of Environment and Climate Change

In accordance with a decree issued by His Highness Sheikh Tamim Bin Hamad Al Thani, the Amir of the State of Qatar, the Ministry of Environment and Climate Change was established in February 2022. The ministry's mission is to safeguard environmental quality and preserve resources for current and future generations through efficient regulatory frameworks [12].

- Qatar Sustainability Week 2023 (QSW)

The Qatar Sustainability Week (QSW), organized by the Earthna Center, involves more than 250 entities and partners in Qatar. The week features over 400 activities and initiatives, including seminars, conferences, and technical events related to water, energy, electric vehicles, green buildings, and sustainable facility management. Its goal is to involve community members, encourage sustainable lifestyles, and increase environmental awareness [14].

Renewable Energy Sources have several advantages over fossil fuels. RES are the optimal option to reduce environmental harm caused by energy production using the traditional methods of using fossil fuels. Moreover, RES are domestically available which secures the energy supply and mitigates the risks of importing fossil fuels for energy production [15]. The major types of RES are solar, wind, biomass, hydropower and geothermal [16]. Solar and wind are the most known renewable energy sources however, they are subject to high variability and intermittency. Solar energy is energy extracted from the sun using technologies to collect and convert sunlight into electricity. Solar energy can be extracted using solar photovoltaic devices (PV) also known as solar cells. Solar cells can power a watch or a calculator, up to an entire house if arranged into PV panels and PV arrays, which consist of multiple PV panels. To produce electricity for several houses/buildings, several PV arrays need to be assembled in one piece of land. Solar energy systems have no harm on the environment, nor do they produce GHG or carbon dioxide. However, they are variable and intermittent depending on the location, time of day, season. Solar panels and arrays require large land areas to produce enough energy to meet the expected amount of supply [16].

Wind energy is energy produced as a result of air movement. The technology used to produce energy from wind is wind turbines. The wind turbines have blades which experience lift force due to the flow of air across them, hence, the blades rotate as a result of the wind's kinetic energy. The blades of the wind turbine are connected to a shaft that is connected to an electric generator. The shaft moves with the movement of the blades and causes the generator to turn and generate electricity [17]. Biomass energy is obtained from the organic and renewable material obtained from animals and plants. This energy can be found in several sources including wood and its processing waste, animal manure and human-generated sewage, agricultural crops such as corn, soybeans, and waste materials such as food processing leftovers, and municipal solid waste such as cotton and paper [18]. The conversion of biomass into energy can be processed in several methods depending on the type of biomass material that is used. The methods include direct combustion, which is the most common method to produce heat, thermochemical conversion, that is used to produce liquid, solid or gaseous fuels, chemical conversion to make liquid fuels, and biological conversions that can make gaseous or liquid fuels. Biological conversions can produce renewable natural gas which has the same features as the fossil fuel natural gas [18]. Hydroelectric power is produced as a result of the movement of water. Hydroelectric dams can be constructed to accumulate water and store it to be released later upon need through hydro turbines to generate electricity. Rivers' current can be used to generate hydropower through applying pressure on turbines. Pumped-storage hydropower facilities can also be constructed to produce electricity [19]. Finally, geothermal power is obtained from the heat produced in the inner layers of earth, which can be used to produce heat or electricity [20].

Despite the many advantages associated with renewable energy generation, some factors hinder the large-scale integration of these resources, such as low efficiency, high infrastructural costs, and supply reliability. In particular, the intermittency, spatial variability and temporal variability of some renewables, such as solar and wind, impose major challenges because they disrupt the conventional energy supply [6]. To address the intermittency of RES, specific strategies of operation are required. Moreover, to use RES for energy production, new infrastructures for the production, storage and transportation of energy are required, as well as the facilitating of the integration with the existing infrastructure [15]. To address variability, the hybridization of two or more RES is recommended in one power station, since RES have a complementary nature. This hybridization, e.g. solar-wind, can increase the system's reliability as the scarcity of one source can complement the absence of the other at certain locations or time periods [21].

The evolution of electricity pricing reveals a promising path for significant advancement with renewable energy. This cost reduction is pivotal for a sustainable future and has the immediate benefit of increasing real income, fostering economic growth, and alleviating poverty. Renewables' cost-efficiency, unlike fossil fuels, is expected to grow due to their steep learning curves. While we've potentially hit the peak of greenhouse gas emissions, the ultimate goal is net-zero, necessitating a rapid shift to renewables to reduce emissions swiftly, improve public health, and enhance economic prosperity [22]. Fossil fuels have already undergone much of their technological development. Their costs are more tied to extraction and market prices, which don't typically decrease in the same way as technology-driven costs.

Recently, many studies have oriented towards creating models that support the decision-making process to establish RES systems that include biomass, solar and wind energies to supply electricity. This orientation is generated by the need to reduce GHG emissions and their impact on the environment and to mitigate the risks of fossil fuel depletion. Under such a perspective, there is a need for reconsidering related energy infrastructure within a context where economical, technological, and environmental factors, involved in the production and the distribution of electric energy, are continuously evolving. These new requirements, along with flexibility in supply and demand, yield new optimization challenges for the future electric power systems infrastructure planning. System flexibility can be defined as the characteristic of the capability of the combined generators' set to act in response to the uncertainty and variation of demand [23]. Standalone renewable energy (RE) systems installations, for example standalone solar power plants or wind power plants, impose several problems, such as, high infrastructure costs, low solar energy systems efficiency due to solar power's intermittency, requirements of large areas for the installation, and noise pollution from wind turbines. Therefore, a hybrid or mixed installation of RE systems is recommended as it impacts the reliable electric power system operations as they can meet the frequently changing demand for electricity and provide contingency reserves for the operations [6][23]. Moreover, the straightforward conventional power plants sizing methodologies involve average and worst-case scenario simulations that are dependent on local historical weather and climate data. However, these strategies may result in RE configurations that are defective or larger in size than required [6]. Therefore, an optimized solution is required.

To meet the climate and development goals, global investment in renewables must triple to meet climate and development goals. During 2013-2022, solar PV and onshore wind continued to consolidate their dominance, attracting 46% and 32% of global renewable energy investments, respectively. Investments in offshore wind have picked up, attracting 8% of the total, followed by solar thermal at 5%. Other renewable energy technologies (including hydropower, biomass, biofuels, geothermal, and marine energy) altogether attracted only 7% of total investment in 2013-2022, with hydropower making a relatively significant portion of the total. More funds need to flow to less mature technologies that have a crucial role to play in the energy transition. The concentration of investments in solar and wind technologies further increased in 2022 as they attracted 95% of the overall investment [24], [25].

The ultimate goal of this paper is to develop an optimization framework that shall be used by energy policymakers for strategic long-term planning of power generation. It is crucial to properly identify the technologies to be selected, and the proper timing of the investment. The proposed optimization problem can be concisely stated as follows: How can we build a long-term plan that simultaneously achieves two contradictory goals: aggressively reduce the greenhouse gas (GHG) emissions, specifically Carbon Dioxide (CO_2), and fulfill all the expected electricity demand? The objective being to minimize the total power generation cost.

Toward this end, this paper shall achieve the following objective.

Development of a mathematical optimization model that integrates technical, economical, and environmental aspects of power generation.

More specifically, the following questions will be addressed by the model:

1 Which new power generators should be set up over the planning horizon? Which types? Which peak production capacity? and in which year?

2 Which power generators shall be constructed to meet the country's increasing demand, while minimizing its carbon print?

3 Which power generators can be integrated at the national grid scale in Qatar, to fully utilize the existing power plants until the end of their time?

4 Which power generator combination is optimal in terms of cost, initial investment and variable operational costs?

This paper will be divided into six chapters. Introduction in Chapter 1, Literature Review in Chapter 2, Chapter 3 overviews different types of power plant types, and Chapter 4 discusses the Methodology. Results and discussion will be presented in Chapter 5. Finally, the sixth chapter will be the conclusion of this paper.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews the existing literature on renewable energy sources (RES) integration and planning into the electric grids from various countries around the world. The literature review is followed by Table 1, which classifies the reviewed papers based on the used renewable sources and the adopted methodology.

The conventional electricity production systems that have been used for decades are negatively impacting the environment by emitting high rates of greenhouse gases (GHG) from the burning of fossil fuels to produce energy. Besides their negative environmental consequences, fossil fuels are anticipated to be depleted in a few decades [26]. These reasons called for finding more eco-friendly and sustainable energy sources to produce electricity. The world is currently directed towards achieving sustainable development, and there is witnessed transformation toward sustainable energy production in the electric power sector which is changing the industry's structure [27]. Renewable energy sources (RES) integration into power systems is perceived as a solution to these concerns [28], and has been studied using different approaches, with case studies from different countries in many instances. Examples of this can be found for a variety of countries and regions such as sub-Saharan Africa, Jordan [29], Iran [30], [31], Spain [32], [33], [34], Italy [35], Portugal [36], Cape Verde [28], France [37], Brazil [38], USA, and South Australia [39].

For countries that decide to go through the renewable energy (RE) integration journey, there is no rule-of-thumb approach to follow. Instead, each country crafts its combination of policies, market designs, and system operations to achieve the required reliability and flexibility. This was illustrated by the cases reviewed in [40], which included South Australia, Spain, Ireland, the United States (Texas and Colorado), Germany, and Denmark. Despite the diversity in the approaches, they meet in five strategic areas [40]. First, engaging with the public (especially in the development of new transmission). Second, integrating the planning of system performance, generation, and transmission to accommodate variable RE. The third area is adopting market designs that support system flexibility. Fourth, expanding access to resources, in terms of type and geographical location, can reduce the effect of variability. The last area is integrating advanced forecasting to reduce the variability impact, and grid codes to ensure system reliability. These areas allow the system to be able to respond to change and variability cost-effectively [40]. Another factor for achieving effective RE integration is having a richly diverse and robust experience base from other countries [40]. In an attempt to understand the perception and behavior of electricity consumers in Qatar about RES integration and implementing smart grid technologies, a survey was conducted by [41] that can be used by decision-makers to learn about the public's perspectives. Smart grids are the next-generation electric grids. They combine information and communication technologies and control systems with the power grid [42]. SG can be defined as a sufficient infrastructure that has a two-way communication system and hierarchical, distributed architectures to perform several applications that are required [34].

In developing countries, the high prices of fossil fuels and the inability to afford them lower the capacity of power generation, which obstructs many sorts of development. Many concerns have been raised in sub-Saharan Africa (SSA) about the occurrence of a long-term energy shortage resulting from an energy supply crisis that is expected to last for an undetermined period of time if no immediate actions were taken [3]. Moreover, in

SSA, there is a low desire and actions taken towards reducing GHG emissions, therefore, it is crucial to explore the feasibility of utilizing local renewable energy resources to increase the generation of electrical energy, reduce emissions, and be in line with the efforts taken globally towards energy development and sustainability. There is a variety of possible renewable energy resources to be used for electricity generation in SSA, and the most sustainable sources are solar energy, biomass, and hydroelectric power. However, there are obstacles affecting the integration of RES into the power system, and these are the absence of financial and infrastructural support, lack of political will, inadequate research, and poor public awareness. EnergyPLAN, a renewable energy planning and management system was employed to find possible ways of utilizing RESs for productive energy generation. The current energy crisis will persist in SSA and other developing countries unless action was taken like integrating RES in power grids due to the potential sustainability of RES [3].

In [29], the authors developed a MILP for optimizing the integration of renewable energy technologies into an existing power plant portfolio. The Hashemite Kingdom of Jordan case is considered in the paper and it is shown that a well-balanced mix of all available renewable resources technologies can decrease significantly Jordan's high electricity generation costs and can make Jordan significantly more independent from fossil fuels.

In Iran, the long-term integration of renewable energy into the 230-400 kV large-scale system of the national power grid was investigated with a multi-objective mixed-integer programming problem, then the epsilon-constraint optimization method was used to solve the problem. The fuzzy satisfying procedure was used to choose the appropriate executive installation plan [30]. Through the development of an integrated simulation-optimization system, a sustainable plan was studied for Iran by 2050 [31]. Future power plants' configurations were simulated by applying a differential evolution algorithm, then a linear programming model was employed to depict the optimal methods to incorporate these configurations. Results showed that the deployment of renewable energy technologies may contribute to 48% of the power generation by the year 2050, namely, wind turbines, solar thermal, and photovoltaics, respectively. Moreover, the results depicted that sustainability enhancement is not guaranteed throughout the whole planning horizon even with the extensive deployment of these sources. This illustrates that supply-side planning should be in line with demand-side strategies [31].

As a contribution to the efforts of decarbonizing European electricity, an assessment of the integration of a hybrid of wind and solar photovoltaic energy and its implications was conducted [43]. The role of transmission grid extension to address the temporal variations and geographical distribution of the variable RES in relation to the penetration level of RES was compared. In fact, major integration challenges occur with increased RES penetration levels, such as large backup capacity requirements as compared to conventional dispatchable power plants, power overproduction, and unmatched supply and demand. Grid extensions can smoothen the temporal fluctuations and resolve the issue of RES geographical distribution. This, in return, alleviates the required backup capacity, overproduction, and the supply-demand misfit [43]. Integrating large penetration levels of RES is possible, however, this requires large power plant capacities. The hybridization of wind and solar energies is crucial for RES penetration of more than

50% as solar energy is unavailable during night times. Grid extensions smoothen the wind supply. The cost of the RES integration increases with the increase of penetration level, however, at very high-RES shares, saturation effects were observed. It is crucial to early plan the grid extensions for RES integration as the transmission lines' acceptance and building process may take up to 10 years [43].

Like many European countries, Spain witnessed significant growth in distributed generation (DG) because of the promotion of electricity generation using RESs and combined heat and power (CHP) production [32]. The possibility and desirability of integrating RES into DG of electricity were proven in Spain because of the expected rise in electricity demand in the coming years, and the scarcity of interconnection with neighboring systems. Hence, an increase in the capacities of RESs distributed generation is anticipated in the coming years in Spain, most likely consisting of on-shore wind, solar photovoltaic, and high-temperature concentrated solar thermal power (CSP) [32]. Wind energy integration was proven to be the most successful in the studied system. However, some challenges associated with RES integration must be taken into consideration. The innovation of smarter DG grids is required as there are high technological uncertainties associated with the currently available technologies. However, the operators of DG and consumers in Spain are given poor incentives, and there is a lack of transparent regulatory rules [32]. The trend toward shifting to DGs instead of the classical connection to the grid has imposed several technical, safety, and financial issues that need to be addressed. The connection of DG to the grid may affect supply quality, reliability, and safety. Similarly, concerns about the environmental impact resulting from the increased demand for electricity in Spain were discussed in [33], concluding the need to develop a method for realistic multi-criteria electricity planning up to the year 2030. Total cost, GHG emissions, and radioactive waste were the objectives of the model. The combination of compromise programming and AHP helped with the conflicting objectives [33].

An integrated planning method was utilized to regulate the exploitation of RES in Italy, which is one of the countries that have the highest RES potential in the region [35]. To meet the current and future hourly energy demand, the classification of climate zones was designed. The system was designed using EnergyPLAN software. TRNSYS 17 and DesignBuilder were used to meet the required hourly energy production of the system plants. The outcome was favorable with a 45% reduction in the 1990 CO_2 emissions in the 2030 transition scenario [35].

For the goal of reaching sustainability through supplying energy from local resources with cost-effective methods, a national scale plan in Portugal was presented that achieves 100% RES electricity production using H_2RES [36]. An open loop system where the intermittent limit was set to 80% and import/export with Spain was considered, along with a closed loop system with no intermittent limit, 100% RES usage, and energy storage technologies (pumped hydro, batteries, and fuel cells (hydrogen loop)). The plants introduced to the model are thermal power plants, wind turbine sites, solar PV plants, wave power plants, hydropower plants, and biomass power plants: using CHP, without CHP, waste incineration, and biogas facilities. The paper assumed the same demand of 2006 in future scenarios; however, it recommended making additional forecasts of the demand [36]. Moreover, energy efficiency measures were suggested to reduce future electricity demand such as improving building insulation to reduce the electricity requirement for air conditioning and heating during summer and winter. Solar thermal collectors for water heating or absorption cooling were another suggestion. Results showed that 100% RES electricity supply needs more effort and costs to be achieved in closed-loop systems than in open systems since it requires the installation of more technologies and doesn't depend on imports. However, it is possible with the right measures taken [36].

Energy storage is beneficial to increase and enhance the security of supply and reduce the dependence on imports to aid in preventing the rejection of renewable potential in the system [28], [36]. Several energy storage methods exist, such as hydro storage. For example, pumped hydro storage was proposed in the case of a 774 m long mountain in S. Vicente Island in Cape Verde, for which desalinated water was proposed to be used for pumping, then supplied to the population [28]. The stored surplus clean power can also be traded among neighboring regions [26].

Conditions, where the utilization of RES could threaten the reliability of power systems, were investigated in France along with finding feasible solutions to increase the penetration of RES from 40-100% in 2050 [37]. According to the paper, high levels of RES that depend on external weather conditions – referred to as Variable Renewable Energies (VREs) – could disturb the management of power systems and dramatically increase the costs of power supply, if they were not carefully predicted. the impact of different levels of RES penetration (40% to 100% in 2050) on the system's reliability was explored by coupling the long-term planning deterministic model with a thermodynamic approach. According to the researchers, this approach was not applied to a large-scale power system before [37]. The modeled system consisted of biomass power plants, with and without Carbon Capture and Storage (CCS), fossil fuel plants, with and without CCS, nuclear power plants, RES power plants, imports from neighboring countries, and storage techniques. To avoid any potential increase in CO_2 emissions, CO_2 upper limits were set in all the examined scenarios. To reduce the complexity of the system, the paper assumed that exports and imports could be used as needed and whenever needed, however, this is not the case in reality. Another assumption made is regarding the collected data of prices, power plant characteristics, etc. that were used in the model. The data is subject to uncertainty and the study could yield different results with a different set of data. Having all these assumptions and constraints in place, a long-term, bottom-up investment planning model was used to illustrate possible interactions between investment and operation decisions [37]. Results showed that RES in the French power system is not capable of meeting future demand without either the help of conventional power plants or a high dependency on imports. Moreover, 65% of RES penetration was found to be the optimal level of penetration in the French power system. Moreover, the installation of new RES power plants along with backup capacities requires very high investment, operational, and maintenance costs, however, other costs (e.g. fuel costs) are significantly reduced. Another drawback of RES penetration is that it leads to a reduction of the kinetic reserves, which jeopardizes the system's stability and capability to deal with disturbances, however, setting limits to RES penetration and increasing biomass usage can solve this issue. Moreover, the model lacks crucial parameters like demand-supply balance, therefore, it cannot be used as a reference to determine the feasibility of high-RES penetration levels [37].

The authors in [38] develop a MILP model aiming at minimizing the operations and investment economic costs and thermal operations emission costs under four main constraints including the energy demand, the power demand, the availability of sources and projects, and GHG emission. The study considers environmental parameters related to GHG in the Brazilian electric sector expansion planning and shows its impact on existing results based only on technical and economic parameters. In Texas, USA – the Electric Reliability Council of Texas (ERCOT) – grid which is a transmission-constrained isolated grid, 80% of the electricity demand is met by different mixes of wind, solar photovoltaic, and concentrating solar power, which is variable renewable energy sources [23].

A residential neighborhood in South Australia was selected to perform a study on distributed energy system planning [39]. The article proposed a deterministic Mixed-Integer Linear Programming model, with the objective of minimizing the total annualized costs of the system to satisfy the yearly energy demand. The model was initially tested for five houses in the neighborhood, and then it was upscaled to 10, then 20 houses, where consistent results were obtained [39].

Given the previous literature review, Table 1 classifies the obtained literature based on country, renewable energy source, and methodology.

Table 1. Literature Classification Based on Country, Renewable Energy Sources, and Methodology

Paper	Country	Hybrid/Single RE system	RES Source	Full/Partial integration	Methodology
[26]	USA	Hybrid	Wind, Solar Power	Partial	MILP and LP models
[27]	USA,	Hybrid	Wind, Solar	Partial	Review

Paper	Country	Hybrid/Single RE system	RES Source	Full/Partial integration	Methodology
	Europe		Power, Biomass		
[28]	Cape Verde	Hybrid	Wind, Hydropower	Partial	H2RES
[29]	Jordan	Hybrid	Solar, Wind Power	Partial	MILP
[30]	Iran	Hybrid	Wind, Solar Power	Partial	multi-objective MILP. Epsilon-constraint optimization method. Fuzzy satisfying procedure.
[31]	Iran	Hybrid	Wind, Solar Power	Partial	Integrated simulation-optimization system (Linear Programming)
[32]	Spain	Hybrid	Wind, Solar Power	Partial	Review
[33]	Spain	Hybrid	Wind, Solar Power	Partial	Multi-criteria methods: *Compromise programming *AHP
[34]	Spain	Hybrid	Wind, Solar Power	Partial	Review Case studies
[35]	Italy	Hybrid	Solar, Wind Power, Hydropower	Partial	EnergyPLAN TRNSYS 17 DesignBuilder
[36]	Portugal	Hybrid	Thermal, Wind, Solar, Wave, Biomass power, Hydropower	Full	H2RES
[37]	France	Hybrid	Biomass, Wind, Solar power, Hydropower	Partial to full	Energy-planning model from the TIMES family
[38]	Brazil	Hybrid	Wind power, Biomass	Partial	MILP
[39]	South	Hybrid	Solar, Wind	Partial	MILP

	Australia		Power		
Paper	Country	Hybrid/Single RE system	RES Source	Full/Partial integration	Methodology
[40]	South Australia, Denmark, Germany, Ireland, Spain, and USA (Colorado and Texas)	Hybrid	Biomass, Wind, Solar power, Hydropower	Both	Review
[41]	Qatar	Single/House application	Solar, Wind Power	Partial	Survery
[42]	Worldwide	Hybrid	Wind, Solar Power, Biomass	Partial	Review
[3]	Sub-Saharan Africa	Hybrid	Solar energy, Biomass, Hydropower	Partial	Review EnergyPLAN
[43]	Europe	Hybrid	Wind, Solar Power.	Partial	Parametric Study
[23]	Texas, USA	Hybrid	Wind, Solar Power	Partial	Simulation using REFlex

CHAPTER 3: ENERGY SOURCES BACKGROUND

Energy Sources

Given the vast witnessed growth in the world, there has been a huge interest in research for finding fuel types that would meet the magnitude of this growth in development and simultaneously sustain sustainability causing minimal impact on the environment. Figure 1 illustrates three categories of energy sources namely, renewable sources, fossil fuels, and nuclear sources. Each category will be explained further below and finally compared in terms of cost, efficiency, land space use, storage capability, and challenges associated with each resource.

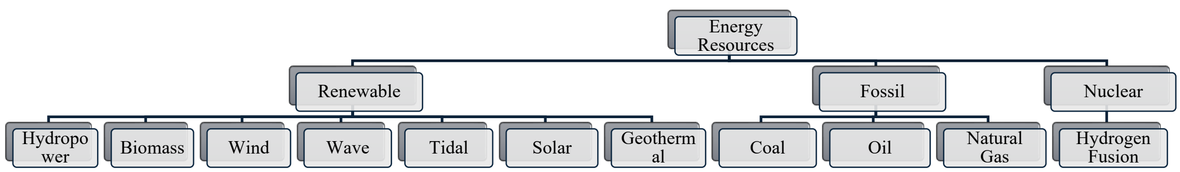

Figure 1. Energy resources categories [44]

I. Fossil Fuel Power Plants

Thermal energy conversion into mechanical energy and eventually electrical energy is the main used method nowadays. Conventionally, thermal energy is created by burning fossil fuels, i.e. coal, oil, or natural gas, and then through turbines, converted into mechanical energy which is finally converted to electrical energy using synchronous generators. Greenhouse gas emissions, thermal pollution, and the millions-of-years lagging regeneration rate as compared to the consumption rate are inevitable fallouts for these types of power plants that require -and have gained- worldwide attention [45].

A gas-fired power plant typically emits around 450 grams of CO_2 per kWh of electricity generated. While this emission level is significantly lower than that of coal-fired power stations, it remains higher than nuclear power plants and renewable energy sources [46].

On the other hand, Coal-Fired Power Stations emit more CO_2 than gas-fired plants, with an average of around 1,000 grams of CO_2 per kWh [47].

II. Nuclear-based Power plants

Similar to fossil fuel power plants, these power plants indeed generate thermal energy. However, without the production of greenhouse gases as a by-product. The same conversion route is taken to finally generate electricity. They have minimal CO2 emissions. However, tremendous efforts are yet required to determine the safety and cleanliness of nuclear energy, along with the establishment of effective radioactive waste disposal and storage techniques [45].

III. Renewable Energy Power Plants

These plants have nearly no direct CO2 emissions during their operation. However, their technologies are still evolving and research in this regard is growing.

i. Wind Power

To produce electricity from wind turbines, kinetic energy is required to rotate them. The result of this rotation is mechanical energy which is then converted into electricity. This final conversion takes place through a coupling magnetic field [45].

The implementation of wind energy systems faces several challenges that must be addressed to optimize their effectiveness and efficiency [48]. The first challenge is the variability of wind speeds. One of the primary limitations of wind energy is the inherent variability of wind speeds. Wind turbines require a minimum wind speed to generate electricity effectively. During periods of low wind speeds, the electricity output of wind turbines diminishes significantly, leading to inconsistent energy production.

Second, spatial requirements; the generation of substantial amounts of electricity via wind energy necessitates the establishment of extensive wind farms. These farms occupy large tracts of land or sea, which makes it challenging to integrate them into densely populated regions or areas with high land value. Consequently, wind energy is not a direct substitute for conventional power stations and is more suited to meeting lower energy demands or powering isolated applications. Third, environmental and economic impact; the initial installation of wind turbines can be an expensive venture, with significant environmental implications, particularly for local wildlife. The construction phase may disrupt natural habitats, and the presence of turbines can pose hazards to birds and bats. Finally, acoustic emissions. Noise pollution is another concern associated with wind turbines. The mechanical and aerodynamic noise generated by turbines can affect nearby residential areas, leading to potential conflicts with local communities over noise disturbances.

In conclusion, while wind energy presents a promising alternative to traditional energy sources, these challenges highlight the need for strategic planning and technological advancements to enhance the viability and acceptance of wind energy solutions.

ii. Solar Power

The most acceptable, and most reliable, source among all renewable energy sources is solar energy. In fact, it is also abundant almost everywhere on Earth around the clock.

It is reported that the amount of energy that Earth receives from the sun can be estimated to be 10,000 times more than the total demanded energy [49]. However, the main drawback of PV solar power is the intermittency of solar energy, which is abundant only during the daytime.

Employing an electromechanical synchronous generator, all electrical energy sources -except PV- convert the mechanical energy produced from spinning turbines i.e. steam, gas, or hydro into three-phase alternating current (AC) electricity allowing the delivery of a total constant instantaneous power. These systems also allow the use of transformers, which facilitate the transmission of high voltage levels to long distances through transmission lines. Photovoltaic arrays generate direct current (DC) electricity, which is then integrated into the existing AC grid through a power electronics inverter [45].

Concentrated Solar Power (CSP) is a technology that harnesses the sun's energy by concentrating sunlight using mirrors or lenses to generate high temperatures. This heat is then used to produce steam that drives turbines to generate electricity. Here's a summary of CSP, its benefits, and improvements over the years:

- Benefits of CSP as illustrated in [50]
  - Sustainable Energy Source. CSP is a renewable energy technology that reduces dependence on fossil fuels, helping to mitigate climate change.
  - Energy Storage. Unlike photovoltaic (PV) systems, CSP can integrate thermal energy storage, allowing for electricity generation even when the sun is not shining.

- Scalability. CSP plants can be scaled up to generate significant amounts of power, suitable for utility-scale power generation.

▪ Improvements of CSP Over the Years [50]

- Technological Advancements. CSP technologies have evolved, including parabolic troughs, solar towers, and linear Fresnel reflectors, each with varying levels of efficiency and cost-effectiveness.
- Economic Analysis. Studies have used the Levelized Cost of Electricity (LCOE) model to evaluate the economics of different CSP technologies, showing a trend towards cost-competitiveness with traditional power sources.
- Policy Implications. Research has highlighted the need for supportive policies such as preferential loans, tax incentives, and R&D fund support to promote CSP development.

▪ Recent Explorations [51].

- Hybrid Systems. There's a growing trend of combining CSP with other forms of renewable energy or with performance-enhancing techniques to increase overall efficiency.
- Global Reach. CSP is gaining attention worldwide, with countries like China and India investing in CSP to meet their energy needs sustainably.

These improvements indicate that CSP is becoming an increasingly viable option in the renewable energy landscape, with ongoing research and development aimed at overcoming economic barriers and enhancing performance [50], [51]. Table 2 compares the mentioned renewable energy sources in terms of efficiency, amount of land used, storage capability, costs when setting up power plants using these sources, and the main challenges associated with each source.

Table 2. Energy Sources Comparison

Energy Source	Capital Cost (USD/kW)	Operational Cost (USD/kW/year)	Efficiency	Land Use	Storage Capability	Main Challenges
Solar PV	$581.25 - $722.29	$9.2	15-22%	Moderate	Low	Space, temperature sensitivity
CSP	$3,910 - $6,355	$71	Up to 20%	High	High	Complexity, cost
Onshore Wind	$1,200 - $2,500	$31	20-40%	Low	Low	Wind variability, noise
Offshore Wind	$3,000 - $5,000	$62	30-50%	N/A	Low	Installation and maintenance costs
Biomass	$2,500 - $5,000	$80 - $120	20-25%	High	High	Feedstock supply, technology readiness
Nuclear	High	Low	30-40%	Low	High	High capital cost, waste management
Gas and Oil	Low	High	30-50%	Low	N/A	Fuel cost, emissions
Coal	Higher than Gas and Oil	High	30-40%	High	N/A	Emissions, fuel cost

Existing Power Plants in Qatar

There are currently nine operating power plants in Qatar and two power plants that fall under the same project are expected to commence electricity production by the end of 2024.

Most of the existing power plants in Qatar depend on natural gas as a source of fuel. The reasons behind this are discussed in [52]. Most power plants in Qatar are thermal power plants, except for the three solar power plants; Al Kharsaah, and the two IC Solar Project power plants. Given the fact that natural gas is considered the cleanest of all fossil fuels, it is also abundant in Qatar, which has the world's third-largest natural gas reservoirs. Only recently has Qatar integrated renewable energy power plants into its electrical grid. The first solar power plant in Qatar is Al Kharsaah Power Plant which is a creditable step towards diversifying Qatar's power sources. Below is more information regarding the eleven power plants in Qatar [53].

I. Mesaieed Combined Cycle Gas Turbine (CCGT).

Combined Cycle Gas Turbine (CCGT) plants are a type of thermal power plant that uses both gas and steam turbines to generate electricity [53]. This power plant was commissioned in September 2009, and is expected to have a lifespan of 20-30 years as per a typical CCGT power plant [54], [55], [56].

II. Ras Laffan A Cogeneration Gas Turbine.

Cogeneration plants, also known as combined heat and power (CHP), are thermal power plants that produce both electricity and thermal energy [53]. This plant is owned by AES Ras Laffan Operating Company and commissioned in 2003, with an expected lifespan of 25 years. This power plant is natural gas fueled [57].

III. Ras Laffan B Combined Cycle Gas Turbine (CCGT).

Owned by Qatar Electricity & Water Co QPSC, Engie Energy Services International, and JERA [58], [59]. Qatar Petroleum provides natural gas to be used as fuel in the CCGT plant. It was commissioned in 2006.

IV. Ras Laffan C (Ras Qartas) Combined Cycle Gas Turbine (CCGT).

Commissioned in 2010 and uses natural gas as fuel.

V. Umm Al Houl Integrated Water and Power Plant (IWPP).

IWPP is a plant that produces both electricity and water. While it's not a distinct category of power plant in terms of energy source, it's a business model that often uses thermal power generation combined with desalination. It was commissioned in May 2017. Gas is the main fuel used in this plant. It is an Integrated Water and Power Plant (IWPP), however, only power generation is considered in this research. Water production is out of scope. The owner of this plant is a joint venture company with local and foreign stakeholder [60], [61], [62].

VI. Ras Abu Fontas B Open Cycle Gas Turbine (OCGT) with Cogeneration.

Open Cycle Gas Turbine (OCGT) cogeneration is a thermal power plant that generates electricity and captures the heat that would otherwise be wasted. The fuel used in this power plant is natural gas. It was commissioned in 1995 and owned by Qatar Electricity & Water Co QPSC [63], [64]. The typical lifetime of an Open Cycle Gas Turbine (OCGT) Cogeneration power plant can vary based on several factors, including the design, maintenance, and operational practices. However, gas turbines, in general, have a lifespan that can range from 20 to 30 years.

VII. Ras Abu Fontas B-1 Open Cycle Gas Turbine (OCGT).

An OCGT plant is a simple cycle plant that typically serves peak load demands; it falls under thermal power plants. Natural gas is also the fuel used in this plant that was commissioned in August 2002 by Qatar Electricity & Water Co QPSC [65], [66], [67].

VIII. Ras Abu Fontas B-2 Open Cycle Gas Turbine (OCGT) with Cogeneration.

It was commissioned in 2007 by Qatar Electricity & Water Co QPSC [68], [69]. Gas is the fossil fuel used in this plant.

IX. Al Kharsaah (Siraj1) PV Power Plant

It is the first large-scale solar power plant which is a significant stride in Qatar's renewable energy generation capacity. It was commissioned in October 2022 by a joint venture of TotalEnergies, QatarEnergy and Marubeni. The plant is located 80 km west of Doha. The Al Kharsaah Solar Power Plant in Qatar has a total installed peak capacity of 800 MW [70]. It was constructed in two phases, each of 400 MW. With this capacity, this plant can supply 10% of Qatar's peak energy demand over its lifetime with more than 1.8 million solar panels and is expected to avoid 26 MtCO2 (million tons of CO2) emissions over its lifetime [71], [72], [73], [74]. As per the latest annual statistics report (2022) issued by Qatar General Electricity and Water Corporation "Kahramaa", Phase-I with an installed capacity of 350 MW was commissioned in 2022 [75].

X. IC Solar Project

With an investment of 2.3 billion Qatari Riyals, an Engineering, Procurement, and Construction (EPC) contract was awarded by QatarEnergy for the IC solar Project. The project involves constructing two large-scale Solar PV power plants in Mesaieed Industrial City (MIC) and Ras Laffan Industrial City (RLIC). Planned to commence electricity production by the end of 2024 [76], [77], [78]. Both plants combined occupy a 10 square kilometres of land space and have a combined peak capacity of 880 MW. Capacities of each plant are as follows [79], [80], [81]:

a. IC Solar Project (MIC): 417 MW

b. IC Solar Project (RLIC): 458 MW

To maximize energy production, these plants utilize high-efficiency bifacial modules to maximize the received solar energy from both sides of the modules. The modules are mounted on single-axis trackers. Cleaning robots are employed to reduce dust accumulation, which reduces Operational and Maintenance (O&M) costs. This project is anticipated to reduce more than 28 MtCO2 throughout its lifespan [80].

The integration of solar power plants in Qatar, such as the Al Kharsaah and IC Solar Projects, is part of Qatar's strategic initiative to diversify its energy sources and reduce carbon emissions. Together, both projects will increase Qatar’s total renewable energy capacity to 1.675 GW by 2024 [82]. The country's abundant solar energy makes it a viable and sustainable option. These projects align with the Qatar National Vision 2030 (QNV 2030), aiming to enhance environmental protection and the efficient use of resources [[9], [79], [83]]. As per QNV 2030, Qatar aimed to generate 2% of its energy demand from renewable resources by 2020. Various projects have also committed to the same purpose including Qatar Rail Development Programme (QDRP) which integrates solar power into the infrastructure of rail [84], [85].

As part of its development, Qatar has set ambitious sustainability goals that demonstrate the country's determination to enfold clean energy and sustainability. First, the country aims to produce 2-4 GW of solar power by 2030. Moreover, 100% electric bus transportation was targeted to be achieved in 2022. Impressive progress has been seen in introducing electric buses but achieving 100% electric bus transportation remains a challenge. The transition involves infrastructure development, fleet replacement, and operational adjustments. In addition, in 2030, 10% electric vehicles is planned to be operating in Qatar with 400 electric charging stations that were planned to be set up by 2022, the exact number of the charging stations is not specified yet, however, Qatar has been working on expanding its electric vehicle (EV) charging infrastructure. Qatar has been promoting EV adoption through awareness campaigns and incentives. However, it is important to highlight that achieving 10% electric vehicles by 2030 requires sustained efforts, including policy support and consumer engagement [86].

A summary of the existing power plants along with the plants that are to be commissioned in 2024 are listed Table 3.

Table 3. Existing Power Plants in Qatar

Power Plant	Year of Installation	Expected Lifetime (Years)	Last Year of Operation	Type	Capacity (MW)
Mesaieed CCGT	2009	20-30	2039	Gas	1,990
Ras Laffan A Cogen GT	2003	20-30	2033	Gas	756
Ras Laffan B CCGT	2006	20-30	2036	Gas	1,025
Ras Laffan C (Ras Qartas) CCGT	2010	20-30	2040	Gas	2,730
Al Kharsaah (Siraj1)	2022	25-30	2052	Solar PV	800 (Phase I: 350 MW in 2022)

Power Plant	Year of Installation	Expected Lifetime (Years)	Last Year of Operation	Type	Capacity (MW)
Umm Al Houl IWPP	2017	25 (with possible extension of 5 years)	2047	Gas	2,520
Ras Abu Fontas B OCGT Cogen	1995	20-30	2025	Gas	609
Ras Abu Fontas B-1 OCGT	2002	20 (with 7-year extension)	2029	Gas	376.5
Ras Abu Fontas B-2 OCGT Cogen	2007	25	2032	Gas	567
IC Solar Project - Mesaieed Industrial City	2024	30	2054	Solar PV	417
IC Solar Project - Ras Laffan Industrial City	2024	30	2054	Solar PV	458

Potential Power Plants in Qatar

As per the latest annual statistics report (2022) issued by Qatar General Electricity and Water Corporation “Kahramaa”, Qatar is witnessing an average growth of peak demand for electricity at a rate of 2-4% annually which emphasizes the steady economic growth of Qatar [75]. In 2021, Qatar pledged in its NDC to decrease its GHG emissions in 2030 by 25% compared to a Business as Usual (BaU) scenario. The base year considered is 2019, in which CO2 emissions reached 89.49 MtCO2 [86]. In the same context, QatarEnergy updated its Sustainability Strategy to decrease GHG emissions by further developing Carbon Capture and Storage (CCS) technology to capture over 11 MtCO2/year by 2035. By these projects, 35% of Qatar's LNG facilities and 25% of its upstream facilities carbon prints will further reduce.

As an initiative to explore various renewable energy sources to diversify Qatar's sources and reduce its carbon emissions legal and regulatory framework has been set up. The Qatar General Electricity and Water Corporation (Kahramaa) has published regulations, standards, and specifications for electricity generation, transmission, and distribution, including solar energy. Qatar may consider creating a tailored legal or regulatory framework to support renewable energy development, drawing from international experiences. Possible schemes include contracts for difference, carbon pricing, green bonds, carbon capture and storage, and renewable energy certification [82].

Given the comparison in Table 1, and the witnessed development in Qatar to achieve a cleaner, greener, and sustainable future, the most promising renewable resources for the next 30 years may be:

I. Solar Energy – PV Solar Power Plants

It has a relatively low complexity. Solar technology is also straightforward to implement and well-understood, especially since recent projects in Qatar have adopted this technology, and the operational ones have shown good and as-expected outcomes. Cost of PV solar technology is competitive and decreasing due to continuous technological research and advancements. However, the space of land required is a significant challenge associated with solar power plants, generally; however, Qatar has ample unused desert land suitable for large solar farms. Solar energy sources are available in abundance;. Furthermore, notable projects such as the Al Kharsaah plant and upcoming the IC project in Mesaieed and Ras Laffan are set to enhance Qatar's solar output significantly [82], [87].

Despite the great strides taken by Qatar in implementing solar power projects, however, from the end of 2024 onwards only 1.675 GW of Qatar's power production will be coming from these projects; Al Kharsaa Power Plant and IC Solar Power Project. Hence, further developments are required to meet the QNV 2030 goal of installing 2-4 GW of solar energy by 2030.

Typically, a large-scale solar PVpower plant has capital costs of $1,516 per kW. This cost is projected to reduce to between $513/kW to just under $700/kW by 2050 [88]. However, Qatar's solar PV plants; the Al Kharsaah Solar Power Project and IC Power Project, have capital costs in the range of $581.25 - $722.29 per kW due to several factors.

- Efficient Technology

  The use of advanced technologies like bifacial solar modules and trackers helps optimize electricity production, which can lead to lower capital costs per unit of capacity.

- Economies of Scale

Large-scale projects often benefit from economies of scale, which can reduce the cost per kW. Al Kharsaah, for example, is an 800MW project, which is quite substantial.

- Competitive Bidding

  The project was awarded through a competitive tender process, which can drive down costs as companies bid to offer the most cost-effective solutions.

- Strategic Partnerships

Partnerships with experienced international firms like Marubeni and Total can bring in expertise and investment, potentially reducing the overall cost.

- Government Support

Government policies and support in Qatar may also contribute to favorable financing conditions and lower capital costs.

- Local Conditions

Qatar's high levels of sunlight and vast unoccupied spaces are ideal for solar power, which can reduce the cost of land and maximize the efficiency of solar panels.

These factors combined can contribute to the competitive capital costs of solar PV plants in Qatar, positioning them favorably in the global market for renewable energy. It's a reflection of Qatar's commitment to diversifying its energy sources and reducing reliance on gas for power generation.

II. Waste-to-Energy – Biomass Power Plants

Involves the conversion of waste materials into electricity. They are moderate in complexity. Although costs are relatively high, it can be offset by the savings on waste disposal and the generation of energy. Land required can be minimized as it can be integrated into existing waste management facilities. Based on the continuous generation of domestic waste, source availability can be considered reliable. Current initiatives in this regard in Qatar include The Domestic Solid Waste Management Centre in Mesaieed and plans for a new waste management centre [82].

Qatar is exploring waste-to-energy solutions as part of its renewable energy portfolio. In fact, the Domestic Solid Waste Management Centre in Mesaieed currently generates 50 MW of electricity per day from waste. In June 2022, Qatar announced plans to enhance its recycling initiative by establishing a new waste management center where electricity will be generated through recycling and processing waste [82].

III. Wind Energy – Onshore/Offshore Wind Turbines

High in complexity; requires detailed studies to ensure viability and efficiency. However, along with other sources, it will support the desired diversification of energy sources in Qatar. It is worth mentioning that onshore wind turbines are lower in complexity compared to offshore turbines in terms of establishment, construction, and maintenance. Initial investment is high, but operational costs are low. Considerable land is required for large-scale wind farms. Studies indicate significant capacity in the northern part of Qatar [82].

Given these factors, solar energy emerges as the most viable renewable resource for Qatar, considering its simplicity, cost-effectiveness, and the high availability of solar radiation. This can explain the reason why the first renewable energy power plants were solar-energy-based. Waste-to-energy also presents a practical solution by addressing waste management and energy production simultaneously. Wind energy, while still in the exploratory phase, could complement these resources if found feasible.

Qatar's commitment to generating 20% of its electricity from renewable sources by 2030 and achieving a carbon-zero footprint by 2050 underlines the strategic importance of these resources. The country's investment in renewable energy infrastructure is expected to continue, driven by the need for sustainable and diversified energy sources [82].

IV. Concentrated Solar Power (CSP)

The possibility of using hybrid Concentrated Solar Power (CSP) systems in Qatar is an intriguing prospect, especially when considering the nation's commitment to diversifying its energy sources. A hybrid CSP system combines the benefits of CSP with

Photovoltaic (PV) technology, potentially offering a more consistent and efficient energy supply. Viability of Hybrid CSP in Qatar can be explained by the following factors. First, Availability of Efficient Systems. With advancements in solar technologies, hybrid CSP systems have become more efficient. The integration of CSP with PV allows for the generation of electricity from direct sunlight while also utilizing the heat from CSP for energy storage or additional power generation [89].

In terms of cost, the initial cost of setting up a hybrid CSP system can be high. However, the long-term benefits, such as the ability to store thermal energy and generate power even during non-sunny periods, can offset the initial investment. The cost-effectiveness of such systems is improving with technological advancements and economies of scale [90]. Key factors to consider include the solar irradiance in Qatar, which is favorable for both CSP and PV technologies. Additionally, land availability for large-scale solar farms is crucial, and Qatar has suitable unused desert areas that could be utilized for this purpose [89].

In conclusion, hybrid CSP systems could be a viable option for Qatar, given the country's high solar potential and strategic initiatives to increase its share of renewable energy. The integration of CSP and PV could offer a robust solution to meet energy demands while supporting Qatar's environmental goals. However, detailed feasibility studies and economic analyses would be necessary to determine the practicality of implementing such systems in Qatar.

CHAPTER 4: METHODOLOGY

In this chapter, the problem of this paper is explained. Then, a model is constructed to target the requirement of developing a framework that enables optimal long-term planning and decision-making of the electric power systems infrastructure. Finally, based on the model, the required data is collected from official government resources in Qatar to be implemented using IBM ILOG CPLEX Optimization Studio.

Problem Description

The proposed planning problem aims to find the optimal long-term investment plan and the power system's operating schedule while meeting the energy demand over the planning time horizon. In this problem, several types of power plant technologies are considered, including existing and potential power plants. Specific sizes/capacities of the same type of technology are also considered. The aforementioned factors add complexity to the problem considered in this paper.

A model is constructed to target the requirement of developing a framework that enables optimal long-term planning of the electric power systems infrastructure that satisfies the electricity demand while conforming to the constraints imposed by the system's operations and the variability and intermittency of renewable energy sources. The model is bound by a finite time horizon and optimizes the use of existing as well as potential power plants to be installed during the planning horizon.

The objective of the optimization problem is to minimize the total cost, annualized fixed cost, and variable cost, of the system by optimizing the combination of power plants in the system including power plants that already exist, and potential power plants that use renewable energy to produce energy. The existing power plants, their energy sources, and their types are known. Potential power plants that are based on renewable energy are considered, with different technologies (types), and capacities. However, the system has several constraints characterized by the necessity to satisfy the electricity demand, not surpassing the maximum amount of allowed CO_2 emissions, and considering the lifetime of the existing and suggested potential power plants. The mathematical model is explained below with the known parameters, decision variables, objective function, and constraints.

Mathematical Formulation

- Parameters

There are several known parameters to the mathematical problem including parameters related to the existing power plants. The parameters of the mathematical model are illustrated below.

T Number of time periods; planning horizon (for instance, 30 years) with $t = 1, 2, \ldots, T$.

P_1 Set of potential power plants, indexed by p, where each plant is characterized by a specific type (technology), capacity, fixed cost, variable cost, lifetime, and CO_2 emissions.

P_2 Set of existing power plants, indexed by p. Characterized by specific types, capacities, and variable costs, and CO2 emissions.

P Set of all power plants combined; existing and potential where $P = P_1 \cup P_2$, indexed by p.

F_p Fixed cost (in USD) for a potential power plant p where $p \in P_1$. Not considered for existing plants as the fixed cost has already been settled.

C_p Variable production cost (USD/MW) for a plant p, where $p \in$ P.

E_p CO_2 emissions in (million tons per MW) from plant of type p based on type and annual generation.

B_t Maximum amount of CO_2 emissions in (million tons) allowed in Qatar during period t.

τ_p The lifetime (years) of a potential power plant for $p \in P_1$.

$\bar{\tau}_p$ Residual lifetime (years) for existing power plants $p \in P_2$.

D_t Forecasted demand of electricity during period t in Qatar in (MW).

Cap_t The capacity of plant p, where p ∈ P in (MW).

λ_p Power loss rate for plant p, where $p \in$ P.

- Decision Variables

The decision variables of the mathematical model are related to the set-up and shutdown times of the power plants to optimize power systems' operating schedules.

s_{pt} Binary variable that represents the set-up time/date decision of plant $p \in P_1$

$s_{pt} = 1$ if plant $p \in P_1$ is set-up at the beginning of period t, and 0, otherwise.

f_{pt} Binary variable that represents the shutdown time/date decision of plant $p \in P_1$

$f_{pt} = 1$ if plant $p \in P_1$ is closed/shutdown at the end of period t, and 0, otherwise.

y_{pt} Binary variable that takes value 1 if plant $p \in$ P is operated during period t, and 0, otherwise.

x_{pt} Amount of electricity (MW) produced by plant $p \in$ P, at year t.

- Objective Function

The objective function of the mathematical model minimizes costs (sum of annualized fixed costs and variable costs), to find the optimal power plants set-up and operating schedules.

$$Min \sum_{p=1}^{P_1} \sum_{t=1}^{T} F_p y_{pt} + \sum_{p=1}^{P} \sum_{t=1}^{T} C_p x_{pt}$$

F_p is not considered for existing power plants since it is out of the model's scope. Only variable cost is considered for existing power plants.

- Constraints

  - Constraint 1

$$\sum_{t=1}^{T} t\, s_{pt} + \tau_p - 1 = \sum_{t=1}^{T+\alpha} t\, f_{pt} \quad \forall\, p \in \mathrm{P}_1$$

This constraint implies that plant p that has a lifetime of τ_p, where $setup\ date\ + lifetime\ =\ close\ date$. Note that the close date can occur after T and up to date $T + \alpha$.

  - Constraint 2

$$\sum_{t=1}^{T} s_{pt} \leq 1 \quad \forall\, p \in \mathrm{P}_1$$

Each plant $p \in \mathrm{P}_1$ that is of a certain capacity can be set up only once during the planning horizon.

  - Constraint 3

$$\sum_{t=1}^{T+\alpha} f_{pt} \leq 1 \quad \forall\, p \in \mathrm{P}_1$$

Each plant $p \in \mathrm{P}_1$ can be shut down only once during the planning horizon. Where $t = 1, \dots, T + \alpha$. Moreover, α is extra time (e.g., 30 years) to account for the power plants that may be shutdown beyond the planning horizon.

- Constraint 4

$$\sum_{h=1}^{t} s_{ph} - \sum_{h=1}^{t-1} f_{ph} = y_{pt} \quad \forall\, t = 1, \dots, T \;\; and\; p \in \mathrm{P}_1$$

This constraint enforces that if any plant p has been set-up during any period between 1 and t, and was not closed between period 1 and $t - 1$, then it is operated during period t.

- Constraint 5

$$\sum_{t=1}^{T+\alpha} y_{pt} = \tau_p \quad \forall\, t = 1, \dots, T \;\; and\; p \in \mathrm{P}_1$$

The summation of y_{pt} throughout the upper bound of the time horizon should be equal to the lifetime of potential plant p.

- Constraint 6

$$\sum_{t=1}^{T+\alpha} y_{pt} = \bar{\tau}_p \quad \forall\, t = 1, \dots, T + \alpha \;\; and\; p \in \mathrm{P}_2$$

The summation of y_{pt} throughout the upper bound of the time horizon should be less than or equal to the remaining lifetime of existing plant p.

- Constraint 7

$$s_{pt} \leq y_{pt} \;\; \forall\, t = 1, \dots, T \;\; and\; p \in \mathrm{P}_1$$

To imply that y_{pt} is 1 when s_{pt} is operated in period p, and zero, otherwise.

- Constraint 8

$$\sum_{p \in \mathrm{P}_1 \cup \mathrm{P}_2} (1 - \lambda_p) x_{pt} \geq D_t \quad \forall\, t = 1, \dots, T$$

The constraint above is to meet the demand for each year t while accounting for the power line losses, where λ_p is the loss rate for plant p that depends on the distance the power is transmitted through.

- Constraint 9

$$\sum_{p \in \mathrm{P}_1 \cup \mathrm{P}_2} E_p x_{pt} \leq B_t \quad \forall\, t = 1, \dots, T$$

Total CO_2 emission is less than the predetermined maximum allowed amount B_t for all t.

- Constraint 10

$$\text{min\_}Cap_t y_{pt} \leq x_{pt} \leq Cap_p y_{pt} \quad \forall\, t = 1, \dots, T \text{ and } p \in \mathrm{P}$$

The supply of each plant p in t is bound by a minimum and a maximum capacity for all plants (potential and existing plants) during all time periods t. The minimum capacity of the power plants is assumed to be 25% of the original capacity, and the maximum capacity is 100% of the same capacity.

- Constraint 11

$$x_{pt} \geq 0 \;\; \forall\, p, t$$

$$f_{pt}, s_{pt} \text{ and } y_{pt} = 0 \text{ or } 1 \;\; \forall\, p, t$$

Implies non-negativity of supply and binary values for the other decision variables.

Data Collection

Several assumptions were made while collecting the data to run the model. The assumptions made in this project are explained below.

1. Maximum expected lifetime is assumed for all power plants.
2. Only CO_2 emissions are considered in this project. Other greenhouse gases (GHGs) are not considered in the model nor data collection. This is because CO_2 is the most dominant GHG produced as a result of burning fossil fuels. Targeting the reduction of CO_2 emissions may also assist in the reduction of other harmful GHGs. However, it is acknowledged that all GHG emissions need to be targeted and studied.
3. CO_2 reductions resulting from the Al Kharsaah Plant and the IC Project Plants are annualized.
4. CO_2 emissions are assumed to be zero for renewable energy sources except biomass power plants.
5. Power plant locations are not considered in this project, however, Qatar has substantial land areas that are not in use.
6. CO_2 emissions from other sectors are not considered. Only electricity generation emissions are.

Regular maintenance and upgrades can extend the plant's life and improve its efficiency and reliability over time. Qatar conducts regular maintenance and upgrades on its power plants. For example, the Qatar Electricity & Water Company (QEWC) signed a contract with GE Gas Power to provide upgrades and maintenance services for nine years for three 9F gas turbines at the Ras Abu Fontas B2 (RAF B2) Cogeneration Plant [91].

This contract is part of Qatar’s efforts to enhance energy security and ensure the reliable operation of its power facilities. Such initiatives demonstrate Qatar’s commitment to maintaining and improving its energy infrastructure to meet the country’s growing demands for electricity. Therefore, all the existing power plants will assume the maximum expected lifetime. For example, for a CCGT power plant, the typical lifetime extends between 20-30 years, in this project, 30 years will be assumed for CCGT plants.

As per the latest annual statistics report (2022) issued by Qatar General Electricity and Water Corporation “Kahramaa”, the total transmitted energy in 2022 was 51,325,203 MWh from the nine existing power plants as illustrated in Table 4. It shows a 4.7% increase compared to 2021 energy transmission which was 48,329 GWh. 2021’s energy transmission was increased by 5.5% compared to the previous year, 2020. This increase can be attributed to several factors. Firstly, the continuous economic growth which leads to energy demand growth across various sectors. Demand growth; specifically residential demand, can also be attributed to population growth. Industrial expansion and the increased infrastructure projects that were held in preparation for the FIFA World Cup 2022 may have also contributed to the increase in electricity demand. Finally, climate factors such as temperature and weather conditions’ variations and may have increased the use of cooling or heating systems which in turn influences the transmission levels [92].

Table 4. Monthly Energy Transmitted in 2022, MWh [75]

Power Plant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total per Year
Mesaieed CCGT	211015	197438	420533	613866	977829	1124216	1233207	1302270	1212557	1019264	798124	742226	9852545
Ras Laffan A Cogen GT	316589	284424	356841	311275	314837	304664	309800	310386	299535	312006	301523	307954	3729834
Ras Laffan B CCGT	502696	433308	468941	525347	608028	561685	620796	628584	602422	613910	469382	383654	6418753
Ras Laffan C (Ras Qartas) CCGT	562735	488737	630631	802054	1130791	1403395	1503655	1482845	1370129	1279497	948898	652644	12256011
Al Kharsaah (Siraj1)	0	0	0	0	0	4489	77827	81192	98653	123163	112268	96613	594205
Umm Al Houl IWPP	567183	510363	666506	683386	868564	977904	1124669	1365461	1135598	960418	886267	582049	10328368
Ras Abu Fontas B OCGT Cogen	189739	157758	187967	251307	250841	258853	241279	263032	293893	246518	229864	170955	2742006
Ras Abu Fontas B-1 OCGT	150084	210758	187895	260405	116193	255942	237817	274425	135010	94656	93294	93202	2109681
Ras Abu Fontas B-2 OCGT Cogen	234188	179665	257954	295424	260757	276558	277570	400391	364681	254931	238804	252877	3293800
Total per Month	2,734,229.00	2,462,451.00	3,177,268.00	3,743,064.00	4,527,840.00	5,167,706.00	5,626,620.00	6,108,586.00	5,512,478.00	4,904,363.00	4,078,424.00	3,282,174.00	51,325,203.00

In 2022, the generated energy illustrated in Table 5 reached 54,623,285 MWh. This shows that in 2022 there were total electricity losses of 3,298,082 MWh, which is around 6% of the generated electricity in 2022. Using the below formula, the total transmission losses in 2022 were around 376.5 MW since 2022 is a non-leap year i.e. with 365 days, hence it had a total of 8760 hours. These losses can be influenced by factors such as the distance electricity travels, the quality of the transmission infrastructure, and environmental conditions. For potential power plants, the transmission losses are assumed to be 2-3%. Location, technology, and the quality of the transmission infrastructure are factors that influence the transmission loss rate of a power plant .

$$Average\ Power\ (MW) = \frac{Total\ Generated\ Energy\ (MWh)}{Hours\ (h)} = \frac{3{,}298{,}082\ \text{MWh}}{8{,}760\ hours}$$

$$\approx 376.5\ \text{MW}$$

Power loss rate is calculated as the following:

$$Power\ Loss\ Rate = \frac{Generated\ Power\ (MW) - Transmitted\ Power\ (MW)}{Generated\ Power\ (MW)}$$

For each power plant, power loss rate is calculated for the monthly generation/ transmission of 2022 and the average rate is considered in the project.

Table 5. Monthly Energy Generation in 2022, MWh [75]

Power Plant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total per Year
Mesaieed CCGT	219510	205222	433726	632277	1005781	1155993	1267530	1338298	1246632	1048488	821188	764210	10138855
Ras Laffan A Cogen	343142	308403	384944	337112	341295	329817	336126	336849	324942	338333	327356	334515	4042834

GT													
Power Plant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total per Year
Ras Laffan B CCGT	534853	462586	499818	556865	645031	597738	660973	668514	641132	653948	502983	413913	6838354
Ras Laffan C (Ras Qartas) CCGT	597994	519427	667006	843335	1181500	1462870	1563716	1542901	1427505	1334438	995509	691820	12828021
Al Kharsaah (Siraj1) - Phase I	0	0	0	0	0	4489	77827	81192	98653	123163	112268	96613	594205
Umm Al Houl IWPP	657106	590811	766373	773118	971690	1077217	1228183	1480683	1247102	1073437	991748	679744	11537212
Ras Abu Fontas B OCGT Cogen	213211	179984	212677	277847	277922	284861	269838	293518	323607	276090	255666	196360	3061581
Ras Abu Fontas B-1 OCGT	150220	210943	188059	260633	116299	256170	238037	274675	135134	95000	93376	93288	2111834
Ras Abu Fontas B-2 OCGT Cogen	248409	189461	272388	311843	277424	293054	292218	413354	381539	269710	253250	267739	3470389
Total per Month	2,964,445.00	2,666,837.00	3,424,991.00	3,993,030.00	4,816,942.00	5,462,209.00	5,934,448.00	6,429,984.00	5,826,246.00	5,212,607.00	4,353,344.00	3,538,202.00	54,623,285.00

As per Kahramaa's previous years' annual statistics reports of 2018 - 2022, Table 6 was generated. The table illustrates key indicators for each year from 2014 – 2022 generated electricity in GWh, transmitted electricity, maximum demand, and minimum demand, with their percentage change as compared to the previous year, respectively, whereever available. There is an evident growth in the energy demand and generation throughout the years. However, a dip in the generation was witnessed in 2020 which can be attributed to the several factors. Firstly, the COVID-19 pandemic impact. Lockdowns, travel restrictions, and reduced industrial production led to a decrease in electricity demand. Many businesses and factories temporarily shut down, resulting in lower electricity consumption. Secondly, the reduced industrial activities where several manufacturing plants, offices, and retail spaces operated at reduced capacity or remained closed altogether. Moreover, with remote work becoming widespread, office buildings consumed less electricity. Reduced office lighting, air conditioning, and other intensive energy-consuming operations contributed to the overall decrease in demand. People have also spent more time at their homes during lockdowns which led to an increased domestic electricity consumption [93]. However, this surge was incomparable to the drop in commercial and industrial demand.

However, Qatar's situation was somewhat unique. As one of the world's largest producers of natural gas, Qatar has abundant fuel resources for its power plants. The country did not report any significant disruptions in the availability of natural gas for power generation during the pandemic. Moreover, despite the dip in 2020, the subsequent years showed a gradual recovery as economic activities resumed, and the country was preparing to host the FIFA World Cup 2022.

Table 6. Qatar's Electricity Growth Key Indicators (2014-2022) [75], [92], [94], [95], [96]

Year	Generated, GWh	% Change	Sent Out, GWh	% Change	Maximum Demand, MW	% Change	Minimum Demand, MW	% Change
2014	38,693		36,125		6,740		2,155	
2015	41,499	7.3%	38,852	7.5%	7,270	7.9%	2,320	7.7%
2016	42,307	1.9%	39,668	2.1%	7,435	2.3%	2,410	3.9%
2017	45,555	7.7%	42,806	7.9%	7,855	5.6%	2,600	7.9%
2018	47,913	5.2%	44,655	4.3%	7,875	0.3%	2,410	-7.3%
2019	49,873	4.1%	46,435	4.0%	8,475	7.6%	2,600	7.9%
2020	49,259	-1.2%	45,826	-1.3%	8,600	1.5%	2,825	8.7%
2021	51,641	4.8%	48,329	5.5%	8,875	3.2%	2,875	1.8%
2022	54,623	5.8%	51,325	6.2%	9,400	5.9%	2,910	1.2%

As official reports have not announced the generated electricity and demand so far for the year 2023, its demand was forecasted along with the years 2024 – 2054 i.e. 30 years from 2024. The used forecasting method was exponential smoothing. This method can be used to forecast data with no clear trend or seasonality [97]. As per the forecasted data, the electricity demand is expected to continue growing in the next 30 years. The forecasted demand is illustrated in Table 7.

Table 7. Forecasted Maximum Demand in MW & % Change

Year	Maximum Demand, MW	% Change
2023	9,678	3.0%
2024	9,833	1.6%
2025	10,292	4.7%

Year	Maximum Demand, MW	% Change
2026	10,447	1.5%
2027	10,905	4.4%
2028	11,060	1.4%
2029	11,519	4.1%
2030	11,674	1.3%
2031	12,132	3.9%
2032	12,287	1.3%
2033	12,746	3.7%
2034	12,901	1.2%
2035	13,359	3.6%
2036	13,514	1.2%
2037	13,973	3.4%
2038	14,128	1.1%
2039	14,586	3.2%
2040	14,741	1.1%
2041	15,200	3.1%
2042	15,355	1.0%
2043	15,813	3.0%
2044	15,968	1.0%
2045	16,427	2.9%
2046	16,582	0.9%
2047	17,040	2.8%
2048	17,195	0.9%
2049	17,654	2.7%
2050	17,809	0.9%
2051	18,267	2.6%
2052	18,422	0.8%
2053	18,881	2.5%
2054	19,036	0.8%

In 2021, Qatar pledged in its NDC to decrease its GHG emissions in 2030 by 25% compared to a Business as Usual (BaU) scenario. The base year considered is 2019, in which CO2 emissions reached 101.02 MtCO2 [86]. Therefore, in 2030, the expected CO2 emissions would be 75.76 MtCO2.

Official data resources have only provided the CO_2 emissions up to the year 2022 [98]. Assuming that the reduced CO_2 emissions resulting from Al Kharsaah plant and the IC Project will be annualized equally from their year of commissionning along their whole lifespan which is assumed to reach 30 years, AlKharsaah would contribute to reducing 0.87 $MtCO_2$ yearly, whereas the IC Project, including both power plants, would reduce 0.93 $MtCO_2$ yearly. These values will be used in setting the maximum allowed CO_2 emmissions. Al Kharsaah CO_2 emissions reduction will be considered from 2023 until the end of the planning horizon, and the IC Project contribution will be considered from 2025 onwards as it will be commisssioned by the end of 2024. These values will be deducted from the average of CO_2 emissions from the year 2000 until 2022. The average CO_2 emissions throughout these years is 103.69 $MtCO_2$. In 2023, it is assumed that the CO_2 emissions should have reduced from the commissionning of Al Kharsaah Power Plant. Hence, the CO_2 emissions will be assumed to be 102.82 $MtCO_2$. In 2025 until 2029, CO_2 emissions should not exceed 101.89 $MtCO_2$. In 2030, the emissions should meet Qatar's NDC and not exceed 25% of 2019's emissions, which is equal to 75.76 $MtCO_2$. In Figure 2, the CO_2 emissions in Qatar have had an increasing trend. This is expected to reduce in the next coming years considering all the efforts and measures taken by Qatar to reduce its carbon print.

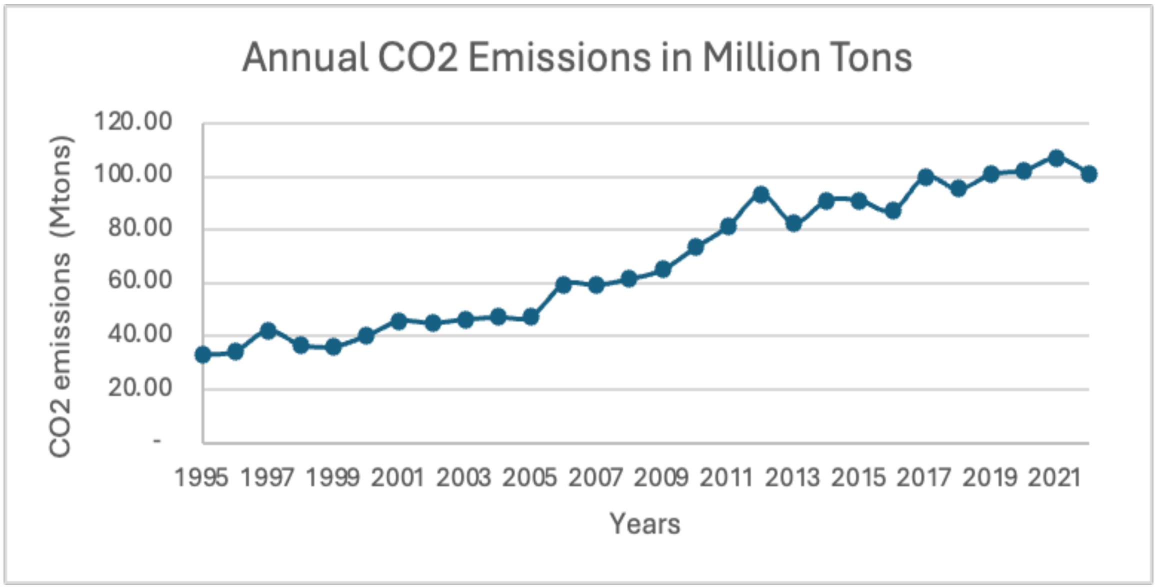

Figure 2. Annual CO2 Emissions in Qatar [98]

Table 8 illustrates the amount of CO_2 emissions based on power plant type and fuel used. Almost all power plants in Qatar are fueled by natural gas, except for the newly established power plants which are powered by solar energy. For the renewable resources power plants, it is assumed that they emit zero CO_2 emissions. Except for biomass power plants [99], which may have negligible near-zero CO_2 emissions; as low as 0.000935 Mtons/MW.

Table 8. Existing Power Plants CO2 Emissions Based on Type & Fuel Used [75]

Power Plant	Type	Fuel	Capacity (MW)	CO2 Emissions Intensity (MtCO2/MW)
Mesaieed CCGT	CCGT	Gas	1,990.00	0.0039
Ras Laffan A Cogen GT	Cogen	Gas	756	0.0039
Ras Laffan B CCGT	CCGT	Gas	1,025.00	0.0039
Ras Laffan C (Ras Qartas) CCGT	CCGT	Gas	2,730.00	0.0039

Power Plant	Type	Fuel	Capacity (MW)	CO2 Emissions Intensity (MtCO2/MW)
Al Kharsaah (Siraj1)	Solar PV	Solar	800	0
Umm Al Houl IWPP	IWPP	Gas	2520	0.0020
Ras Abu Fontas B OCGT Cogen	Cogen	Gas	609	0.0039
Ras Abu Fontas B-1 OCGT	OCGT	Gas	376.5	0.0057
Ras Abu Fontas B-2 OCGT Cogen	Cogen	Gas	567	0.0039
IC Solar Project - Mesaieed Industrial City	Solar PV	Solar	417	0
IC Solar Project - Ras Laffan Industrial City	Solar PV	Solar	458	0

Table 9 illustrates the estimated annual variable cost (O&M cost) for the existing power plants in Qatar. Fixed costs are assumed to be zero as they have already been remunerated. Table 10 illustrates the same information for the potential power plants; Solar PV, CSP, Onshore Wind, Offshore Wind, and Biomass. Fixed costs are annualized over their lifetime. Lifetime is expected as 30 years for all potential power plants as it is the typical maximum lifespan for these powerplants given the necissity of regular maintenance. Moreover, the assumed capacity for all potential power plants is 2000 MW. The eleven potential power plants consist of 3 Solar PV, 2 CSP, 2 Onshore Wind, 2 Offshore Wind, and 2 Biomass.

Table 9. Estimated Annual Variable Costs of Existing Plants (in USD)

Power Plant	Type	Estimated Operational Cost (USD/kW)	Capacity (MW)	Estimated Annual O&M Cost (Million USD)
Mesaieed CCGT	CCGT	$11.00	1,990.00	$21.89
Ras Laffan A Cogen GT	Cogen	$20.00	756	$15.12

Power Plant	Type	Estimated Operational Cost (USD/kW)	Capacity (MW)	Estimated Annual O&M Cost (Million USD)
Ras Laffan B CCGT	CCGT	$11.00	1,025.00	$11.275
Ras Laffan C (Ras Qartas) CCGT	CCGT	$11.00	2,730.00	$30.03
Al Kharsaah (Siraj1)	Solar PV	$17.00	800	$13.6
Umm Al Houl IWPP	IWPP	$30.00	2520	$75.6
Ras Abu Fontas B OCGT Cogen	Cogen	$20.00	609	$12.18
Ras Abu Fontas B-1 OCGT	OCGT	$13.00	376.5	$4.8945
Ras Abu Fontas B-2 OCGT Cogen	Cogen	$20.00	567	$11.34
IC Solar Project - Mesaieed Industrial City	Solar PV	$17.00	417	$7.089
IC Solar Project - Ras Laffan Industrial City	Solar PV	$17.00	458	$7.786

Table 10. Potential Power Plants Fixed & Variable Costs [25], [100], [101]

Energy Source	Fixed Cost (USD/kW)	Operational Cost (USD/kW/year)
Solar PV	$581.25 - $722.29	$9.2
CSP	$3,910 - $6,355	$71
Onshore Wind	$1,200 -$2,500	$31
Offshore Wind	$3,000 - $5,000	$62
Biomass	$2,500 - $5,000	$80 - $120

CHAPTER 5: RESULTS & DISCUSSION

The objective function yielded an optimal cost; fixed and variable, of $546,337.01 Million. The resulting power plant combination will be discussed in this chapter.

As per the results illustrated in Table 11, a solar PV power plant of 2000 MW is required in the fourth year of the planning horizon, followed by another solar PV power plant in the ninth year of the same capacity. Since these capacities are substantially high, each plant can be divided into two large-scale plants, each with 1000 MW capacity.

New solar PV power plant(s) need to be set up and start operations from year 2028. Taking this into account, the goal of installing 2-4 GW of solar energy by 2030 would be met. 2000MW from the planned power plant, 800MW from Al Kharsaah power plant, and 875MW from the IC Solar Power project. Hence, a total of 3,675MW; 3.675MW of solar energy would be installed by 2030.

Then at year 2033, another 2000 MW of solar PV technology is expected to start operating. This can also be divided into two large-scale power plants. In the eleventh year, another solar PV plant is required to start operating.

Two onnshore wind power plants of 2000MW each would be required in years 15 and 16, consecutively. Then, two 2000MW biomass power plants during the 17th and 19th years, followed by two 2000MW offshore wind power plants in years 24 and 25. Finally, during the years 29 and 30, CSP power plants can be set-up. However, if their costs remain high, they can be replaced by other renewable energy plants, this also applies to all other potential power plants.

Solar PV is optimal due to its reduced costs resulting from technology advancements. Other technologies are expected to have reduced costs by the year they are required given the vast research efforts the world is witnessing to shift towards greener and more sustainable ways to generate power. Moreover, it is crucial to diversify the renewable resources while accounting for optimal costs and efficiencies.

Table 11. Start-up / Shutdown Times of Potential Power Plants

Potential Plant	Start-up year	Shutdown year
Solar PV	11	40
CSP	29	58
Onshore Wind	15	44
Offshore Wind	25	54
Biomass	19	48
Solar PV	4	33
CSP	30	59
Onshore Wind	16	45
Offshore Wind	24	53
Biomass	17	46
Solar PV	9	38

The total generated electricity (in MW) from year 2025 to 2030 is shown in Table 12. With the losses, the transmitted amount would be exactly equal to the demand.

Table 12. Generated Power & Forecasted Demand

Planning Year	Year	Total Annual Generation x_{pt} (MW)	Forecasted Demand (MW)
1	2025	10816.7	10291.8
2	2026	10993.9	10446.8
3	2027	11509.3	10905.3
4	2028	11489.9	11060.3
5	2029	11995.7	11518.8
6	2030	12216.1	11673.8
7	2031	12731.5	12132.3
8	2032	12905.7	12287.3

Planning Year	Year	Total Annual Generation x_{pt} (MW)	Forecasted Demand (MW)
9	2033	13255.1	12745.8
10	2034	13457.3	12900.8
11	2035	13800.5	13359.3
12	2036	13955.5	13514.2
13	2037	14515.1	13972.7
14	2038	14689.3	14127.7
15	2039	15003.7	14586.2
16	2040	15152.8	14741.2
17	2041	15708.1	15199.7
18	2042	15866.3	15354.7
19	2043	16334.1	15813.2
20	2044	16492.3	15968.2
21	2045	16960.1	16426.7
22	2046	17118.3	16581.7
23	2047	17586.1	17040.2
24	2048	17511.9	17195.1
25	2049	17979.7	17653.6
26	2050	18137.9	17808.6
27	2051	18605.7	18267.1
28	2052	18763.9	18422.1
29	2053	19248.1	18880.6
30	2054	19406.2	19035.6

The generation throughout the time horizon from all power plants is shown in Table 15. Taking the 15th year of the planning horizon as an example, Table 13 illustrates the operative power plants at that time, and their generation. After accounting for the losses, the total generation from all power plants during the same year is equal to the forecasted demand, which is 14586.22 MW. The same applies to the other years within the 30-year planning horizon.

Table 13. Generated Electricity in MW At Year 15 (2039)

Plant Type	Loss rate	x_{pt} at T= 15 (2039)	Net generation with losses
Solar PV	0.02	2000	1960
Onshore Wind	0.02	1978.67357	1939.10
Solar PV	0.02	2000	1960
Solar PV	0.02	2000	1960
Mesaieed CCGT	0.03	1990	1930.71
Ras Laffan C (Ras Qartas) CCGT	0.05	2730	2600.94
Al Kharsaah (Siraj1)	0	800	800
Umm Al Houl IWPP	0.11	630	560.46
IC Solar Project - Mesaieed Industrial City	0	417	417
IC Solar Project - Ras Laffan Industrial City	0	458	458
Total Generation at T = 15			14586.22

The Gantt chart in Figure 3 represents the start-up and shutdown times of all power plants. Existing power plants are already in operation and by the beginning of the planning horizon, they would have already started. This ensures the maximum utilization of the existing power plants, considering their CO2 emissions are within the allowable limits throughout their lifetime. Then, new plants that are set up are of renewable energy sources which ultimately the country may have a fully renewable energy network grid that is efficient, meets the continuously increasing demand, and with optimal costs.

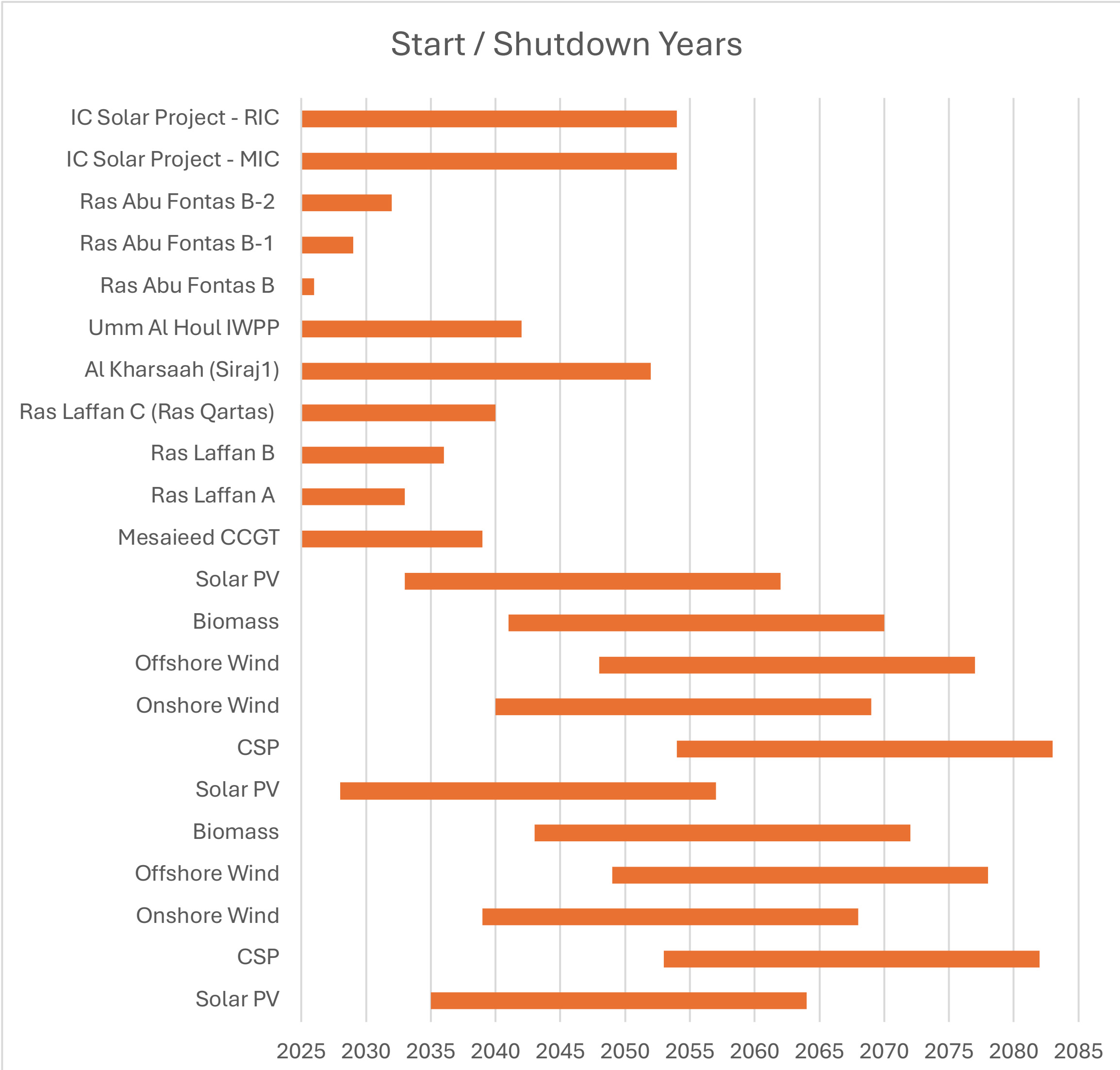

Figure 3. Gantt Chart Representing the Start-up / Shutdown Years of All Power Plants

As depicted in the Gantt chart, by the year 2048, the country could achieve a 100% renewable energy power grid if the necessary measures were implemented and infrastructure requirements were met. This includes Al Kharsaah, and IC solar power plants.

CHAPTER 6: CONCLUSION

In conclusion, given that human activities are the main driver of climate change, primarily through the release of greenhouse gases (GHGs), it is everyone's responsibility to mitigate the risk of increasing GHG emissions. Qatar's commitment to generating 20% of its electricity from renewable sources by 2030 and achieving a carbon-zero footprint by 2050 underlines the strategic importance of these resources. The country's investment in renewable energy infrastructure is expected to continue, driven by the need for sustainable and diversified energy sources.

Qatar has implemented several programs and projects to control CO2 emissions and air pollution, and to increase the renewable energy sources integration. All these efforts are being made to transform Qatar into an advanced country by the year 2030. In the 2018 Environmental Performance Index, Qatar was the first ranking GCC country by its positive performance in performing measures of sustainable development and environmental protection. Qatar has been showing advancements in the sustainability and environment protection through several actions. Including the set-up of three remarkably efficient solar PV power plants and setting reasonable goals to reach a specific amount of generated electricity from solar PV panels. In addition to the goal set by 2030 to reduce CO2 emissions of the country from all sectors.

This project focused on the power generation sector. Five renewable power plant types were considered to find the optimal power plants to be set up in Qatar to satisfy the increasing demand and cope up with the significant development of the country, and simultaneously reduce the global carbon print of Qatar. Three solar PV, and two of each CSP, on-shore wind, off-shore wind, and biomass power plants were considered as potential power plants. A Mixed-Integer Linear Programming (MILP) model was formulated to find the optimal power plant setup in terms of cost and CO_2 emissions. The results were in favor of solar PV technology, which may be resulting from the enhancements and reduced costs that solar PV technologies are witnessing as a result of the continuous research and development efforts. The same is expected to be seen in the future for other renewable energy systems. As per the results, solar PV was followed by onshore wind turbines, biomass, offshore wind, and Concentrated Solar Power (CSP), respectively. This is due to their fixed and variable costs which are still very high for CSP. It is worth mentioning that diversifying the energy sources used in the national power grid is crucial for the stability of the system, therefore more funds need to flow to less mature technologies that have a crucial role to play in the energy transition. Moreover, there is a good possibility of transitioning into a 100% renewable power grid in Qatar in year 2048. Although renewables have zero CO_2 emissions, biomass power plants have negligible CO_2 emissions. This can be because of the burning of the feedstock which releases the stored carbon into the atmosphere, and possibly other factors.

This project can be further enhanced by considering other GHG emissions, more accurate demand forecasts from the government authorities, more accurate loss rates depending on the distance the generated power travels and the location of power plants, and exact figures of the expected maximum allowed CO_2 emissions in the country, and the exact amount of CO_2 emissions from each power plant. Moreover, detailed feasibility studies and economic analyses can be implemented to determine the practicality of implementing hybrid CSP and solar PV technologies in Qatar, as well as storage technologies to increase the supply's security.

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APPENDIX I

Input data used in CPLEX model.

Table 14. Official Electricity Demand, Generation and Transmission Data (2014 - 2022) & Forecasted Data (2023 - 2064)

Year	Generated, GWh	% Change	Sent Out, GWh	% Change	Maximum Demand, MW	% Change	Minimum Demand, MW	% Change
2014	38,693		36,125		6,740		2,155	
2015	41,499	7.3%	38,852	7.5%	7,270	7.9%	2,320	7.7%
2016	42,307	1.9%	39,668	2.1%	7,435	2.3%	2,410	3.9%
2017	45,555	7.7%	42,806	7.9%	7,855	5.6%	2,600	7.9%
2018	47,913	5.2%	44,655	4.3%	7,875	0.3%	2,410	-7.3%
2019	49,873	4.1%	46,435	4.0%	8,475	7.6%	2,600	7.9%
2020	49,259	-1.2%	45,826	-1.3%	8,600	1.5%	2,825	8.7%
2021	51,641	4.8%	48,329	5.5%	8,875	3.2%	2,875	1.8%
2022	54,623	5.8%	51,325	6.2%	9,400	5.9%	2,910	1.2%
2023	55,999	2.5%	52,362	2.0%	9,678	3.0%	3,011	3.5%
2024	57,875	3.4%	54,118	3.4%	9,833	1.6%	3,103	3.1%
2025	59,751	3.2%	55,875	3.2%	10,292	4.7%	3,195	3.0%
2026	61,627	3.1%	57,631	3.1%	10,447	1.5%	3,287	2.9%
2027	63,503	3.0%	59,387	3.0%	10,905	4.4%	3,379	2.8%
2028	65,380	3.0%	61,144	3.0%	11,060	1.4%	3,472	2.7%
2029	67,256	2.9%	62,900	2.9%	11,519	4.1%	3,564	2.7%
2030	69,132	2.8%	64,657	2.8%	11,674	1.3%	3,656	2.6%
2031	71,00	2.7%	66,413	2.7%	12,132	3.9%	3,748	2.5%

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Year	Generated, GWh	% Change	Sent Out, GWh	% Change	Maximum Demand, MW	% Change	Minimum Demand, MW	% Change
2032	72,885	2.6%	68,170	2.6%	12,287	1.3%	3,840	2.5%
2033	74,761	2.6%	69,926	2.6%	12,746	3.7%	3,933	2.4%
2034	76,637	2.5%	71,682	2.5%	12,901	1.2%	4,025	2.3%
2035	78,513	2.4%	73,439	2.5%	13,359	3.6%	4,117	2.3%
2036	80,389	2.4%	75,195	2.4%	13,514	1.2%	4,209	2.2%
2037	82,266	2.3%	76,952	2.3%	13,973	3.4%	4,301	2.2%
2038	84,142	2.3%	78,708	2.3%	14,128	1.1%	4,393	2.1%
2039	86,018	2.2%	80,464	2.2%	14,586	3.2%	4,486	2.1%
2040	87,894	2.2%	82,221	2.2%	14,741	1.1%	4,578	2.1%
2041	89,770	2.1%	83,977	2.1%	15,200	3.1%	4,670	2.0%
2042	91,647	2.1%	85,734	2.1%	15,355	1.0%	4,762	2.0%
2043	93,523	2.0%	87,490	2.0%	15,813	3.0%	4,854	1.9%
2044	95,399	2.0%	89,247	2.0%	15,968	1.0%	4,947	1.9%
2045	97,275	2.0%	91,003	2.0%	16,427	2.9%	5,039	1.9%
2046	99,151	1.9%	92,759	1.9%	16,582	0.9%	5,131	1.8%
2047	101,028	1.9%	94,516	1.9%	17,040	2.8%	5,223	1.8%
2048	102,904	1.9%	96,272	1.9%	17,195	0.9%	5,315	1.8%
2049	104,780	1.8%	98,029	1.8%	17,654	2.7%	5,408	1.7%
2050	106,656	1.8%	99,785	1.8%	17,809	0.9%	5,500	1.7%
2051	108,532	1.8%	101,541	1.8%	18,267	2.6%	5,592	1.7%
2052	110,4	1.7%	103,298	1.7%	18,422	0.8%	5,684	1.6%

	09							
Year	Generated, GWh	% Change	Sent Out, GWh	% Change	Maximum Demand, MW	% Change	Minimum Demand, MW	% Change
2053	112,285	1.7%	105,054	1.7%	18,881	2.5%	5,776	1.6%
2054	114,161	1.7%	106,811	1.7%	19,036	0.8%	5,868	1.6%
2055	116,037	1.6%	108,567	1.6%	19,494	2.4%	5,961	1.6%
2056	117,913	1.6%	110,324	1.6%	19,649	0.8%	6,053	1.5%
2057	119,790	1.6%	112,080	1.6%	20,108	2.3%	6,145	1.5%
2058	121,666	1.6%	113,836	1.6%	20,263	0.8%	6,237	1.5%
2059	123,542	1.5%	115,593	1.5%	20,721	2.3%	6,329	1.5%
2060	125,418	1.5%	117,349	1.5%	20,876	0.7%	6,422	1.5%
2061	127,295	1.5%	119,106	1.5%	21,335	2.2%	6,514	1.4%
2062	129,171	1.5%	120,862	1.5%	21,490	0.7%	6,606	1.4%
2063	131,047	1.5%	122,618	1.5%	21,948	2.1%	6,698	1.4%
2064	132,923	1.4%	124,375	1.4%	22,103	0.7%	6,790	1.4%
Average % Change	-	4.4%	-	4.5%	-	4.3%	-	4.0%

Table 15. Annual CO2 Emissions in Qatar (2000 - 2022) & Expected Maximum CO2 Emissions (2023 –2054) [98]

Year	Annual CO2 emissions in tons	Annual CO2 emissions in Mtons
2000	40314500	40.31
2001	45817316	45.82
2002	45066684	45.07

Year	Annual CO2 emissions in tons	Annual CO2 emissions in Mtons
2003	46514956	46.51
2004	47320412	47.32
2005	47550748	47.55
2006	59630004	59.63
2007	59383044	59.38
2008	61636948	61.64
2009	65073668	65.07
2010	73421576	73.42
2011	81493320	81.49
2012	93320950	93.32
2013	82808080	82.81
2014	91177600	91.18
2015	91194280	91.19
2016	87385144	87.39
2017	100111260	100.11
2018	95463944	95.46
2019	101018984	101.02
2020	102501230	102.50
2021	107218140	107.22
2022	101340350	101.34
2023	102819906.7	102.82
2024	102819906.7	102.82
2025	101886573.3	101.89
2026	101886573.3	101.89
2027	101886573.3	101.89
2028	101886573.3	101.89
2029	101886573.3	101.89
2030	75764238	75.76
2031	75764238	75.76
2032	75764238	75.76
2033	75764238	75.76
2034	75764238	75.76
2035	75764238	75.76
2036	75764238	75.76
2037	75764238	75.76
2038	75764238	75.76
2039	75764238	75.76
2040	75764238	75.76
2041	75764238	75.76
2042	75764238	75.76
2043	75764238	75.76

Year	Annual CO2 emissions in tons	Annual CO2 emissions in Mtons
2044	75764238	75.76
2045	75764238	75.76
2046	75764238	75.76
2047	75764238	75.76
2048	75764238	75.76
2049	75764238	75.76
2050	75764238	75.76
2051	75764238	75.76
2052	75764238	75.76
2053	75764238	75.76
2054	75764238	75.76
2055	75764238	75.76
2056	75764238	75.76
2057	75764238	75.76
2058	75764238	75.76
2059	75764238	75.76
2060	75764238	75.76
2061	75764238	75.76
2062	75764238	75.76
2063	75764238	75.76
2064	75764238	75.76

APPENDIX II

IBM ILOG CPLEX Optimization Studio results.

Table 16. Annual Power Plant Generation During the Planning Horizon (30 years)

Plant Type\ Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Solar PV	0	0	0	0	0	0	0	0	0	0	2000	2000	2000	2000	2000
CSP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Onshore Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1978.674
Offshore Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar PV	0	0	0	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
CSP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Onshore Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Offshore Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar PV	0	0	0	0	0	0	0	0	2000	2000	2000	2000	2000	2000	2000
Mesaieed CCGT	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990
Ras Laffan A Cogen GT	756	756	756	496.382	756	756	756	756	756	0	0	0	0	0	0
Ras Laffan B CCGT	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	0	0	0
Ras Laffan C (Ras Qartas) CCGT	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730
Al Kharsaah (Siraj1)	800	800	800	800	800	800	800	800	800	800	550.4687	800	800	800	800
Umm Al Houl IWPP	1088.2132	1874.3704	2389.7	630	876.17	1473.1	1988.5	2162.7	1079.1	2037.3	630	630	2220.0	2294.3	630

	99	82	63		27	24	16	28	37	09			97	09	
Ras Abu Fontas B OCGT Cogen	609	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant Type\ Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ras Abu Fontas B-1 OCGT	376.5	376.5	376.5	376.5	376.5	0	0	0	0	0	0	0	0	0	0
Ras Abu Fontas B-2 OCGT Cogen	567	567	567	567	567	567	567	567	0	0	0	0	0	0	0
IC Solar Project - Mesaieed Industrial City	417	417	417	417	417	417	417	417	417	417	417	417	417	417	417
IC Solar Project - Ras Laffan Industrial City	458	458	458	458	458	458	458	458	458	458	458	363.4503	458	458	458
Plant Type\ Year	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Solar PV	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
CSP	0	0	0	0	0	0	0	0	0	0	0	0	0	2000	1531.215
Onshore Wind	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Offshore Wind	0	0	0	0	0	0	0	0	0	2000	2000	2000	2000	2000	2000
Biomass	0	0	0	1639.137	1797.282	2000	2000	2000	1836.877	500	500	930.7403	1088.885	500	500
Solar PV	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
CSP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2000
Onshore Wind	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

Offshore Wind	0	0	0	0	0	0	0	0	2000	2000	2000	2000	2000	2000	2000
Biomass	0	1513.133	1671.278	500	500	765.1412	923.2858	1391.145	2000	1804.736	1962.881	2000	2000	1873.071	500

Plant Type\ Year	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Solar PV	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Mesaieed CCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ras Laffan A Cogen GT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ras Laffan B CCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ras Laffan C (Ras Qartas) CCGT	2730	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Al Kharsaah (Siraj1) (Phase I: 350 MW in 2022)	800	800	800	800	800	800	800	800	800	800	800	800	800	0	0
Umm Al Houl IWPP	747.7985	2520	2520	2520	2520	2520	2520	2520	0	0	0	0	0	0	0
Ras Abu Fontas B OCGT Cogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ras Abu Fontas B-1 OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ras Abu Fontas B-2 OCGT Cogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IC Solar Project - Mesaieed Industrial City	417	417	417	417	417	417	417	417	417	417	417	417	417	417	417
IC Solar Project - Ras Laffan Industrial	458	458	458	458	458	458	458	458	458	458	458	458	458	458	458

City

APPENDIX III

IBM ILOG CPLEX Optimization Studio, OPL Mixed-Integer Linear Programming (MILP) model code.

```
// .dat file

U=60;

SheetConnection my_sheet("ModelData.xlsx");

nperiods from SheetRead(my_sheet, "'ModelData1'!B1:B1");
//Number of periods in the planning horizon
Number of existing power plants
Fixedcost from SheetRead(my_sheet, " 'ModelData1'!B16:B26");
//Annualized fixed cost of power plants
Variablecost from SheetRead(my_sheet, " 'ModelData1'!B39:B60");    //Variable
cost of power plants during the planning horizon
co2emissions from SheetRead(my_sheet, " 'ModelData1'!B62:B83");    //CO2
emissions of power plants during the planning horizon
co2allowed from SheetRead(my_sheet, " 'ModelData1'!B180:AE180");   //Maximum
allowed amount of CO2 emissions per year
pplifetime from SheetRead(my_sheet, " 'ModelData1'!B85:L85");
//Total expected lifetime of a potential power plant
eplifetime from SheetRead(my_sheet, " 'ModelData1'!B86:L86");
//Remaining expected lifetime of an existing power plant
Demand from SheetRead(my_sheet, " 'ModelData1'!B87:AE87");
//Expected demand during the planning horizon
Capacity from SheetRead(my_sheet, " 'ModelData1'!B88:B109");
//Capacity of power plants (existing+potential)
Losses from SheetRead(my_sheet, " 'ModelData1'!B111:B132");


// .mod file
//Parameters

int nperiods=...;                                        //Number of periods in the
planning horizon
range periods=1..nperiods;                               //Range of the number of
periods in the planning horizon

int U=...;
       //Planning horizon upper bound, U = nperiods + m ; where m is any number
to consider plants that may shutdown at a time beyond the planning horizon

//tuple to represent the type of plant and its row index
tuple PlantType {
  string type;                                                           //
type: "pp" for Potential Plants or "ep" for Existing Plants
  int row;                                                               // Row
index
}
//1..2       1..3
```

```
{PlantType} Plant = {<"pp", row> | row in 1..11} union {<"ep", row> | row in
1..11}; // first rows represent potential plants, while last rows represent
existing plants
{PlantType} PotentialPlants = {p | p in Plant: p.type == "pp"};
{PlantType} ExistingPlants = {p | p in Plant: p.type == "ep"};

float Fixedcost[PotentialPlants]=...;            //Annualized fixed cost of
power plants
float Variablecost[Plant]=...;                   //Variable cost of
power plants during the planning horizon
float co2emissions[Plant]=...;                   //CO2 emissions of
power plants during the planning horizon
float co2allowed[periods]=...;                   //Maximum allowed
amount of CO2 emissions per year
int pplifetime[PotentialPlants]=...;             //Total expected lifetime
of a potential power plant
int eplifetime[ExistingPlants]=...;              //Remaining
expected lifetime of an existing power plant
float Demand [periods]=...;                      //Forecasted
demand during the planning horizon in MW
float Capacity[Plant]=...;                       //Capacity of
power plants (existing+potential)
float Losses[Plant]=...;                         //Transmission line
losses of power plants (existing+potential)


//Decision Variables

dvar boolean s[PotentialPlants][periods];   //Set-up time decision of a
potential plant
dvar boolean f[PotentialPlants][1..U];           //Shutdown time decision
of a potential plant
dvar boolean y[Plant][1..U];                     //Indicates if a power
plant is operating in a time period during or beyond the planning horizon
dvar float+ x[Plant][periods];                  //Amount of electricity
produced by a power plant (potential or existing) during a time period


//Objective Function                             //Minimize
total cost to find the optimal power plants set-up and operating schedules.

minimize ((sum(p in PotentialPlants, t in periods) (Fixedcost[p]*y[p][t])) +
(sum(p in Plant, t in periods)(Variablecost[p]*x[p][t])));

//Constraints

subject to{

  // C1: Lifetime and setup/shutdown constraints for potential power plants
  forall (p in PotentialPlants)
    ( sum(t in periods) t*s[p,t] ) + ( pplifetime[p] -1 ) == sum(t in 1..U)
(t*f[p,t]);

  //C2: Ensure that any potential power plant is set up only once during the
planning horizon
```

```
  forall (p in PotentialPlants)
    sum(t in 1..nperiods) (s[p,t]) <= 1;

  //C3: Ensure that any potential power plant can be shut down only once during the planning horizon.
  forall (p in PotentialPlants)
    sum(t in 1..U) (f[p][t]) <= 1;

  //C4: If any potential power plant has been set-up during period t, and was not closed between period 1 and t-1, then it is operated during period t
  forall(p in PotentialPlants, t in periods)
   (sum(h in 1..t) s[p,h])-(sum(h in 1..(t-1)) f[p,h]) == y[p,t];

  //C5: Sum of y throughout the upper bound of the time horizon should be less than or equal to the lifetime of potential plant p
   forall(p in PotentialPlants)
    sum(t in 1..U) y[p][t] == pplifetime[p];

  //C6: at the upper bound of the planning horizon, sum of y should be less or equal to the remaining lifetime of an existing power plant
   forall (p in ExistingPlants, t in 1..eplifetime[p])
       y[p][t] == 1;

 forall (p in ExistingPlants, t in eplifetime[p]+1..U)
       y[p][t] == 0;


  //C7: to imply that y is 1 when s is operated in period t
   forall(p in PotentialPlants, t in periods)
     s[p,t] <= y[p,t];

  //C8: Supply should meet demand considering power losses.
 forall (t in periods)
    sum(p in Plant) (x[p,t] * (1 - Losses[p]) ) >= Demand[t];

  //C9: CO2 emissions should not exceed the maximum allowed CO2 emissions per MW in year t
  forall (t in periods)
       sum(p in Plant) (co2emissions[p] * x[p,t] ) <= co2allowed[t];

  //C10: Capacity constraints to ensure power plants are optimally utilized
    forall (p in Plant, t in periods)
       {
       (Capacity[p] * 0.25 * y[p,t] ) <= x[p][t];
        x[p][t]  <= (Capacity[p] * y[p,t]);
    }
 }
```