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ECONOMIC ENERGY ALLOCATION FOR A POWER SYSTEM CONSIDERING TECHNO-ECONOMIC CONSTRAINTS

BY

OMAR M. JOUMA ELHAFEZ

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COMMITTEE PAGE

The members of the Committee approve the Dissertation of
OMAR M. JOUMA ELHAFEZ defended on 12/01/2023.

Dr. Tarek ElMekkawy
Chair, Thesis/Dissertation Supervisor

Dr. Ahmed Massoud
Thesis/Dissertation Supervisor

Dr. Mohamed Kharbeche
Thesis/Dissertation Supervisor

Dr. Mohamed Haouari
Committee Member

Dr. Murat Kucukvar
Committee Member

Dr. Murat Gunduz
Committee Member

Dr. Kadir Ertogral
Committee Member

Dr. Hussein A. Kazem
Committee Member (External Examiner)

Dr. Galal Abdella
Graduate Studies Representative

Approved:

Khalid Kamal Naji, Dean, College of Engineering

ABSTRACT

JOUMA ELHAFEZ, OMAR, M., Doctorate: June [2023:], Doctorate of Philosophy in Engineering Management

Title: ECONOMIC ENERGY ALLOCATION FOR A POWER SYSTEM CONSIDERING TECHNO_ECONOMIC CONSTRAINTS

Supervisor of Dissertation: Dr. Tarek ElMekkawy, Dr. Ahmed Massoud and Dr. Mohamed Kharbeche.

During the past few decades, rapid progress in reducing the cost of photovoltaic (PV) energy has been achieved. At the megawatt (MW) to gigawatt (GW) scale, large PV systems are connected to the electricity grid to provide power during the daytime. These large numbers of PV cells can be installed on sites with optimal solar radiation and other logistical considerations. However, the electricity produced by the PV power plant has to be transmitted and distributed by the grid, which leads to more power losses. With the widespread commissioning of large-scale solar PV power plants connected to the grid, it is crucial to have an optimal energy allocation between the conventional and the PV power plants. The electricity cost represents the most significant part of the budget of the power distribution companies, which can reach many countries billions of dollars. This optimal energy allocation is used to minimize the electricity cost from the point of view of buyers (distribution companies) rather than sellers (owners of power plants, i.e., investors). However, some constraints have to be considered and met, such as water demand, network limitations, and contractual issues such as minimum-take energy. The main contribution of this thesis is developing an optimization model for the energy-economic allocation of conventional and large-scale solar PV power plants. The developed model is generic and could apply to any country or electricity system having the same conditions. Furthermore, Al-Kharsaah power plant in Qatar and Al-Dhafra in the UAE will be discussed as two cases to validate the claimed contribution. For Al-Kharsaah and Al-Dhafra cases, the cost reduction percentage were 1.65% and 6.5% respectively. This is due to the different in size and energy price.

In addition, the COVID-19 pandemic has brought several global challenges, one of which is meeting the electricity demand. Millions of people are confined to their homes, in each of which a reliable electricity supply is needed to support teleworking, e-commerce, and electrical appliances such as HVAC, lighting, fridges, water heaters, etc. Furthermore, electricity is also required to operate medical equipment in hospitals and perhaps temporary quarantine hospitals/shelters. Electricity demand forecasting is a crucial input into decision-making for electricity providers. This thesis discusses the impact of the COVID-19 pandemic on Qatar’s electricity demand and forecasting. The results and findings will help decision-makers and planners manage future electricity demand and support distribution networks’ preparedness for emerging situations. The forecasting part will be used as a supporting tool for the proposed optimization model. The input for this model is the amount of energy that has to be distributed between the different power plants. Therefore, a good forecasting model and technique will result in a better economic energy allocation.

DEDICATION

I dedicate this thesis to the people working in the electricity sector to support Qatar’s economy.

Name: Omar Jouma ElHafez

Place: Doha, Qatar

Date: June 2023

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In addition, I want to thank the company I am working in, KAHRAMAA, which supports researchers to enhance Qatar's economy.

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NOMENCLATURE

BOOT	Build Own Operate Transfer
BTU	British Thermal Unit
CSP	Concentrating Solar Power
GCC	Gulf Cooperation Council
GW	Gigawatt
J	Joule
KAHRAMAA	Qatar General Electricity and Water Corporation
kWh	Kilowatt-hour
LP	Linear Programming
MTE	Minimum-take Energy
MW	Megawatt
NPV	Net Present Value
O & M	Operation and Maintenance
PV	Photovoltaic
QEWC	Qatar Electricity and Water Company
QP	Qatar Petroleum
QR	Qatari Riyal
RO	Reverse Osmosis

Sets and Indices

cp	a set of conventional power plants, indexed by p
PV	a set of PV power plants, indexed by v
TL	a set of transmission lines, indexed by l

CCp	Unit cost of purchased energy from conventional plant p, $\forall p \in \mathrm{CP}$

Parameters

CVv	Unit cost of purchased energy from PV plant *v*, $\forall v \in \mathrm{PV}$
D	Annual Energy demand
PFl	Load on the transmission line *l*, $\forall l \in TL$
CPFl	Maximum load the transmission line l can carry, $\forall l \in \mathrm{TL}$
ECPp	Maximum annual energy capacity of conventional plant *p*, $\forall p \in \mathrm{CP}$
ECVv	Maximum annual energy capacity of PV plant v, $\forall v \in \mathrm{PV}$
MTEp	Take-or-pay energy amount of conventional plant p, $\forall p \in \mathrm{CP}$
MTEv	Take-or-pay energy amount of PV plant v, $\forall v \in \mathrm{PV}$
EP	Evacuation factor: a factor that defines the maximum evacuation energy
WP	Water factor: a factor that defines the minimum energy needed to meet water demand

Decision variables

ECp	purchased energy from conventional plant p, $\forall \mathrm{p} \in \mathrm{CP}$
EVv	purchased energy from PV plant p, $\forall \mathrm{v} \in PV$

CHAPTER 1: INTRODUCTION

Electricity is one of the crucial inputs to a nation's social and economic well-being. The availability of surplus electricity or electricity on demand gives confidence among people in the ability to invest in new industrial or trade ventures, which ultimately leads to economic development. Electricity demand forecasting plays a vital role in helping electricity providers operate and manage the supply to their customers [1].

The electricity network or grid is the system operated to transmit and distribute electricity from generating power stations to electricity consumers. Figure 1 shows a diagram of an electricity network with generation, transmission, and distribution components.

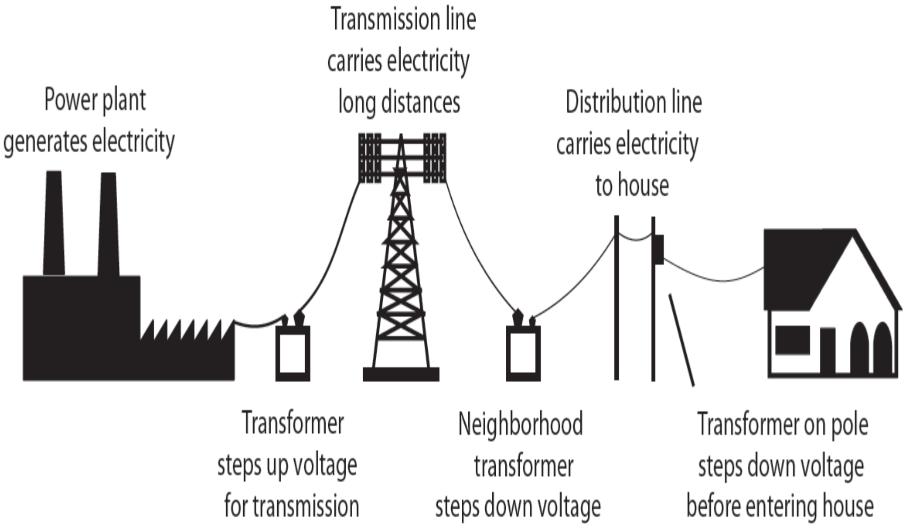
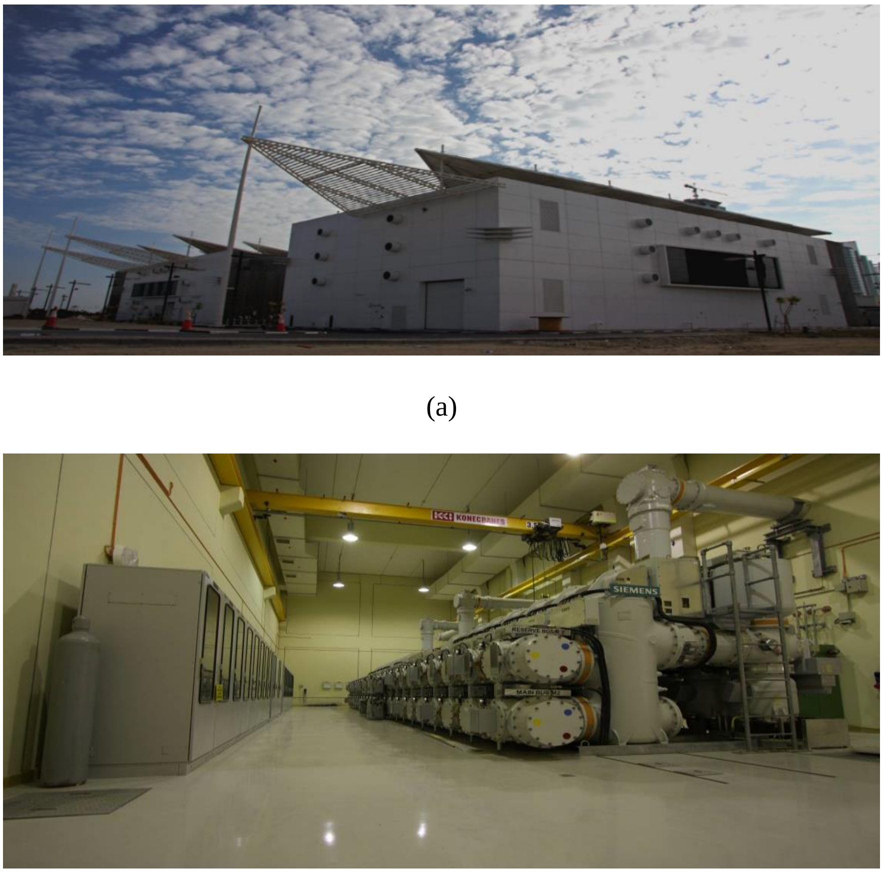


Figure 1. Electricity network diagram [1]

A power station is a plant wherein electrical energy is produced. Figure 2 shows the Ras Abu Fontas power station in Qatar.

Figure 2. Ras Abu Fontas power station in Qatar [2]

Moreover, the transmission and distribution systems combine overhead lines, cables, and substations to transfer electrical energy from power stations to consumers. Figure 3 shows outside and inside views of a transmission substation.



(a)

(b)

Figure 3. A transmission substation. (a) Outside view and (b) Inside view [3]

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). The 17 Sustainable Development Goals (SDGs) set by the United Nations General Assembly cover social and economic development issues, including poverty, education, global warming, energy, and social justice. Qatar has focused on sustainable development since its independence in 1971, covering the three dimensions of sustainable development: social, economic, and environmental [4,5].

SDG 7 ensures access to affordable, reliable, sustainable, and modern energy. Renewable energy is clean and environmentally friendly, does not affect temperature levels, and has multiple uses. As a result, Qatar started using this energy and developing its necessary technologies by focusing on investments and expenditure on its generation and development projects. This promotes people's well-being and reduces CO_2 emissions [6,7,8].

1.1 Statement of the Problem

With the low cost of renewable energy projects, most electricity distribution companies started and tuned to these types of projects. However, low economic efficiency is one of the main arguments against renewable energy sources.

The electricity cost is a major part of the electricity distribution companies' budget. Therefore, economic efficiency is a crucial aspect of renewable energy project planning. Electricity distribution companies seek to reduce the total cost and achieve the highest profit through the optimal electricity allocation between the different power plants. This optimal energy allocation is used to minimize the operation cost.

For example, KAHRAMAA is purchasing electricity from 8 different generation power plants with varying contracts in terms of energy prices. After the proposed solar power station's commissioning with no energy storage facility, providing an optimal operation cost is an essential issue. During the daily period of obtaining energy from the solar power plant, what is the optimal energy allocation between the different generation plants. Moreover, is there a need to shut down generating units and restart them again or run these units with less generation. Therefore, this thesis discusses and solves an operational cost optimization problem considering variables such as energy cost, minimum-take energy, and water demand. The previous variables are the constraints for the optimization problem, and the objective function is to minimize the total energy cost.

1.2 Research Questions

The list of the research questions is as follows:

1- How do energy stakeholders deal economically with each other?

2- What is the economic impact of integrating large-scale PV power plants with the existing power grid?

3- Is it economically worth adding more PV power plants to the existing power grid?

4- What is the amount of money saved by building and commissioning a new PV power plant?

5- What is the impact of the COVID-19 pandemic on electricity demand?

6- How did the COVID-19 pandemic affect electricity demand forecasting?

1.3 Research Methodology

In this thesis, the following research methodology will be adopted:

1. Problem assessment and understanding the needs along with visiting the relevant power plants and distribution companies.

2. Review of literature to understand the importance of connecting PV power plants to the electricity grid, difficulties, economic energy allocation and the factors that affect the electricity demand.

3. Collect the data from the official sources for the distribution companies and power plants.

4. Develop an optimization model for economic energy allocation of conventional and large-scale solar PV power plants.

5. Validate the proposed model and implement it as a case study.

Figure 4 describes the research methodology and its graphical abstract.

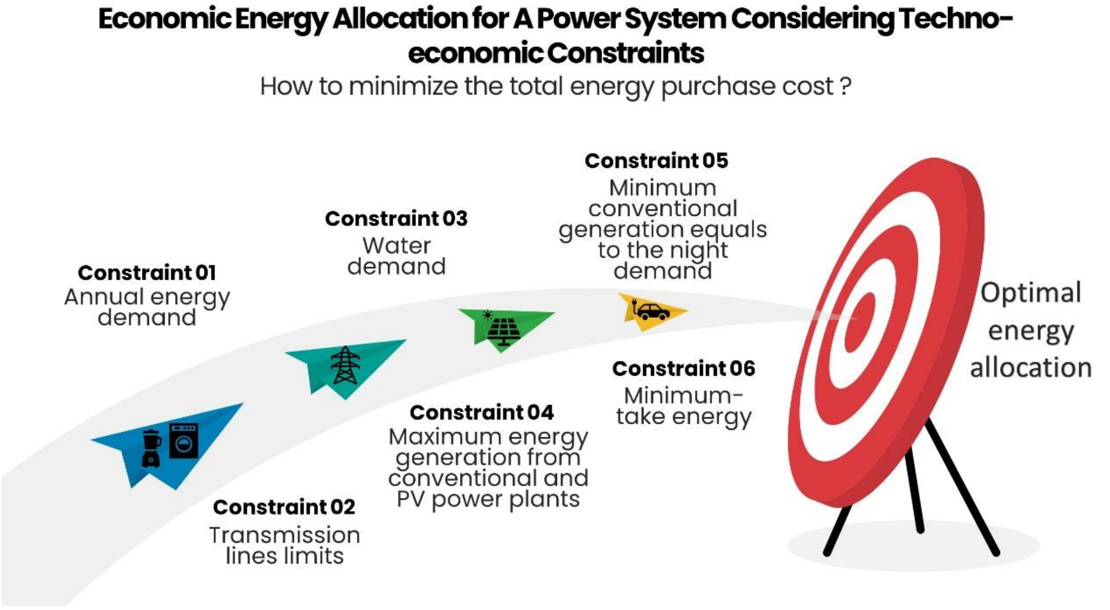


Figure 4. Graphical abstract of the research methodology

1.4 Research Objectives

The primary aim of this thesis is to study the feasibility of adding a new PV power plant to the grid. and develop an optimization model for the economic energy allocation of conventional and large-scale solar PV power plants. Electricity distributors purchase electricity from power plants with different contracts and prices. The power plants are the responsible parties for the generation phase. Then, the distributors sell electricity to their consumers to meet their demand. The distributors are the responsible parties for the transmission and distribution phases.

This research is motivated by the rapid and widespread penetration of PV power plants. Electricity distributors are trying to cut costs by making maximum use of PV power plants. Many factors affect the optimal power allocation among the different generation plants. For example, if the PV power plant is connected to the grid and there is no storage facility, generation production will be reduced at conventional power plants. However, the critical question is based on generation production reduction. The electricity supply price is the main factor (price per kilowatt). In some contracts between electricity distributors and generation power plants, a minimum amount of energy should be purchased annually, called minimum-take energy. If the minimum-take energy is not utilized, the cost will be paid to the power plants. Therefore, energy purchases should be distributed to minimize the total cost. The following present the main objectives:

- Studying the feasibility of adding a new PV power plant to the grid
- Minimizing the operation cost by the economic energy allocation
- Preparing the Electricity distributors’ budgets
- Studying the impact of the COVID-19 pandemic on Qatar electricity demand

1.5 Thesis Structure

The thesis is composed of five chapters summarized as follows. Chapter 2 consists of a literature review concerning optimization and electricity forecasting. Chapter 3 discusses electricity forecasting and the impact of the COVID-19 pandemic on Qatar's electricity demand. Chapter 4 describes the proposed optimization model. Chapter 5 discusses and validates the proposed model with Al-Kharsaah case study. Chapter 6 concludes the work and discusses the potential research direction. Figure 5 demonstrates the thesis structure.

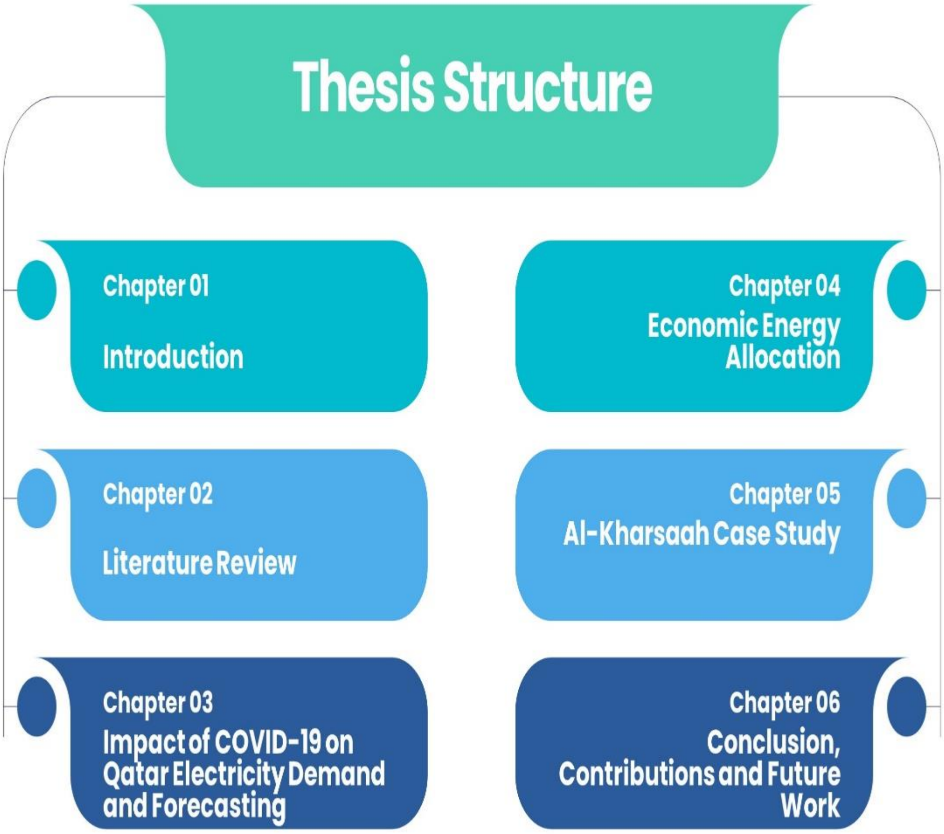


Figure 5. Thesis structure

Chapter 2: LITERATURE REVIEW

2.1 Optimization of Energy Systems

The word ‘photovoltaic’ consists of two words: photo and Volta. Photo stands for light and Volta is the unit of the electrical voltage. In other words, photovoltaic means the direct conversion of sunlight to electricity. The common abbreviation for photovoltaic is PV [68,69].

Energy is a primary part of our life and provides an economic role for the nation’s development [9]. Solar energy obtained through the use of PV panels is the most flexible renewable energy source, and it can be used in approximately all power classes up to GW and in most locations around the world [10,11]. Large-scale PV power plants have been extensively investigated in the literature, particularly considering the Middle East and North Africa (MENA) region.

From technical and economic perspectives, Kazem et al. [12] discussed the optimal configuration of 1 MW PV connected to the grid in Adam city in Oman from both technical and economic points of view. They found that the energy cost for the PV plant is near 0.2258 USD/KWh. The authors collected data on hourly bases for global horizontal irradiance, temperature, relative humidity, and wind speed for the 2015 year. They used MATLAB as an optimization software. The proposed PV system has a payback period of 10 years.

Shouman [13] compared electricity costs using PV panels and diesel generators in rural areas in Egypt. It was concluded that PV systems could provide a cost-effective alternative to the high-cost grid -connections in the rural areas in Egypt. Furthermore, Ma et al. [14] proposed a solar PV system model to optimize the PV generator and pumped storage system’s capacity and minimize the power supply cost in remote areas. They considered the following variables in the optimization process: PV module number, upper reservoir size, and water pump size. Then, they applied the proposed model to a case study on an island's renewable energy power generation system. Mellouk et al. [15] developed an optimization algorithm for micro-grids sizing and energy management problems. The objective is to meet the electricity demand with the lowest cost and maximize renewable energy penetration. Since it is a micro-grid case, they considered the storage facility.

In Poland, due to the gradual increase for electricity prices, small consumers searched for alternative energy sources. Izdebski et al. [16] studied the possibilities of producing electricity form small PV (up to 10 KW) based on socio-economic analysis. They recommended that PV installations can be an alternative clean energy source due to its low levelized cost of electricity compared with the electricity grid price.

Al Anazi et al. [17] studied the PV installation with battery storge facility in two cases which are grid-connected and grid-disconnected systems. They conducted the study in Saveh village in central of Iran on a residential-agricultural area. They concluded that the grid-connected system is cheaper due to the low-investment cost.

In addition, Eriksson et al. [18] proposed a Particle Swarm optimization algorithm for renewable energy optimization. The economic objective of the proposed model is minimizing the levelized cost of energy by selecting the optimal confirmation energy mix.

Delfín-Portela et al. [19] designed a grid-connected PV system for tilapia farms in Mexico. There are 4,623 aquaculture farms in Mexico. The goal of their system is to minimize the energy cost. With the proposed PV system, they found that it is possible to reduce the energy cost by 50 %. Furthermore, they mentioned that the capital investment is recovered in less than 5 years.

Iakovleva et al. [20] developed an algorithm for conducting solar power plant modernization. A Case Study from the Republic of Cuba was considered. The following indicators was taken into consideration: solar module efficiency, solar tracking system, losses, inflation rate and energy cost. They found that an inflation change from 3.5% to 6% caused an increase of the NPV of 1.8-2 %.

For more extensive penetration of renewable energy sources, Lude et al. [21] developed an optimization methodology for the Shagaya renewable energy park in Kuwait with a mix of power (wind, PV, and CSP) of 2 GW on 100 km² of land. The authors used the GenOpt software for the optimization, built on a social-techno-economic evaluation. They determined eight criteria for the optimization method: yield per area, full load hours, peak load shaving capability, levelized cost of electricity, O&M jobs, construction jobs, water consumption, and plant availability. The first phase of this mega-project is completed with a mix of 70 MW of power connected to the Kuwait grid, where the expected completion time for the project is 2022. Moreover, Jordan faces challenges in meeting its electricity demand due to limited fossil fuel resources, the financial challenges of the energy entities, and the fast-growing population. Al-Omary et al. [22] discussed the status of the electricity sector and the future role of renewable energy sources (PV and wind) in Jordan. The electricity peak demand in Jordan increased from 1,287 MW in 2005 to 3,088 MW in 2015, with a total generation of 3,997 MW in 2015. Due to the availability of favorable solar and wind resources, the authors analyzed and then concluded that renewable energy sources have the potential to contribute significantly to the electricity system.

Jain et al. [23] studied the feasibility of meeting 100% of India’s electricity consumption from PV by 2050. The authors developed an energetic flow model to simulate inputs and outputs of electricity from the PV system from 2016 to 2050. They found that this will require large amounts of investment in the PV system and the associated storage infrastructure. In the short term, this will cause a lack of electricity supply. The authors mentioned that India had an 8 GW total installed capacity of PV in 2016 with zero storage facilities. Coester et al. [24] developed a new market design for the German electricity market. They aimed to ensure energy supply security and renewable energy expansion. They concluded that conventional power plants are still needed to ensure system stability due to the intermittent nature of renewable energy sources. Furthermore, Forough et al. [25] addressed an optimization model for increasing renewable energy penetration in a hybrid system. The proposed model concluded that increasing the prediction horizon length increases the renewable energy penetration and share. Rui et al. [26] proposed an optimization model for energy allocation of multiple microgrids. The aim of this study is to maximize the profit of the energy operator. They used mixed integer programming and Stackelberg game theory to solve the optimization problem. Since they are dealing with microgrids, the storage facility was considered with the PV generation. They concluded that the PV utilization ratio was improved with the proposed model.

Benitez et al. [27] discussed the hybrid CSP-PV plants in Jordan, Tunisia, and Algeria. They took meteorology, cost, and electricity demand into consideration. They noticed that the LCOE of Tunisia is 23% higher than that of Algeria due to the gas price difference, solar resource, and high electricity demand. Also, they concluded that counties in sunny regions with huge gas reserves can utilize the solar energy and export the saved amount of gas other countries.

Vargas-Salgado et al. [28] discussed the optimal energy mix of PV and wind generation with pumping storage facility and mega-batteries. They considered Grand

Canary Island (Spain) as a case study. The optimal configuration for the assumed case is 3,700 MW of PV, 700 MW of wind, 607 MW of pump storage and 2,300 MW of batteries. The payback period of this investment is 12.4 years.

Tafazoli et al. [29] mentioned that there are 3 main categories for the energy resources which are: fossil, nuclear and renewable energies. They compared the electricity generation between fixed and tracking structures for selected PV power plants in Iran for daily, monthly, and yearly values. The authors concluded that by using east-west trackers, the energy production increased by 20%. They found that the limited number of tracking PV power plants in Iran and limited operation period of that plants are the main limitations for their research.

Regarding the relationship between the electricity distributors and the power plants, Ma and Cui [30] proposed a novel hierarchical distributed method under the Progressive Second Price (PSP) auction mechanism. The generation provider or the retailers obtain their electricity allocation through the PSP auction method by submitting a multi-dimensional bid profile instead of telling their own cost or valuation function. The retailers economically distribute the electricity acquired in the PSP auction. Moreover, the valuation function of retailers depends on the revenues that they sell the electricity to users. The auction between generation provider and retailers is a double-sided auction in which the generation provider A_0 act as a seller and all the retailers A_i (I =1,2,...N) act as the buyers. A_0 submits a (2-dimension) sell-bid profile $a_0 \equiv (\alpha_0, s_0)$, where α_0 is the per-unit sell-bid price, and s_0 is the maximum quantity offered for sale. As a buyer, each retailer A_i submits a 2-dimension bid profile $b_i \equiv (\beta_i, d_i)$ where β_i is interpreted as the per-unit bid price and d_i as the maximum quantity wanted. The retailer A_i can then directly assign electricity for the users A_{ij} (j =1,2,..., M_i) in an economical way since the complete information of users is opened to their unique retailer.

In the same context, Guo et al. [31] have highlighted that large consumers could choose to purchase electricity among the following three methods:

- Spot market
- Long-term contract trade power market
- Independent power plants.

The authors studied the direct power purchase strategy for large consumers, taking electricity uncertainty in the power market into account. The purchase price is divided into annual, monthly, and online. A direct power purchase strategy probabilistic optimization model based on a multi-state model for purchase price was proposed, and the optimization goal was to minimize the expected purchase cost. Wang et al. [32] mentioned that power distribution companies should have proper strategies to maximize profit.

Ju et al. in [33] proposed a model to maximize the operation profit for a system of different energy sources. They considered wind, PV, hydropower, and thermal power plants combined with storage devices. They took system demand, capacity of power plants and capacity of storage devices as constraints.

From the investors' perspective, Muneer et al. in [34] have proposed an optimization model to support a prospective investor in arriving at an optimal investment plan in large-scale solar photovoltaic (PV) generation projects. The optimal decisions include the location, sizing, and investment time that yields the highest profit. The mathematical model considers various relevant issues associated with PV projects, such as location-specific solar radiation levels, detailed investment cost representation, and approximate representation of the transmission system. Grid-connected solar PV systems provide a quiet, low-maintenance, pollution-free, safe, reliable, and independent alternative to conventional generation sources. Generally, in decentralized power systems, private investors do not own or operate the transmission -grid. Therefore, they are not responsible for its performance, security, and reliability. As a result, the traditional centralized planning aspects, such as minimizing overall system losses and system security, are not considered. Therefore, the proposed model does not incorporate transmission constraints, power angle constraints, and power flow criteria.

Besides that, the authors in [34] have suggested economic criteria for solar PV investment analysis, namely the Net Present Value (NPV) analysis, as it incorporates the entire lifecycle of the projects and the time value of money. NPV is the discounted sum of the -income from selling the -total generated energy—of all costs -related to the energy delivery system. Thus, NPVs are calculated for all the proposed projects, and the project with the highest NPV is selected. The proposed optimization model is linear, and most decision variables are continuous. The investment selection variables are binary. These results in a mixed-integer linear programming (MILP) model solved in GAMS using the CPLEX solver. The objective is to maximize the NPV of the investor's profit. Moreover, a comprehensive case study considering the investment in PV projects in Ontario, Canada, was discussed, demonstrating the practical application and importance of the proposed methodology.

This thesis will focus more on applied research and engage essential stakeholders in the field, such as KAHRAMAA, QEWC, SIRAJ Energy, Development Planning and Statistics Authority, Qatar meteorology department, and others. This is one of Qatar University goals to conduct research relevant to Qatar and address current issues with relevant stakeholders. Furthermore, this research will provide insight into the Qatar network and system to external researchers and provide essential data and conclusions for future research.

Qatar will be considered a case study to validate the proposed model. For a better understanding and demonstration, the factors that cause the change in the electricity demand will be studied. Moreover, a comparison between the cost of the electricity tariff with and without the commissioning of the Siraj PV power plant will be analyzed.

2.2 Forecasting Electricity Demand

The electric utility industry is probably the largest and most complex globally [1]. Qatar has witnessed a massive transformation over the past 20 years, wherein the country's economy has multiplied due to natural gas exports. Peak demand for Qatar's electricity system has grown from 1,244 MW in 1995 to 8,875 MW in 2021, and the installed capacity reached 10,576 MW in 2022 [35,36]. This has created many challenges for the electricity network, from generation to distribution. This trend will likely be sustained if the economy keeps growing at the same rate. Qatar's electricity sector has undergone a remarkable development in recent years, with generation reaching 42.3 TWh in 2016, almost double that of 2008. Qatar's annual rate of increase in electricity demand is about 8%, among the world's highest growth rates. For example, in India, power generation is growing at an annual average rate of 5.17% between 2018 and 2022 [37].

Qatar faces significant challenges related to the consumption and availability of natural resources while having the world's highest per capita electricity and water consumption [5,38]. As part of the arrangements to host the FIFA 2022 World Cup, Qatar has invested heavily in infrastructures, such as stadiums, housing, transportation, roads, and other service facilities. In response to this, the electricity generation sector should be ready to meet the exponential rise in electricity demand, which calls for a proper peak demand forecasting approach that considers population and GDP growth along with the number of electricity meters. Forecasting helps to define potential obstacles and opportunities and establish the premises for future plans [39,40]. Based on the time horizon, there are three forecasting terms: short, medium, and long. Short-term forecasting is one hour to one week. The short-term electricity demand forecasting objective is to forecast the daily electricity demand to provide the required amount of generated power. This forecasting type depends on comparing the previous day's demand values and considering temperature, humidity, day type (working/weekend), and demand from industrial consumers like QASCO (Qatar Steel Company) [41,42]. Figure 6 shows the effect of the day type on the domestic peak demand. It is noted that the demand was almost the same for the working days form Sunday to Thursday. The lowest demand was on Friday which is a vacation for both government and private sectors.

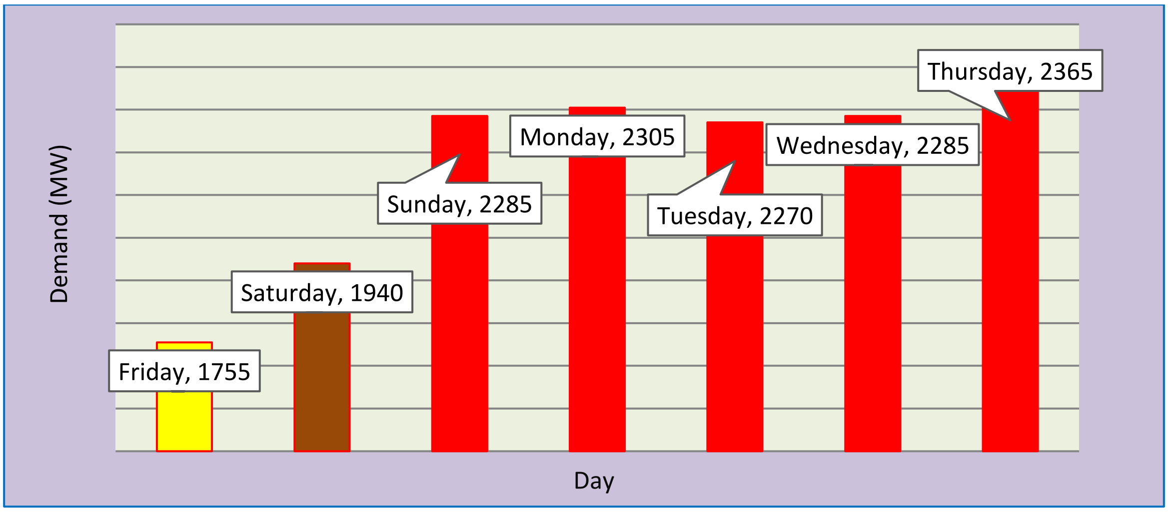


Figure 6. The effect of day type on the domestic peak demand

Figure 7 shows the load variation through a day for QASCO. QASCO has 3 electric furnaces that are operating separately.

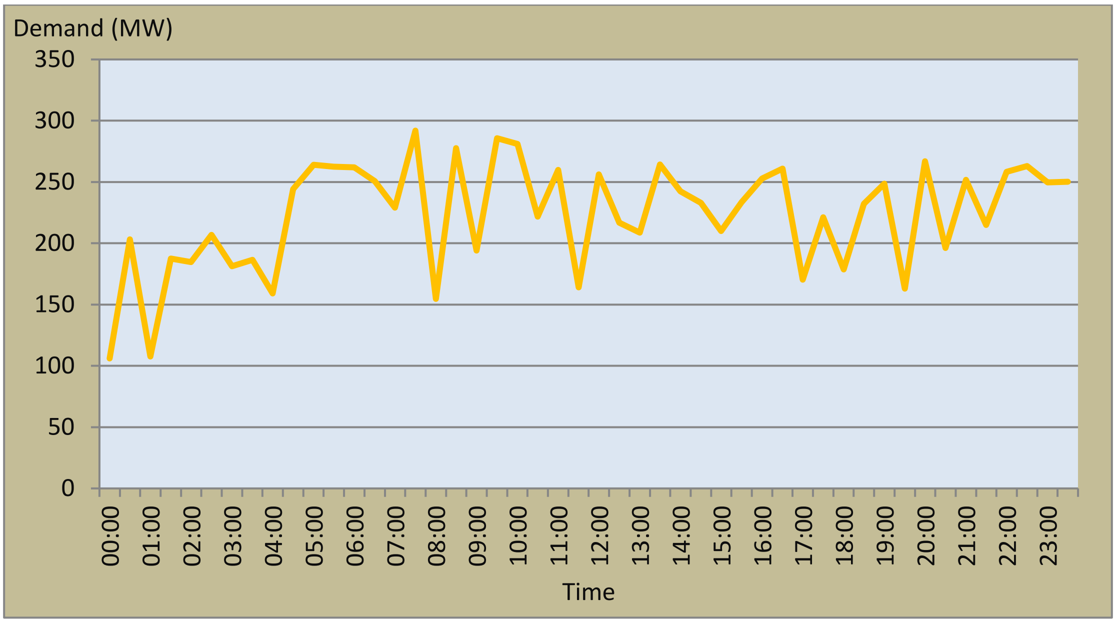


Figure 7. Qatar Steel Company load behavior throughout a day

Figure 8 shows Qatar's domestic demand for two consecutive days 3rd and 4th March 2019).

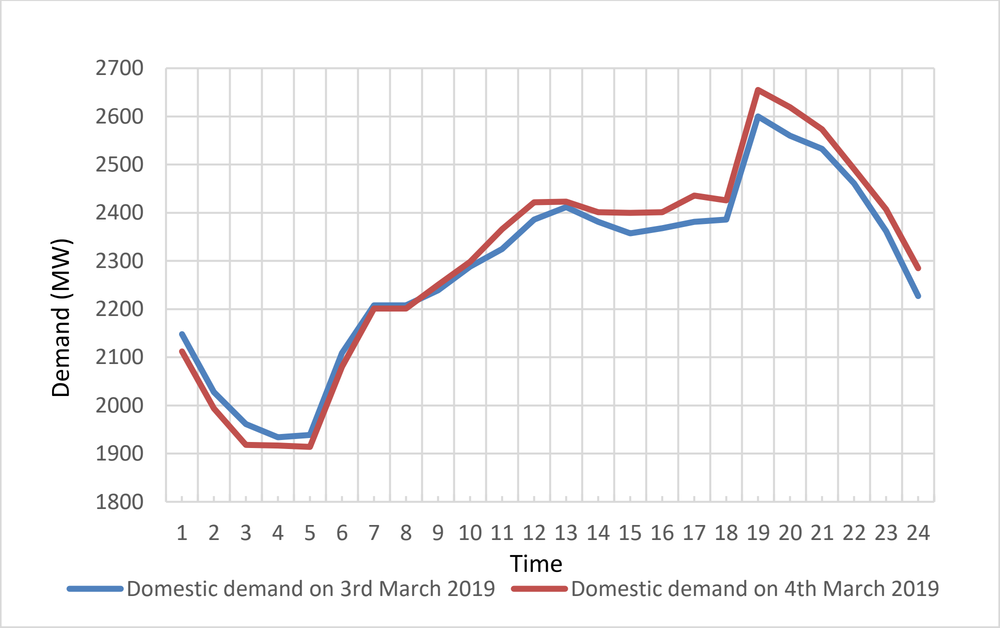


Figure 8. Daily domestic load curve for two consecutive days in Qatar

From Figure 8, it is noted that the electricity demands for the two days are almost identical. Short-term electricity load is affected by natural and social factors, making load forecasting more complex [43,44]. For medium-term forecasting, the time horizon is one week to one year. It is made based on (i) historical load demand (both domestic and industrial); (ii) planned new load (bulk consumers, big commercial projects, government projects); (iii) outage programs of the bulk industrial consumers; and (iv) temperature and humidity. The time horizon for long-term forecasting is longer than a year and is based on (i) historical load demand (both domestic and industrial); (ii) planned new load (bulk consumers, big commercial projects, government projects); (iii) population growth; (iv) oil prices; (v) gross domestic product (GDP); and (vi) the number of electricity meters [45,46].

Forecasting methods can also be classified into three main categories: subjective, objective (time series), and objective (causal). The subjective forecasting method is based on human judgment, such as the Delphi method and cross-impact analysis. On the other hand, the time series method is based only on a phenomenon's past values. Causal methods are based on data and independent variables (factors) that affect a dependent variable that is being forecasted [47,48]. Bayram et al. [49] studied and analyzed Qatar's electricity consumption patterns and future renewable energy integration. In addition, they proposed a methodology to estimate the cooling load. The authors used the Gulf Cooperation Council Interconnection Authority (GCCIA) data. They got the peak demand, only from 2009, after establishing the GCCIA [50].

To gain a better understanding and more accurate forecasts for this thesis, Qatar General Electricity and Water Corporation (KAHRAMAA, responsible for Qatar's electricity transmission and distribution network) was approached. Total peak demand and domestic peak demand data were obtained, ranging from 1954 and 2001, respectively, to 2020. They also found a significant difference between summer and winter electricity demand, caused by the cooling demand in summer, with more than half of the electricity consumption in summer coming from cooling. Inglesi [51] used regression modeling to forecast electricity demand in South Africa up to 2030, using historical data from 1980 to 2005. In 2008, South Africa faced problems supplying domestic and industrial consumers with electricity. The author used five variables: real GDP, actual electricity consumption, average electricity price, real disposable income, and population. The analysis showed that a unit percentage increase in electricity price could reduce the electricity demand by about 0.5%. The author also found that a unit percentage increase in the population's disposable income can increase electricity demand by more than 0.4%. The evaluation was based on two scenarios: the average growth of the economy (4%), and accelerated growth (6%), between 2009 and 2030, with 1% population growth and increased electricity prices. The results showed that income and price significantly impact the demand in the long term, whereas, in the short term, electricity demand is impacted by GDP and population size.

Wood and AlSayegh [52] studied Kuwait's electricity and water demand behavior based on historical data on oil income, GDP, population electricity load, and water demand for ten years. The authors classified the population as Kuwaiti citizens and expatriate citizens. Kuwait's energy load is similar to that of Qatar due to its geographical nature. The demand behavior was simulated under three oil price cases: high price, low price, and the base price, and was projected until 2030. Based on the calculated correlation coefficients, the authors found that the demand highly depends on the GDP. This analysis shows that when a country is more dependent on oil-based revenues and mostly non-citizen workforce, a better representation of the demand forecast can be obtained through the patterns of GDP.

Aslan et al. [53] used regression models for forecasting the long-term electricity peak load for Kutahya city in Turkey. The authors used four regression models: simple, multiple, quadratic, and exponential. The authors used the historical data of demand, temperature, and population growth from 2000 to 2007 to forecast the monthly peak load for the 2008 year. By having the actual values of the 2008 monthly peak demand, the authors used a mean absolute percentage error (MAPE) to measure the forecast error.

Abu-Shikhah et al. [54] used daily loads to forecast the next year's daily loads and the peak load. The methodology is based on implementing multivariable regression on the previous year's hourly loads. The authors investigated three methods: linear, polynomial, and exponential. The authors applied the proposed models to load data of the Jordanian power system for 1994-2008 to find the best-fit forecasting model with the three methods. Based on these results, the authors concluded that the exponential method does give good results for the given dataset compared to the other two methods. The authors highlighted that the error produced from the linear regression method is reasonable.

Bhardwaj and Bansal [55] proposed a model to forecast the electricity consumption of Lucknow City in the Uttar Pradesh state of India till the year 2023. Uttar Pradesh is a state located in the northern part of India, with a population of over 19 million. In June 2007 and June 2008, the state had a power shortage of 12.6% and 13.6% of the total demand, respectively. Moreover, the transmission and distribution losses in 2002-2003 were 36.64%, and in 2005-2006 it reached 37.17% of the total demand. For the modeling, the authors used population estimation based on data available as per the 2001 Indian Census and the load demand survey. The survey was conducted in

June 2008 by the Transmission Sub-station situated on the western side of Lucknow City. The authors used electricity demand, population, and temperature to develop the forecasting model.

Salgado et al. [56] proposed a short-term bus load forecasting methodology. The main idea is to add the buses, form groups with similar daily load profiles, and adjust one load forecasting model for each group. The authors used two stages to arrive at the forecast values. In the first stage, they use the bus clustering process. In the second stage, a forecasting model is adjusted for each group or cluster. This approach was tested on bus load data from the Brazilian North/ Northeast system. The solution obtained through the aggregate approach is similar to that obtained by the individual bus load forecasting model but with lower computational effort.

Ghanbari et al. [57] used the regression (Linear and Log-Linear) approach for annual electricity load forecasting in Iran. The authors mentioned that the electricity load forecast could also be categorized into three groups, which are short, medium, and long-term forecasts. Short-term forecasting identifies cost-saving potential and secures the power system’s operation. Medium-term forecasting is used to schedule fuel supplies and maintenance operations. Long-term forecasting is used for planning operations. The authors have proposed two models (Linear Regression and Log-Linear Regression) to have a long-term forecast of electricity requirements for four years (from 2004 to 2007). They used two economic parameters, real-GDP and population, for regression methods. In addition, they stated that using Real-GDP instead of nominal GDP is more accurate because the effects of inflation are considered. The forecasting accuracy of each of the three approaches was calculated using the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), and the Mean Absolute Percentage Error (MAPE), which showed that Log-based regression is better than the linear regression. Other authors also consider the use of population and GDP as factors for demand forecasts for forecasting electricity demand.

Li et al. [58] highlighted that accurate load forecasting is essential for an electricity market operator's dispatch planning. They proposed two Bayesian quantile regression models to forecast the quantiles of electricity load. They then applied their proposed models to the National Electricity Market of Australia. Cabral et al. [59] explored the balance between demand and supply, especially with the unavailability of cost-effective energy storage systems. In addition, Elkamel et al. [60] proposed a multiple linear regression model and a neural network model to forecast electricity demand in Florida state. The proposed models used economic, social, and climatic variables. Hadri et al. [61] investigated three approaches to forecasting electricity consumption in buildings. Their goal was to assess the forecasting accuracy of the models at the smart meter level. Lin et al. [62] studied how to improve the accuracy of forecasting air conditioning and lighting power consumption in a high-rise office building in Shanghai. They concluded that adding relative humidity and scheduling to the forecasting model would improve accuracy.

On 30 January 2020, COVID-19 was identified by the World Health Organisation as an international public health emergency [63]. Malec et al. [64] studied the impact of COVID-19 on electricity demand profiles for selected business clients in Poland. They concluded that the drop in electricity consumption against the expected values was 15–23% in the first lockdown. For the second lockdown, the percentage drop was less, with a maximum value of 11%. Nevertheless, the impact of abnormal conditions such as the COVID-19 pandemic on electricity demand and load forecasting has not been thoroughly investigated in relation to preparedness for such situations.

In Qatar, Abulibdeh et al. [65] studied the impact of COVID-19 pandemic on electricity demand and forecasting accuracy for buildings using machine-learning (ML) techniques and empirical big data. They concluded that the monthly residential electricity consumption was increased due to the stay-at-home policy. On the other hand, there was a decrease in the electricity consumption for the industrial and commercial sectors due to the declining of the economic activities.

Kim et al. [66] proposed a hybrid Long Short-Term Memory (LSTM) and Convolution Neural Network (CNN) short-term forecasting model. The proposed model gave better forecast accuracy than ARIMA and LSTM models. As a future work, the authors want to modify the model to be suitable for medium-term forecasting. Moalem et al. [67] mentioned that accurate electrical demand forecasting of basic metal industries in Iran is important to balance the electrical supply chain. They proposed a coupled model to forecast the demand. This first part of the model consists of wavelet decomposition. Then the output is divided into three parts which are training, validation, and test data sets. They used daily historical data of the electrical demand for 40 months. They concluded that the obtained results are better than the other methods' results like Decision Tree and Boosted Tree.

Piotrowski et al. [68] studied the impact of e-mobility development on the Polish power system. They forecasted the number of electric vehicles, annual power demand and daily profiles with and without the impact of e-mobility growth using Multi-Layer Perceptron (MLP) and LSTM models. They found that due to e-mobility, annual power demand could grow by nearly 7%. In addition, they concluded that the development of e-mobility in Poland may lead to a shortage of energy. Xu et al. [69] proposed an Informer model for electricity load forecasting. The Informer model is based on the historical load data to forecast the future load values. The proposed model gave better accuracy compared to 3 neural network models.

2.3 Summary

The power markets’ trades and issues were discussed before. Two main issues describe the power markets and large-scale PV projects: the technical and contractual aspects. The studies that discuss both aspects have not been elucidated. This is because the contracts between the power distribution companies and the power plants are confidential, making their studies rare.

Mega power plants are crucial and vital projects for countries. The investments of these power plants are very high that can reach multi-billions of dollars. Therefore, the contracts between the different stakeholders are usually confidential and long-term contracts. The confidentiality of the contracts between the power distribution companies and the power plants makes the research task difficult.

Furthermore, due to the high overhead costs of the power plants, the minimum-take energy provision is added to share the risk. From Table 1, it is concluded that the clause of minimum-take energy “take-or-pay”, and its impact have not been widely researched. Therefore, this clause will be discussed and taken into consideration in the proposed model.

Thus, this study combines the technical aspects (the transmission network capacity, the power station capacity, and the water demand) and the contractual provisions (energy cost and minimum-take energy). Also, the model developed in this study can be used in the design or operation phases to minimize operating costs.

The proposed optimization model requires input data which is the forecasted electricity energy. The amount of energy is the input that has to be distributed between the different power plants. Table 1 shows a summary of the reviewed studies. Furthermore, Table 1 can be considered as a thematic literature review matrix that contains the differenet constraints of the reviewed studies. The studies that mentioned in Table 1 are the ones that are highly related to the proposed model and the selected constraints.

In addition, COVID-19 has affected all sectors of life, and researchers in numerous fields have begun studying the impact of the pandemic, especially with the spread of coronavirus variants. Since it is a new strange pandemic, there is a lack of research on its impacts. This thesis discusses the impacts of the COVID-19 pandemic on Qatar's electricity demand. Qatar was selected for this study due to having the required data. In addition, the factors that need to be considered for electricity demand forecasting are studied. In the end, this thesis addresses the impact of the COVID-19 pandemic on Qatar's electricity demand and demand forecasting.

Table 1. Summary of the reviewed studies

Title	Year	Demand	TOP	Maximum generation	Water requirement	Energy Price	Lines
Techno-economic feasibility analysis of 1 MW photovoltaic grid connected system in Oman	2017			×		×	
International and national renewable energy for electricity with optimal cost effective for electricity in Egypt	2017	×				×	

Title	Year	Demand	TOP	Maximum generation	Water requirement	Energy Price	Lines
Design and energy management optimization for hybrid renewable energy system–case study: Laayoune region	2019			×		×	
Optimization of the technology mix for the Shagaya 2 GW renewable energy park in Kuwait	2015			×	×	×	×
Electricity system in Jordan: Status & prospects	2018	×		×		×	×
Challenges in meeting all of Indi’’s electricity from solar: An energetic approach	2018	×		×		×	
An optimal mix of conventional power systems in the presence of renewable energy: A new design for the German electricity market	2018	×		×		×	
Lifetime optimization framework for a hybrid renewable energy system based on receding horizon optimization	2018	×		×		×	
Optimal Hierarchical Allocation in Deregulated Electricity Market under PSP Auction Mechanism	2014					×	

Title	Year	Demand	TOP	Maximum generation	Water requirement	Energy Price	Lines
Optimal Model of Power Purchase Strategy for Direct Power Purchase by Large Consumers Based on the Multi-state Model of Electricity Price	2016					×	
Chinese power-grid financial capacity based on transmission and distribution tariff policy: A system dynamics approach	2019	×		×		×	×
Large-Scale Solar PV Investment Models, Tools, and Analysis: The Ontario Case	2011	×		×		×	×
A Multi-Objective Scheduling Optimization Model for a Multi-Energy Complementary System Considering Different Operation Strategies	2018	×		×			
Analysis and Evaluation of the Possibility of Electricity Production from Small Photovoltaic Installations in Poland	2023	×	×			×	
Technical, Economic, and Environmental Analysis and Comparison of Different Scenarios for the Grid-Connected PV Power Plant	2022	×		×		×	
Optimization of renewable systems	2019	×		×		×	×

Title	Year	Demand	TOP	Maximum generation	Water requirement	Energy Price	Lines
Grid-Connected Solar Photovoltaic System for Nile Tilapia Farms in Southern Mexico: Techno-Economic and Environmental Evaluation	2022	×				×	
Hierarchical Optimization Method for Energy Scheduling of Multiple Microgrids	2019	×		×		×	×
Hybrid CSP—PV Plants for Jordan, Tunisia and Algeria.	2023	×		×		×	
Modeling and Economic Operation of Energy Hub Considering Energy Market Price and Demand.	2022	×		×		×	×
Optimization of All-Renewable Generation Mix According to Different Demand Response Scenarios to Cover All the Electricity Demand Forecast by 2040: The Case of the Grand Canary Island.	2022	×		×		×	
Technical and Economic Analysis of Modernization of Solar Power Plant: A Case Study from the Republic of Cuba.	2022	×				×	
Techno-Economic Analysis of Electricity Generation by Photovoltaic Power Plants Equipped with Trackers in Iran.	2023					×	

Chapter 3: IMPACT OF COVID-19 ON QATAR ELECTRICITY DEMAND

This chapter will discuss the impact of COVID-19 on Qata’s electricity demand and load forecasting. Two forecasting models will be developed.

3.1 Data Acquisition

Several factors affect the pattern and magnitude of electricity demand such as weather factors, economic status and social activities. For the models development, several data were collected and obtained for the analysis purpose. The data of electrical energy demand and the number of electricity meters were obtained from KAHRAMAA. Furthermore, the population and GDP data were obtained from the Qatar Planning and Statistics Authority and International Monetary Fund (IMF). In addition, the power plants data was collected from Qatar Electricity and Water company and Emirates Water and Electricity Company.

3.2 The Impact of COVID-19 on Electricity Demand

COVID-19 affected all life sectors worldwide. Electricity demand is one of these sectors. There was a direct impact on the industrial demand due to the lack of global demand for many commodities and products, such as oil and gas. The impact on domestic demand varied from country to country according to the severity of restrictions imposed. In response to the pandemic, some countries closed schools and universities, and some jobs were transferred to remote working systems. Some countries took more stringent precautions based on the number of current and expected COVID-19 cases and had partial or entire curfews or even complete shutdowns in some cases. In Qatar, the government transferred academic study to distance learning and suspended public transport services for schools and universities

[70]. Qatar also reduced the presence and attendance of workers in the government and private sectors to 20% of the total employees, with the rest working from home [71]. Qatar also closed many shops and malls, keeping pharmacies and foodstuff sales outlets open with relatively limited opening hours. This changed the shape of the curve and the magnitude of electricity demand. Figure 9 is an example of how the shape of the curve changed with the advent of the pandemic.

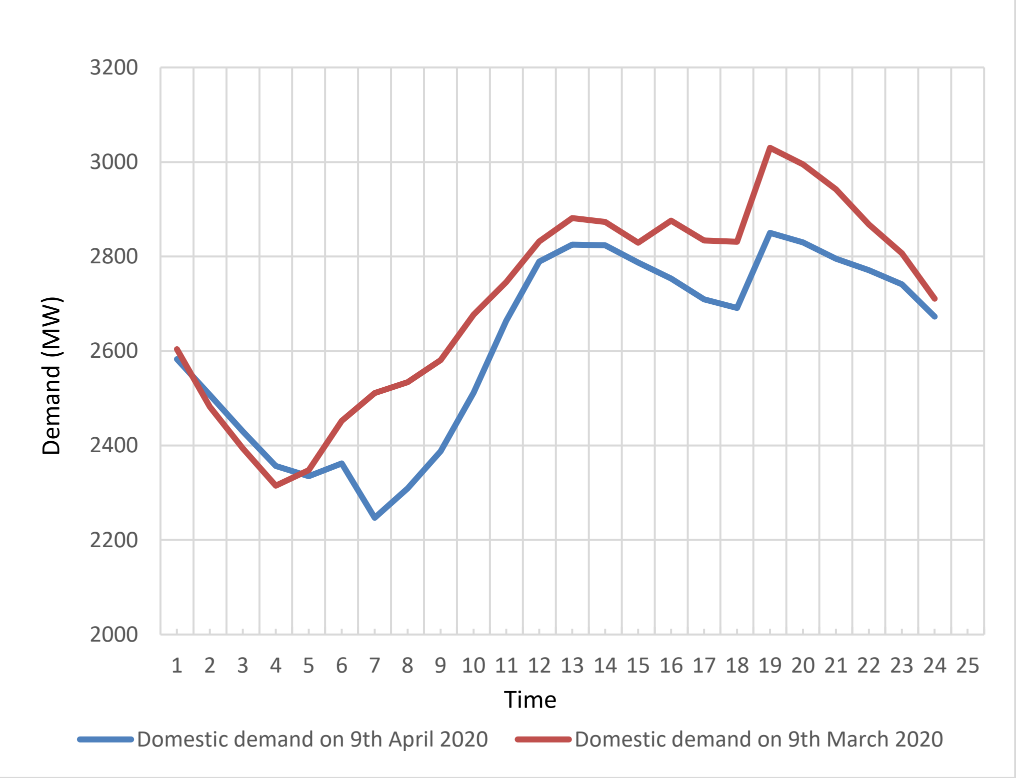


Figure 9. Daily domestic demand curves for two days (9 March and 9 April 2020)

The orange curve represents the domestic demand on 9th March 2020, when people started preparing for schools, universities, and offices after 4 a.m., where the demand started increasing. However, this demand decreased in the blue plot (representing the domestic demand on 9th April 2020) after remote working and education started. Regarding the change in the magnitude of demand due to COVID-19, there were difficulties and restrictions on travel and transportation activities. Monthly figures for the population within Qatar’s boundaries at the end of each month are shown in Table 2. Thses data was collected from Planning and Statistics Authority.

Table 2. Qatar’s population in millions for the 2019 and 2020 years

Month End	2019	2020	Change in Percentage (%)
January	2.766459	2.773221	0.24
February	2.772947	2.782106	0.33
March	2.760586	2.795484	1.26
April	2.772294	2.805202	1.19
May	2.740479	2.807805	2.46
June	2.638657	2.794148	5.9
July	2.475063	2.749215	11.08
August	2.666938	2.735707	2.58
September	2.747282	2.723624	−0.86
October	2.753045	2.717360	−1.3
November	2.773885	2.715919	−2.1
December	2.687871	2.684329	−0.13

The figures do not include:

1. Qatari nationals who are outside Qatar.
2. Non-Qataris with residency permit who are outside Qatar.

In 2019, it was notable that the difference between April and July was almost 300,000 people, which is more than 10% of the total population. In 2020, due to the COVID-19 epidemic, there were restrictions on travel and transportation activities, and, therefore, most families spent their summer vacation in Qatar. This was reflected in

June and July's population growths of approximately 6% and 11%, respectively. As a result, the 2020 total peak demand was recorded on 30th July 2020 as 8.6 GW. Moreover, a new domestic peak was recorded on 22nd July 2020, equal to 7.32 GW, with 5.6% annual growth. However, the decrease in industrial demand balanced the total demand. Energy consumption increased by more than 5% in July 2020 compared to July 2019 (from 5,231 GWh to 5,502 GWh). Qatar developed a four-phase plan to normalize life and lift the COVID-19 restrictions gradually. The first phase started on 15th June 2020, when shopping malls, public parks, and some mosques were reopened. Figure 10 shows the impact of the Phase 1 implementation as the domestic demand increased on 15th June 2020, compared to the previous day.

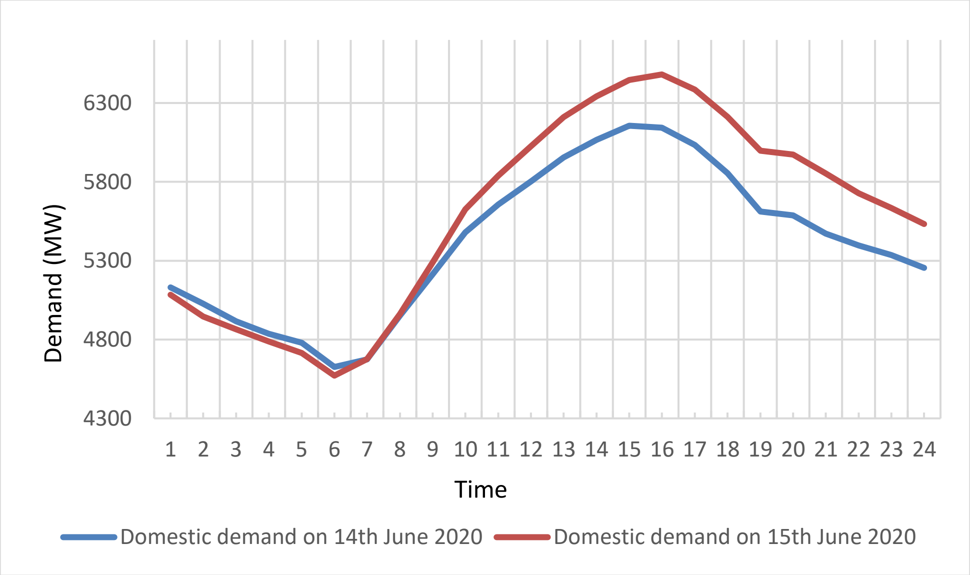


Figure 10. Domestic demand curves for two days (14th June before lifting the COVID-19 restrictions and 15th June after lifting the COVID-19 restrictions)

In Figure 10, the increase in domestic demand started at 8 a.m., the time of the shopping malls opening. Further, the electricity demand is expected to increase in parallel with the four phases. With the signs of a second wave of coronavirus, on 24th

March 2021, Qatar announced a series of restrictions on education, social gatherings, and business activities. The restrictions included closing gyms, spas, swimming pools, and driving schools. In addition, all social gatherings in enclosed places, and weddings, were banned. Moreover, public transport continued to operate at a maximum capacity of 30% during the weekdays and 20% during weekends. Later, on 1st April 2021, Qatar decided to suspend blended learning and implement distance learning (online) for schools and universities. Qatar imposed new restrictions on 9th April 2021. The restrictions included reducing workplace attendance to 50% capacity for both government and private sectors. This also included closing beauty and hair salons, cinemas, theatres, libraries, and public museums. In addition, the dine-in service at restaurants and cafés was stopped, and children under 16 years were forbidden from entering malls and markets. On 9th May 2021, Qatar declared a four-phase plan to gradually lift the restrictions in response to a reduced number of COVID-19 cases. The first phase started on 28th May 2021, and the last phase was on 3rd October 2021, in which all employees and students returned to their offices, schools, and universities.

Figures 11 and 12 show the daily domestic peak for 2020 and 2021, along with the restrictions and lifting phases. The phase effect depends on its measures and actions. Furthermore, seasonality plays a vital role in the phases' impact. In Qatar, as with the whole world, the severity of restrictions was less for the third (Omicron) wave.

Figure 11. The daily domestic electricity peak for 2020 and the phases of lifting restrictions

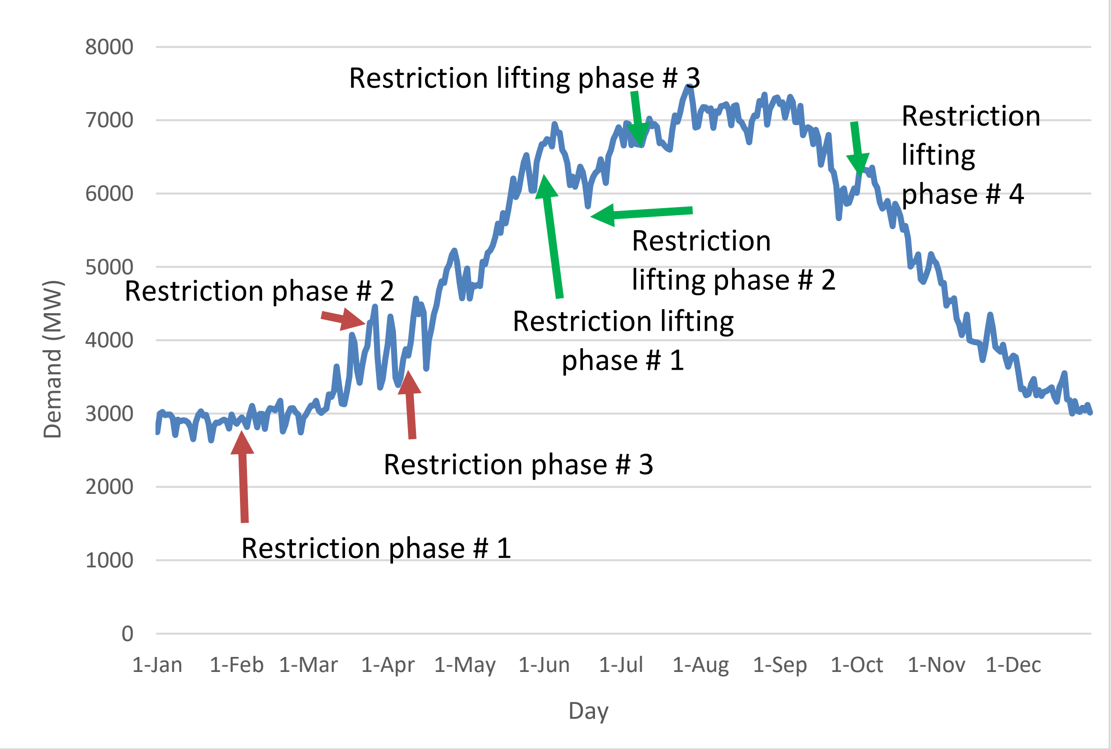


Figure 12. The daily domestic peak for 2021 and the phases of lifting restrictions

Figure 13 shows the daily domestic peak for 2019, 2020, and 2021. A Kruskal–Wallis H test showed a statistically significant difference in domestic electricity peak demand between the three years, with a mean rank score of 499.29 for Year 1, 541.88 for Year 2, and 602.83 for Year 3. This confirms that 2019 had a lower domestic electricity peak than 2020 and 2021, indicating that the domestic electricity peak increased during COVID-19. Two-sample Kolmogorov–Smirnov tests between each pair of years were performed to see whether there was a statistical difference between the distributions for each year. The results show that the distribution of domestic electricity peaks for the years (2019 and 2020) and (2019 and 2021) are unequal. However, the distribution functions for the years (2020 and 2021) are equal. This shows a clear impact of the Covid pandemic on the domestic electricity peak.

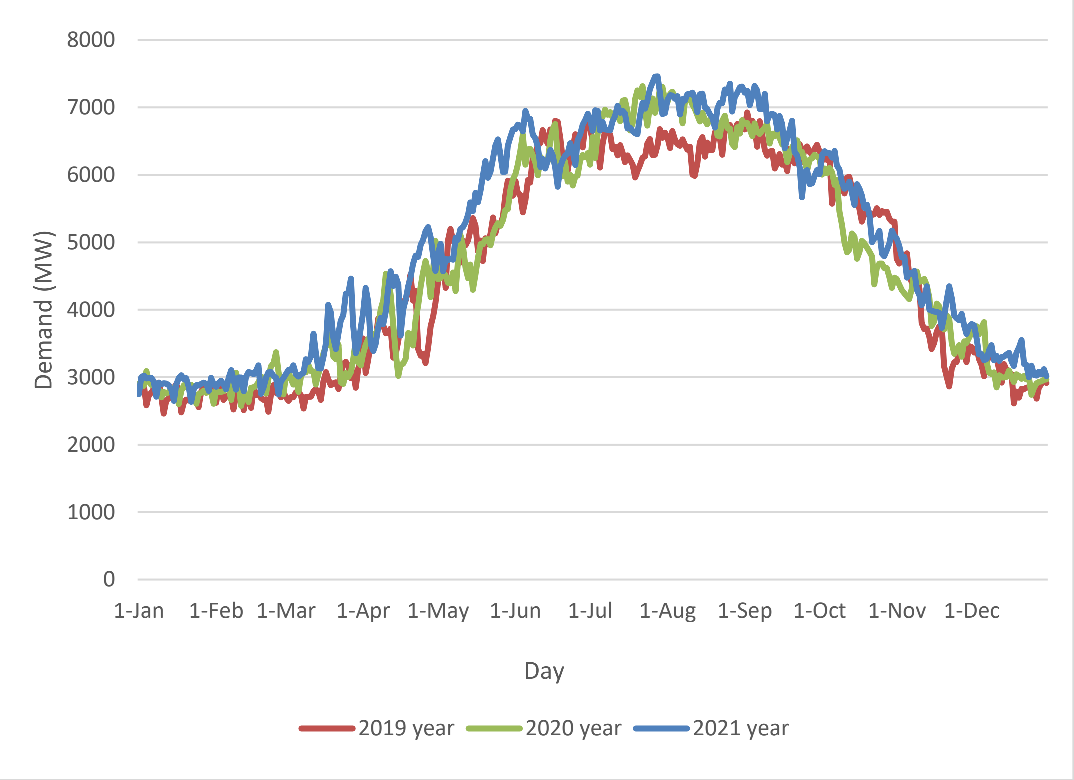


Figure 13. The daily domestic peak for the years 2019, 2020 and 2021

Table 3 summarizes the impact of COVID-19′s response measures on the domestic electricity peak demand. This is done by comparing the demand during the COVID-19 period with the previous period’s demand using SPSS software. Once the attendance of 30% of school students was implemented, the domestic peak demand increased by 28.3%. Furthermore, implementing the 20% and 80% employee attendance measure caused increases in the domestic electricity peak of 29.8% and 10.5%, respectively.

Table 3. The impact of COVID-19 response measures on domestic peak demand

Response Measures	Difference in Domestic Electricity Peak (%)	Remarks
Attendance of 30% of school students	28.3	This shows that partial or full online study and work systems are increasing the domestic peak due to switching on computers, lights, and air-conditioners in homes. Furthermore, the electric appliances in schools and offices are switched on due to the attendance of some parties.
Attendance of 20% of employees	29.8	
Attendance of 80% of employees	10.5	

The impact of the month of Ramadan (Hijri year), and the closing of shops, museums, parks, mosques, and restaurants, were statistically examined and were found to be insignificant compared with the response measures outlined in Table 3 [72].

3.3 Domestic Electricity Peak Demand Forecasting

Electricity demand forecasting is an essential issue for electricity providers. Without an accurate forecast of electricity demand, over-capacity or shortages in the power supply may result in high costs, network bottlenecks, instability, and power blackouts (see section 3.4 for more detail).

In this thesis, data of electrical energy demand and the number of electricity meters were obtained from KAHRAMAA. The population and GDP data were obtained from the Qatar Planning and Statistics Authority [73]. As the focus here is to forecast energy demand for the domestic sector, the discussion on peak demand relates only to the domestic sector. Figure 14 shows a sharp rise in system peak electricity demand from the year 2000. This could be mainly due to the development path that Qatar has adopted over the past two decades to increase its GDP from both the oil and non-oil sectors.

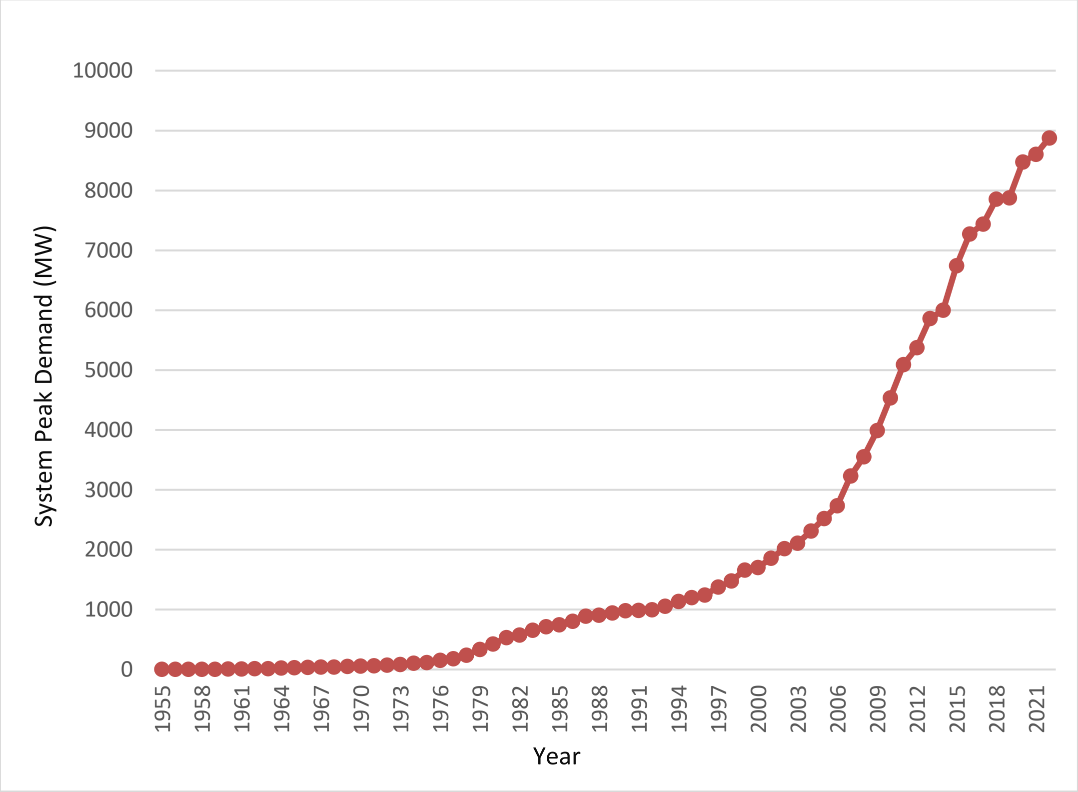


Figure 14. Historical electricity peak growth between 1954 and 2021

Figure 15 shows the changes in electricity demand throughout 2018. There is a considerable difference in system peak demand between the winter and the summer months, which is expected, given Qatar's hot summers, when a massive air-conditioning load is required. This also shows that the baseload during the summer months is almost double that during the winter, indicating that space conditioning is the most crucial electricity-consuming end-use in Qatar.

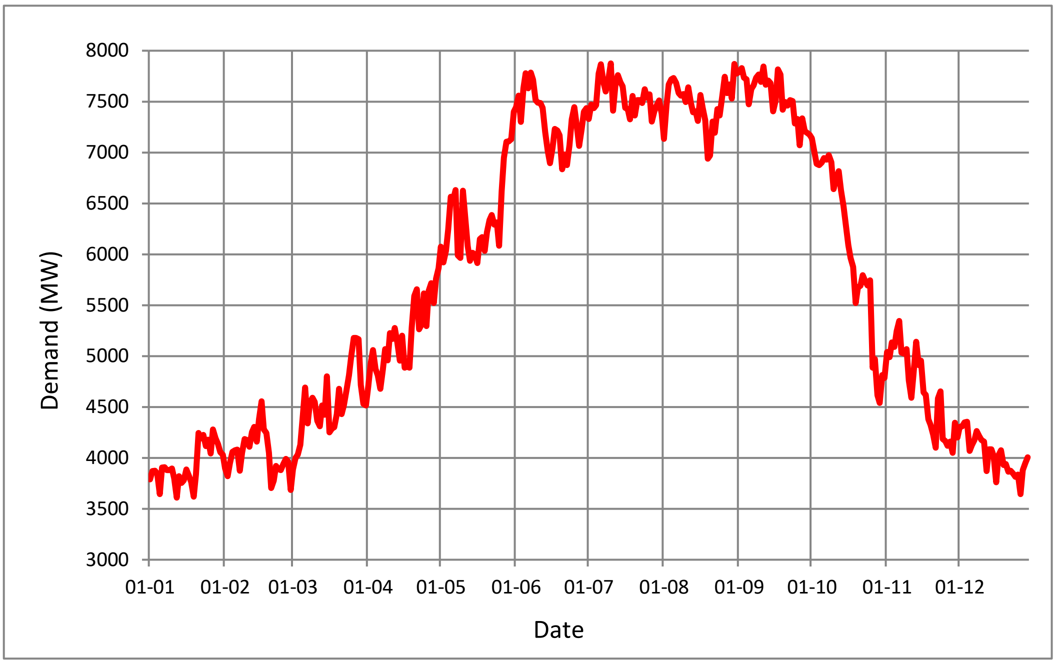


Figure 15. System peaks for the year 2018

Figure 16 shows how the electricity demand changes throughout the day in a typical summer month (July, in this case). The graph shows that the load demand rises quickly as the day progresses and peaks during the day's hottest hours. The daily baseload is almost 4 GW, rising to higher levels during the day because of the office and commercial sector's electricity use and the industrial sector's electricity use.

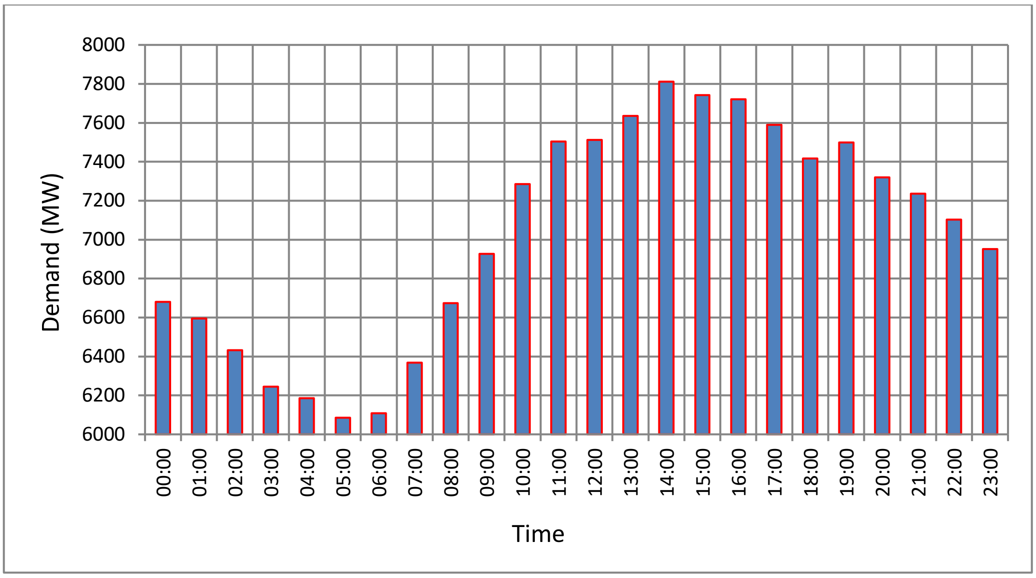


Figure 16. Hourly demand on system peak day for the year 2018

In addition, based on the peak timing, there are 2 patterns in Qatar. The first is the summer pattern, where the peak is in the afternoon, caused by the cooling load. Figure 17 demonstrates the peak summer pattern.

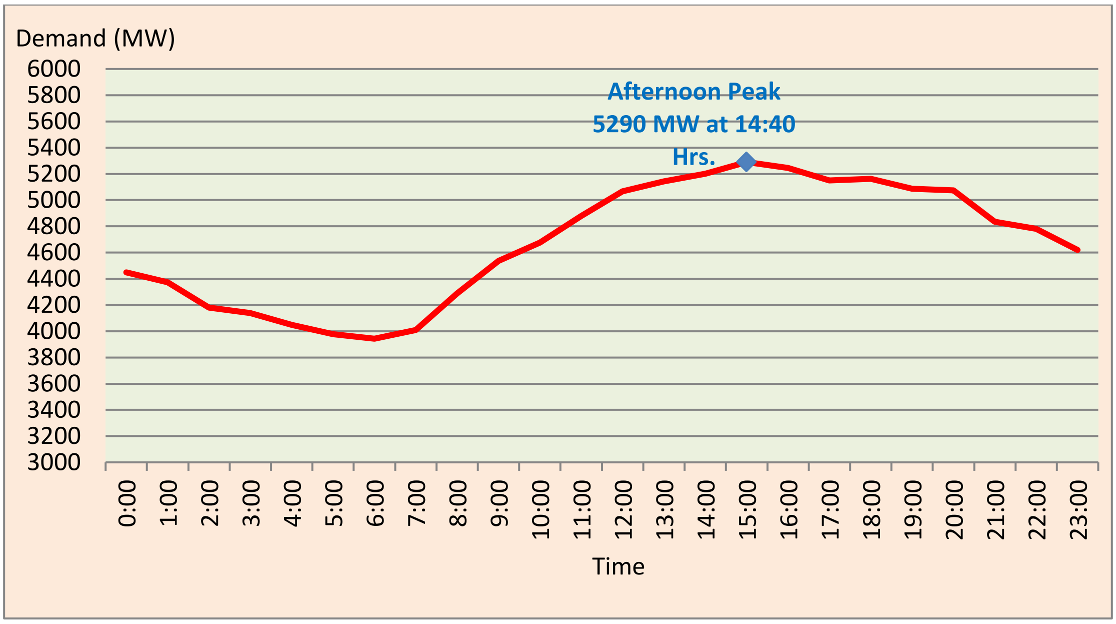


Figure 17. Summer pattern of peak

The second is the winter pattern, where the peak is in the evening, caused by the lighting load. Figure 18 demonstrates the peak winter pattern.

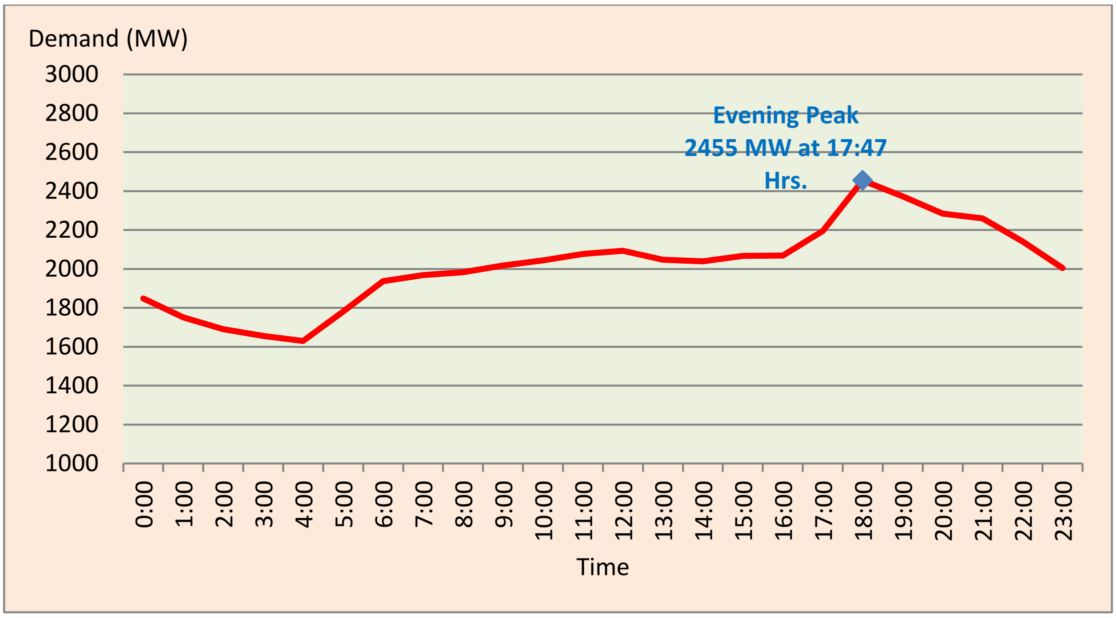


Figure 18. Winter pattern of peak

From the above, it is notable that electricity demand changes through years, months, days, and hours. Regarding domestic demand, peak demand grew from 1.8 GW in 2001 to 7.3 GW in 2020. Data show that in the past 20 years, the domestic peak electricity demand has grown by more than 350% in Qatar, attributed to Qatar's rise in population. The massive influx of residents working in other economic sectors could be one of the main reasons for this demand. Therefore, in the following demand assessment, population size is considered one of the independent variables for the rise in domestic peak demand. Table 4 shows Qatar's historical electricity domestic peak demand, population, GDP, and the number of electricity meters between 2006 and 2020. Qatar's population and GDP are growing at significant rates, due firstly to the influx of non-Qatari employees in the country and secondly to the government's increasing effort to invest in the oil and gas sector and other infrastructural and service projects. The expectation is that electricity demand will grow in the future.

Table 4. Qatar’s domestic electricity peak demand, population, GDP, and number of electricity meters between 2006 and 2020 Years [74]

Year	Domestic Peak (MW)	Population	GDP (Billions of QR)	Number of Electricity Meters
2006	2,400	1,042,947	221,611	56,182
2007	2,805	1,218,250	290,151	68,035
2008	2,960	1,448,479	419,582	86,108
2009	3,245	1,638,626	355,986	114,160
2010	3,580	1,715,098	455,445	136,850
2011	4,015	1,732,717	624,173	156,756
2012	4,250	1,832,903	700,345	175,144
2013	4,630	2,003,700	723,369	194,171
2014	4,795	2,216,180	750,658	209,585
2015	5,170	2,437,790	599,295	229,314
2016	5,905	2,617,634	552,305	255,723
2017	5,965	2,724,606	609,200	275,138
2018	6,455	2,760,170	698,900	294,699
2019	6,430	2,799,202	667,817	317,582
2020	7,315	2,684,329	526,000	333,198

GDP is an indirect measure of the population’s average affluence and activity, supported by other sectors such as commerce, agriculture, government, transport, and industry. As activity grows, GDP also starts to increase. Aware that it has an industrial impact, it is also assumed that the overall GDP will impact overall and sectoral electricity demand [17]. A constant GDP, with an increase in population, will generally mean decreasing the overall income of the population. Therefore, in this analysis, GDP is used as a proxy for economic growth that requires electricity as one of the main ingredients. Based on the above discussion, GDP is another independent variable for assessing peak electricity demand. The domestic peak electricity demand models for load forecasting are developed based on historical data of domestic peak demand, population, GDP, and the number of electricity meters over 15 years (2006–2020). The population and GDP data forecasts were obtained from the International Monetary Fund (IMF) Country Report No. 18/135 [75].

The regression analysis determines the relationship between dependent and independent variables [76,77]. The dependent variable is the single variable being explained by the regression. The independent variables are used to explain the dependent variable [78].

From Table 3, there are 3 independent variables which are: population, GDP and number of electricity meters. The multicollinearity and significance for the independent variables will be checked before developing the model.

The multicollinearity occurs when the independent variables are highly correlated to each other. Table 5 describes the correlation values between the variables.

Table 5. Correlation matrix

Variables	Domestic Peak	Number of electricity meters	Population	GDP
Domestic Peak	1	0.994	0.956	0.646
Number of electricity meters	0.994	1	0.970	0.688
Population	0.956	0.970	1	0.702
GDP	0.646	0.688	0.702	1

It is noted from Table 5 that the independent variables population and number of meters are highly correlated to each other with a correlation value equals to 0.970.

Furthermore, the analysis showed that population and GDP variables are not statistically significant with p-values equal to 0.275 and 0.086 respectively.

As a result, this thesis outlines developing a simple forecasting regression model using Minitab software. The developed model is a linear regression model based on the number of electricity meters.

The developed model is given by Equation (1):

$$\text{Domestic electricity peak demand} = 1{,}401.293 + (0.0169167 * \text{number of electricity meters}) \quad (1)$$

To measure the forecast error for the developed model, the domestic electricity peak demand will be calculated for the year 2021 and compared with the actual value.

By having the values for the year 2021 and using (1):

$$\text{Domestic electricity peak demand} = 1{,}401.293 + (0.0169167 * 346{,}159) = 7{,}257 \text{ MW}$$

The actual value of the domestic electricity peak demand for the year 2021 is 7,460 MW.

Mean Absolute Percentage Error (MAPE) is used when errors need to be put into perspective. For example, an absolute error of 1 in a forecast of 10 is substantial, relative to an absolute error of 1 in a forecast of 2,000, which is insignificant [47]. The

$$\text{Mean Absolute Percentage Error (MAPE)} = \sum \left(\frac{|Actual - Forecast|}{Actual} \right) \quad (2)$$

MAPE is calculated as given in Equation (2):

Therefore, MAPE = ((7,460 – 7,257)/(7,460)) * 100 = 2.71%

In addition, the Mean Absolute Error equals to 203 MW.

It is notable from the previous section that there is a direct and substantial relationship between domestic electricity peak demand and the number of electricity meters.

In addition, a validation Python regression model was developed (Appendix A). The forecasted value equals to 7,204 MW which is very close to the forecasted value of the previous model.

It is necessary to mention that the forecast error was calculated based on one year's forecast only, which is 2021. Therefore, in future work, the forecast error should be calculated for five years, from 2021 to 2025, to better evaluate the developed model.

3.4 Bottleknecks and Power Blackouts

3.4.1 Bottleneck

Bottleneck is the slowest (or minimum capacity) stage in the process. In the Electricity network, the bottleneck is defined as the circuit or feeder that limits the flow of the electricity. Figure 19 demonstrates the electricity network bottleneck concept.

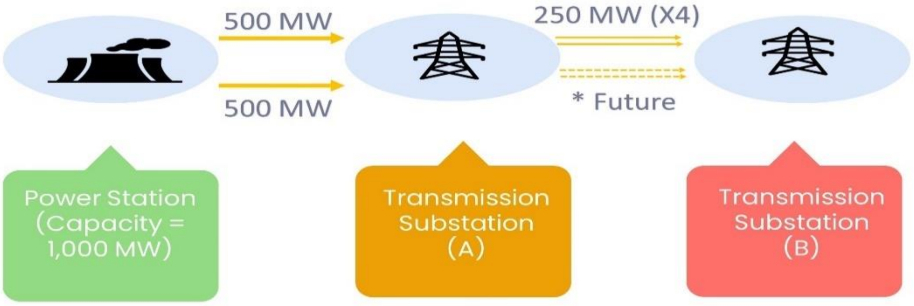


Figure 19. Example of an electricity network with a bottleneck circuit

It is noticed that the capacity of the power station is 1,000 MW. However, the maximum power that can be utilized is 500MW due to the bottleneck between transmission substation (A) and transmission substation B. Therefore, according to the "Process Capacity = Bottleneck Capacity" formula, the previous network capacity is 500MW. * The dashed lines are future circuits but not yet energized.

Another type of bottleneck can happen when a feeder is composed of two different capacities. For example, 400 KV overhead lines usually have a capacity of 1,400 MW, but sometimes it is required to have a small part of the feeder as an underground cable, which has a maximum capacity of 700 MW. In the above case, the entire feeder is considered to have a capacity of 700 MW only, which limits the power transfer capability.

3.4.2 Power Blackout

Power blackout is the absence of electrical power all over the network. Power blackout has the following causes:

1- Electrical faults

2- Power station'' gas supply failure

The power blackout has many impacts on our life, such as:

- Traffic Confusion
- Effect on Lives of People in Hospitals
- Factories & Refineries Shut Down
- Power Supply Interruption to Homes [79]

3.5 Electricity control centers and FIFA world cup 2022

Qatar hosted the FIFA world cup 2022 championship in November and December

2022. KAHRAMAA is monitoring and managing the electricity network through 3 control centers. The three control centers are:

1- NCC (National Control Center) is responsible for 400KV and 220KV voltage levels.
2- DGCC (Doha Grid Control Center) which is responsible for 132KV, 66KV, and 33KV voltage levels
3- DCC (Distribution Control Center) which is responsible for 11KV and 415V voltage levels

The control centers are equipped with the latest technological applications and the technical cadres with the highest level of expertise and competence. They are set up to secure and safely operate the electricity network. In addition, they are responsible for monitoring and controlling the electricity network generating and transmitting 24 hours and responding to emergency cases. Also, they are coordinating with major industrial consumers for their load demands. Moreover, NCC is responsible for setting up load generation unit' programs and sharing loads through local and regional networks [3,80].

Most of these tasks are done in the control room using the SCADA (Supervisory Control and Data Acquisition) System. This system provides control and gathers operational data (such as system frequency, voltage, load flows, and breaker positions) and processes and displays it in the control rooms.

3.6 Gulf Cooperation Council Interconnection (GCCI)

In July 2009, the 6 gulf countries were electrically interconnected, forming one network. Figure 20 is the GCCI network scheme. Overhead line circuits were used to interconnect the 6 electricity systems.

Figure 20. GCCI network scheme [50]

The GCCI network has the following advantages:

1- Sometimes it is much cheaper to import electrical energy from other countries than to build a new power station. Also, it is faster considering the required time for the building process. This is especially true if the electrical power is needed for a short period (e.g., due to maintenance reasons and weather conditions).

2- If there is a power supply loss in a country and this loss cannot be compensated by the country itself, electrical energy can be imported from other countries.

3- This project will facilitate chances to interconnect with other regions in the future, such as North Africa.

4- It will provide the basis for the exchange of electrical power among the member states in such a way as to serve the economic aspects and strengthen the reliability of the electrical supplies.

The GCC Interconnection Authority (GCCIA) is a joint stock company subscribed by the six Gulf countries. The Head Office of the Authority is in the city of Al Khobar, Saudi Arabia [50].

The authorized share capital of the Authority is fixed at $1,100,000,000 divided into 1,100,00 shares, subscribed as shown in Figure 21.

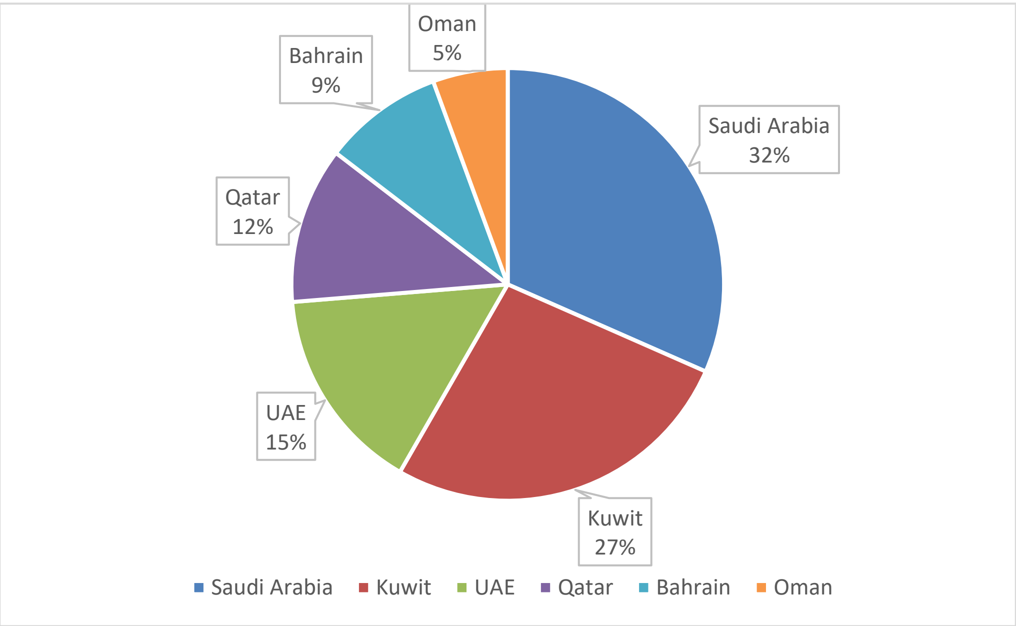


Figure 21. GCCI share capital [50]

Table 6 shows the utility-scale renewable energy projects in the GCC as of January 2019.

Table 6. Utility-scale renewable energy projects in the GCC as of January 2019 [8]

Country	Project/site	Technology	Size (MW)	Price (US cents/kWh)
United Arab Emirates (Dubai)	Mohammed bin Rashid Al Maktoum Solar Park, Phase IV	CSP Solar PV	700 250	7.3 2.4
	Mohammed bin Rashid Al Maktoum Solar Park, Phase III	Solar PV	600 of 800 200 of 800	2.99
	Mohammed bin Rashid Al Maktoum Solar Park, Phase II	Solar PV	200	5.85
	Mohammed bin Rashid Al Maktoum Solar Park, Phase I	Solar PV	13	
United Arab Emirates (Abu Dhabi)	Noor Abu Dhabi, Sweihan	Solar PV	1,177	2.42 (non-weighted price of 2.94)
	Shams 1	CSP	100	
Oman	Dhofar, Phase I	Wind	50	
	Dhofar, Phase II	Wind	150	
	Miraah Solar Thermal	Solar Thermal	1,000	
	Ibri PV Plant	Solar PV	500	
	PDO Amin PV Plant	Solar PV	100	
Saudi Arabia	Sakaka	Solar PV	300	2.34
	Dumat Al Jandal	Wind	400	
Qatar	Siraj	Solar PV	700	
	Mesaieed Waste to Energy	Waste to energy	38	
Kuwait	Shagaya	CSP	50	
		Solar PV	10	
		Wind	10	
	Al Dibdibah/ Shagaya Phase II	Solar PV	1,200-1,500	
Bahrain	Askar Landfill	Solar PV	100	
	Al Dur	Solar-wind hybrid	5	

3.7 Summary

In this chapter, the impact of the COVID-19 pandemic on Qatar’s electricity demand has been addressed. Furthermore, the importance of forecasting demand was discussed, and a forecasting model based on population, GDP, and the number of electricity meters was developed. The output of this model will be used as an input for the optimization model discussed and developed in Chapters 4 and 5.

Chapter 4: ECONOMIC ENERGY ALLOCATION

The word ‘photovoltaic’ consists of two words: photo and Volta. Photo stands for light and Volta is the unit of the electrical voltage. In other words, photovoltaic means the direct conversion of sunlight to electricity. The common abbreviation for photovoltaic is PV [81,82].

PV is evidently the most flexible renewable energy source, and it can be used in approximately all power classes up to GW and in most locations around the world [83]. Large-scale PV power plants have been extensively investigated in literature.

Linear programming (LP) is a mathematical technique for solving a broad class of optimization problems [84,53]. LP is one of the most common optimization methods where the objective function is linear, and the constraints are specified using only linear equalities and inequalities.

4.1 Mathematical Model

4.1.1 Objective Function and Constraints

The low economic efficiency of renewable energy sources is an important issue for electricity distribution companies. Their goal is to reduce the total cost through the optimal electricity allocation between the different power plants, as shown in the following objective Function (3):

$$\sum_{p=1}^{CP} CC_p EC_p + \sum_{v=1}^{PV} CV_v EV_v \tag{3}$$

Minimize the total energy purchase cost (C),

Where:

CC_p: the unit cost of purchased energy from conventional plant p, $\forall p \in CP$

EC_p: purchased energy from conventional plant p, $\forall p \in CP$

CV_v: the unit cost of purchased energy from PV plant v, $\forall v \in PV$

EV_v: purchased energy from PV plant p, $\forall v \in PV$

CP: a set of conventional power plants, indexed by p

PV: a set of PV power plants, indexed by v

The unit cost is the summation of capital recovery, operation and maintenance (O & M), and gas consumption costs.

The constraints are:

1- Annual energy demand (D) has to be met by the generation from the different power plants during the whole year.

$$\sum_{p=1}^{CP} EC_p + \sum_{v=1}^{PV} EV_v = \mathrm{D} \tag{4}$$

As a result, the generation from both conventional and PV power plants has to be equal to the annual energy demand. The demand can be divided into 2 main demand which are day demand and night demand. This constraint will be an input to the proposed model.

2- Transmission lines (TL) limits: Each network has many transmission lines to transfer the generated energy from the power plants to consumers. Sometimes, maintenance activities or tripping incidents will restrict the power flow, and not all power will be evacuated. The power transfer on the transmission lines should not exceed the transmission lines' maximum power transfer limits.

$$PF_l \leq CPF_l \qquad \forall l \in TL \tag{5}$$

Where:

PF_l: load on the transmission line l, $\forall l \in TL$

CPF_l: maximum load the transmission line l can carry, $\forall l \in TL$

TL: a set of transmission lines, indexed by l

Therefore, transmission lines-limit affect the power stations' evacuation. As a result, this constraint will be used as a percentage of the power stations' maximum capacities, as shown in (6) and (7).

$$EC_p \leq EP.\ ECP_p \quad \forall p \in CP \tag{6}$$

$$EV_v \leq EP.\ ECV_v \quad \forall v \in PV \tag{7}$$

where:

EP: evacuation factor: a factor that defines the maximum evacuation energy

$ECPp$: maximum annual energy capacity of conventional plant p, $\forall p \in CP$

$ECVv$: maximum annual energy capacity of PV plant v, $\forall v \in PV$

Figure 22 shows a single line diagram of a part of Qatar grid.

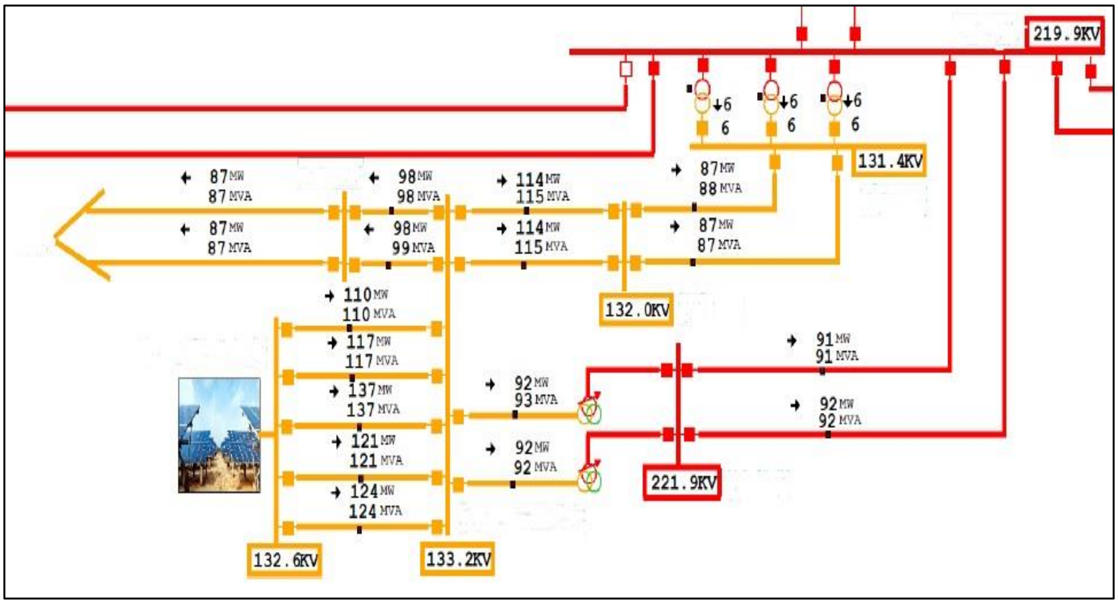


Figure 22. Single line diagram of a part of Qatar grid

3- Water demand (WD): cogeneration (combined-cycle or combined heat and power) is the concept of generating electricity and heat or steam for water desalination. Conventional power plants have both turbines and water distillers. The turbines and distillers are connected in a combined cycle. To produce water, it is required to generate steam from the side of the turbine. However, power companies sometimes require electricity only due to the country's requirements. In this case, there will be no water distillers. As a result, the electricity distributors attempt to meet the consumers' water demand with the best energy allocation to the power plants. Usually, power plants need a minimum amount of energy to produce the required heat to meet the water demand. Therefore, this constraint will be expressed as a percentage of the power stations' maximum capacities, as shown in (8) and (9).

$$EC_p \geq WP.\ ECP_p \qquad \forall p \in CP \tag{8}$$

$$EV_v \geq WP.\ ECV_v \qquad \forall v \in PV \tag{9}$$

WP: water factor: a factor that defines the minimum energy needed to meet water demand

The minimum energy required for water production is considered a must-run generation.

4- Maximum energy generation from conventional or PV power plants: the maximum energy generation from a power plant can be considered to run at its full capacity throughout the year, as shown in (10) and (11).

$$EC_p \leq ECP_p \qquad \forall p \in CP \tag{10}$$

$$EV_v \leq ECV_v \qquad \forall v \in PV \tag{11}$$

For example, if the power plant capacity is 500 MW, then the maximum energy generated is expressed as follows:

Maximum energy = (Full Capacity (FC)) * (number of hours in a year)

= 500 * 8,760 = 4,380 GWh

5- Minimum conventional generation equals to the night demand: this constraint was added to the model to ensure the meeting of the night demand due to the absence of the PV generation during night. This constraint is represented by (13).

$$P_{\text{conv}} \geq D_{\text{night}} \tag{13}$$

The Transmission lines (TL) limits is taken into consideration for the power plants maximum evacuation.

6- Minimum-take energy (MTE): the power plant investors pay much money to build and operate the plants and take many operating risks. Therefore, they add a minimum-take energy concept to the contracts to ensure they can profit from these projects. This amount also is called a take-or-pay (TOP) amount. A take-or-pay contract with high overhead costs is common in the energy sector. The buyers guarantee to take an agreed minimum portion of goods during a specific period.

$$\text{MTEp} \leq \text{ECPp} \quad \forall p \in CP \tag{14}$$

$$\text{MTEv} \leq \text{ECVv} \quad \forall v \in PV \tag{15}$$

In this type of contract, the risk is shared between the buyers and sellers where:

MTE_p: take-or-pay energy amount of conventional plant p, $\forall p \in \text{CP}$

MTE_v: take-or-pay energy amount of PV plant v, $\forall v \in \text{PV}$

LP is a commonly used optimization method where the objective function is linear, and the constraints are specified using only linear equalities and inequalities [38,73].

If the electricity distributor did not reach the MTE amount through the specific period, the cost of the minimum-take energy would be paid to the power plant. As a result, it is a loss for the electricity distributor, and it has to be avoided. Figure 23 is an example to demonstrate the MTE concept for eight power plants (A to H). The blue part represents the MTE amount for each power plant as a percentage of the total generated energy. The orange bars represent the remaining amount of the total generated energy. The percentages differ based on the contracts between the power distributor and power plants.

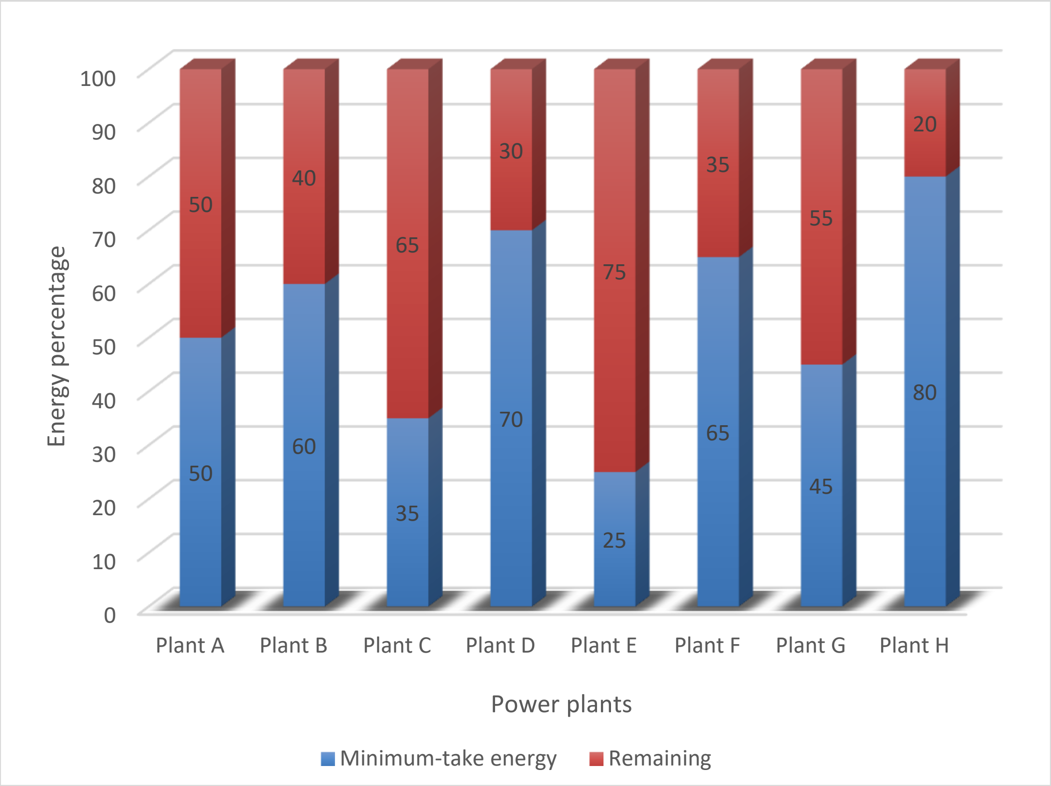


Figure 23. Minimum-take energy concept for the power plants' contracts

The following is the mathematical form of the proposed model:

Minimize EC I_i

Subject to:

- $P_{conv} + P_{PV} \geq D$
- $L_{trans\ line} \leq L_{trans\ line\ max}$
- $WP \geq WD$

- $\mathrm{E}_{\mathrm{allocated,N}} \leq \mathrm{E}_{\mathrm{max,\ N}}$
- $\mathrm{E}_{\mathrm{allocated,N}} \geq \mathrm{MTE}_{\mathrm{N}}$
- $\mathrm{P}_{\mathrm{conv}} \ \geq \mathrm{D}_{\mathrm{night}}$

Where $E_{allocated,\ N} \geq 0$

The first five constraints will be considered hard constraints, whereas the last will be considered soft one. The decision variables are the energy amounts allocated to the conventional and PV power plants. Moreover, two essential parameters, unit rate and heat rate need to be considered. The electricity distributors purchase energy from different power plants at different cost rates per the contracts. As a result, the electricity distributors aim to meet their consumers' demands at the cheapest cost. The energy rate includes capital recovery, operation, and maintenance (O & M), and gas consumption costs.

In addition, heat rate is the amount of fuel required to generate one unit of electricity. It is commonly used in power stations to indicate power plant efficiency. The heat rate is the inverse of the efficiency, and a lower heat rate is better.

$$\text{Heat rate} = \frac{\text{Input energy}}{\text{Output energy}} = \frac{\text{Thermal energy in (BTU)}}{\text{electrical output energy (KWh)}} \qquad (16)$$

The heat rate constraint requires excessive data about the gas turbines, power plant configurations, and weather conditions. Therefore, this constraint will not be considered in the optimization problem to keep the model generic.

4.1.2 Experimental Results

The proposed optimization model can be used in the design or operation phases. During the design phase, if an investor bids to build a PV power plant with a specific energy cost ($/KWh), is it feasible and worth accepting that bid, and the total cost will be reduced, or will the total energy cost be increased, and the minimum-take energy will not be well utilized? In other words, the model can be used to study the feasibility of new renewable energy project proposals.

The model will be used to allocate the energy between the different power plants to minimize the operating cost for the operation phase. The model's inputs will be the forecasted or estimated energy, water demand requirements, evacuation limitations, energy rate, and minimum-take amounts. The outputs are the energy amounts allocated to each power plant considering the constraints. The pseudocode for the developed MATLAB model is shown below:

```
START
READ  Power_stations_capacities
READ  Water_requirements_energy
READ  Take_or_pay_energy
READ  Yearly_Maximum_Energy
READ  Evacuaction_limits
READ  Energy_rates
GET     Total_electricity _energy
GET     Day_electricity _energy
GET     Night_electricity _energy
Calculate D = (Total_electricity _energy)—(Water_requirements_energy)
IF D ≤ Take_or_pay_energy THEN
    Allocate energy between the power plants based on Take_or_pay_energy
Else allocate the energy based on Take_or_pay_energy and Energy_rates concepts
```

```
15. ENDIF
16. REPEAT Steps 9,10,11 and 12
17. UNTIL Total_electricity _energy is distributed, and Evacuaction_limits are considered
18. WRITE energy allocated to each power plant “optimal solution”
19. WRITE the corresponding cost
20. DISPLAY sum = sum of energy allocated to all power plants
21. Ensure sum = Total_electricity _energy
22. STOP
```

Figure 24 shows the flowchart for the developed model.

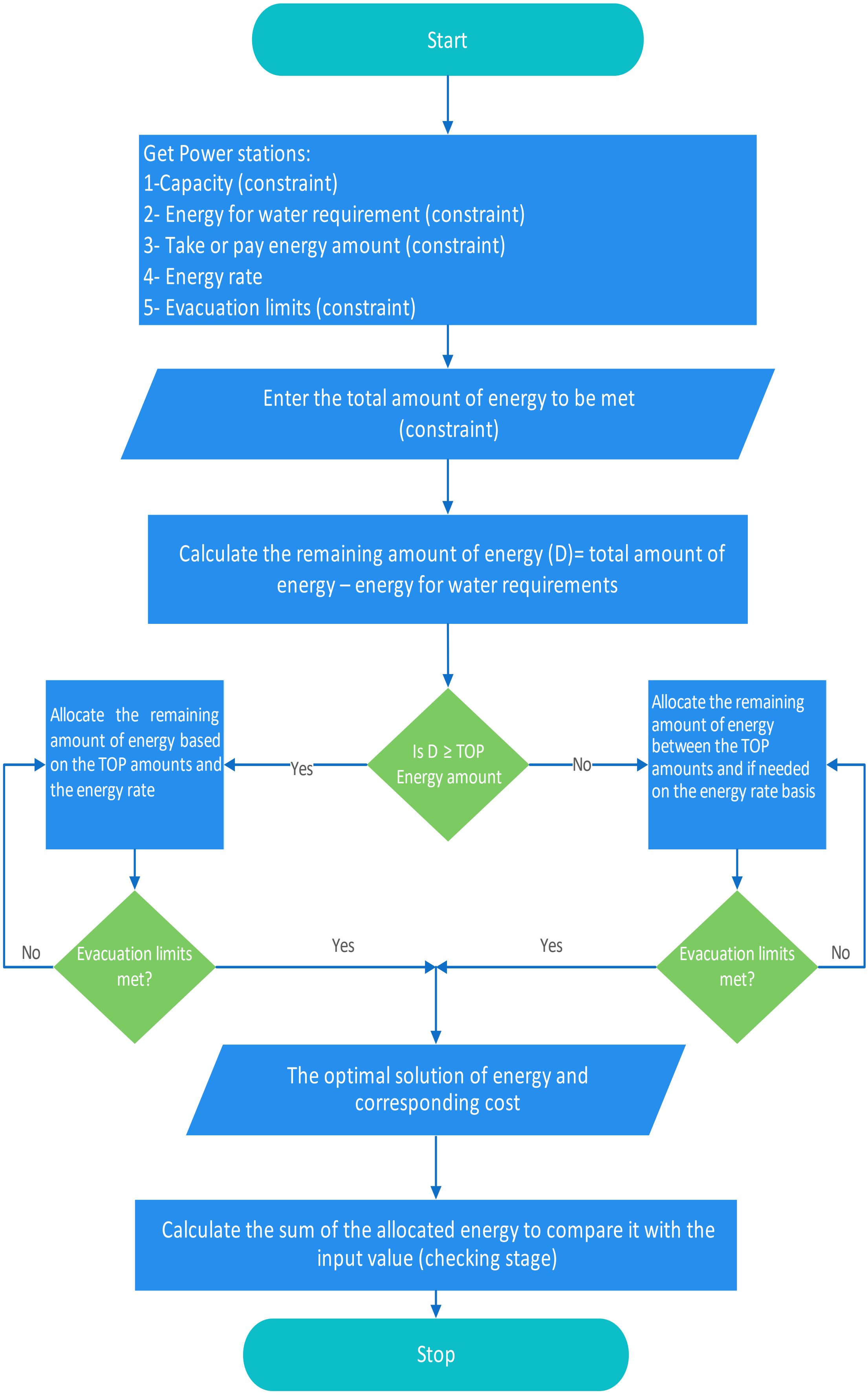


Figure 24. Flowchart of the proposed model

In Figure 24, the inputs for the proposed model are power stations' capacity, the energy of water requirements, TOP energy amounts, evacuation limits, energy rate, and the total amount of energy demand. The model will be used to allocate the energy requirement considering the different constraints to get the optimal solution. The optimal solution is the energy allocation that has the lowest cost. After completing the energy allocation process, a checking step is to ensure that the energy requirement equals the total energy allocated. The power systems can be classified into two main groups according to the power source and the renewable energy share, which are:

1- Group A: number of conventional power plants ≤ number of PV or renewable power plants

2- Group B: number of conventional power plants > number of PV or renewable power plants.

The proposed model can optimize the energy cost for both groups. In conclusion, the proposed model can be used for any power system with the required excessive power plants' data. Table 7 is an example of group A power system.

Table 7. An example of Group A power system data

Power Station	Capacity (MW)	Yearly Maximum Energy (GWh)	Water Requirements (%)	Minimum-Take Amount (%)	Evacuation Limitation (%)	Energy Cost ($/MWh)
A	700	6,132	20	35	100	36
B	420	3,679	25	30	95	33
PV1	400	1,000	0	0	100	15
PV2	500	1,250	0	0	100	13.9
PV3	250	625	0	0	100	19

The assumed power system has 2 conventional power plants (A and B) and 3 PV power plants (PV1, PV2, and PV3). The result of using the proposed model to allocate 10,000 GWH as demand is shown in Table 8 and Figure 25.

Table 8. Energy allocated to power plants

Power Station	Available Generation (MWh)	Allocation (MWh)	Allocation Percentage (%)	Unit Price (S/MWh)	Cost ($)
A	6,132,000	3,629,760	59	36	130,671,360
B	3,679,200	3,495,240	95	33	115,342,920
PV1	1,000,000	1,000,000	100	15	15,000,000
PV2	1,250,000	1,250,000	100	13.9	17,375,000
PV3	625,000	625,000	100	19	11,875,000
Total		10,000,000			290,264,280

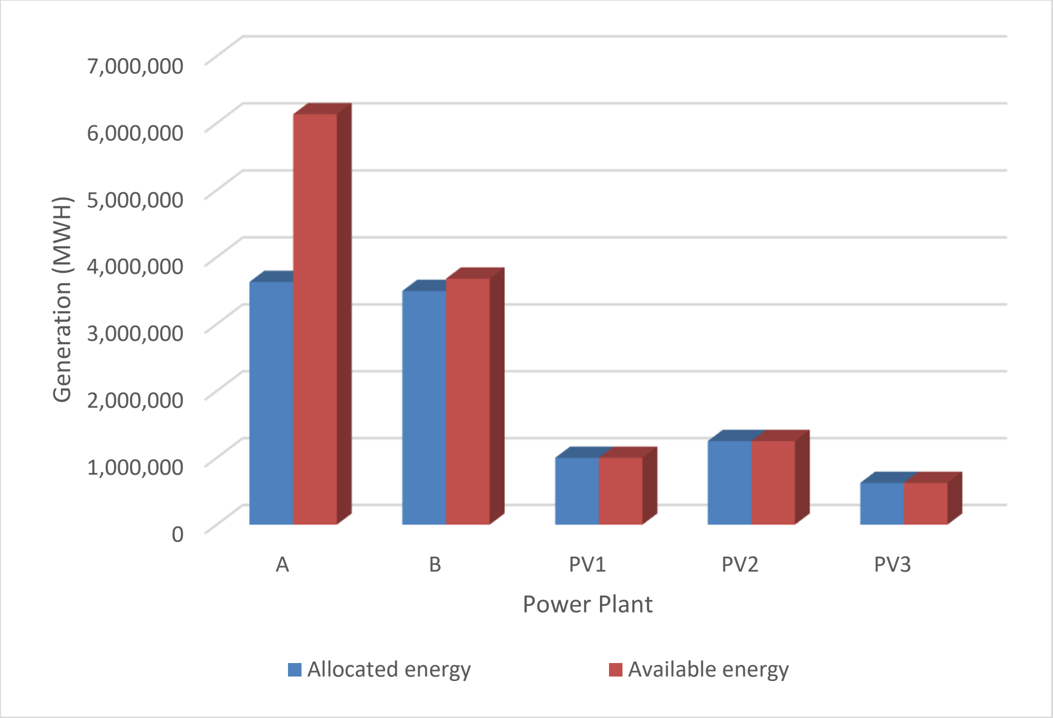


Figure 25. Available and allocated energy for the Group A example

Initially, the energy-water requirement was allocated for power plants A and B. Then, due to the low energy price of the PV power plants, the whole generation was utilized. After that, the energy price of the B power plant is cheaper than the A power plant. However, 5% of the total generation of the B power plant could not be utilized due to the evacuation limit. The remaining required energy was allocated to A power plant. Table 9 is an example of Group B power system.

Table 9. An example of Group B power system data

Power Station	Capacity (MW)	Yearly Maximum Energy (GWh)	Water Requirements (%)	Minimum-Take Amount (%)	Evacuation Limitation (%)	Energy Cost ($/MWh)
A	700	6,132	20	35	100	36
B	420	3,679	25	30	95	33
C	400	1,000	50	35	100	50
D	500	1,250	29	40	100	18
E	900	6,132	20	35	100	36
F	680	3,679	25	30	95	33
G	400	1,000	40	35	100	15
H	630	1,250	33	25	100	45
PV1	250	912	0	40	100	40
PV2	300	1,095	0	45	90	25
PV3	200	730	0	50	85	28
PV4	300	1,095	0	45	60	9

The assumed power system has 8 conventional power plants (AI, ..., H) and 4 PV power plants (PV1,…, PV4). Using the proposed model to allocate 20,000 GWH as a demand, the result is shown in Table 10 and Figure 26.

Table 10. Energy allocated to power plants

Power Station	Available Generation	Allocation (MWh)	Allocation Percentage (%)	Unit Price (S/MWh)	Cost ($)
A	6,132,000	5,072,820	83	36	182,621,520
B	3,679,200	3,495,240	95	33	115,342,920
C	1,000,000	500,000	50	50	25,000,000
D	1,250,000	1,250,000	100	18	22,500,000
E	6,132,000	2,146,200	35	36	77,263,200
F	3,679,200	3,495,240	95	33	115,342,920
G	1,000,000	1,000,000	100	15	15,000,000
H	1,250,000	412,500	33	45	18,562,500
PV1	912,500	365,000	40	40	14,600,000
PV2	1,095,000	985,500	90	25	24,637,500
PV3	730,000	620,500	85	28	17,374,000
PV4	1,095,000	657,000	60	9	5,913,000
Total	27,954,900	20,000,000			6,344,157,560

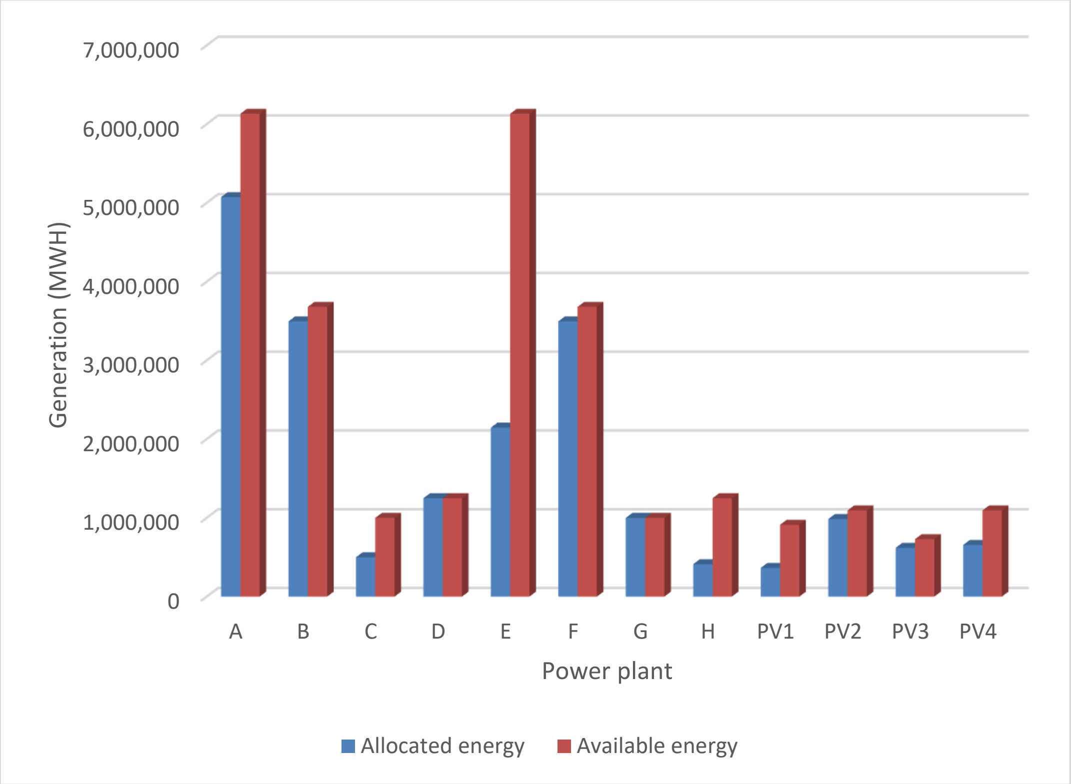


Figure 26. Available and allocated energy for the Group B example

It is noted that the lowest unit price is for the PV4 power plant. However, only 60% is the energy allocation due to the evacuation limit. On the other hand, the most expensive unit price is for the C power plant. However, 50% is the energy allocation due to the water requirement.

Qatar's power system consists of 8 conventional power plants and 1 PV power plant [3]. Based on the previous classification, Qatar's power system belongs to Group B. This case will be discussed in detail in Section 3. Two scenarios will be considered for the energy allocation before and after integrating the planned large-scale PV power plant.

The developed MATLAB model is shown in detail in Appendix B.

4.2 Model Validation

AMPL (A Mathematical Programming Language) programing language has been chosen to validate the proposed MATLAB optimization model.

The AMPL program has 5 components which are:

1- Sets: like conventional power plant set and PV power plant set.
2- Parameters: like the water demand and the installed capacity pf power plant.
3- Variables: which are the purchased energy from the power plants
4- Objective function: which is minimizing the total energy purchase cost.
5- Constraints: such as the maximum limit of energy that can be evacuated from conventional power plant.

The full AMPL program the data file are shown in Appendix C and Appendix D respectively.

4.3 Summary

This chapter developed an optimization model to minimize the electricity cost from the distribution companies' point of view. The developed model can be used in both the operation and planning phases. The input for the model is an energy value to be distributed between different power plants. The outputs are the allocated energy values to the different power plants considering the constraints. In chapter 5, Al-Kharsaah PV power plant in Qatar will be used and discussed as a case study.

Chapter 5: AL-KHARSAAH CASE STUDY

5.1 Al-Kharsaah PV Power Plant

Qatar's National Vision 2030 aims to create a balance between an oil-based and a diversified, knowledge-based economy. The vision includes economic, social, and environmental aspects and focuses on the ideal utilization of the country's oil and gas resources. In addition, Qatar's National Development Strategy 2018–2022 sets out a plan to increase renewable energy use for better natural resources management [7].

Qatar, represented by QatarEnergy and Qatar Electricity and Water Company (QEWC), established a joint venture company called Siraj Solar Energy to generate electricity from solar power. Siraj Power Energy will be a strategic national investor. The solar power plant's location will be west of Doha near Al-Kharsaah area (shown in Figure 27), with 10 km² of land.

Figure 27. Location of Al-Kharsaah PV power plant [2]

The estimated cost of that power plant is $467 million. It will be developed in two phases. The first phase started the generation on 27th June 2022 with 350 MW, and the second phase started the generation in November 2022 reaching the plant's full capacity (700 MW). The previous data was collected from Qatar Electricity and Water company [2]. Figure 28 shows the generation curve of Al-Kharsaah PV power plant on 4th September 2022.

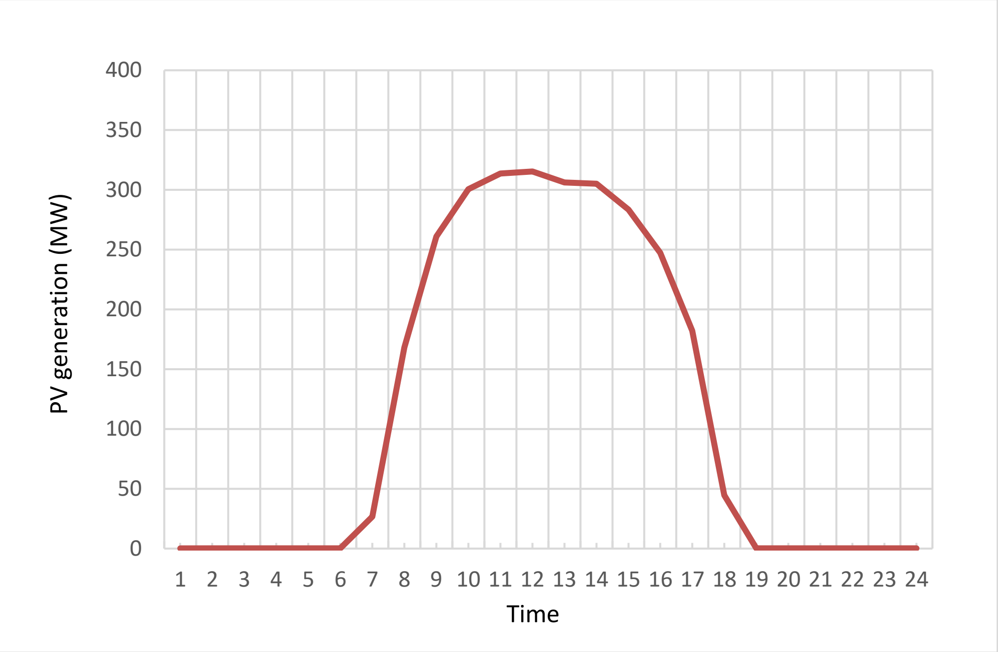


Figure 28. Al-Kharsaah generation curve on 4th September 2022

By that time, the PV generation will be about 7% of the total available generation, as shown in Figure 29. The installed conventional generation in Qatar is 10.576 GW.

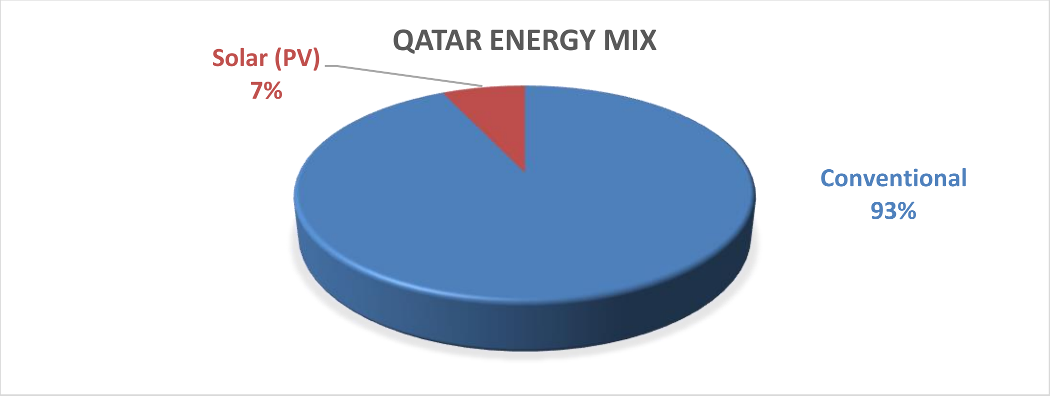


Figure 29. Qatar energy mix

This project’s energy rate is approximately 14.49 $/MWh, which is one of the lowest prices globally for these types of projects [3]. It is a public-private partnership project with a Build Own Operate Transfer (BOOT) contract for 25 years. Then, the ownership will be transferred to KAHRAMAA. In this project, there is no storage facility. Although solar power plants are in many countries worldwide, large-scale power plants are relatively new, especially in the GCC region. This ’s Qatar's first plant with a substantial capacity of 700 MW or more. Since Qatar’s maximum electricity demand is 8,600 MW, the solar power plant will meet more than 8% of that demand. It is essential for Qatar, and especially KAHRAMAA as the national utility, to be prepared to accommodate this large-scale plant. Therefore, its impact on the national grid should be studied carefully, and optimal methods to forecast the output and mitigate any effects of the plant on the network need to be established.

Furthermore, Qatar produces almost all of its potable water through desalination. Although reverse osmosis (RO) plants are now being implemented, most of the desalinated water is produced using multi-stage flash or multi-effect distillation techniques, which require turbines to be running to operate. Therefore, the entry of a large-scale solar power plant into the generation dispatch will affect the “must-run units' required for water production. This is further compounded by the fact that water demand does not vary seasonally as much as electricity demand (water demand varies 10–15% between summer and winter). For example, the electricity peak demand was 4,220 MW on 14th March 2021 and 8,210 MW on 6th June 2021. On the other hand, the water consumption was 376.8 million imperial gallons per day (MIGD) on 14th March 2021 and 416.2 MIGD on 6th June 2021. As a result, the electricity peak demand growth is almost 95%, whereas the water consumption growth is only 10% [25,39]. In Qatar, KAHRAMAA purchases electricity from eight different generation power plants with varying contracts in terms of energy prices. After the proposed solar power station's commissioning and without the storage facility, providing an optimal operation cost will be essential. The optimal energy allocation between the different generation plants needs to be determined daily to obtain energy from the solar power plant. Moreover, the need to shut down generating units and restart them again or run them with less generation has to be determined.

Due to the confidentiality of the power purchase agreements, the power plants' names will be presented in letters (A, B, C, etc.). Moreover, some data will be tuned and modified. The input data for the developed model are shown in Table 11.

Table 11. Power stations data with Al-Kharsaah

Power Station	Capacity "MW"	Yearly Maximum Energy (GWh)	Water Requirements (%)	Minimum-Take Amount (%)	Evacuation Limitation (%)	Energy Cost ($/MWh)
A	600	5,256	15	30	100	35.6
B	375	3,285	20	30	100	34.2
C	560	4,905	15	40	100	35.3
D	740	6,482	25	20	100	19.2
E	990	8,672	30	40	100	27.7
F	1,950	17,082	0	25	90	24.9
G	2,700	23,652	15	20	85	25.5
H	2,490	21,812	20	20	75	24.4
Al-Kharsaah	800	2,000	0	0	100	14.5

The forecasted or estimated energy for Qatar's system in 2022 is approximately 50,000 GWh. Using the developed model, the energy allocated to each power plant without and with Al-Kharsaah power station is shown in Tables 12 and 13 and Figures 30 and 31, respectively.

Table 12. Energy allocated to power plants without Al-Kharsaah

Power Station	Allocation (MWh)	Unit Price (S/MWh)	Cost ($)
A	1,576,800	35.6	56,134,080
B	985,500	34.2	33,704,100
C	1,962,240	35.3	69,267,072
D	6,482,400	19.2	124,462,080
E	3,468,960	27.7	96,090,192
F	14,434,400	24.9	359,416,560
G	4,730,400	25.5	120,625,200
H	16,359,300	24.4	399,166,920
Total	50,000,000		1,258,866,204

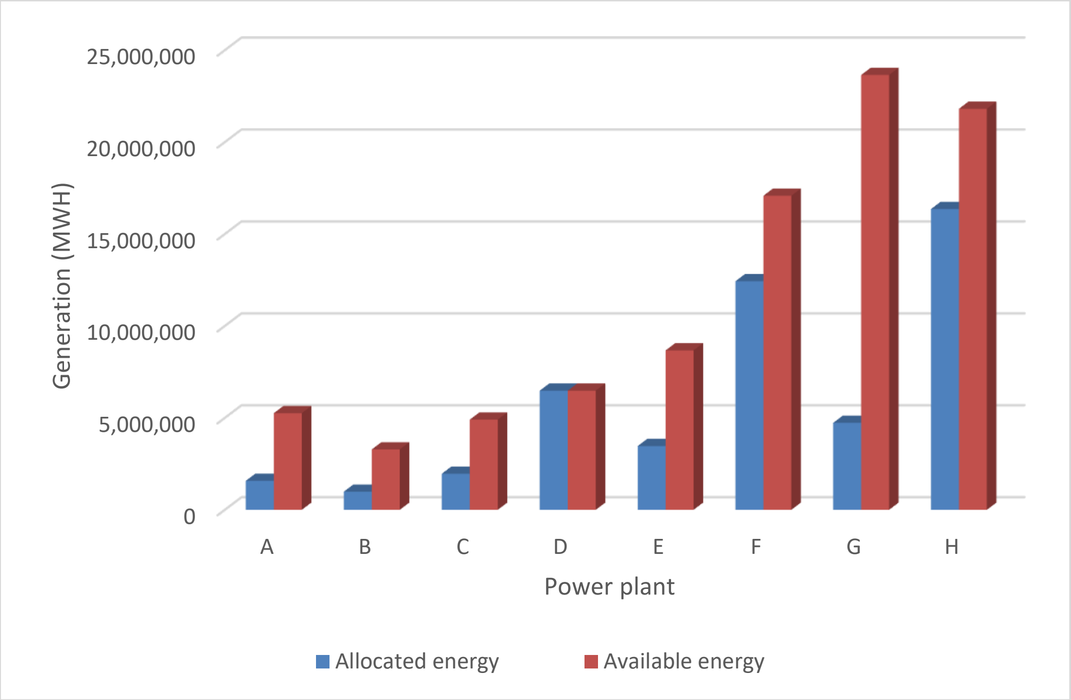


Figure 30. Available and allocated energy to power plants without Al-Kharsaah

Table 13. Energy allocated to power plants with Al-Kharsaah

Power Station	Allocation (MWh)	Unit Price ($/MWh)	Cost ($)
A	1,576,800	35.6	56,134,080
B	985,500	34.2	33,704,100
C	1,962,240	35.3	69,267,072
D	6,482,400	19.2	124,462,080
E	3,468,960	27.7	96,090,192
F	12,434,400	24.9	309,616,560
G	4,730,400	25.5	120,625,200
H	16,359,300	24.4	399,166,920
Al-Kharsaah	2,000,000	14.5	29,000,000
Total	50,000,000		1,238,066,204

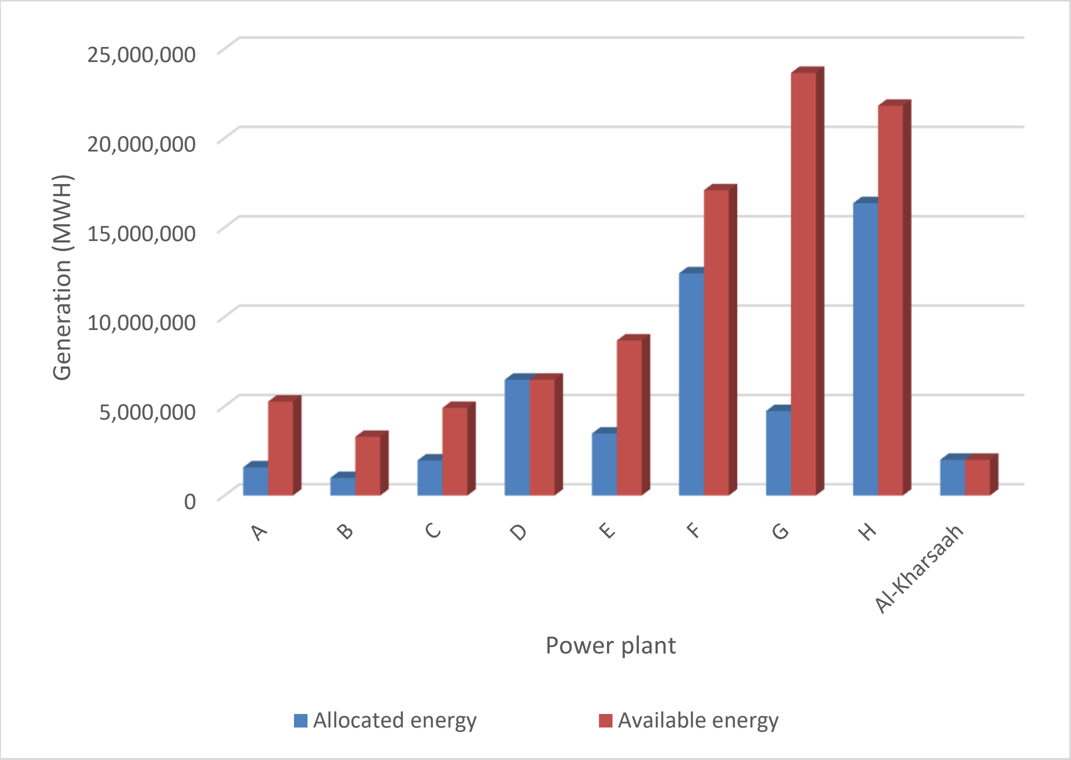


Figure 31. Available and allocated energy to power plants with Al-Kharsaah

As discussed in Section 2.3, the proposed model considers both the technical aspects and the contractual provisions. The confidentiality of the contracts between the power distribution companies and the power plants makes the research task difficult.

For the assumed case, it is noticed that after the commissioning of Al-Kharsaah, the total cost was reduced by 20,800,000 $, representing a 1.65% cost reduction as reported in Tables 12 and 13. Even though the energy price is not the highest for the F power station, the energy reduction is from the F power station. This is because there is no water constraint for that power station. The cost reduction will be much higher if the water demand constraint is lesser in the different power plants. This shows the importance of producing and desalinating seawater using RO technology. Energy generation and water production are connected. There are two main technologies for seawater desalination: the conventional thermal using multi-stage flash (MSF) and reverse osmosis (RO). For the thermal technology, there is a minimum amount of energy to be generated to produce the required amount of water. However, for the RO technology, the minimum amount of energy to be generated to produce the same amount of water is much less. This will lead to a better energy allocation for the new power plants [85].

When the PV contribution is higher, the energy reduction will be more from the different power stations. Moreover, if there is a storage facility with the PV power plant, there will be less power reduction from the other power plant. However, the storage facility is significantly expensive. Therefore, there are no storage batteries for the PV mega projects (5 MW and above) in which the generating energy will be injected directly into the power grid [86].

Furthermore, the electricity demand pattern differs between summer and winter in Qatar. For the summer period, the peak demand period is in the afternoon period. The peak is coming during that period due to the air-conditioning load due to the extremely high temperature and humidity values. On the other hand, the winter peak demand is in the evening due to the lighting load since the weather is fine with moderate temperature values. As a result, the power from Al-Kharsaah PV power plant will be easily evacuated during the summer since there is no storage facility. However, during winter, there will be no PV generation during the peak period since it comes after sunset. This will lead to more power reduction from the other power plants during the day in winter. However, the six gulf countries have been electrically interconnected since 2009, and the Arab countries' interconnection is in the implementation phase [50]. Therefore, this will facilitate exchanging the power between the different countries and better utilization of Al-Kharsaah PV power plant and any new renewable energy projects.

As a result, additional renewable energy plants would drive down the purchase costs even further; however, optimization studies would be required to quantify the cost savings and ensure that the constraints mentioned in Section 4.1.1 do not hinder these cost savings.

It is noted that the proposed model requires excessive data for the power plants. Therefore, Qatar’s electricity system with Al-Kharsaah PV power plant was considered a case study due to having the required data.

5.2 Al-Dhafra PV Power Plant

Al-Dhafra PV power plant is in the United Arab Emirates (UAE) with a total capacity of 2,000 MW. The approximate annual energy generation is 7 TWh with an energy rate equals to 13.2 \$/MWh [87].

Due to the difficulties in getting the UAE grid data and the confidently of the contracts, Al-Dhafra PV plant will be assumed as a part of Qatar grid to solve the optimization problem. Table 14 shows the power stations data with Al-Dhafra PV power plant.

Table 14. Power stations data with Al-Dhafra

Power Station	Capacity “MW”	Yearly Maximum Energy (GWh)	Water Requirements (%)	Minimum-Take Amount (%)	Evacuation Limitation (%)	Energy Cost ($/MWh)
A	600	5,256	15	30	100	35.6
B	375	3,285	20	30	100	34.2
C	560	4,905	15	40	100	35.3
D	740	6,482	25	20	100	19.2
E	990	8,672	30	40	100	27.7
F	1,950	17,082	0	25	90	24.9
G	2,700	23,652	15	20	85	25.5
H	2,490	21,812	20	20	75	24.4
Al-Dhafra	2,000	7,000	0	0	100	13.2

From the previous case study of Al-Kharsaah, the amount of demand that has to be met equals to 50,000 GWh with 55% and 45% as percentages of day and night demand respectively.

Using the proposed model, table 15 shows the optimal solution of the allocated energy to the different power plants.

Table 15. Energy allocated to power plants with Al-Dhafra

Power Station	Allocation (MWh)	Unit Price ($/MWh)	Cost ($)
A	1,576,800	35.6	56,134,080
B	985,500	34.2	33,704,100
C	1,962,240	35.3	69,267,072
D	6,482,400	19.2	124,462,080
E	3,468,960	27.7	96,090,192
F	7,434,400	24.9	185,143,950
G	4,730,400	25.5	120,625,200
H	16,359,300	24.4	399,166,920
Al-Dhafra	7,000,000	13.2	92,400,000
Total	50,000,000		1,176,993,594

For the Al-Dhafra case, it is noticed that after the commissioning of PV power plant, the total cost was reduced by 81,872,610 $, representing a 6.5% cost reduction as reported in Table 12 and Table 15.

It is noticed that the cost reduction was increased for Al-Dhafra case due to two main reasons which are the increased capacity and the lower price compared to Al-Kharsaah case.

Qatar system demand is much lower compared to the UAE electricity system. Therefore, building a PV power plant with a capacity of 2,000 MW in one location requires studies to mitigate the operation difficulties.

5.3 Distribution Companies' Difficulties in Operating PV Power Plants

Economically from the distribution companies' point of view, the operation of PV power plants is very beneficial due to the low operational cost compared to conventional power plants. However, there are difficulties and problems facing this direction. Each electricity system has a limit for the penetration of renewable energy. This is required to secure the electricity grid [88,89]. In addition, with the high cost of energy storage, distribution companies face problems in providing the required energy during peak hours. For example, in Qatar and all the Gulf countries in general, the highest annual demand is recorded during the summer in the afternoon, which is commensurate with the availability of PV energy. On the other hand, and during winter, the highest daily demand is recorded during the evening after sunset, which is the same time as stopping generating energy from PV power plants [90,91]. Figure 32 shows an example of the patterns of the summer and winter peaks along with Al-Kharsaah generation.

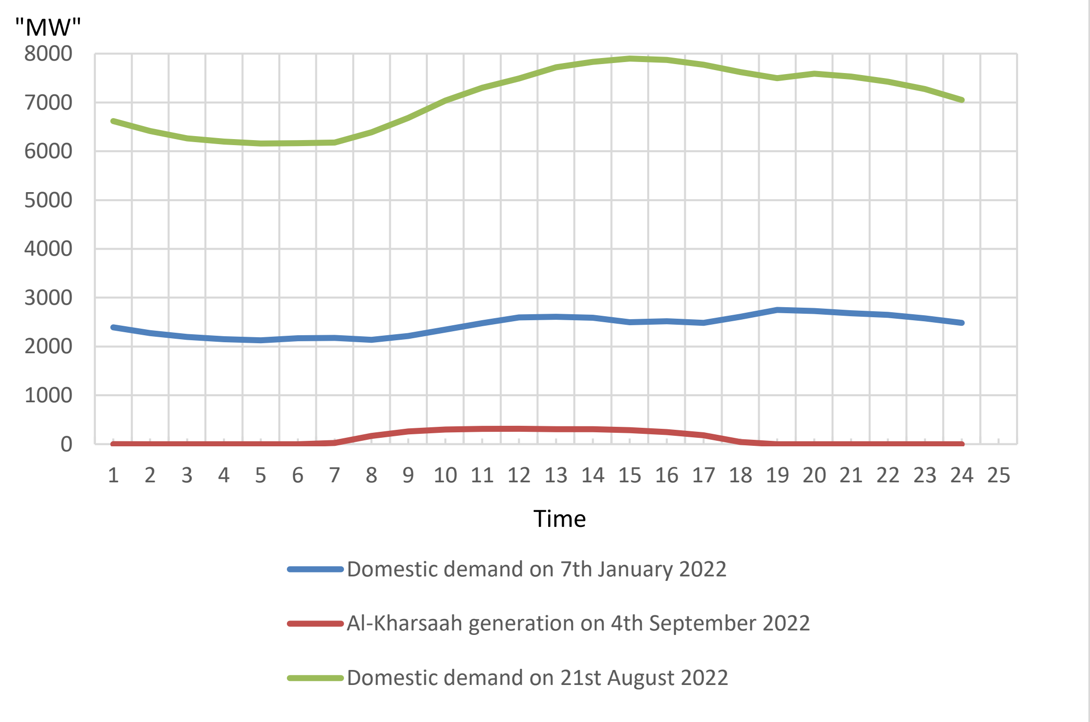


Figure 32. Al-Kharsaah generation with two domestic demand curves

This causes many problems for distribution companies to provide and compensate for the required energy from conventional power plants. The daily cost of starting the generation units is high. Furthermore, operating these units ineffectively with a high heat rate is a loss that has to be minimized to reduce the consumed gas.

Moreover, and due to the intermittent nature of renewable energy, the distribution companies are maintaining a higher spinning reserve which is an additional cost. Spinning reserve is the total amount of generation available from all the system synchronized units on the grid minus the current load and losses [92]. Spinning reserve must be maintained to save the electricity system from frequency drop that leads to load shedding and blackouts in the extreme generation loss.

5.4 Summary

In this chapter, Al-Kharsaah and Al-Dhafra PV power plants were considered as case studies. For Al-Kharsaah case, it was noticed that the cost was reduced by 20,800,000 $, representing a 1.65% cost reduction. Also, for Al-Dhafra case study, the cost reduction percentage was 6.5%. for Al-Kharsaah case and as a first milestone of renewable energy sources in Qatar, this reduction will be a motivation step for the following renewable energy projects.

Chapter 6: CONCLUSION, CONTRIBUTIONS, AND FUTURE WORK

In this chapter, the thesis will be concluded. Furthermore, the main contributions will be listed, and the potential future work will be discussed.

6.1 Conclusion

Nowadays, energy is one of the leading topics for debate at all levels of society. Electricity generation patterns are changing, considering global warming. Solar energy is clean energy as it reduces carbon emissions. It is noticed that different factors affect the economic importance of PV power plants. These factors are different from one country to another. The two main factors are the cost of building the PV power plants and the difference in electricity purchase contracts.

In power distribution companies, electricity cost minimization is the main challenge. This thesis contributes to developing a model that minimizes the electricity cost through optimal energy allocation. This model is a tool that can be used by power distribution companies in the design phase or the operation phase. Furthermore, the proposed model's essential role is preparing budgets for future years or periods, especially if there are new players, such as new power plants or interconnections with other countries. The model strength is elucidated by considering the operational and contractual aspects. Furthermore, with the higher penetration of renewable energy, electricity distribution companies focus on increasing water production from RO and reducing the minimum-take energy amounts. This leads to better utilization of renewable energy sources and decreases the total energy cost. The main limitation in model implementation is collecting the required extensive data. The model requires energy demand, transmission lines limits, water demand, maximum energy generation from the power plants, energy cost, and minimum-take energy. The output for that model is the energy allocated to the different power plants. Al-Kharsaah PV power plant and Qatar electricity system was considered a case study.

The Al-Kharsaah PV power plant is the first project of its kind in Qatar. Therefore, there is a lack of studies and research on this project. Moreover, any project of this size requires thorough research and studies to show the advantages and benefits and avoid future problems. It was observed that Al-Kharsaah project reduced the cost by approximately 21 million $, representing a 1.65% cost reduction. In addition, for the Al-Dhafra case, the cost reduction was nearly 82 million $, representing a 6.5% reduction.

COVID-19 has affected all life sectors worldwide, electricity demand being just one of these sectors. This thesis discusses the impact of the COVID-19 pandemic on Qatar's electricity demand and forecasting. This study collected historical data of Qatar's electricity demand, population, and GDP, along with information on COVID-19 restrictions. Statistical analysis was used to unfold the impact of the COVID-19 pandemic. Notably, the restrictions and actions taken had an impact on electricity demand. Students' and employees' attendance are the restrictions that most impact electricity demand. The attendance of 30% of school students caused an increase of approximately 28% of the domestic peak. This increase was due to the high use of electrical appliances at home. As a result, the performed analysis will help assess and evaluate the impact of future measures due to new diseases, such as monkeypox, and mega-events, such as the FIFA World Cup 2022.

For the developed forecasting model, the absolute forecast error percentage equals 2.71% for the year 2021. This accuracy is consistent with the calculated coefficient of correlation, R, representing the strength of the linear relationship between the the domestic electicity peak demand of number of electricty meters. However, due to the

COVID-19 pandemic, the impact on electricity demand and its forecasting will be noted after the end of the crisis and its immediate consequences. Therefore, in other waves of coronavirus, or new pandemics, medium-term and long-term electricity forecasts will have to be revised to consider the updated situations and plan for the demand increase.

It can be concluded that power demand forecasting helps in estimating the required amount of generation to meet the demand. Due to the high cost of energy storage facilities, electricity must be consumed at the same time of its generation. Therefore, appropriate demand forecasts are prerequisites for energy dispatching plans to reduce the energy purchase cost.

6.2 Contributions

The main contributions of this thesis can be listed as follows:

1- Developing an optimization model for the economic energy allocation of conventional and large-scale solar PV power plants. The model considers technical aspects (the transmission network capacity, the power station capacity, and the water demand) and the contractual provisions (energy cost and minimum-take energy). The proposed model can be used to study the feasibility of commissioning a new PV power plant. to the grid. Furthermore, the developed model in this thesis can be used in the design or operation phases to minimize operating costs. Also, the model is used for preparing the Electricity distributors’ budgets as a planning tool.

   In addition, the developed optimization model was implemented on Al-Kharsaah and Al-Dhafra PV power plants’ cases. This work resulted in the publication of a journal paper entitled Economic Energy Allocation of Conventional and Large-Scale PV Power Plants (more details in Appendix E).

2- Studying and assessing the impact of the COVID-19 pandemic on Qatar electricity demand and load forecasting. The COVID-19 pandemic has affected all life sectors. There is a lack of research and studies on its impacts. Another journal paper entitled Impact of COVID-19 Pandemic on Qatar Electricity Demand and Load Forecasting: Preparedness of Distribution Networks for Emerging Situations was published (more details in Appendix E). In conclusion, this thesis can be considered as a part of the link between the academic research and the industrial sector.

6.3 Future Work

Future research work in this direction could be modifying the proposed model according to the new contract provisions. For some new contracts between the electricity distribution companies and power plants, the minimum-take provision is replaced by the capacity charge. Therefore, the minimum-take constraint could be replaced by the capacity charge variable.

The second line of future research is adjusting the model for a 100% renewable energy system considering the storage facility. The proposed model is used for the hybrid system that has both conventional and renewable sources to ensure a supply for the night demand.

Moreover, the impact of the interconnection of electricity grids on PV generation growth can be discussed. The impact of this interconnection has to be assessed, especially with the variation in the daily peak timing between the countries. This variation helps in reducing the required generation to meet the electricity demand. As a result, the open electricity market will impact PV growth, which has to be assessed and studied. Furthermore, Lithium prices reached high levels. This will limit the expansion of the battery storage facility [93]. Therefore, future investment in renewable energy sources will be affected.

On the other side, grant energy companies like Shell and ExxonMobil started the renewable energy business. In Qatar, QatarEnergy company is the new name for Qatar Petroleum. QatarEnergy awarded the contracts for two large-scale PV power plants with a total generation of 875MW. The 2 PV power plants will be at Mesaieed and Ras Laffan industrial cities and to start production by the end of 2024. Moreover, QatarEnergy plan is to have 5GW of solar energy by 2035 [94]. Therefore, the tendency of grant energy companies to produce renewable energy will increase expansion and competition in this field. This impact has to be studied and how it will affect the power distribution companies and the conventional power plants.

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APPENDICES

Appendix A: The Python Algorithm

```
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
from sklearn.linear_model import LinearRegression
# Input data
meters = np.array([56182, 68035, 86108, 114160, 136850, 156756, 175144, 194171,
209585, 229314, 255723, 275138, 294699, 317582, 333198])
domestic_peak = np.array([2400, 2805, 2960, 3245, 3580, 4015, 4250, 4630, 4795,
5170, 5905, 5965, 6455, 6430, 7315])
# Reshape the data
X = meters.reshape(-1, 1)
y = domestic_peak
# Create and fit the linear regression model
regressor = LinearRegression()
regressor.fit(X, y)
# Generate predictions
y_pred = regressor.predict(X)
# Calculate statistical measures
residuals = y - y_pred
mse = np.mean(residuals**2)
rmse = np.sqrt(mse)
r2 = regressor.score(X, y)
```

```
# Plotting the actual vs predicted values
plt.scatter(X, y, color='blue', label='Actual')
plt.plot(X, y_pred, color='red', linewidth=2, label='Predicted')
plt.xlabel('Meters')
plt.ylabel('Domestic Peak')
plt.title('Actual vs Predicted Domestic Peak')
plt.legend()
plt.show()
# Residual plot
plt.scatter(X, residuals)
plt.axhline(y=0, color='r', linestyle='-')
plt.xlabel('Meters')
plt.ylabel('Residuals')
plt.title('Residual Plot')
plt.show()
# Print the statistical measures
print("Mean Squared Error (MSE):", mse)
print("Root Mean Squared Error (RMSE):", rmse)
print("Coefficient of Determination (R^2):", r2)
coefficients = regressor.coef_
intercept = regressor.intercept_
# Number of digits to display
num_digits = 5

# Regression equation
```

```
regression_eq = "Domestic Peak = "

for i in range(len(coefficients)):

    regression_eq += f"({coefficients[i]:.{num_digits}f} * X{i+1}) + "

regression_eq += f"{intercept:.{num_digits}f}"

print("Regression Equation:")

print(regression_eq)
```

Appendix B: The MATLAB Program

```
K= sum(Water_requirement_energy_MWH)/1000,L
=sum(Yearly_Maximum_energy_MWH)/1000
prompt=("Please Enter Total Load Less than L and Greater than K, Total Load in
GWH =  ");
Load= input(prompt);Load= Load* 1000;Day_Energy_Percent= input(prompt);
Load_Day= Day_Energy_Percent*Load/100;
 Load_Night = Load- Load_Day ; Load_Day = Load_Day * 1000;Load_Night =
Load_Night * 1000;
D = Load - sum(Water_requirement_energy_MWH);N = length(PowerStation);
Total_Av_Conv_Gen=sum (Evacution_limit_energy_MWH)-
Evacution_limit_energy_MWH(N-1);
if  Total_Av_Conv_Gen < Load_Night
Message “ Night Demand cannot be met”;break
elseif Total_Av_Conv_Gen >= Load_Night
Allocation =
Water_requirement_energy_MWH;u=zeros(N,1);X=zeros(N,1);t=zeros(N,1);o=0;
k =zeros(N,1);V = zeros(N,1);H=zeros(N,1);r(1)=1;D_new_X=D;
[Y,I] = sort(Energy_cost_in_QR_per_MWH);Diff_bet_W_TOP = zeros(N,1);
for q=1:N
   if take_or_pay_energy_MWH(q) > Water_requirement_energy_MWH(q)
      o=o+1;
      Diff_bet_W_TOP(q) = take_or_pay_energy_MWH(q) -
Water_requirement_energy_MWH(q); r(o)=q;
   end
```

```
end
if o==0
    for s= 1:N
        if Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X > (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
            D_new_X = D_new_X - (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)));
            Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));
        elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X < (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
            Allocation(I(s)) = Allocation(I(s)) + D_new_X;break
        elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X == Evacution_limit_energy_MWH(I(s)) - Allocation(I(s))
            Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));break
        end
    end
elseif D < sum(Diff_bet_W_TOP)
    for q=r
        H(q) = (Diff_bet_W_TOP(q)*D)/sum(Diff_bet_W_TOP) + Water_requirement_energy_MWH(q);
    end
    for q=r
        if H(q) > Evacution_limit_energy_MWH(q) || H(q) == Evacution_limit_energy_MWH(q)
            V(q) = H(q) - Evacution_limit_energy_MWH(q);
```

```
            Allocation(q) = Evacution_limit_energy_MWH(q);
        end
        D_new = sum(V);
    end
    for q=r
        if H(q) < Evacution_limit_energy_MWH(q) && Evacution_limit_energy_MWH(q) < take_or_pay_energy_MWH(q)
            X(q) = Evacution_limit_energy_MWH(q) - H(q); u(q)=1;
        elseif H(q) < Evacution_limit_energy_MWH(q) && (take_or_pay_energy_MWH(q) < Evacution_limit_energy_MWH(q) || take_or_pay_energy_MWH(q) == Evacution_limit_energy_MWH(q))
            X(q) = take_or_pay_energy_MWH(q)- H(q); t(q)=1;
        end
    end
    for q=r
        if (sum(X) < D_new || sum(X) == D_new) && u(q) == 1
            Allocation(q) = Evacution_limit_energy_MWH(q);
        elseif (sum(X) < D_new || sum(X) == D_new) &&  t(q) == 1
            Allocation(q) = take_or_pay_energy_MWH(q);
        elseif sum(X) > D_new && (u(q) == 1 || t(q) == 1)
            Allocation(q) = (X(q)*D_new)/sum(X) + H(q);
        end
    end
    D_new_X = Load - sum(Allocation);
    if D_new_X > 0
```

```
    for s= 1:N
      if Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X >
(Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
        D_new_X = D_new_X - (Evacution_limit_energy_MWH(I(s)) -
Allocation(I(s)));
        Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));
      elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X <
(Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
        Allocation(I(s)) = Allocation(I(s)) + D_new_X;break
      elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new_X
== Evacution_limit_energy_MWH(I(s)) - Allocation(I(s))
        Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));break
      end
    end
  end
elseif D == sum(Diff_bet_W_TOP)
   for q = r
     Allocation(q) = take_or_pay_energy_MWH(q);
   end
   for q = r
     if Allocation(q) > Evacution_limit_energy_MWH(q)
       V(q) = Allocation(q) - Evacution_limit_energy_MWH(q);
       Allocation(q) = Evacution_limit_energy_MWH(q);
     end
   end
```

```
   D_new = sum(V);
   if D_new > 0
     for s= 1:N
       if (Evacution_limit_energy_MWH(I(s)) > Allocation(I(s))) && D_new > (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
         D_new = D_new - (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)));
          Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));
       elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new < (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
         Allocation(I(s)) = Allocation(I(s)) + D_new;break
       elseif  Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new == Evacution_limit_energy_MWH(I(s)) - Allocation(I(s))
         Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));break
       end
     end
   end
elseif D > sum(Diff_bet_W_TOP) && o >0
  T = D - sum(Diff_bet_W_TOP);
  for q = r
    Allocation(q) = take_or_pay_energy_MWH(q);
  end
  for q = r
    if Allocation(q) > Evacution_limit_energy_MWH(q)
      V(q) = Allocation(q) - Evacution_limit_energy_MWH(q);
```

```
      Allocation(q) = Evacution_limit_energy_MWH(q);
    end
  end
  D_new = T + sum(V);
  for s= 1:N
    if (Evacution_limit_energy_MWH(I(s)) > Allocation(I(s))) && D_new > (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
      D_new = D_new - (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)));
      Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));
    elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new < (Evacution_limit_energy_MWH(I(s)) - Allocation(I(s)))
      Allocation(I(s)) = Allocation(I(s)) + D_new;break
    elseif Evacution_limit_energy_MWH(I(s)) > Allocation(I(s)) && D_new == Evacution_limit_energy_MWH(I(s)) - Allocation(I(s))
      Allocation(I(s)) = Evacution_limit_energy_MWH(I(s));break
    end
  end
end
Bill=Allocation.*Energy_cost_in_QR_per_MWH;Sum_Bill=sum(Bill);
sum(Allocation)/1000
end
```

Appendix C: AMPL Mathematical Model

```
# PV power plants
# PVP created by Omar

param p; #Conventional Power Plants
param v; #PV Power Plants
param l; #PV Transmission lines

set CP := 1..p;   #Conventional Power Plant Set
set PV := 1..v;   #PV Power Plant Set
set TL := 1..l;   #Transmission lines Set

param D;          # Annual Energy demand

param CCP{CP};    #The installed capacity of conventional power plant in MW
param ECP{CP};     #The maximum annual energy capacity of conventional power plant in MWH
param PriceP{CP}; #Unit cost of purchased energy from conventional power plant
param Evlimit{CP};#Evacuation limit
param WR{CP};          #Water Requirement
param TorP{CP};   #Take or pay of the conventional power plant

param CCV{PV};    #The installed capacity of PV power plant in MW
param ECV{PV};     #The maximum annual energy capacity of PV power plant in MWH
```

```
param PriceV{PV}; #Unit cost of purchased energy from PV power plant

var EP{CP}>=0;    #Purchased energy from conventional plant
var EV{PV}>=0;    #Purchased energy from PV power

minimize OBJ: sum{j in CP}EP[j]*PriceP[j] + sum{j in PV}EV[j]*PriceV[j]; #Minimize the total energy purchase cost

subj to c01: sum {j in CP} EP[j]+ sum {j in PV} EV[j]>=D; #Demand should be met

subj to c02 {j in CP}: EP[j]<=Evlimit[j]*ECP[j]; #Maximum limit of energy that can be evacuated from conventional power plant

subj to c03 {j in PV}: EV[j]<=ECV[j]; #Maximum limit of energy that can be evacuated from PV power plant

subj to c04 {j in CP}: EP[j]>=WR[j]*ECP[j]; #Must run energy to meet water demand

subj to c05: sum{j in CP} EP[j]<=sum{j in CP}(TorP[j]+WR[j])*ECP[j];
```

Appendix D: AMPL Data File

```
param p := 8;
param v := 1;
param l := 1;

param D :=50000000;

param CCP:=
1 600
2 375
3 560
4 740
5 990
6 1950
7 2700
8 2490;

param ECP:=
1 5256000
2 3285000
3 4905600
4 6482400
5 8672400
6 17082000
7 23652000
```

```
8 21812400;

param PriceP:=
1 130
2 125
3 129
4 70
5 101
6 91
7 93
8 89;

param Evlimit:=
1 1
2 1
3 1
4 1
5 1
6 0.9
7 0.85
8 0.75;

param WR:=
1 0.15
2 0.2
```

```
3 0.8
4 0.25
5 0.3
6 0
7 0.15
8 0.4;

param TorP:=
1 0.3
2 0.3
3 0.4
4 0.2
5 0.6
6 0.25
7 0.2
8 0.2;

param CCV:=
1 700;

param ECV:=
1 6132000;

param PriceV:=
1 200;
```

Appendix E: Dissertation Publications

Journal Papers:

1- El-Hafez OJ, ElMekkawy TY, Kharbeche MBM, Massoud AM. Economic Energy Allocation of Conventional and Large-Scale PV Power Plants. *Applied Sciences*. 2022; 12(3):1362. https://doi.org/10.3390/app12031362 (IF: 2.838)

2- El-Hafez OJ, ElMekkawy TY, Kharbeche M, Massoud A. Impact of COVID-19 Pandemic on Qatar Electricity Demand and Load Forecasting: Preparedness of Distribution Networks for Emerging Situations. *Sustainability*. 2022; 14(15):9316. https://doi.org/10.3390/su14159316 (IF: 3.889)