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OPTIMAL INTEGRATION OF SOLAR ENERGY WITH DISTRICT COOLING SYSTEM: MATHEMATICAL MODELING APPROACH

BY

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ABSTRACT

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Title: Optimal Integration of Solar Energy with District Cooling System: Mathematical Modeling Approach

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The outstanding development witnessed in various sectors across the globe caused mankind to increase their need to cooling energy and hence, consume unsustainable energy resources excessively. That raised the fears on the potential presence of these resources and on how to combat global warming caused by fossil fuel energy. Therefore, industries are shifting toward using renewable energy resources as they are widely available and environmentally friendly. This research addresses the integration of solar energy into conventional cooling systems. Three mixed integer linear programming (MILP) models are developed to represent different configurations of solar thermal and electric cooling systems combined with the conventional cooling systems to minimize annual total system cost. The models are fed with actual data collected on the parameters of the models. Moreover, four different case studies which represent low, medium, high and very high cooling demand scenarios are selected and solved using the CPLEX solver. Furthermore, sensitivity analysis are carried out on the different parameters of the models. The results of the research indicated that the solar electric cooling system connected to the grid is the most economical system compared to other system configurations.

DEDICATION

To My Family.

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Chapter 1: Introduction

1.1 Background

The outstanding development observed in various sectors across the globe caused mankind to consume unsustainable energy resources excessively. This raised the fears on the future presence of these resources in terms of utilizing them wisely without impacting the environment significantly or depleting them. In addition, the world is currently combating global warming phenomena. Hence, industries are shifting toward using renewable energy resources as they are widely available and environmentally friendly. There are many types of renewable energy resources such as solar energy. It is considered to be the most common and abundant renewable energy source. It is a natural resource of thermal energy that can be converted to various energy forms. Though solar energy is being widely used in various applications, the usage of solar energy in the District Cooling System (DCS) applications remains relatively overlooked while offering a very interesting topic to be investigated.

1.2 District Cooling System (DCS)

District Cooling System (DCS) is defined as a closed loop network system where cold water is generated in the main plant and then transferred through a network of pipes to the customer demand point that is indicated by energy transfer stations (Skagestad & Mildenstein, 2002). However, after the cold water dissipates its coldness in the demand point, it moves back into the piping distribution network to be chilled and pumped again. A complementary component is added to the system which is the thermal energy storage tank (TES) and it is used to store the cold or hot water. It enhances the system's performance by offering advantages to both customers and supplier (Chan et al., 2006).

1.3 Economical and Environmental Benefits of DCS

District cooling systems are employed to solve various issues related to climate, electricity consumptions, and CO2 emission levels. To explain in details, Qatar has been reported to have the highest CO2 emissions per capita (38.17 tones of CO_2 per capita) in the world as a result of not establishing controlled policies or penalties back then to constraint different sectors from exceeding a certain emission level (Houari & Khir, 2014). Besides that, Qatar possesses a desert climate which leads to have a continuous cooling energy throughout the year. Besides the climate challenges, the rapid urbanization processes the state of Qatar is currently going through leads to the necessity of providing cooling energy to the urbanized areas promptly. Furthermore, the economic activities are increasing and expected to grow more in Qatar in the upcoming years resulting in high living standards. That has put a crucial burden on the electricity sector in Qatar to meet high electricity demands. It is estimated that cooling energy accounts for up to 70% of peak electricity demands in summer months (Al Sada, 2017). To add on, according to Qatar National Vision 2030, Qatar needs to become an advanced society capable of achieving sustainable development at four main pillars, one of them is environmental development. That highlights how employing such technology is crucial to the State of Qatar. The District Cooling System (DCS) is currently used as an alternative solution to the traditional cooling systems such as split units, and window air conditioning. The advantages of using DCS are recognized in providing high-quality and a reliable cooling source along with the continuous maintenance provided by the service experts to achieve the best operation. DCS helps to abolish any vibrating or loud equipment close to the client which accomplishes a quiet environment in commercial and residential areas. Furthermore, DCS is considered to be more reliable than traditional cooling systems as it functions with highly dependable equipment managed by experts in the cooling company (Spurr et al., 2008). There are many advantages where the DCS out weights the traditional system, both economic and environmental benefits. From economical aspects, it was found out that the district cooling system could save 15 QR billion by 2030 for Qatar, based on 50% District Cooling penetration. In 2016, Qatar estimated that District Cooling systems cover 14% of the total cooling capacity with a major potential for growth in the upcoming years (Al Sada, 2017). Moreover, statistics showed that the monthly cooling energy charge for providing a space cooling using traditional systems such as air-cooled split air conditioner is around 10.30 QR/m^2. While the monthly cooling energy charge for providing a space cooling using a district cooling is 5.46 QR/m^2 (Al Sada, 2017). So, the user would save money through using the district cooling systems. In addition, DCS utilizes advanced technologies like Treated Sewage Effluents (TSE) which contributes to water resources sustainability and cutting the district cooling bill by using TSE as an alternative to potable water (Al Sada, 2017). It is very important to highlight that DCS minimizes the demand of power by 50% to 87% compared to traditional cooling system depending on the type of technology used in DCS (Spurr et al., 2008). For the environmental benefits, DCS plays a significant role in reducing the CO_2 emission, since it contributes in reducing the consumption of electrical power, and in detection of leakages from system's components which will lead to a higher energy efficiency. Statistics have showed that the annual CO_2 emissions from a DCS which produces around 100 Giga Watt of cooling energy are around 5,378 tones while it reaches 32,297 tones from traditional cooling systems, as a result of the DCS gives the flexibility to the operator to choose the appropriate industrial system with a better environmental performance (Area, 2006). In addition, efficient DCS has a lot of benefits reflected in reducing the cold water for the cooling towers, minimizing the footprints for the dry coolers and reducing the chemical used for water treatment (Spurr et al., 2008). DCS has shown its effectiveness in phasing out refrigerants such as CFSs

(Chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) which are being utilized extensively in the traditional cooling system. These refrigerants contribute to depleting the ozone layer which causes serve harms to health and environment, along with its contribution in the phenomenon of global warming (Euroheat, 2006). With all the aforementioned benefits, DCS represents an appropriate choice to replace the traditional cooling systems. Hence, DCS is catching the attention of many researchers and engineers to develop various methods and techniques to increase its competency and flexibility. Current and future researches recommend incorporating it with different energy sources such as sustainable resources of energy which is an area of interest to many researchers.

1.4 Challenges of DCS

There are a lot of challenges arise during the process of designing a district cooling system. The challenges are divided in terms of the numerous numbers of options and technologies available in the markets, and the operational challenges which include the design specifications and requirements related to the various components of the system. To further explain the first challenge, there are many technologies available in the market for each component installed in the DCS. There are two main aspects that need to be considered during the selection of a component. The first aspect is selecting the suitable technology for each component as there are many technologies available in the market at various costs depending on how well the technology is matured. Hence, selecting the right technology to satisfy the need and the requirements of the system and the user is a challenge, as the user has to compromise between the selection of a reliable and a suitable technology and at the same time choosing a component at a lower cost. The other aspect is related to the parameters that need to be considered during the selection process of a specific component. Considering all parameters together at the same time during the selection of a component is a challenge as the user has to optimize all the parameters together at the same time. The other challenge is related to the operational challenges, many components are involved in the DCS with different technical specifications. Hence, the compatibility issues of these technologies when they are installed together become crucial. The owner of the system must ensure that all the components are compatible with each other in terms of how they can function properly with each other. Another aspect besides the compatibility, is the capacity of the components. It is important to select the right capacity for each component to satisfy the cooling demand otherwise the system will fail to function optimally. So, finding the optimal parameters including types, efficiency, capacity, and fixed cost of each component of DCS and the optimal system configuration which indicates what component will exist in the system are very challenging decisions that should be thought of carefully. These decisions have to be made in a way to minimize the annual total system cost which includes the annual fixed cost of each component and annual variable cost of storing hot/ cold water and producing cold/hot water.

1.5 DCS Integration with Renewable Energy

This research addresses the integration of a DCS with a renewable energy source which is the solar energy to allow energy efficiency improvements. The reason for selecting the solar energy out of the other renewable energies is that Qatar along with the other Gulf countries has the highest solar potentials in the world. Therefore, employing solar assisted cooling in the scope of district system in Qatar is justified for future research. The advantages of employing the solar energy in the district cooling system are enormous where it offers outstanding energy savings, decreases greenhouse gasses emissions, and eliminates the use of chillers that employs refrigerant gases which cause ozone depletion (Gang et al., 2017; Paksoy et al., 2000).

1.6 Research Objectives

The research aims to obtain the optimal design and operation of a solar assisted cooling system (SAC) and that includes the optimal system configuration and selection of the component to function within the appropriate level of efficiencies while achieving the minimum annual investment and operational costs. The option of integrating an auxiliary boiler to the DCS is recommended as a substitute to enhance the system efficiency. The research will address the aforementioned challenges by developing a mixed-integer linear programming (MILP) models for solar thermal and solar electric cooling systems to capture all relevant problems and seeks to find an optimal system design and operation. The developed models will study the system over annual cooling demand (8784 hours/year). In addition, the models will be fed with actual collected data on the components of the systems from various reliable sources. Moreover, several case studies taken from Qatar's environment, that represent different cooling demands behaviors, will be solved for optimization. The final solution will specify the optimal area of the solar collectors or photovoltaic panels, absorption chiller or compression chiller capacity, capacity and presence of cold and hot water TES tank and the auxiliary boiler. Moreover, the solution will indicate the hourly produced and stored hot and cold water by different components. Finally, the thesis will conduct a comparison between the three developed solar thermal, solar cooling and conventional cooling systems models to find the most economical system. Lastly, several sensitivity analyses will be carried out on various systems' parameters.

1.7 Thesis Outline

The structure of this research is divided into seven chapters which are introduction chapter, literature review chapter, DCS configuration chapter, solar thermal cooling system model chapter, conventional cooling system model chapter, solar electric cooling system model and conclusion chapter. Chapter 2 focuses on reviewing the most relevant papers related to District Cooling systems and Solar Assisted Cooling System and that includes solar thermal and solar electric cooling systems. Chapter 3 is divided into two main sections which are system components and data collection. The system component sections provide detailed descriptions on the components that will be used in developing the models. While the data collection section shows the data collected on the system components and will be used in the modeling chapters. Chapter 4 focuses on introducing the scope, operation, mathematical model formulation of the solar conventional cooling system, and the experiments that are conducted on the model. Also, a sensitivity analysis is carried out on the parameters of the model. Chapter 5 and 6 follow the same structure and sections as the conventional cooling system chapter, but for solar thermal cooling system and solar electric cooling system, respectively. A comparison between the three models is made in chapter 6 to determine the most economical system. Lastly, the chapter 7 summarizes and highlights the main results obtained from each model and proposes possible extensions for future work.

Chapter 2: Configuration of District Cooling Systems

This chapter is divided into two main sections which are system components and data collection. The first section aims to define and describe the various system components that will be used in developing the different solar assisted cooling system configurations. While the other section explains and shows the data collected on different system components and it highlights the value of data and how the data were collected.

2.1 System Components

2.1.1 Cooling Technologies

There are two majors cooling technologies that are employed in the District Cooling System (DCS) which are compression cooling technologies and thermally cooling technologies where they are also known by sorption cooling ("District Cooling Best Practice Guide," 2008). However, there is a third cooling source known by free cooling which depends on cold sources like deep lakes or rivers. This type of cooling is applied in some countries where the ambient cooling causes the water to decrease to a relatively low temperature (Mildenstein, 2002). Figure (1) shows the different available types of cooling technologies.

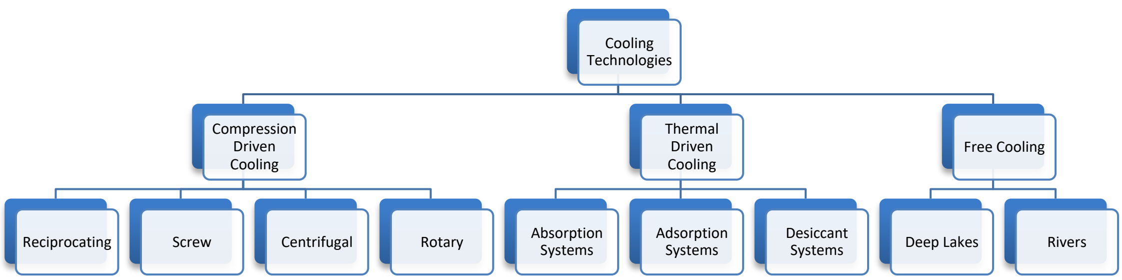

Figure 1: Types of avaliable cooling technologies

2.1.1.1 Cooling System Efficiency. The cooling effect is measured in TR (Tones of Refrigeration). This unit is based on the hourly available cooling rate from 1 tone of ice when it melts over a period of 24 hours. The refrigeration and air conditioning engineers use the British measuring unit where 1 tone of refrigeration (TR) is equivalent to 3023 kcal/h and its equal to 3.51 kWthermal and 12000 Btu/ hr (Ningegowda, 2013).

The Coefficient of Performance (COP) is a crucial criterion for comparing between the quality of different chiller technologies. The COP is defined as the proportion of work or useful output to the amount of work or energy input. The COP of commercial compression mechanical chiller is in between 4.0 and 5.0 where the COP of the absorption chillers is much lower between 0.65-1.2 (Mildenstein, 2002).

2.1.1.2 Compression Driven Cooling Technologies. Vapor compression refrigeration cycle is a part of the compression driven cooling technologies operations. The reciprocating, screw scroll (rotary) and centrifugal compressors are the most commonly used compressors for vapor compression systems ("District Cooling Best Practice Guide," 2008; Mildenstein, 2002). These compressors are powered by various sources such as electricity, gas, steam turbines, reciprocating engines or combination of these. The capacities of the different types of compressors are shown in the below table (1). The COP of the compressors range between 4.0 to 5.0 ("District Cooling Best Practice Guide," 2008).

Table 1: Avaliable Compressor Chillers

Compressor Chiller Type	Capacity Range (TR)
Reciprocating Compressor	50- 230
Screw Compressor	70-400
Centrifugal Compressor	200-6000

The compression chillers are available at compact sizes and reasonable prices. Also, they are easy to install and maintain. However, they have a bad effect on the environment represented in global warming potential related to CFCs and HCFCs refrigerants used in vapor compression system. Another negative impact is the ozone layer depletion (Sarkar et al., 2013).

2.1.1.3 Thermal Driven Cooling Technology. The thermal driven cooling chiller is also referred to as sorption chiller. These technologies use heat to make the cooling effect. The basic cooling cycle of compression chiller and absorption chiller is the same. However, the main difference between the two chillers is that the absorption chillers are thermally driven while the compression chiller are electricity driven. Therefore, it highlights a major advantage of the minor power consumed by thermal-driven chillers (Athukorala, 2012). This technology has been used for many years in various fields of air conditioning and refrigeration. However, their application has not been extended widely due to their very high initial fixed cost and low efficiencies compared to the conventional compression systems (Best & Rivera, 2015). The thermal driven cooling system could be powered by a solar thermal energy, district heating networks, or waste heat from industrial processes (Nunez, 2010). Nonetheless, thermal cooling system are not always considered a viable and attractive alternative compared to traditional cooling systems. These systems are considered when there are significant ready amounts of heat from sources of waste/ surplus or caught from sustainable energy sources such as heat from solar thermal energy.

The thermal driven cooling technology are categorized into thermomechanical processes and heat transformation processes as illustrated in figure (2) (Nunez, 2010). The heat transformation processes are divided into adsorption systems, absorption systems and desiccant systems. The scope of the research is on the absorption systems since they are more developed and appropriate for combination and integration with different source of heat in chilled water production in the framework of district energy.

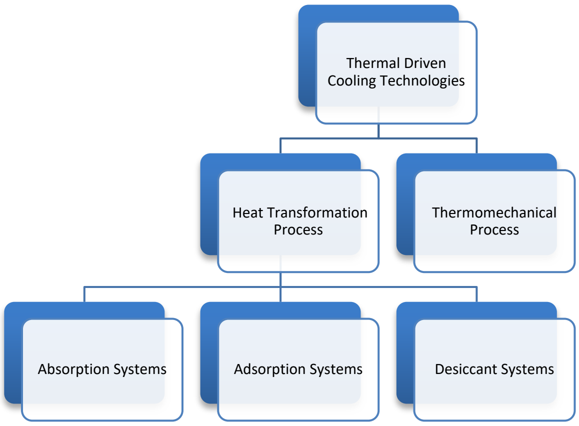

Figure 2: Avaliable type of thermal driven cooling technologies

The absorption chillers cooling technology can be categorized into direct and indirect fired system based on the source of thermal energy used. In the direct fired chillers, the thermal energy is obtained from gas burners. In the indirect fired chillers, thermal energy is obtained from different resources. These types of chillers are the most commonly used in the production of the chilled water due to their capability to combine heat from different resources. The advantage of this study is to have the opportunity to exploit the industrial waste heat in cogeneration system and renewable energy such as solar thermal energy. Moreover, the sorption refrigeration technologies are categorized into adsorption technology and absorption technology, where these technologies are used for convenient cooling, and food storage. The adsorption technology is employed in low temperature applications, but the absorption technology is used for convenient cooling applications. Furthermore, it is very important to point out that the absorption chiller uses only natural refrigerants which don't have a negative impact on the ozone layers or global warming (Sarkar et al., 2013). Hence, this technology has a significantly lower CO_2 emission level. The most common employed refrigerants in absorption technology are water – ammonia absorption NH_2 – H_2O and lithium bromide- water LiBr-H_2O. The first absorption is used in air conditioning application and the second one is used in refrigeration and industrial applications. So, the lithium bromide – water refrigerant absorption chiller is examined in this study (Best, 2007).

The lithium bromide – water absorption chiller consists of absorbers, evaporators, generators and condensers. The structure of the chiller is shown in figure (3). The working principle of the chiller as follows, the evaporator will produce the water vapor which in turn will be absorbed by a very strong LiBr solution in the absorber. Hence, it will become a weak solution and will flow and heat in generators. The process of heating will generate vapors of water from the weak solution. Then, the produced vapor will move to condensers where it will be condensed and will move into expansion valves to decrease its pressure. However, the concentrated LiBr solution will flow to the absorber from the generator and the vapor will be absorbed again (Deng et al., 2011).

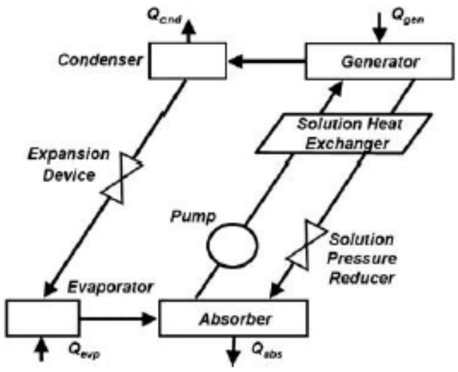

Figure 3: The structure of absorption chiller

The commercial LiBr-H_2O absorption chillers are categorized according to the number of refrigerant (water) vapor generation process and are known as single, double and triple effect cycle which is still under development. The absorption chiller coefficient performance depends on number of stages in the refrigeration cycle and it increases with the increase of number of stages. The COP ranges between 0.65 to 1.3. The main differences between the three types of cycle are the COP, driving heat source (water) and the cooling capacity (Deng et al., 2011).

The main features of the absorption and adsorption technologies are shown in table (2).

Table 2: Comparsion Between Different Types of Sorption Technology

Category	Absorption Technology			Adsorption Technology
	Single Effect Stage	Double Effect Stage	Triple Effect Stage	
Absorbent	Liquid	Liquid	Liquid	Solid
COP	0.5 – 0.7	1.0 – 1.2	1.4 – 1.7	0.5 – 0.6
Capacity (kW)	5 -7000	20 – 12000	530 – 1400	Greater than 70 kW
Driving Temperature	80^{o}C – 120^{o}C	120^{o}C - 170^{o}C	200^{o}C – 230^{o}C	Starting from 60^{o}C
Technology	Well developed	Well developed	Experimental	Less developed
Suitable for	Combined with CHP or district heating, or Solar thermal system	Tri-generation systems	-	-

The lithium bromide absorption chiller performance is significantly affected by the temperature of hot water or a heat source, and the greater number of cycles the absorption chiller has, the more temperature is required to power it. Moreover, the heat source temperature should be kept above a certain value otherwise the chiller will not function properly. Nevertheless, above this value, the chiller's performance will improve until it arrives a saturated value (maximum performance) irrespective of how much the hot water temperature would increase. Hence, the single effect absorption chillers performance is optimal when the hot water temperature is between 80 and 120^{o}C, but the minimum temperature for the double effect absorption chiller should be 120^{o}C and below this value, a significant reduction in the performance of the chiller will be observed (Grossman, 2002). In addition, the chiller's performance is effected by the chiller size required to satisfy the cooling demand. Therefore, it is very critical to select the proper size of the chiller. It was found out that the load rate associated with the chiller impacts its performance. The below figure (4) illustrates the different type of effects of the absorption chiller developed by Kawasaki Thermal Engineering. It shows that each effect stage has a certain COP associated to a load rate (Yabase, 2012).

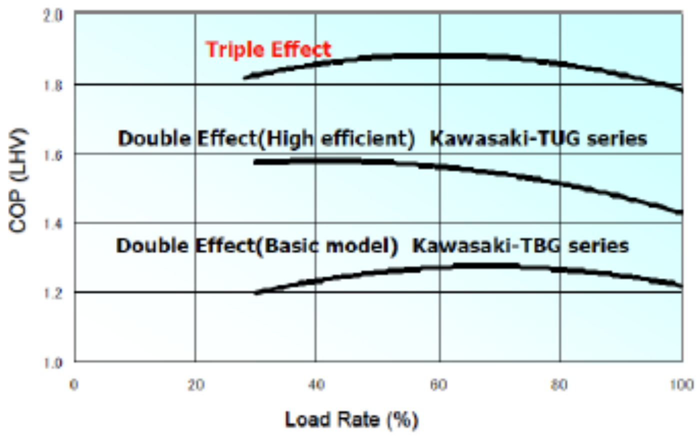

Figure 4: Different types of effects of absorption chillers

The absorption chiller COP is considered a key characteristic where it is described as the proportion of capacity of refrigeration to the required driving thermal power. More specifically, the COP is explained as the proportion of the thermal energy generated and used by the chiller. The high effect stage absorption chiller possesses a high COP. The previous studies show the single effect absorption chiller has COP between 0.5 to 0.7 while the double effect has a COP between 1 to 1.2. However, the triple effect absorption chiller has a COP which is higher than the others and it reaches to 1.7. The triple effect is still in the experimental stage. To conclude, the three types of effects cycle of absorption chillers are widely accessible and used in DCS to offer cooling for different sectors (Deng et al., 2011).

2.1.1.4 Comparison between Compression Chillers and Absorption Chillers. The below table (3) compares between the two types of cooling technologies, compression chillers and absorption chillers (Athukorala, 2012; Best, 2007; "District Cooling Best Practice Guide," 2008; Mildenstein, 2002)

Table 3: Comparison Between Compression and Absorption Chillers

Criteria	Compression Chillers	Absorption Chillers
Driving Energy	Electricity	Heat
COP	4 - 5	0.5 – 1.7
Capacity	2500 – 6000 tones	1 – 3300 tones
Sensitivity to Ambient Conditions	Less Sensitive	More Sensitive
Electrical Requirements	High Consumption	Insignificant
Initial Cost (per tone)	500 – 800 $	1,000 – 1,400 $
Operating Cost	High cost/ Electricity	Less Cost
Noise, Sound and Vibration	High Levels	Low Levels
GHC and Refrigerant Emission	High Levels	Low Levels

2.1.2 Thermal Energy Storage. The incorporation of thermal energy storage (TES) in a solar assisted cooling system enhances the system's efficiency and the reliability as in the traditional cooling systems. Two forms of TES could be integrated in the SAC system for the purpose of satisfying the need for cold and hot water. In this section, various TES kinds are explained to highlight their associated characteristic.

There are three common technologies of thermal energy storage to store thermal energy which are employed in various applications with temperature ranges between -40^{o}C - 400^{o}C. The three technologies are thermo-chemical energy storage (TCS), storage in phase change materials (PCM), and sensible thermal energy storage (STES). The STES would be a suitable solution for hot water storage, because its cost effectiveness and achieve a proper efficiency level when the optimum water stratification in the tank is satisfied along with having an efficient thermal insulation. The STES is usually used for domestic hot water application and its volume ranges between 500 liters to a few cubic meters. However, it can be also used for large applications where its volume can reach up to thousands of cubic meters. Nonetheless, STES has some drawbacks like low temperature and energy density uncertainty during discharging, but PCM solves such issues, but it has a relatively high cost compared to sensible thermal energy storage. It is very important to highlight that PCM storage period includes long (seasons) and short term (days). The thermo-chemical energy storage depends on performing chemical reactions to store chilled water and that is a huge advantage, because of its capability to transform heat into cold while sustaining a high efficiency. The main feature that differentiate the TES technologies from each other are storage period, capacity, efficiency, cost, and power charge and discharge time. These features are presented in table (4) (Irena, 2015).

Table 4: Comparison Between Different Types of TES

TES Type	STES	PCM	TCS
Capacity (kWh/t)	10 - 50	50 – 150	120 – 250
Efficiency (%)	50 – 90	75 – 90	75 – 100
Power (MW)	0.001 – 10	0.001 – 1	0.01 – 1
Storage Period (h, d, m)	Day/ Month	Hour/ Month	Hour/ Day

The capacity indicates the quantity of energy stored, the power refers to the discharging and charging power, efficiency indicates the proportion of the energy stored to the energy supplied and the storage period is given in hours, days, and months (Irena, 2015).

2.1.3 Renewable energy

The renewable energy technologies included in this section are solar collector and photovoltaics panels.

2.1.3.1 Solar Collector. The solar collectors (SC) are a device that transforms the solar irradiance into thermal energy by using a hot water as a medium. Collectors with high efficiency converts the energy with lowest energy losses. The SC are classified into two types according to their motions which are stationary collectors and sun tracking collectors (Kalogirou, 2014). Usually small and medium solar collectors with temperature ranges between 60 and 250^{o}C are employed for comfort cooling application. For power generation application, two-axis tracking types of solar collector are used since they are famous for their indicative temperatures range. The below table (5) shows the different SC types along with their features (Kalogirou, 2014).

Table 5: Comparison Between Different Types of Solar Collectors

Motion	Collector Type	Absorber Type	Concentration Ratio	Indicative Temperature Range (^{o}C)
Stationary	Flat-Plate (FPC)	Flat	1	30 – 80
	Evacuated Tube (ETC)	Flat	1	50 – 200
	Stationary Compound Parabolic (CPC)	Tubular	1-5	50 – 240
Single-axis tracking	Compound Parabolic (CPC)	Tubular	5-15	60 – 300
	Linear Fresnel Reflector (LFR)	Tubular	10-40	60 – 250
	Cylindrical Trough (CTC)	Tubular	15-50	60 – 300
	Parabolic Trough (PTC)	Tubular	10-85	600 – 400
Two-axis tracking	Parabolic Dish Reflector (PRD)	Point	600-2000	100 – 1500
	Heliostat Field Collector (HFC)	Point	300-1500	150 – 2000

Several aspects are taken into consideration while choosing an appropriate solar collector for a solar cooling system which are efficiency, ranges of temperature and costs. Stationary collectors especially FPC and ETC are known by their capability to gather diffuse and direct irradiance at a really low output temperature, regardless that the material of ETC enables a greater output water temperature compared to FPC. Furthermore, the ETC has a daylong performance which is an advantage over the FPC, because of their high efficiency at low incidence angles. Also, the thermal efficiency of ETC is better than FPC, so the ETC has a relatively high cost compared to FPC. The stationary solar collectors' efficiency can be calculated using the following formula:

$$\eta = \frac{Q_u}{A_c * G_t}$$

Where G_t is the solar irradiance in W/m^2, A_c is the area of the collector in m^2 and Q_u is the collected energy by the solar collector in watt, (Irena, 2015).

The single – axis concentrating collectors show their capability of tracing the sun with very high output temperature ranges. Also, the way these collectors are manufactured enables them to reduce heat losses and increase the delivery of energy. For the same area of a concentrating collector and FPC, the transfer medium in the concentrating collector can achieve higher temperatures, hence resulting in a higher thermal efficiency for it. Furthermore, the materials used in making the concentrating collectors have simpler structure compared to the materials used in FPC and that means the concentrating collectors have a lower cost per unit area. However, concentrating collectors require a continuous maintenance reflected in cleaning the surface of the collectors as they lose their reflectance and disability to collect diffuse radiation (Irena, 2015).

The below figure (5) shows a comparison between five types of SC versus two different radiation levels. The solar collectors are advanced flat plate (AFP), flat plate (FP), ETC, stationary CPC and PTC (Kalogirou, 2014).

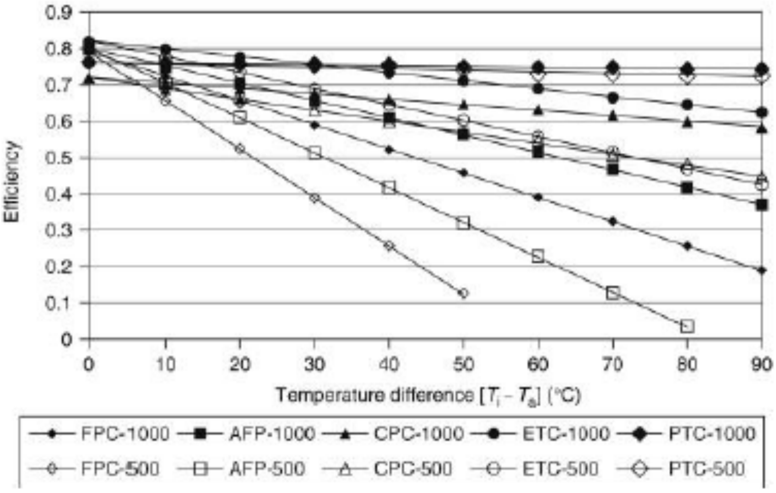

Figure 5: Comparison between types of solar collectors

2.1.3.2 Photovoltaics Panels. The PV panel is a solid semi-conductor device which transforms the sun light to electrical energy. The outcome of the PV is usually a direct current electricity; however, the appliances used in residential and industrial areas use alternating current. So, the PV system usually composes of a battery, PV panels and an inverter circuit (Kumar & Rosen, 2011). The PV panel is made from PV cells that allow the transformation of sun light coming from the sun into direct current electrical energy. The other component is the battery which stores direct current voltages at charging mode during the sunlight and supply the direct current electrical energy at a discharging mode when daylight is absent. In addition, a battery charge regulator is used to for the purpose of protecting the battery from getting overcharged. Also, an inventor is included in the PV system which is an electrical circuit that transforms the direct current electrical power into alternating current and then supplies the converted electrical power to the different point loads (Kumar & Rosen, 2011).

There are four types of PV installation that currently exist which are off-grid commercial such as power plants in isolated areas, off-grid such as standalone roof/ ground systems for houses, grid-connected centralized such as large power plants and grid-connected decentralized such as roof/ ground mounted small installation. Each installation type has different balance system requirements for instances off-grid standalone system need an alternative electrical storage capacity or a battery bank (Kumar & Rosen, 2011).

Moreover, the PV system can be also classified according to the solar cell technology. One of the common solar technology is silicon. This technology can be classified into thin film or crystalline silicon and amorphous silicon. This technology is the most mature technology in market. There are different types of crystalline structures for the crystalline silicon cells which are single crystalline silicon, multi-crystalline silicon and ribbon cast multi-crystalline silicon. One of the main features of the PV system is their capability to offer instantaneous and direct transformation of solar energy to electricity without requiring complex mechanical parts (Kumar & Rosen, 2011).

The performance of the photovoltaic panels is influenced by climatic parameters and module structure. The primary parameters are packing factor, module temperature and solar radiation. The efficiency of PV increases when the solar irradiance increases as more photons exist with the higher solar irradiance. So, more current flows in the PV panels. The PV packing factor is the portion of area of absorber occupied by the PV cell which critically impacts the electrical output. When the packing factor increases, the temperature of the module increases which will decrease the efficiency of the PV and the electrical output per unit collector area increases. This is caused by a higher cell temperature will reduce the voltage greatly (Kumar & Rosen, 2011).

2.1.4 Auxiliary Heating Unit. Integrating an auxiliary unit for heating in the system is crucial due to several reasons related to the facts that the solar energy is only available during the daytime and the climatic conditions might be unstable. Hence, adding such unit will enhance the system's reliability. The auxiliary heating unit could be LPG heating unit, Electric boiler, or Biomass boiler. Nevertheless, integrating an auxiliary heating unit like electric boiler reduces the system's efficiency. Whereas employing a sustainable energy source like biomass gas fired boiler helps in reducing greenhouse gas emissions (Zhai et al., 2011).

2.2 Data Collection

The data collected in this research includes the aforementioned system components and other parameters as well.

2.2.1 Importance of the Collected Data. The collected data are valuable to other researchers who are conducting researches in this area. The value of the collected data comes from various aspects:

- Most of the collected data on the parameters of the model such as hourly cooling demand over the year and the hourly global solar radiation over the year are not available on government websites, commercial websites or journal papers. These types of data are essential and the core of any research conducted in this area. Hence, having an easy access to this data would save a lot of time on the researcher in terms of spending hours or days searching or obtaining access to this actual data. In addition, the collected data can be used as benchmarking cases by other researchers in the future.
- The collected data combines all types of data such capacity, fixed costs, variable costs, and efficiency required for each component of the system. The complete data of each component in the system are collected from various sources such

as commercial websites, government websites, real-life case studies, and journal papers. Hence, having all this data in one resource would provide an easy access to other researchers in the future.

- The collected data are filtered and ready for use. Most of the data collected on different parameters were collected and obtained from various sources, so most of the parameters had different measurements units such as capacity and currency units. Hence, the collected data on different parameters are already consistent with each other in terms of no conversion of units is required. The researcher can directly input the data into their developed models without the need for any conversion.
- The collected data will open doors to other researchers through encouraging them to conduct researches in this area as most of the data that could be used in this area of research are already available in this paper. Hence, the researcher could focus on other aspects of the research rather than pouring his attention in collecting the data. This will contribute and add value to the scientific community at many levels.
- One of the most crucial data collected and derived is the hourly cooling demand over the year. Most of the cooling demand available at different source is either the cooling demand for a single month or the cooling demand for an application like a hospital, or a school. So, there is no cooling demand available which shows the hourly cooling demand for each day in the month over the year. Gaining access to such data, would make it convenient for the researcher to carry out researches in this area, as the cooling demand data represents the core of any research carried in this area. The researcher can scale down or up the generated cooling demand pattern as per his requirement, since the pattern of

the demand would remain valid.

2.2.2 Data Collected. The data collected and presented in this research are based on the parameters of the mathematical model. The type of data collected are related to hourly cooling demand over year in kW, hourly global solar radiation over the year, hourly variable cost of producing and storing cold and hot water over year. Moreover, data specific to absorption chiller component such as fixed cost of the chiller ($), capacity of the chiller (kW), and COP of chiller are collected. In addition, data related to solar collectors' component such as type of solar collectors, efficiency of solar collector and fixed cost ($/m2) of solar collector. Furthermore, data on hot and chilled water TES tank such type of TES, capacity (kWh) of TES and fixed cost of TES ($). Finally, data on auxiliary boiler such as fixed cost of auxiliary boiler (kW), efficiency of auxiliary boiler, and capacity of auxiliary boiler (kW). Hence, data on five main components of the system are collected. These five components represent a part of the parameters of the models.

2.2.3 Experimental Design, Materials and Methods. Most of the data were obtained from commercial websites, governmental websites, real-life case studies and journal papers. However, there are some data which were generated using a specific method such as the hourly cooling demand over the year. This method will be explained later in this section. This section will overview and explain the collected data on each parameter of the system.

- **Absorption Chiller Component**

The data collected on absorption chiller component includes the following parameters, fixed cost of installing a chiller of capacity k, the capacity of a chiller and COP of chiller of k capacity. They are collected from different resources such as commercial websites and real-life case studies ("Broad X Absorption Chiller Model Selection and Design

Manual," 2008; "Combined Heat and Power Technology Fact Sheet Series," 2017; Gmbh, 2009; He et al., 2008). Data are collected on different types of chiller including single effect, and double effect with a focus on lithium bromide- water type of chiller since they are less toxic compared to other absorbers. The collected data are filtered and refined, it means all the inputs have the same and consistent units. The number of inputs collected is 46. The complete collected data are shown in appendix A.

- **Solar Collectors Component**

The data collected on solar collector component includes the following parameters, fixed cost of installing a unit area of solar collector, efficiency of a solar collector and maximum installed area of solar collectors. They are collected from different resources such as real-life case studies and commercial websites ("Central Solar Hot Water Systems Design Guide," 2011; "Distributed Generation Renewable Energy Estimate of Cost," n.d.; Rockenbaugh, 2016; "Solar Thermal Product Guide," n.d.). There is only one input for the maximum area of installed solar collector parameter and it is equal to the area of the building available to install the solar collectors. However, for the other parameters, there are 65 inputs. Data are collected on various types of solar collectors including FPC, ETC, and PTC. The collected data are filtered and refined, it means that all the inputs have the same and consistent units. The complete collected data are shown in appendix B.

- **Cold and Hot Water TES Tank Component**

The collected data on thermal energy storage component includes the following parameters, investment cost of cold-water TES tank installed, investment cost of hot water TES tank installed, cold water TES tank capacity and hot water TES tank capacity. They are collected from different resources (Akbari & Sezgen, n.d.; "Cost Functions for Thermal Energy Storage in Commercial Buildings," n.d.; "Evidence

Gathering: Thermal Energy Storage (TES) Technologies," 2016; Habeebullah, 2005; "Home," n.d.; Kensby, 2015; Lizana et al., 2018; Noranai & Yusof, 2011; Rouleau, 2015; Thermal Energy Storage," n.d.; "Thermal Energy Storage Technology Brief," 2013). Most of the collected data are obtained from real-life case studies from all around the world. There are different types of TES that can be used for commercial aspects such as TTSE, PTE, and BTES. These types differ in the way they function, installation and duration of storing the heat of water in the tank (Inter day, seasonal, etc.). The collected data are filtered and refined, it means that all the inputs have the same and consistent units. The number of inputs collected for hot water TES tank is 61 and for the cold-water TES tank is 48. The complete collected data are shown in appendix C.

- **Auxiliary Boiler Component**

The collected data on auxiliary boiler component includes the following parameters, investment cost of installing boiler, the boiler capacity and the boiler efficiency. They are collected from different resources such as real-life case studies and commercial websites (Bautista, 2014; "Best Available Technologies for the Heat and Cooling Market in the European Union," 2012; "Energy Distribution: District Heating and Cooling – DHC," 2012; Fleiter, 2016; Kazan, n.d.; Lahdelma, 2011; "Off-grid Heating," n.d.; Parker & Blanchard, 2012; "Residential and Commercial Building Technologies – Advanced Case," 2018; Soysal, 2016;). There are different types of boiler such as oil, gas, electric, and biomass boiler. The collected data are filtered and refined, it means that all the inputs have the same and consistent units. The number of inputs collected is 46. The complete collected data are shown in appendix D.

- **Variable Cost of Producing and Storing Chilled and Hot Water**

The variable cost of producing or storing chilled or hot water at TES is related to the cost of electricity consumption. The cost of electricity is constant throughout the year which and it doesn't vary in Qatar. The cost of electricity is obtained from the electricity and water service provider at Qatar - Kahramaa's website. So, the variable costs per unit of producing chilled water from a chiller or hot water from an auxiliary boiler will be the same as the cost of electricity consumption. Moreover, the variable cost per unit of storing chilled water at cold TES or storing hot water at hot TES will be the same as the cost of electricity consumption. According to Kahramaa's website the cost of electricity consumption for commercial industry is 0.055 $/kWh (Qatar General Electricity and Water Corporation, n.d.).

- **Global Solar Radiation (W/m^2)**

The data required for global solar radiation is the hourly global solar irradiance over the year. It is collected from the government sector Kahramaa's database - the water and electricity service provider at Qatar. The data obtained has solar irradiance values from December 2014 to December 2016. However, the data was filtered and only data related to the 2016 year was extracted and used in the mathematical model. The graphs are shown in appendix E. We can notice that the global solar radiation is usually obtained during the daytime period.

- **Cooling Demand**

The hourly cooling demands over the year for Qatar state were collected over 8784 hours per year. However, the only cooling demand data was available for state of Qatar is the hourly cooling demand for only a day in the month for the 2016 year and they were obtained from a graph included in Saffouri et al. (2017) shown in the below figure (6).

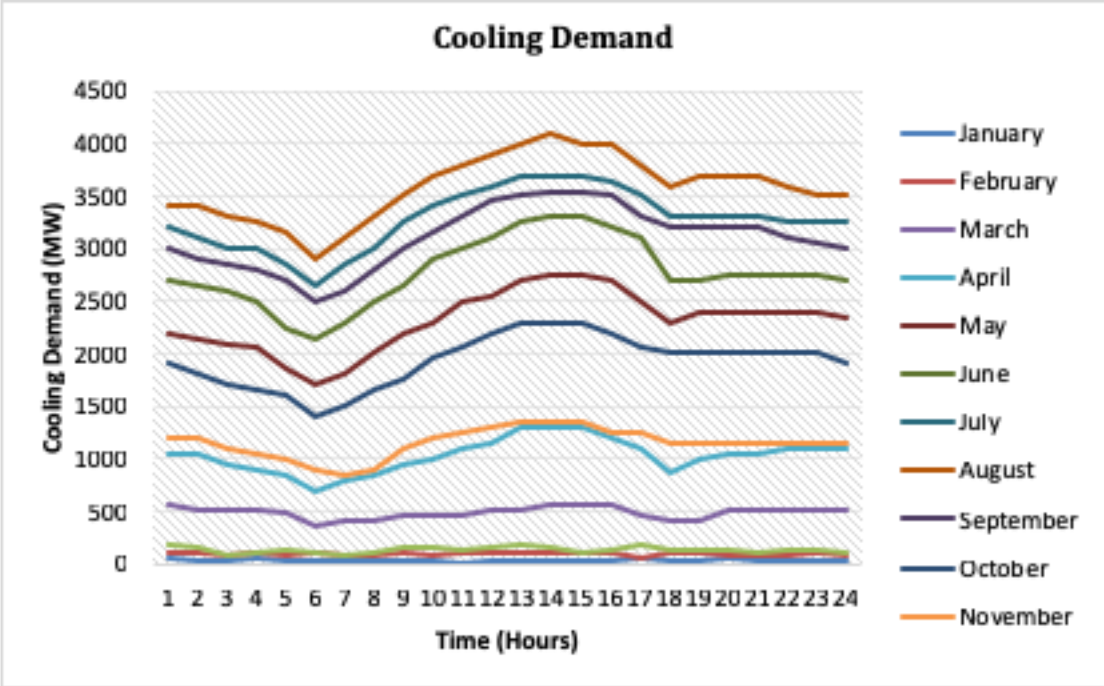

Figure 6: Hourly cooling demand over the year for qatar

Nevertheless, the required cooling demand data is the hourly cooling demand for all days of months through the year (8784 hours). So, to find the cooling demands for the other days in the month, the average temperature for each day in the month is calculated and the day with highest average temperature in the month is assigned to the cooling demand which is already given in the graph. This day is considered a reference day where the cooling demand for the other days is calculated based on this day. For the rest of the days in the month, a ratio of hourly temperature of the day – the day to find the cooling demand for – to the hourly temperature of the reference day multiplied by the cooling demand of that hour of the reference day.

$$Cooling\ Demand\ for\ a\ day\ i\ at\ an\ hour\ j =$$

$$\frac{Temperature\ of\ a\ day\ i\ at\ an\ hour\ j}{Temperature\ of\ reference\ day\ at\ an\ hour\ j}\ x\ Cooling\ demand\ of\ reference\ day\ at\ an\ hour\ j$$

The hourly temperature of Qatar was obtained from Hour-by-Hour Forecast for Doha, Qatar (n.d.) and these temperatures correspond to the year 2016 to ensure that it is consistent with the data of global solar radiation and cooling demand as they represent the year 2016. The hourly cooling demands for each day in the month for the 2016 year are shown in the appendix F and the pattern is the same as the cooling demand obtained from Saffouri et al. (2017).

Chapter 3: Literature Review

The literature review is categorized into two sections; the first section covers the conventional district cooling system. This section discusses design and operation optimization of the system. The second section covers solar assisted cooling systems which includes two types; solar thermal, and solar electric cooling system. This section covers the design and operation optimization of the systems.

3.1 Conventional District Cooling System (DCS)

The conventional district cooling system is currently used across the world. It uses compression chillers which supply the chilled water to residential, commercial and industrial districts. In case if excess cold water generated by the chillers, the chilled water is stored in the TES tank. The main focus of this literature is on the papers that address the optimal design and operation of district cooling systems.

Magori et al. (2000) developed a method to solve the optimization problem of designing and planning a district heating and cooling system. The goal of the study was to find the optimal combination of various types of heating and cooling components that minimize the fixed cost of the components, construction costs and operating costs of heat generation while satisfying the heating and cooling demand. The model was described as non-linear combinational model with four types of components both single use (cooling/ or heating) and multiple use (heating and cooling). To formulate the model, the Extended Dynamic Programming (DP) was employed. The effectiveness of the solution was validated with the help of the simulation against the conventional design case regardless of the limitation of the DP to formulate large size problems.

Powell et al. (2013) employed optimization methods to optimize distributing the cooling loads on multiple chillers. Particularly, the thermodynamic semi-empirical model developed by Gordon was used for chiller performance. The result of the optimization indicated that more efficiency in energy consumption can be obtained at minimum cost. The employed model was adjusted to four industrial electric driven centrifugal chiller system. At first, the developed model was solved for static operation for the purpose of minimizing the energy consumption by using the optimal allocation of cooling demands through the 4 chillers at a certain period. A mixed integer non-linear programming model was formulated, but it was simplified to a simple quadratic programming. Later on, the model was extended to be solved dynamically over a time horizon for the purpose of minimizing energy consumptions by optimally loading the chillers. Moreover, a TES was added to provide more flexibility in shifting the cooling load between chillers. The results of the paper indicated that a decrease of total energy consumption up to 9.4% in dynamic chiller loading with a TES can be obtained. In addition, the results highlighted the impact of including TES on shifting cooling loads. Söderman (2007) studied the design structure and operation optimization of DCS in an urban area. The cooling demand can be satisfied from a compressor driven cooling plant or from main cooling plants. The author developed a Mixed Integer Linear Programming (MILP) model where the objective was to minimize the total cost which included the annual operating and investment cost of all the components. The developed model used to determine the structure of the DCS which included the capacity and location of cooling plants, the location and capacity of cold storage, and the pipelines network routing to consumers. Moreover, the model was also used to determine the operation of the DCS which included the charge and discharge of the storage, optimal operation of cooling plants in different periods of the year, and the cold medium flow rates in the district cooling pipelines. Two cases related to actual demand and forecasted demand were used during testing the developed MILP. Moreover, branch and bound method was used to solve the problem using CPLEX 9.0 solver. The optimization was done at seasonal level during the study. However, the study would be more accurate and reliable if the optimization would be done on daily or hourly scale.

Gang et al. (2016) reviewed papers that were related to application of DCS. One of their major contributions was highlighting the incorporation of the renewable energy technologies into a DCS, TES system and combined heat and power system. The authors evaluated the optimization of DCS from various aspects such as designing and operational. From the designing perspective, the focus was on global system design optimization with the aim of finding the best technology employed for producing chilled water or finding the best capacity and location of chillers plant and TES systems as MILP could be used. From the operational aspects, the focus was to minimize the consumption energy and operational cost where Multiple Objective Non-Linear Programming (MONLP) could be employed. Nevertheless, the authors did not shed lights on controlling optimization which included the DCS and the end user. Also, the design optimization with uncertainties like uncertainties in estimating cooling demand, cooling load profile and the chiller's performance components were not considered.

Khir and Haouari (2015) studied the optimization of a single DCS plant. The objective of the optimization problem was minimizing the fixed and operating costs of the proposed system. It included decision variables such as chiller plant and TES capacities, the production and storage of chilled water at every period and the configuration of the chilled water distribution network. The optimization problem was expressed as Mixed Integer Problem where hydraulic and thermal features were taken into consideration and that needed the implementation of Reformulation Linearization Technique. The results of the paper showed that an optimal solution could be obtained with a short computational time.

3.2 Solar Assisted Cooling System (SAC)

This section focuses on two crucial systems which are solar thermal system and solar electric system. In both cases, the system utilizes and uses the sun energy either in the form of heat to operate SC in case of solar thermal system or PV panels in case of solar electric system. In addition to those components, the solar thermal system employs an absorption chiller, a cold and a hot TES tank, and an auxiliary boiler. While the solar electric system employs a compression chiller, and a cold TES tank, in addition it is connected to the grid.

3.2.1 Solar Thermal System. The paper in this section are categorized according to the adopted modeling and solution approaches:the general approaches; the simulation modeling; and the mathematical modeling.

General Approaches:

Raja and Shanmugam (2012) conducted many investigations on solar cooling system which consists of single effect LiBr-H_2O absorption chiller paired with FPC and ETC to minimize the operational and capital costs and to enhance the absorption chiller COP. The paper showed that there were two critical parameters that have the most influence on the economical aspect of the solar cooling system 1) the cost of storage technologies and solar collectors, and 2) the cooling technologies performance. Several suggestions were considered with reference to the aforementioned parameters i) the hot water tank can be placed on top of SC to convey the heat from the SC to the tank, ii) placing the generator inside the insulated storage tank would reduce heat loss due to flow of hot water from storage tank to generator, so the cost of the insulation of the generator can be reduced. In this paper, three electrical equipment were used; cooling coil fan, a pump, and a condenser fan. This system had a significantly low operational cost when compared to the conventional compression system. However, the initial cost of the solar assisted system was high. Thus, solar cooling system would be compared to the conventional compression cooling system on long term operation basis.

There are other papers that focus on incorporated an auxiliary boiler. Prasartkaew and Kumar (2010) conducted a simulation study to assess the solar absorption cooling system performance that incorporated a biomass gasifier hot water boiler for residential applications. The system composed of three major parts; solar water heating with a storage tank, biomass gasifier hot water boiler and a single effect absorption chiller. The auxiliary boiler was placed between the absorption chiller and hot water storage tank. The boiler had two main functions which were operating as an auxiliary system when the solar energy was not enough and operating as a main heat source when the solar energy was absent. The performance of these components and the overall performance of the system were evaluated hourly and monthly using Bangkok climatic data. Based on that, the COP of the overall system and the chiller was estimated to be 0.55 and 0.7 respectively. In order to validate this model, experimental observations of similar system with the same chiller size were compared to the model results. This study indicated that the proposed system was possible to replace the conventional vapor compression system to reduce the necessity of fossil fuel usage. Moreover, Sun et al. (2015) proposed a solar cooling system that incorporated an auxiliary boiler when the solar energy was not sufficient.

Simulation Modeling Approach:

Tsoutsos et al. (2010) used TRaNsient SYstem Simulation program (TRNSYS) software to simulate the solar cooling and heating system of a hospital in Crete with an overall surface of 1250 m^2. The aim of this simulation was to optimize the different parameters of the system; collector area, collector slope, back-up heater, size of storage tank, and capacity of absorption chiller. Four different scenarios were simulated, examined and compared for the purpose of minimizing the cost of the system and increasing the environmental benefits. The fourth scenario optimized both objective functions. This scenario had a solar fraction cooling and heating of 74.23% and 70.78%, respectively. The optimized parameters of this scenario were the number of solar collectors required to cover an area of 500 m^2 was 179, a 70-kW lithium bromide-water single effect absorption chiller, a 50-kW back-up compression chiller was employed in case if the absorption chiller didn't provide the required cooling load, and an auxiliary fossil fuel heater of 87 kW was added.

Qu et al. (2010) used TRNSYS to simulate a system that incorporated a 52 m^2 of PTC, a 16-kW double effect lithium bromide - water absorption chiller and a heat recovery heat exchanger that generated hot water or cold water depending on the requirements. The simulation results were used to investigate the parameters that improved the system performance which were, the area and orientation of solar collectors, thermal storage volume, and pipe diameter and length. Furthermore, the proposed system was found to provide 39% of cooling and 20% of heating to the building i, when the system included a suitable storage tank size and short and small diameter pipes.

Another study conducted by Ortiz et al. (2010), where they developed a numerical model on TRNSYS for a solar cooling system to serve a 7000 m^2 educational building in a desert climate. The numerical model was developed to speculate the performance of the system and to optimize the parameters of the system. The system consisted of FPC and ETC, a 70-kW absorption chiller which worked with hot water supply temperature ranged from 70 to 95°C. The results of the model indicated that, the system performance increased when the heat medium temperature decreased. Also, it was found that the solar cooling system can decrease the exterior cooling energy needs by around 33% to 43%.

Praene et al. (2011) studied the idea of developing a cost-effective solar absorption cooling system to be planted on the roof of a school in the Reunion Island, under a tropical weather. The study compared three different types of solar collectors; FPC, PTC and ETC. These collectors were connected to a single effect absorption chiller. The results from TRNSYS program and from a techno-economical study showed that ETCs are preferred over PTCs where they were cheaper and had flexibility to be installed on the roof. However, due budget constraints along with the space availability, the FPCs were preferred at the end. The system composed of 90 m^2 of FPC, a lithium bromide- water single effect absorption chiller with a cooling capacity of 30-kW and an operating temperature of 70 to 95^o, a cooling power with a capacity of 80-kW, 1500L hot water TES tank, and 1000L of cold-water TES tank. From the experimental installation, in the afternoon periods, the performance of the system was reduced to its half which was around 17-kW with a shutdown at 4:30 pm. However, this cooling energy was sufficient to provide cooling services for the class rooms.

Martinez et al. (2012) discussed the two main purposes of their study; the first aim was to design the parameters of the proposed solar cooling and heating system- constructed to serve 200 m^2 of offices and laboratories at in Spain- using TRNYS program. The parameters were designed based on energy saving during the cooling periods. The second aim was to record the performance data of the system. By using TRNSYS program, the authors found the optimal design parameters of the system (i.e. TES volume and are of collectors) from an energy efficiency side. The proposed system was equipped with 38.4 m^2 of FPC, a 17.6 kW lithium bromide- water single effect absorption chiller with a coefficient of performance of 0.691, and 1000 L hot water tank. A 29% of the solar energy exerted on the solar collector surface was converted to hot water storage.

Vasta et al. (2015) used the TRNSYS program to conduct a dynamic simulation for the design of a proposed solar cooling system to determine the impact of various operational and design parameters on the system performance in three cities in Italy. The proposed system was installed to serve a flat with a size of 130 m^2 and occupied with four residents and had the following parameters an absorption chiller, a cooling tower, a backup gas heater, 1m^3 storage tank, and 27.52 m^2 of solar collector which was equivalent to 16 collectors. The simulation results indicated the area of the collectors influenced mainly solar fractions and absorption chiller COP.

Sokhansefat et al. (2017) simulated a solar cooling system design on TRNSYS program to be installed in Tehran. The proposed design composed of 4 major elements which were 49.86 m^2 of ETC organized in four series, 5 RT of single effect absorption chiller, 15 tones closed circuit cooling tower, and1000 L of hot water TES tank. A parametric analysis was performed and resulted in finding the optimum values of the parameters affected on the performance of the system. The parameters were the storage tank volume, collector slope, area and mass flow rate, and auxiliary boiler set point temperature.

Soussi et al. (2017) studied a solar cooling system that was used to provide chilled water for a 126 m^2 laboratory building in Tunisia. The proposed system was composed of 39.3 m^2 of PTC with COP, 1 m^3 hot water storage tank, 16-kW LiBr-H_2O double effect absorption chiller and an auxiliary heater. The system was modeled on TRNSYS program. The simulated results were compared with results collected from an experimental campaign. The results showed that the collector efficiency was between 26- 35%, the efficiency of the absorption chiller was between 0.65 and 1.29 and the solar efficiency was around 35%. Nevertheless, the solar collectors were only able to deliver 32.3% of the cooling demand and the absorption chiller was operating 53.8%

of its total operating time. Two improvements to the existing system were considered, an auxiliary boiler was added and the area of the solar collectors was increased which improved the driving temperature to the chiller. Hence, the operating time of the chiller increased to 75.8%, the solar COP reached to 57%, the cooling power increased by 75.6% and the solar fraction reached to 87%. This improved system accomplished 82.3% of energy savings compared to the conventional air conditioning system.

Khan et al, (2018) simulated two configurations for solar cooling systems using TRNSYS program. The proposed systems were installed in an educational building in Iran. The two configurations were modeled in TRNSYS and dynamic simulations were replicated under the summer climate. The different system factors like solar collector efficiency, solar fraction and energy savings were assessed to optimize the major system variables such as tilt, type and size of the solar collectors and the storage volume. The results showed that during the summer season the second configuration with ETC or FPC always had a higher energy saving compared to the first configuration. Nevertheless, the difference between the first and the second configuration was in terms of solar fraction and collector efficiency. Overall, the second configuration coupled with the ETC resulted in a minimum solar collector area per kW of cooling demand and a higher collector efficiency than the first configuration.

The following papers focus on the thermal energy storage tank. Molero et al. (2012) compared various solar cooling system configurations with coefficient of performance of 0.695 for a residential building in Spain and impact of cold and hot storages were investigated. The comparison between the two configurations was carried out on TRNSYS program. The first configuration had only a hot storage tank with a capacity of 40 L/m^2 of solar collector surface area. The other configuration had both hot and cold storages. The advantages of a cold storage disappeared, when the collector area increased. However, as the collector area increased, the temperature of hot storage increased which caused a high thermal loss in the tank and the collectors. The impact of other variables on the optimal configuration were investigated; solar collector area and efficiency, size of thermal storage tank, COP of absorption chiller, and temperature set points of chiller. The results demonstrated that when a cold storage tank was used in the system, a better system performance was observed, especially when the solar collector area was small and the storage size was large during the summer season. However, this configuration required two storage tanks. This configuration was more sensitive to changes in the COP of the absorption chiller and to changes in the efficiency of solar collectors, because of the small hot water storage size.

Hang and Qu (2011), studied the effect of hot and cold-water TES on the performance of the solar absorption cooling system for a building located in Los Angeles. The system composed of 200 m^2 area of ETC and the capacity of the system was 120 kW. The system was designed to provide 50% of the total cooling demand of the building. The system was simulated using TRNSYS program. The system had a hot tank in the solar collection loop and a cold storage tank in the load loop. A sensitivity analysis was carried out on the two tanks by changing the storage tanks volume, solar collector area and the capacity of the chiller. The results of the study showed that an appropriate cold storage tank size could decrease the capacity of the chiller. However, the effect of the cold storage tank on the system's energy performance was not critical compared to hot water storage tank. The solar fraction only changed around 2% when the volume of cold storage tank varied between $4m^3$ and $22m^3$. Nevertheless, the solar fraction varied between 51% and 57% when the volume of the hot storage tank increased from $2m^3$ to $22m^3$. Furthermore, the sensitivity analysis showed that the system performance was affected the most by the solar collector followed by capacity of the chiller, hot water storage tank and cold-water storage tank.

The following papers considered the climatic conditions in their study. Balghouthi et al. (2008) designed a solar powered absorption cooling system under Tunisian weather conditions. The proposed system was simulated using TRNSYS and Engineering Equation Solver programs using climatic data of Tunis. The outcome of the software was the optimized system's parameters for a building of 150 m^2 which had 11 kW lithium bromide-water single effect absorption chiller, 30 m^2 of FPC tilted at 35^o from the horizontal and a 0.8 m^3 hot water storage tank. The system employed a boiler with a capacity of 18 kW. The selected size of the absorption chiller was found to have an enough capacity to meet the demand of the building for cooling. The absorption chiller cycle was modelled on EES to assess the system performance. Also, the area and slope of collectors and tank size parameters were obtained from running many simulations on TRNSYS program.

Moreover, Marc et al. (2012) pointed out that the solar absorption chiller performance was impacted by the climate conditions as the climate effected heat rejection and the driving energy of the absorption chiller. The author proposed a solar driven absorption chiller system to cool four classrooms in Reunion Island located in a tropical climate. The proposed system included; 90 m^2 of FPC, a 30-kW lithium bromide single effect absorption chiller, two buffer tanks with sizes of 1500 L to store the hot water, 1000 L to store the cold water, 13 fan coil units, and an 80-kW cooling tower. This system didn't employ any backup system.

Sim (2014), presented a study on a thermal cooling system for an office space in Qatar. The system was simulated on TRNSYS using the meteorological data through-out the year for the purpose of determining the optimum values of the system parameters. The studied parameters were solar collector slope and area, tank volume, heat exchanger effectiveness and water flow rate. The results indicated that the optimum values for the proposed system were 4.5 kW adsorption chiller, 23.4 m^2 of ETC, the collector tilted at 24^o from horizontal, and 0.3 m^3 water storage tank. The water tank was able to provide hot water for 4 hours continuously without requiring for an auxiliary heater. The weather data between May and June were recorded and used to study and find the best values for the parameters. The study demonstrated that the adsorption chiller can decrease the electricity consumption by 47% compared to the conventional compression cooling system.

Asaee et al. (2014) developed a solar cooling system for a house in Canada. The solar system provided both heating and cooling and domestic hot water. A preliminary study was carried out to assess the thermal performance of the proposed system for such climate. The system was simulated using TRNSYS. An auxiliary heating and cooling system was incorporated during sun absence. By using a realistic control algorithm, the operation of solar system and the auxiliary systems was controlled. Moreover, a sensitivity analysis was conducted to identify the impact of area of solar collectors and storage capacity on the solar system performance. The results of the paper showed that the solar system provided a significant fraction of the required heating, cooling and domestic hot water demand for the house. The performance of the system was impacted by the climatic condition as predicted. Furthermore, the results indicated that increasing solar collector area enhanced the solar fraction. Finally, the paper determined the optimal configuration of the system by optimizing the design parameters.

The following papers design the capacity of the system based on the maximum cooling demand. Pongtornkulpanich et al. (2008) designed a solar cooling system with a cooling power of 35 kW in Thailand using TRNSYS program. The system consisted of 72 m^2

of ETC field mounted on the roof, 35-kW lithium bromide-water single effect absorption chiller, 400 L water tank to store the hot water, and a LPG-fired backup heating unit. The demand of the absorption chiller for the hot water was covered by 81% from the solar collectors and 19% from LPG-fired backup heating unit. The component sizes were estimated based on the required maximum cooling load of the building and information on local meteorological conditions. The economic cost of this system depended on the initial cost of the solar collectors and the absorption chiller which was higher than a conventional vapor compression system.

Agyenim et al. (2010) built a solar cooling domestic-scale prototype which composed of 12 $m^2$of ETC installed on the roof at a slope of 45^o, 4.5 kW LiBr/H_2O single effect absorption chiller, 1000 L buffer tank to store the cold water and 6-kW fan coil. The system was designed to supply cooling to an office with a size of 82 m^3 in Cardiff University. The selection of the chiller size depended on the cooling demand of the building and the demand in the summer which estimated to be 1472 kWh with a maximum of 2.1 kW. Also, the selection was based on the cooling requirement that might occur when the solar energy is unavailable. Hence, the dimensions of the other components were established based on the cooling capacity of the chiller with a COP of 0.7. The size and the area of the solar collectors were designed to cover 100% of the thermal energy required by the chiller. The size of the cold-water tank was estimated based on the maximum cooling load of 2.1 kW, assuming that the water would be cooled from 18 to 7^{o}C and cooling demand would occur from 5 pm to 10 pm when the solar energy is unavailable. This study employed the data acquisition system in order to measure the parameters of the system to allow assessment of the system performance. This system didn't employ any backup system. The results showed that the system is able to generate 4.09 kW of cooling power for 7.5 h. Also, the system thermal COP was 0.58 and the electrical COP was 3.6.

Hang et al. (2010) performed a systematic economic, environmental and energetic evaluation on a solar cooling system for an average sized building with an area of 4983 m^2 in Los Angeles. The proposed system consisted of ETC, a hot water TES, an auxiliary gas fired heater and a lithium bromide-water single effect absorption chiller. In this paper, TRNSYS program was used to simulate the building model. The selection of the parameters of the system depended on the following, the chiller's capacity was selected based on the maximum cooling load which was 150-kW, the solar collector type was chosen based on the collector efficiency and the heat source temperature needed by the chiller, and the power of the auxiliary heater was defined based on the efficiency of the heater and the capacity of the chiller. To assess the system performance, two critical parameters were varied; storage tank volume and solar collectors. The results proposed that there was a compromise between the economic performance which included equivalent uniform annual cost and environmental/ energetic performance which included solar fraction and CO_2 reduction. Therefore, using the CO_2 emission reduction cost as an economic criterion, the optimized parameters of the solar cooling system were 280 m^2 of solar collector and 11 m^3 of hot water buffer tank. This caused to provide 100,014 kWh annual cooling.

Shirazi et al. (2016) proposed four different configurations of solar cooling and heating system based on an ETC, a single effect lithium bromide- water absorption chiller, and a storage tank. The first configuration used a gas fired heater as the back-up system with a thermal efficiency of 0.9. The second configuration used a compression chiller as an auxiliary cooling system with a cooling capacity of 1023 kW. In the first two configurations, the capacity of the absorption chiller was based on the maximum cooling load of the building which was 1023 kW with a COP of 0.76. The third and fourth arrangements had close results to the second arrangement, but the size of the absorption chillers decreased by 50% and 20%, respectively. The area of the solar collector was 2.83 m^2 at a slope of 25^o. The cooling tower with a size of 0.2 m^2 was used in all configurations. The configurations were modeled on TRNSYS program. The results indicated that the second configuration achieved the highest energy saving with a solar fraction of 71.8% and 54% energy saving compared to the traditional cooling system. However, all the configurations had an unsatisfactory economic performance due to their high capital cost.

Mathematical Models Approach:

The following papers develop mathematical models to find the optimized systems with considering single objective function. Calise et al. (2011) presented a single objective optimization method of a solar cooling system for both single effect and double effect absorption chiller to find their best economic performance. The objective function was to minimize the system total cost or the simple pay-back period. The authors used the TRNOPT software which paired the TRNSYS software with the GenOpt algorithm. The authors employed an economic model included the equipment cost, integration cost and piping cost. However, the economic model did not include the expenditure and fuel price escalation rates.

Hang et al. (2011) developed a method to optimize the design of a SAC system under a constrained budget. The authors employed a regression analysis to determine the connection between the system factors and the solar fraction based on the data given by experiments. The method of central composite design from design of experiment was employed to attain a correct model of the problem. The TRNSYS program was used to conduct the experimental tests. Finally, the optimization problem was developed and solved where the objective function highlighted the connection between the solar fraction and the system variables. The system variables were the solar collectors' area and slope, and the hot and cold TES tank volumes. The objective function was to maximize the solar cooling system's solar fraction. The results of the paper showed that the optimized model was similar to the physical model in TRNSYS. This optimization method showed the impact of various parameters on the objective function and determined their sensitivity mathematically.

Arsalis et al. (2015) used MATLAB to develop a mathematical model to test a single effect lithium bromide-water absorption chiller paired with a FPC and had a hot water TES tank to meet the load requirements of a standalone residential house in Cyprus under summer climates. The heating demand was moderate while the cooling demand was high. The hot storage tank was coupled with an auxiliary diesel boiler to complement the solar heating when required. The main objective of the paper was to model the system and to conduct a parametric study that determine the optimal economic performance based on the design parameters. The design parameters were the area and slope of collectors, and the size of the TES tank. The results of the study indicated that the optimum combinations of solar collector area and volume of hot water storage tank were 70 m^2 and 2000L, respectively. Also, the paper indicated that the total annual cost for the optimal solar heating and cooling system was 3,719$. The sensitivity analysis showed that the capital cost of the collector must be around 360$/unit area for the proposed system to be compared with the traditional electrical compression system economically.

Hang et al. (2013) developed a solar absorption cooling and heating systems, which utilized the energy of the solar to offer comfort cooling and heating and water heating. This study examined a formal method to optimize the system by considering energy, environmental and economic aspects. The proposed formal method included central composite design, regression and multi-objective optimization. The CCD was used for the selection of the critical experimental data. Linear regression model was used to expect the functional relationship between the key system variables and the system performance. Moreover, the multi-objective optimization model was developed and solved using the weighted-Tchebycheff approach to find the best system structure by maximizing energy, environmental and economic benefits. By using the weighted sum method, the objectives were combined into a single objective. The results of the model showed that achieving a small reduction in economic value implied a large reduction in environmental and energy aspects.

Xu et al. (2015) constructed a stochastic multi-objective optimization model for a solar absorption chiller system. The authors used a stochastic model to include in the optimal design of the system the uncertainties and to verify the deterministic optimization approach. The design variables were the design layout such as the solar collectors' area and slope, and the volume of the central and heating storage tank. The SMOO was developed to determine the optimal values of these variables. Three objective functions were considered; minimizing present worth cost, life cycle energy consumption and life cycle CO_2 emission. Genetic Algorithm was used to solve the optimization problem and a Pareto Front was obtained. The results yielded the optimal solution which included the solar collector's area and the main tank's volume. Also, the results indicated that when the size of the proposed system increased, the economic performance became poorer, but the energy and the environment performance got enhanced. The cost of the proposed system was around 60 – 120% more than the traditional system, but it reduced the consumption of energy by 45 – 75% and CO_2 emissions by 40 – 70%. The authors recommended that the deterministic approach to be used if the owner of the system wanted to enhance the system performance more than to manage the uncertainties. However, the stochastic approach should be used if the owner of the system wanted to avoid risk.

Gebreslassie et al. (2010) introduced a decision support tool which was based on using optimization models to design and optimize a solar absorption cooling system to replace the traditional cooling technologies with solar energy. The solar thermal system was modeled using a bi- criteria MILNP model to optimize the environmental impact and economic performance. In the proposed system, the absorption chiller was powered by a natural gas boiler as a primary energy and by solar collectors of different types as a substitute source of energy. The objective of the study was to find the optimal design and the operation that minimized both total capital and operating costs and the emissions. The operation of the absorption system was varied during the time horizon depended on the solar radiation. By using epsilon constraints, trade-off solutions were determined where a set of pareto optimal points were found with the help of the customized branch and bound technique. A case study was used for the purpose of demonstrating the performance of the solution approach. The results of the paper showed that the emission level associated with solar energy had reduced significantly. Also, through solving the integrated solar assisted absorption system, short computational times for various conditions were obtained.

Iranmanesh and Mehrabian (2014) studied an absorption chiller with a double effect powered by ETC. A sensitivity analysis was conducted on the designed system to study the effect of various parameters on auxiliary energy. The parameter considered were the volume of storage tank, area of solar collectors and mass flow rates of water moving through the generator and the collectors. Furthermore, the authors developed a multi-objective optimization model. The two objectives considered for the genetic algorithm were the auxiliary energy consumption and the net profit attained from the system. However, the environmental aspect of the system was not considered. The computer code was developed on MATLAB which was linked to ESS to maximize the profit and minimize the auxiliary energy. Also, Non-dominated Sorting Genetic Algorithm was used to optimize the system.The results of the optimization showed that the optimal mass flow rates had a critical impact on decreasing the auxiliary energy. The ETC had a negative effect on the solar field size, so they were not recommended for applications with high temperature due to high heat losses. Finally, it was impossible to operate the solar absorption chiller without employing any auxiliary energy source to provide the needed energy for the chiller during the day.

Shirazi et al. (2017) conducted a systematic simulation which was founded on multi-objective optimization. The authors modeled three proposed configurations; LiBr/ H_2O single effect powered by FPC, double effect powered by ETC, and absorption chillers with triple effect powered by PTC respectively. In addition to that, a cooling tower, and storage tanks were installed. In the first arrangement, a compression chiller was employed as a backup cooling system. However, a gas boiler was employed in the second and third layouts. By using TRNSYS and MATLAB, a multi-objective optimization model was developed and a genetic algorithm was used to minimize the total annual cost and the energy consumption. The second objective function included fixed investment, fuel cost, penalty cost due to CO_2 emissions and operating and maintenance cost. Six design parameters considered; area and slope of solar collectors, storage tank specific volume, nominal flow rate of a solar pump and set point temperature of collectors. The authors used a traditional decision-making method to select a final best solution from the pareto frontier of each layout. Also, the authors performed a sensitivity analysis to evaluate the impact of capital cost of components, annual interest rate and fuel cost on the optimal solutions. The optimization results showed that the double effect chiller system satisfied both objective functions, where the total cost of the system was between 0.7 to 0.9 million dollars/ year and decreased the energy consumption by 44.5-53.8% annually and CO_2 emissions by 49.1-58.2% compared to the conventional system. The selected system had a relatively high COP and non-concentrating collectors which were able to capture beam and diffuse radiations. These two factors resulted in having the lowest solar field size thus this improved the economics of the second layout.

3.2.2 Solar Electric System. The paper in this section are categorized according to the adopted modeling and solution approaches: the general approaches; the simulation modeling; and the mathematical modeling.

Simulation Modeling Approach:

Fong et al. (2010) carried out a comparison between five various types of solar thermal cooling systems and solar electrical cooling systems which included solar electric compression, and solar thermal absorption. These systems were developed to provide cooling for an office in Hong Kong. The solar electric compression system consisted of PV panels, power regulator, vapor compression chiller, and air handling unit (AHU). The PV panels were proposed to supply the electric chiller with the required electric power; however, when the supply was not sufficient, electrical power was drawn from the city grid using a power regulator. Also, the power regulator fed the excess power back to the grid. Therefore, this system was not a standalone system. The proposed systems were simulated in TRNSYS and their performance was assessed during the year. The assessment criteria were solar fraction, COP, solar thermal gain and primary energy consumption. The results demonstrated that the two cooling systems had the highest possible energy savings between 15.6% and 48.3% compared to traditional electric driven water-cooled system.

Hartmann et al. (2011) made an evaluation between two solar cooling systems; solar thermal and solar electric cooling system. The systems were proposed to provide space cooling for a small office in Europe. The first system consisted of a traditional compression chiller powered by solar PV panels connected to the grid and the other system consisted of an absorption chiller driven by FPC. The comparison was made to find the primary energy and cost savings to satisfy the demand for heating and cooling which were compared also to a conventional reference system composed of conventional compression chiller powered by the electricity grid. The two systems were simulated in TRNSYS program. The study results showed that the solar electric system achieved a better performance compared to the other system in terms of energy savings and economical aspects.

Eicker et al. (2014) performed an economic assessment of solar photovoltaic and solar thermal cooling systems through simulations based on energy savings for a building with 309.9 m^2 floor area. This paper had three different systems; the first system was the reference system consisted of a 30-50 kW compression chiller powered by grid electricity and had a 1500 L of cold-water TES tank. The second system was a PV cooling system composed of compression chiller and PV panel and the last system included a FPC or CPC, 5000 L solar storage tank, 25 kW absorption chiller and 1000 L cold water storage tank. The PV system was simulated in INSEL and FORTRAN while the thermal system was simulated in TRANSOL 3.0 and TRNSYS. The results showed that the PV cooling system covered half of the electricity demand. Hence, the relative savings in energy was around 50%. While in the solar thermal system, the relative savings in energy was around 30%.

Noro and Lazzarin (2014), conducted a comparison between solar electrical and thermal cooling systems performances. The systems were designed to operate under Mediterranean climatic conditions and to satisfy the cooling demand of a building with area of 230 m^2. The proposed systems were single or double effect LiBr/ H_2O coupled with ETC or PTC and water or air-cooled compression chiller coupled with PV mono-crystalline or amorphous silicon panels systems. The systems were modeled in TRNSYS program. The results indicated that the best performance in terms of the highest overall system efficiency was achieved by the solar LiBr/ H_2O double effect absorption chiller coupled with PTC where the COP of chiller observed to be 0.53. However, in terms of the collector surface area, the optimal system was achieved from both electric system and thermal system. Furthermore, the net present value of electric cooling systems was preferred over the conventional solutions and the discounted payback periods were all lesser than the economic analysis for water cooled chillers. Finally, a sensitivity analysis was conducted on the investment cost of the collectors, the solar ratio and the interest rate. The results of the analysis highlighted that the specific cost of the PV panels was by far lower than the thermal collectors. Moreover, the solar electric cooling system achieved better economic results in terms of NPW and DPB compared to the solar thermal cooling systems.

General Approaches:

Mokhtar et al. (2010) performed a performance evaluation on different solar cooling technologies. It included solar thermal cooling system and electric cooling system. The solar thermal cooling system composed of FPC and ETC, and single, double and triple effect absorption chiller with COP 0.7, 1.4, and 2.0, respectively. The solar electric cooling system composed of PV and compression chiller with COP of 4. The approach of this paper was based on evaluating each solar cooling technologies performance as a system by taking into consideration specific aspects such as cost, performance parameters, weather and cooling demands. The proposed approach assessed the techno-economic performance of the solar collector/ chiller system. The assessment process was done on 25 solar cooling technologies under Abu Dhabi climate. The analysis indicated the importance of storage size and solar load fraction in the design of the solar cooling system. Also, the study highlighted the significance of examining the relationship among demand for cooling and availability of solar resource. Nevertheless, the paper concluded that neglecting this relationship would lead to overestimating the capability of a solar cooling system with a range of 22% to 100% of the actual potential. Furthermore, the results of the paper showed that Frensel concentrators and thin film PV cells where the most economical options on smaller scales. While, the multi-crystalline PV panels with vapor compression chillers were the most efficient option in terms of overall efficiency.

Otanicar et al. (2012) conducted an economic and technical comparison between the available solar cooling systems which covered both electrical and thermal driven technologies. The comparison was based on initial cost of each technologies which included the solar electric and thermal systems future costs. Also, the comparison covered the environmental effects of the main parameters of the systems. The solar photovoltaic system was composed of PV modules, inverter, battery and compression cooling system. The solar thermal system was consisted of a solar collector, a TES tank, a thermal air conditioning unit and heat exchanger system. The results of the paper indicated that the cost of the solar electric system was highly reliant on the COP of the system when the PV prices remained at the current levels. However, when the prices were decreased, the effect of COP became neglectable. From the environmental perspective, the solar electric cooling system had a lower carbon dioxide per kWh emission compared to the thermal cooling technology and it was due to the large COP values related with the solar electric cooling. Also, the panels footprint of the PV system was between 24 and 48m^2 which depended on the COP of the system. However, the collector footprint of the solar thermal system was between 78 m^2 and 106 m^2. Hence, if solar thermal systems were to compete with the solar electric system, improvement related to COP and thermal collector cost need to be considered in the future.

Fumo et al. (2013) made a comparison between a solar thermal cooling system which included an absorption chiller powered by SC and a solar photovoltaic cooling system which included a vapor compression powered by PV panels. Both of the systems were compared with a conventional cooling system that was powered by the grid electricity. The paper highlighted that 7 m^2 of PV panels were required to produce 1 TR for solar electric cooling system. While, 12 m^2 of ETC were needed to generate 1 TR. This showed how the solar electric cooling system was more efficient than the solar thermal cooling system.

Eicker (2014), performed a comparison between the economic performances of solar PV cooling system with the solar single, double effect and triple effect absorption chiller system to provide space cooling to a big building in Egypt. The authors varied the chiller capacity and the volume of the storage tank to find the best size of each configuration. However, no data was provided on how the ideal size of these configurations was attained. Moreover, in the parametric study, the impact of varying one parameter at a time on the system performance was evaluated while the remaining parameters were fixed. The paper's result indicated that the PV cooling system had the lowest energy savings while the triple effect chiller had the highest energy ratio. Furthermore, the annual cost of cooling in all solar cooling configurations was higher than the conventional cooling system, because of the massively subsidized electricity prices in Egypt.

Porumb et al. (2016) assessed the idea of using solar cooling systems to supply cooling to a building in Romania. The authors made a comparison between two solar systems. The first system included an absorption chiller powered by solar collectors and the second system included a compression chiller powered by photovoltaic panels. The paper showed the method followed to find the efficiency of solar thermal collectors and solar PV collectors placed on the roof of the building tilted at 45^o. The authors studied the impact of the surrounding temperature and solar irradiance on the solar thermal collectors and PV panels. The results of the study indicated that the annual solar cooling fraction for thermal system was about 24.5% achieved at a lower initial investment and around 36.6% for the photovoltaic system, but at a higher initial investment.

Al-Ugla et al. (2016) compared three different air conditioning systems which were traditional vapor compression, solar lithium bromide-water and solar photovoltaic vapor compression. The latter system composed of PV panels, controller, inverter, battery and compression chiller. The system was proposed to satisfy the cooling load of 940 kWh. The comparison was made based on a thermo-economic analysis for a standard size building in KSA and had a constant cooling load during the daytime. The study used two economic approaches; payback period and net present value. The economical evaluation was carried out on the critical components sizes; vapor compression chiller and PV system. The size of the compression chiller was selected to receive the highest solar energy during noontime. Hence, it had a maximum power of 1500 kW to satisfy the peak cooling load. The PV system was proposed to have a power of 940 kW based on coefficient of performance of 2.5 for the compression chiller and daily sun hours around 4h/day. The cooling demand beyond the daytime hours was met from the electric battery storage. The results of the paper showed that the solar absorption chiller system was more economically compared to solar PV vapor compression chiller systems. Furthermore, the viability of two solar cooling technologies improved as the size of the building and the electricity rate increased.

Papoutsis et al. (2017) examined and studied three different solar cooling systems performances which were solar electrical, solar thermal and a hybrid solar electrical-thermal cooling system. The solar electrical system composed of PV panels coupled with a conventional compression chiller. This system was designed to serve Greece climate during the summer period. The system composed of PV panels, inverter, battery and the electrically driven chiller. The study results indicated that the solar electrical cooling system achieved the best performance using mono-Si PV panels with a maximum solar coefficient of performance of 0.47 and a maximum capacity of 22.2kW compared to the other solar cooling systems. The reason behind that was due to the relatively low temperature of May which enhanced the electrical chiller operations. So, the system performance was impacted by the COP of the chiller which also was affected by the surrounding temperature. Moreover, the mono-Si solar cooling system achieved the highest cooling energy produced in a day 235.07 kWh/ day in May. However, the lowest performance was achieved by a Si PV panel with a minimum solar COP of 0.3.

Bilgili (2011) investigated and analyzed the solar electric vapor compression system from May to September. The system was located in Turkey. The hourly cooling demand for the 23rd day of May to September were obtained by using climatic data like atmosphere temperature and average solar radiations. The proposed system was composed of PV panels and a compression chiller.The results of the analysis indicated that the coefficient of performance of the system during July was between 3.04 - 4.07. Also, it was noticed that the area of the PV panels increased as the evaporating temperature decreased. Therefore, the area was estimated to be 18.691 m^2 for the 23rd of July when the evaporating temperature was 10°C and it became around 38.65 m^2 when the evaporating temperature was -10°C. Finally, the cooling energy demand was covered by the electricity produced from the solar electric cooling system.

Mathematical Model Approach:

Abdollahi et al. (2013) conducted a multi-objective genetic algorithm optimization for a residential combined cooling, heating and power generation system. The proposed system had an extra electric boiler and auxiliary chiller powered by a grid to meet the peak demand. Therefore, this system was not a standalone system. The objective of this paper was to find the capacities of the components employed in the proposed system by maximizing exergetic efficiency, and minimizing economic and environmental impact of the system. The decision variables were the absorption chiller capacity, micro turbine power generation capacity, auxiliary boiler capacity, electrical chiller capacity and HRSG capacity. The genetic algorithm was used to obtain the pareto optimal solutions sets. A decision-making tool was used to select the final optimal solution from the set of solution attained from the pareto optimal frontier. Finally, a sensitivity analysis was performed on the optimal solution. The results of the analysis indicated that the proposed solution was highly sensitive to the changes of thermal efficiency of the auxiliary boiler, and the COP of the absorption chiller had a moderate impact on the thermo economic and the exergetic efficiency and must be maintained as high as possible to have an optimal solution.

Brandoni et al. (2015) studied and evaluated a hybrid residential photovoltaic micro combined cooling, heating, and power. Several criteria, parameters, and constraints were considered during the sizing phase such as energy prices, energy demand and electricity grid constraints. The system composed of an electrical solar device (PV panels), and micro- combined heat and power connected to a cooling chiller. The proposed system was dependent on the grid electricity for an additional power. Also, the system used a boiler, vapor compression chillers and a TES tanks as additional equipment. The PV panel was a poly crystalline module with an area of 1.47 m^2 and an efficiency of 14.6%. The chillers used in the system were compression chiller with coefficient of performance of 3 and absorption chiller with coefficient of performance of 0.7. The authors developed a linear programming to obtain the optimal size of the proposed system. The electricity demands could be fulfilled by solar PV panels, micro – CHP unit and grid electricity, but the PV panels had the priority. The objective function was to minimize the addition of the annual capital cost and operation costs of all equipment. The results of the paper indicated that coupling solar energy devices to the micro-CHP technology could reduce the energy consumptions of the application. Moreover, the algorithm showed that the TES tank was never selected, because of its high capital cost. However, only when CHP unit had a high electrical efficiency, then a TES was used to cover the electrical and thermal demand.

3.3 Summary and Research Contributions

The literature review is summarized in a table included in appendix G. The structure of the table consists of columns for authors of the paper, district energy system discussed, cooling technology utilized, optimization objectives considered, used optimization methods and the considered parameters.

Many papers exist on the design and operation optimization of DCS. However, there is a shortage of research that examines Solar Thermal Cooling system and Solar Electric Cooling System in the design and operation optimization stages which is a recommended topic to investigate. The available papers on solar thermal and electric cooling system are related to simulation and optimization of cooling systems using

TRNSYS program. To the best of our knowledge, there are almost no papers on developing mathematical models to simultaneously optimize the design and operation of solar thermal and eclectic cooling system. Therefore, this research contributes to developing mathematical models for the complete solar thermal and electric cooling system separately and in solving the Mixed – Integer Linear Programming (MILP) models with the aim of finding the best design of solar thermal and electric cooling system separately. The outcome of this research will focus on the global view of solar thermal and electric cooling system to attain the best arrangement that will have all the components of the system and their correlation concurrently. Moreover, this research contributes to studying the optimization of the solar thermal and electric cooling system on hourly basis over a period of a year (8784 hr/year). All collected data on the models' parameters are actual data. They are collected from valid and reliable resources to obtain accurate and realistic results.

Chapter 4: Conventional Cooling System Model

This chapter is divided into seven main sections which are problem scope, system's operation, model formulation, assumptions and observations, mathematical model, numerical results and discussion and sensitivity analysis. The first section identifies the model's scope in details. The second section explains how the proposed model would operate in real-life. The third section shows and explains how the proposed model is formulated. The fourth section states the assumptions and observations made during the model formulation and solving. The fifth section demonstrates the parameters, decision variables, the objective function and the constraints of the mathematical model. The sixth section shows the different scenarios along with their design cases considered for optimizing the proposed model. Also, this section discusses the results obtained from the optimized models. Lastly, the seventh section carries out a sensitivity analysis on the parameters of the model.

4.1 Problem Scope

The aim is to obtain the conventional district cooling system optimal design. This includes finding the optimal configuration for the system components with a target to obtain the minimum annual investment and annual operational cost while obtaining the best possible efficiency level.

I. The optimal solution will specify the following:

II. The compression chiller, and thermal energy storage (if any) optimal capacities

III. The chilled water quantities to be stored and produced at each point of time

The objective is to minimize the addition annual of the fixed cost of installing a compression chiller and a chilled TES tank along with the annual variable cost of producing cold water from the compression chiller, annual variable cost of storing cold water at TES tank and annual variable cost of supplying electricity from the main grid. Moreover, the scope of the research is studying and analyzing the system over 8784 hours/year to gain a better understanding on how the system would operate and behave during the different months of the year. Hence, the selection of the optimal system would be based on the cooling demand observed throughout the year.

4.2 Operation of System

The proposed conventional district cooling system is composed of two main components which are a compression chiller and a cold-water thermal energy storage tank. The below figure (7) illustrates the assembly of the conventional district cooling system.

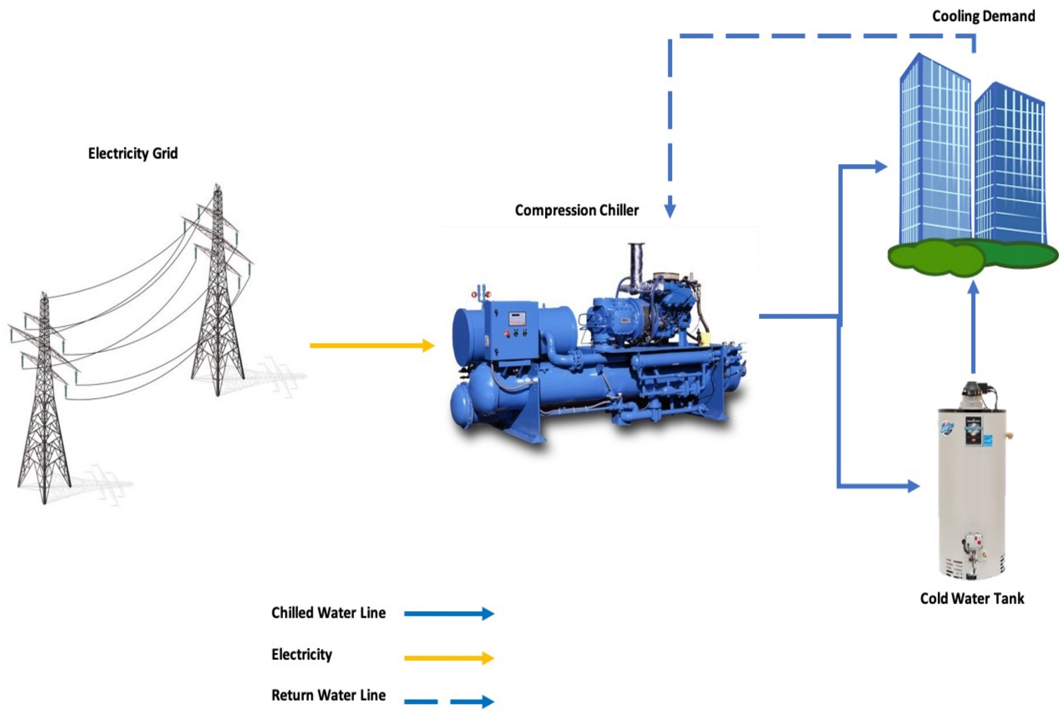

Figure 7: Conventional cooling system layout

The operation of the proposed conventional cooling system starts with the main grid supplying the required electricity to the compression chiller. So, the chiller will be powered by the electricity and starts to produce cold water. The chiller will either produce the required chilled water to meet the cooling demand or will produce more chilled water than it is required. This additional chilled water will be stored in the cold-water TES tank to be used at later periods during the day to satisfy the cooling demand. The COP of the compression chiller is considered during the operation of the system.

4.3 Model Formulation

Figure (8) shows the configuration of the proposed conventional district cooling system. It highlights the energy flow in the form of cold water among the system components. The amount of electricity delivered from the main grid to the chiller is denoted by ($\boldsymbol{B_t}$). The total quantity of energy the chiller consumed from the electricity grid is given by ($\boldsymbol{F_t^{In}}$). The cooling energy generated by the chiller ($\boldsymbol{F_t^{o}}$) is distributed in such way to directly meet the demand of the customer ($\boldsymbol{S_t^{CW}}$), or the cold water is stored into the cold water TES tank ($\boldsymbol{E_t}$), in case of excess cooling energy production to meet the customer cooling demand at later periods ($\boldsymbol{D_t^{CWT}}$).

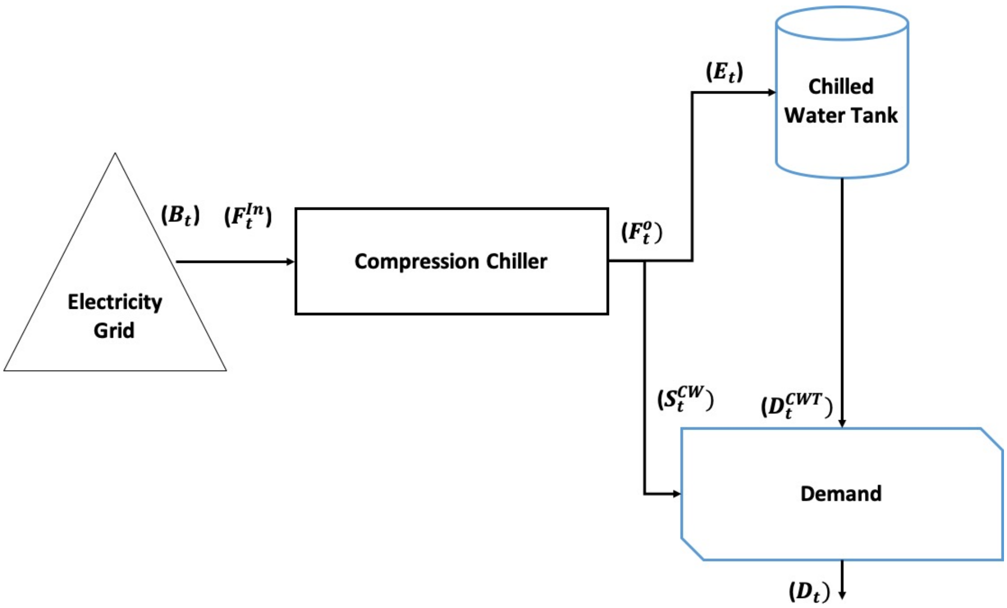

Figure 8: Conventional cooling system model formulation

4.4 Assumptions and Observations

The following assumptions considered during the model formulation:

- The cooling demands are known in advance and deterministic
- TES tanks function with full efficiency where no losses would happen
- The system operates in a steady state
- The system's transient state is not considered

The observations made during the model formulation:

- The peak cooling hours occur from 1 pm to 4 pm according to our generated cooling demand data

4.5. Mathematical Model

This section contains the sets, parameters, decision variables, objective functions and constraints included in the proposed mathematical model.

1. Sets

The below table (6) shows the sets and indices used in the model formulation

Table 6: The Set of Mathematical Model

Indices	*Definition*
T	*: Set of time periods, indexed by t.*
K	*: Set of chiller capacities, indexed by k.*
H	*: Set chilled water TES tank capacities, indexed by h.*

2. Parameters

The below table (7) shows the parameters used in the model formulation.

Table 7: The Parameters of Mathematical Model

Parameters	*Definition*
$\boldsymbol{FC_k^{Ch}}$	*: Fixed cost of a chiller installed of capacity,* $\forall k \in K$.
$\boldsymbol{FC_h^{CW}}$	*: Fixed cost of a cold-water TES tank installed of capacity,* $\forall h \in H$.
$\boldsymbol{VC_t^{Ch}}$	*: Variable cost per unit of producing chilled water at a chiller in a period,* $\forall t \in T$.
$\boldsymbol{VC_t^{Chsto}}$	*: Variable cost per unit of storing cold water at a cold-water TES tank in a period,* $\forall t \in T$.
$\boldsymbol{VC_t^{Gr}}$	*: Variable cost per unit of supplying electricity from the main grid in a period,* $\forall t \in T$.
$\boldsymbol{Q_k}$	*:* k^{th} *capacity of a chiller given in KW,* $\forall k \in K$.
$\boldsymbol{COP_k}$	*: Coefficient of performance of chiller of* k^{th} *capacity,* $\forall k \in K$.
$\boldsymbol{D_h}$	*:* h^{th} *capacity of a cold-water TES tank given in KWh,* $\forall h \in H$.
$\boldsymbol{D_t}$	*: Quantity of cooling demand of a customer in a period, given in KW,* $t \in T$.
$\boldsymbol{\tau}$	: The duration of time periods, given in hour (h).

3. Decision Variables

The below table (8) shows the decision variables used in the model formulation

Table 8: The Decision Variables of Mathematical Models

Decision Variables	*Definition*
$\boldsymbol{y_k}$	*: Binary variable that will take value of 1 if a chiller having capacity* $Q_{\boldsymbol{k}}$ *is installed, k∈ K.*
$\boldsymbol{g_h}$	*: Binary variable that will take value 1 if a cold-water storage tank having capacity of* $D_{\boldsymbol{h}}$ *is installed, h∈ H.*
$\boldsymbol{F_{kt}^{In}}$	*: Quantity of power consumed by a chiller k∈ K in a period t∈ T, given in KW*
$\boldsymbol{F_t^o}$	*: Quantity of cooling produced by a chiller in a period t∈ T, given in KW.*
$\boldsymbol{F_t^{In}}$	*: Quantity of power consumed by a chiller in a period t∈ T, given in KW.*
$\boldsymbol{S_t^{CW}}$	*: Quantity of cooling consumption of a customer satisfied from a chiller in a period t∈ T, given in KW.*
$\boldsymbol{I_t^{CW}}$	*: Storage level of stored cooling energy at storage tank at the end of a period t∈ T, given in KWh.*
$\boldsymbol{E_t}$	*: Quantity of cooling production from a chiller, supplied to cold water storage tank in a period t∈ T given in KW.*
$\boldsymbol{D_t^{CWT}}$	*: Quantity of cooling consumption of a customer, satisfied from a cold-water storage tank in a period t∈ T given in KW.*
$\boldsymbol{B_t}$	*: Quantity of power electricity supplied by the main grid in a period t∈ T, given in KW.*

4. Objective Function

The objective function (1) minimizes the addition annual of the fixed cost of installing a compression chiller and a chilled water thermal energy storage tank along with the annual variable cost of producing cold water from the compression chiller, annual variable cost of storing cold water at thermal energy storage tank and annual variable cost of supplying electricity from the main grid. The present value of the investment cost of the components is multiplied by a ratio to convert it to an annual value. The ratio has two important parameters to consider, the interest rate and the life cycle of a component. In this research, all the components are assumed to have the same interest rate and life cycle. Hence, the fixed costs of all components are multiplied by the same ratio.

Minimize $\frac{i*(i+1)^n}{(1+i)^n-1} * [\sum_{k\in K} FC_k^{Ch} y_k + \sum_{t\in T} FC_h^{CW} g_h] + \sum_{t\in T} VC_t^{Ch} F_t^o + \sum_{t\in T} VC_t^{Chsto} I_t^{CW} + \sum_{t\in T} VC_i^{Grid} B_t$ (1)

Where $\boldsymbol{i}$:interest rate = 8% and $\boldsymbol{n}$: life cycle = 20 years

5. Constraints

5.1 Existence Constraints

$\sum_{k\in K} y_k = 1$,(2)

Constraint (2) enforces the installation of only one chiller

$\sum_{h\in H} g_h \leq 1$, (3)

Constraint (3) enforces that the chilled water TES tank will be assigned with only one capacity if it is installed

5.2 Capacity Constraints

$F_t^o \leq \sum_{k\in K} Q_k y_k, \forall \boldsymbol{t} \in \boldsymbol{T}$,(5)

Constraint (5) ensures that the production of cooling does not go beyond the installed chiller capacity

$I_t^{CW} \leq \sum_{h \in H} D_h g_h, \forall \boldsymbol{t} \in \boldsymbol{T}$, (6)

Constraint (6) ensures that the amount of cold-water storage level does not go beyond the capacity of the installed tank

$F_t^o = \sum_{k \epsilon K} COP_k \, F_t^{In} y_k, \forall \boldsymbol{t} \in \boldsymbol{T}$, (7)

Constraint (7) introduces the chiller's COP. However, it needs to be linearized. This is achieved as follows:

$0 \leq F_{kt}^{In} \leq My_k, \forall t \in T, \forall k \in K$ (7a)

$\sum_{k \epsilon K} F_{kt}^{In} = F_t^{In}, \forall t \in T$, (7b)

$F_t^o = \sum_{k \epsilon K} COP_k \, F_{kt}^{In}, \forall t \in T$, (7c)

$F_{kt}^{In} \geq F_t^{In} - ((1 - y_k)\, M) \; \forall t \in T, \forall k \in K$(7d)

M: Is a very big number M

5.3 Balance Constraints

$I_{t-1}^{CW} + \tau E_t = I_t^{CW} + \tau D_\tau^{CWT}, \forall t \in T$, (8)

Constraint (8) imposes the energy balance constraint for the cold-water storage tank

5.4 Supply Demand Constraints

$S_t^{CW} + D_t^{CWT} = D_t, \forall t \in T$,(9)

Constraint (9) enforces that customer cooling demand could be satisfied by cold water storage tank or chiller.

$B_t = F_t^{In}, \forall t \in T$, (10)

Constraint (10) enforces that chiller demand of electricity is satisfied by main grid

$S_t^{CW} + E_t = F_t^o, \forall t \in T$,(11)

Constraint (11) enforces that chiller's cooling production could be stored into cold water storage tank or directly pumped to meet customer demand

5.5 Non-negativity and integrality Constraints

$y_k, g_h \in \{0,1\}$ k∈ K; h∈H; (12)

$x, F_t^o, F_t^{In}, S_t^{CW}, L_t, L_t^c, I_t^{CW}, E_t, D_t^{CWT}, B_t, F_{kt}^{In} \geq 0$, t∈T (13)

4.6 Experimentation and Numerical Results

Four different scenarios are considered in the experiments that represent very high cooling demand, high cooling demand, medium cooling demand and low cooling demand scenarios. For that purpose, the following applications are selected, a health service center located at Mekkah, KSA represented the low cooling demand scenario. Texas A&M University at Qatar represented medium cooling demand scenario. Lusail District located at Qatar represented the high cooling demand scenario. The campus of Qatar University represented the very high cooling demand scenario.

A. Low Cooling Demand

A health service center located in Gabal Al Sharashf region at Mekkah in KSA is selected to represent the low cooling demand scenario. The health service center has a construction area of 12,410 m^2 and one floor. The daily cooling demand of this center is around 1655 TR which is equivalent to 5820.3 kW according to Mohamed and Almarshadi (2017). Our generated cooling demand pattern is scaled down where the maximum cooling demand of our pattern is equal to the cooling demand of the center which is 5820.3 kW.

The below table (9) shows the obtained results from the design case where all the components are presented in the system.

Table 9: Results of Main Design Case of Health Center

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	5,300kW	903,409	6.7
Chilled Water Thermal Energy Storage Tank (PTES Type)	63,000 kWh	24,948	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	1,303,429 (94,555 + 1,208,874)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 326,512 iterations and using CPLEX 12.6.3 Solver, solving time is 4822.02 seconds, total time is 4852.20 seconds and the memory used is 1466.4 Mb
- There is cold water TES tank installed in the system with a capacity of 63,000 kWh and a cost of 24,948$
- The annual investment cost of the components represents 7% of the annual total cost while the annual operational cost of the components represents 93% of the annual total cost of the system
- The annual investment cost of compression chiller represents 97% of annual total investment cost which is equivalent to 92,014$

- The annual investment cost of cold-water tank represents 3% of annual total investment cost which is equivalent to 2,541$
- The annual operational cost to produce cold water from the compression chiller represents 87% of the annual total operational cost which is around 1,048,739$
- The annual operational cost to supply electricity from the main grid to the chiller represents 13% of annual total operational cost which is equivalent to 156,528$

B. Medium Cooling Demand

Texas A&M University at Qatar is selected to represent the medium cooling demand scenario. The University has an academic section with an area of 30,800 m^2 and consists of 4 floors where the height from one floor to other is 5 m. The outer area consists of labs and classrooms while the inner area consists of student lounge located on the first floor, computer labs located on the second floors and a library located on the third floor. The building's operation hours are from 8:00 am to 5:00 pm, from Sunday to Thursday where the building is occupied mainly by students. The number of students enrolled at TAMUQ is around 450 students and there are around 150 faculties and staffs which make the total occupancy of the academic section is around 600 people. Although there are classes offered in the summer, the number of students decreases significantly in the mid of May when the spring semester ends. Moreover, there are several breaks offered during the semester where both the student and non-student population decreases such as Eid Al-Fitr and Eid- Al-Adha holiday which result in week-long breaks. Also, there is a semester break that occurs from mid of December to mid of January and there is a week- long spring break in beginning of March.

The monthly chilled water consumption data of the University was measured by installing chilled water meters at different location around the building. From their collected data, the below figure (9) was established. The figure shows the maximum cooling demand is occurring in August with around 12,500 GJ which is equivalent to 3,472,222 kWh and that's equal to 3,472,222/ (31*9) = 12,445 kW according to Bible (2011). Our generated cooling demand pattern is scaled down where the maximum cooling demand of our pattern is equal to the cooling demand of the center which is 12,445 kW.

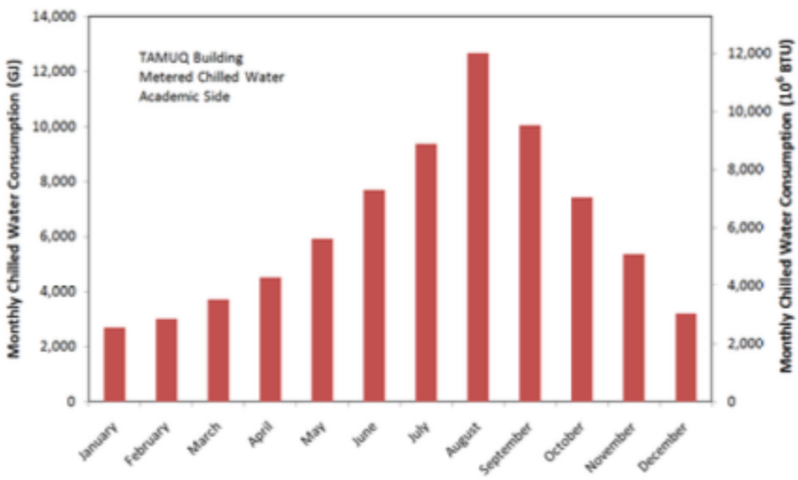

Figure 9: Monthly chilled water consumption for TAMUQ

The below table (10) shows the obtained results from the main design case where all the components are presented in the system.

Table 10: Results of Main Design Case of Texas A&M University at Qatar

Component	Capacity	Investment Cost	Efficiency
Compression Chiller (Centrifugal)	12,300kW	$2,096,591	6.7
Chilled Water TES (PTES Type)	63,000 kWh	$24,948	N/A
Annual Total Cost (Annual Investment & Operational Cost)		$2,791,014 (216,084 + 2,574,930)	

The main observations of the obtained results are:

- The results obtained from AIMMS software after 49,469 iterations and using CPLEX 12.6.3 Solver, solving time is 454.25 seconds, total time is 464.86 seconds and the memory used is 1500.7 Mb
- There is a chilled water TES tank installed in the system with a capacity of 63,000 kWh and a cost of 24,948$
- The annual investment cost of the components represents 8% of the annual total cost while the annual operational cost of the components represents 92% of the annual total cost of the system
- The annual investment cost of compression chiller represents 99% of annual total investment cost which is equivalent to 213,542$
- The annual investment cost of cold-water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The annual operational cost to produce cold water from the compression chiller represents 87% of the annual total operational cost which is around 2,240,489$
- The annual operational cost to supply electricity from the main grid to the chiller represents 13% of the annual total operational cost which is equivalent to 334,401$

C. High Cooling Demand

Lusail Marina District Cooling system at Qatar is selected to represent the high cooling demand. Lusail city is the largest single development created by Qatari Diar. It symbolizes Qatar's National Vision 2030 in the area of development of the real estate. The city has a water taxi transportation system, pedestrian, cycle network and rail network. Lusail city extends over 38 km^2 and more than 200,000 residents will live in the city and more than 170,000 people will work in the various districts of the city.

Also, more than 80,000 people are predicted to visit the entertainment and recreation facilities at the city. Lusail city will have 19 districts of residential, commercial, hospitality and retail shops. Also, the city will have schools, mosques, sport, entertainment, shopping centers, and medical facilities. The cooling demand of Lusail District is estimated to be around 5000 TR currently which is equivalent to 17,590 kW and to be extended to 300,000 TR by the end of 2022 ("Qatar District Cooling Industry Seeks to Build on Growth," 2018). Hence, the current maximum cooling demand is 17,600 kW. Our generated cooling demand pattern is scaled down where the maximum cooling demand of our pattern is equal to the cooling demand of the city which is 17,600 kW.

The below table (11) shows the obtained results from the main design case where all the components are presented in the system.

Table 11: Results of Main Design Case of Lusail District

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	19,350 kW	3,298,295	6.7
Chilled Water Thermal Energy Storage Tank (PTES Type)	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	3,982,778$ (335,939 + 3,646,840)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 14,646 iterations and using CPLEX 12.6.3 Solver, solving time is 170.20 seconds, total time is 176.69 seconds and the memory used is 1449.1 Mb
- There is no chilled water TES tank installed in the system
- The annual investment cost of the components represents 8% of the annual total cost while the annual operational cost of the components represents 92% of the annual total cost of the system
- The annual investment cost of compression chiller represents 100% of total investment cost which is equivalent to 335,939$
- The annual operational cost to produce cold water from the compression chiller represents 87% from the total operating cost which is equivalent to 3,173,224$
- The annual operational cost to supply electricity from the main grid to the chiller represents 13% which is equivalent to 473,616$

D. Very High Cooling Demand

Qatar University's District Cooling Plant at Qatar is selected to represent the very high cooling demand scenario. Qatar University was founded in 1973 with one college and had 150 students. Now days, Qatar University has around nine colleges with more than 20,000 students and 40,000 alumni. Also, Qatar University has around 2,000 faculties who teach at the campus. Besides that, Qatar University has student activities centers, sport complex and event buildings, food courts and libraries. The operation hours of the university are from 8 am to 8 pm, from Sunday to Thursday where Friday and Saturday are weekends. Qatar University extends over 8.1 km^2. Although there are classes offered in the summer, the number of students decreases significantly in the mid of May when the spring semester ends. Moreover, there are several breaks offered during the semester where both the student and non-student population decreases such as Eid Al-Fitr and Eid- Al-Adha holiday which result in week-long breaks. Also, there is a semester break that occurs from mid of December to mid of January and there is a week- long spring break in beginning of March. The cooling demand is estimated to be 6,000 TR is equivalent to 21,101 kW according to Takyeef Electromechanical Executed Projects Overview (n.d.).

The below table (12) shows the obtained results from the main design case where all the components are presented in the system.

Table 12: Results of Main Design of QU District Cooling Plant

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	19,350 kW	3,298,295	6.7
Chilled Water Thermal Energy Storage Tank (PTES Type)	63,000 kWh	24,948	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	4,704,371$ (338,479 + 4,365,892)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 29,662 iterations and using

CPLEX 12.6.3 Solver, solving time is 186.48 seconds, total time is 192.83 seconds and the memory used is 1531.8 Mb

- There is a chilled water TES tank with a capacity of 63,000kWh and a cost of 24,948$ installed in the system
- The annual investment cost of the components represents 7% of the annual total cost while the annual operational cost of the components represents 93% of the annual total cost of the system
- The annual investment cost of compression chiller represents 99% of annual total investment cost which is equivalent to 335,939$
- The annual investment cost of cold-water tank represents 1% of total annual investment cost which is equivalent 2,541$
- The annual operational cost to produce cold water from the compression chiller represents 87% of the total annual operational cost which is around 3,791,596$
- The annual operational cost to supply electricity from the main grid to the chiller represents 13% of the total annual operational cost which is equivalent to 565,910$

To conclude this section, we can notice from the results generated that design case 3 representing the high cooling demand scenario is the only design case where no chilled water TES tank is installed in the system. The reason is a compression chiller with a high capacity exceeds the maximum cooling demand of the application installed in the system. Hence, it eliminates the need to install a chilled water tank in the system. Another observation to highlight is the type and the capacity of chilled water thermal energy storage installed for the other design cases is the same which is PTES type with a capacity of 63,000 kWh.

4.7 Sensitivity Analysis

The sensitivity analysis is performed on the fourth scenario which is the very high cooling demand. The analysis is carried out on the electricity prices which are reflected on the following model parameters, the variable cost per unit of producing chilled water from the compression chiller, the variable cost per unit of storing chilled water in the chilled water thermal energy storage tank and the variable cost of supplying electricity from the main grid to the chiller. Currently, the price of the electricity is around 0.055 $/kW according to kahramma website. The price of the electricity is varied from this base value to a maximum value of 20% of the base value. The electricity prices always increase and never decrease. The purpose of this analysis is to examine and measure how the changes of these three parameters are sensitive to the optimal solution. The sensitivity analysis is performed on the annual total system cost. The graph is generated using the below equation:

$$PTCD = \frac{New\ Cost - Base\ Cost}{Base\ Cost}\ x\ 100$$

The below table (13) shows the parameters studied during the sensitivity analysis along with the maximum values the base value varied at using the incremental values.

Table 13: Parameters Studied During Sensitivity Analysis

Parameter	Base Value	Maximum Value	Incremental Value
Variable cost per unit of producing chilled water	0.055	0.066	0.00055
Variable cost per unit of storing chilled water	0.055	0.066	0.00055
Variable cost of supplying electricity from main grid to chiller	0.055	0.066	0.00055

The below graph (10) shows the relationship between varying the prices of electricity and the annual total cost of the system. Increasing the prices of the electricity will increase the annual total system cost. Hence, it is a linear relationship between the electricity prices and the annual total system cost with a $R^2 = 1$. If the electricity prices increase by 20%, the annual total system cost will increase by 18.364%. To view whether this change in the annual total system cost is significant or not, the changes will be represented as numbers instead of percentages. The optimal solution has an annual total system cost of 4,704,371$, when the electricity prices increase by 20%, the new electricity price will be 0.066$, the annual total system cost will increase by 873,178$. So, the new annual total system cost will be around 5,577,549$. To conclude, when the electricity price is varied between the base and the maximum value which is between 0.055$ and 0.066$, the annual total system cost changes between 4,704,371$ and 5,577,549$.

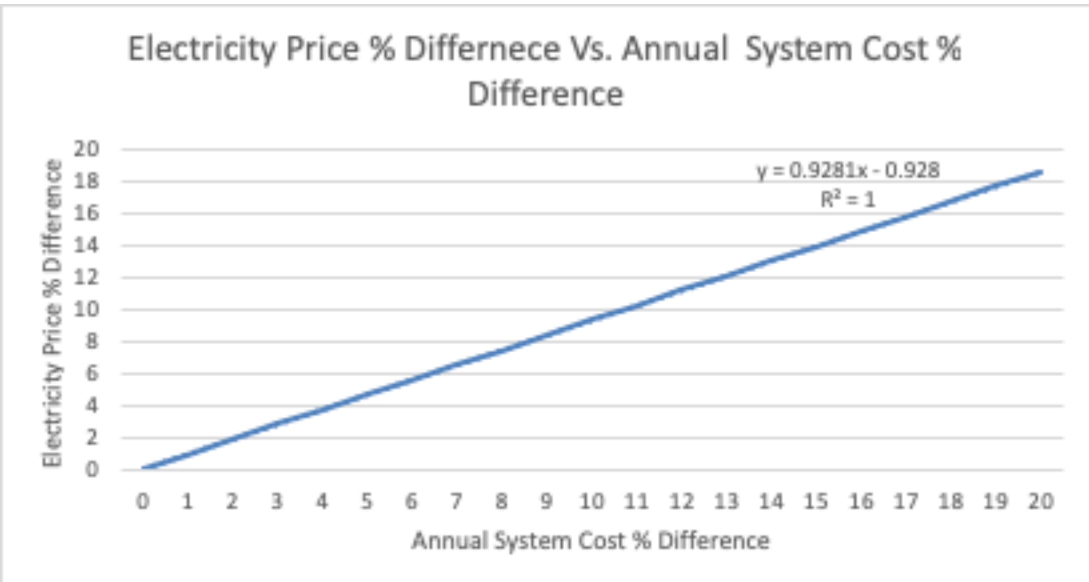

Figure 10: Electricity prices sensitivity analysis

Chapter 5: Solar Thermal Cooling System Model

This chapter is divided into seven main sections which are components selection, problem scope, system's operation, model formulation, assumptions and observations, mathematical model and numerical results and discussion. The first section aims to describe the important factors considered during components selection. The second section identifies the model's scope in details. The third section explains how the proposed model would operate in real-life. The fourth section shows and explains how the proposed model is formulated. The fifth section states the assumptions and observations made during the model formulation and solving. The sixth section demonstrates the parameters, decision variables, the objective function and the constraints of the mathematical model. Lastly, the seventh section shows the different scenarios along with their design cases considered for optimizing the proposed model. Also, this section discusses the results obtained from the optimized models and carries out a sensitivity analysis on the parameters of the model.

5.1 Component Selection

The components selection of the proposed system relays mainly on two important factors. The first factor is the absorption chiller's size and type to satisfy the required demand for cooling. The other factor is the employment of the suitable type of solar collectors which should have the ability to match the selected absorption chiller, and the needed solar collectors' area to offer the required thermal energy to power the absorption chiller. Nevertheless, incorporating the TES tank into the system could have a crucial part in the selection of the absorption chiller size, the solar collector area and impacting the global system performance. Also, integrating an auxiliary boiler with the proper efficiency and capacity showed an impact on the performance and reliability of the system.

The temperature consistency between the components of the system should be maintained to operate as required since the solar thermal cooling system is powered by the thermal energy. Therefore, the temperature of heat supplied by the solar collector to power the absorption chiller should be sustained at certain levels to enable the chiller's COP to operate at a satisfactory range. The system performance is impacted by the performance of each component since all components are connected together.

5.2 Problem Scope

This research aims to find the solar assisted district cooling system optimal design. This includes finding the optimal configuration for the system components with a target to obtain the minimum annual investment and annual operational cost while attaining the best possible efficiency level. The optimal solution will specify the following:

I. The solar collector's optimal area

II. The absorption chiller, auxiliary boiler (if any) and thermal energy storage (if any) optimal capacities

III. The chilled water and hot water quantities that will be produced and stored at each point of time

The objective is to minimize the addition of the annual fixed cost of installing an absorption chiller, solar collectors, a chilled and hot water TES tank and an auxiliary boiler along with the annual variable cost of producing hot and cold water from the absorption chiller and auxiliary boiler and annual variable cost of storing hot and cold water at TES tanks.

The idea of integrating an auxiliary boiler into the system is recommended to enhance the efficiency of it. The incorporation of a sustainable source of energy as the auxiliary system would be a good decision that will help reduce greenhouse gases and achieve high levels of efficiencies. Nevertheless, such incorporation is not included in the research scope, where a fuel boiler is employed in the system.

Moreover, the scope of the research is studying and analyzing the system over 8784 hours/year to gain a better understanding on how the system would operate and behave during different months of the year. Hence, the selection of the optimal system would be based on the cooling demand observed throughout the year.

5.3 Operation of System

The proposed solar-assisted district cooling system is made from multiple components including solar collectors, an absorption chiller, an auxiliary boiler, a hot water thermal energy storage tank and a cold-water thermal energy storage tank. The below figure (11) shows the layout of the system.

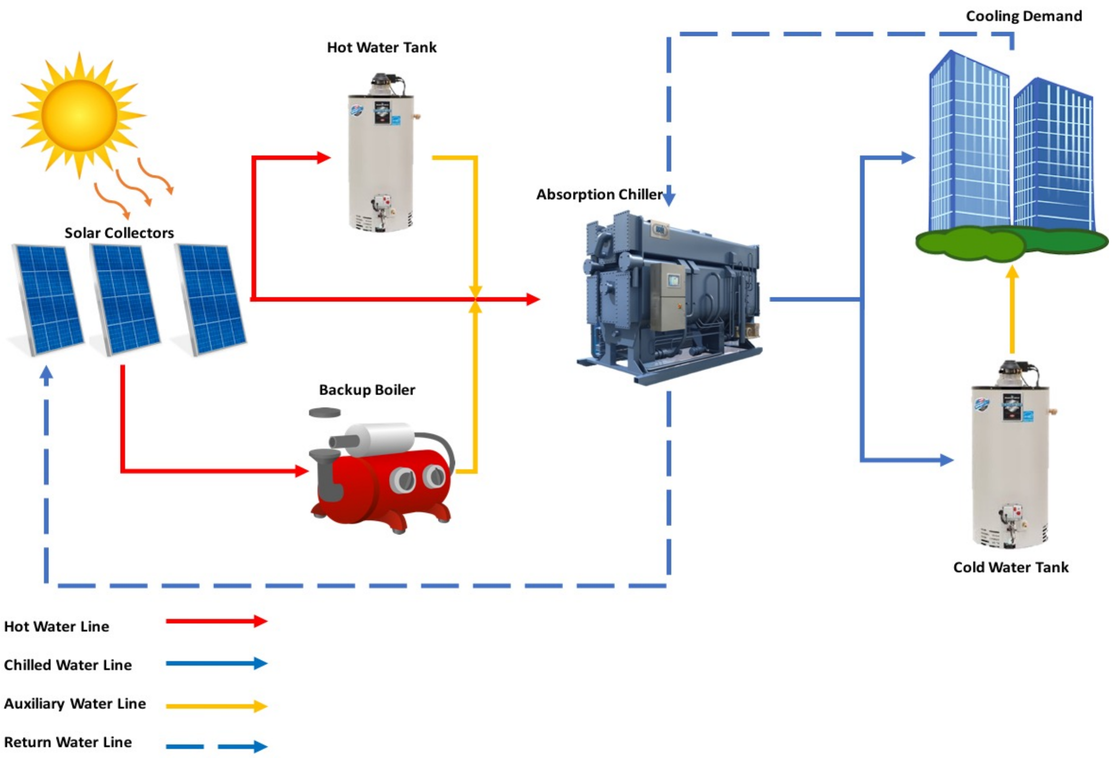

Figure 11: Proposed solar thermal cooling system layout

The operation of the proposed solar assisted system starts with the solar collectors absorbs the thermal energy that is collected through the solar irradiance. As a result, the water flowing through the solar collector will heat up. If the hot water is at the needed temperature to drive the absorption chiller, then the hot water will be fed directly to the absorption chiller. However, in case if the hot water is not at the required temperature, then it will be fed to the auxiliary boiler where the boiler will heat up the water to the required temperature and then it will be fed to the absorption chiller. In case of high solar irradiance and the chiller is functioning with the needed thermal energy and it is less than the thermal energy generated by solar collectors, then the additional thermal energy will be stored at the hot water TES tank to be used later in scarce sun radiation periods. Once the hot water with the needed temperature is pumped into the chiller, then the chiller will either produce the required chilled water to satisfy the cooling demand directly or will produce more chilled water than it is required. This additional cold water will be stored in the cold-water TES tank to be used at later periods during the day to meet the cooling demand.

An important point to be highlighted during the operation of the system is that, thesolar collector efficiency impacts the absorption chiller performance. A high solar collector efficiency will allow the water flowing through it to be heated at the required temperature to operate the absorption chiller with a high COP. On the other hand, a low solar collector efficiency will make the water temperature to drop below the required temperature needed to drive the chiller. Thus, it will prevent the absorption chiller from operating properly and producing the required chilled water.

5.4 Model Formulation

The below figure (12) displays the configuration of the proposed solar thermal cooling system. It highlights the energy flow in the form of hot and cold water among the system components. It specifically shows the movement of hot water generated by the solar collector ($\boldsymbol{L_t}$) is directly fed into the absorption chiller ($\boldsymbol{L_{ct}}$) or stored in the hot water TES tank ($\boldsymbol{M_t}$) in case of excess heat production for later consumption ($\boldsymbol{D_t^{HWT}}$). However, if these two sources fail to satisfy the demand for the hot water, then the auxiliary boiler will operate to provide hot water ($\boldsymbol{B_t}$) to satisfy the demand of the chiller. The total amount of energy consumed by the chiller is given by ($\boldsymbol{F_t^{In}}$). The cooling energy generated by the chiller ($\boldsymbol{F_t^{o}}$) is distributed to meet the customer demand directly ($\boldsymbol{S_t^{CW}}$), or it is stored in the chilled water TES tank ($\boldsymbol{E_t}$), in case of excess cooling energy production to meet the customer cooling demand at later periods ($\boldsymbol{D_t^{CWT}}$).

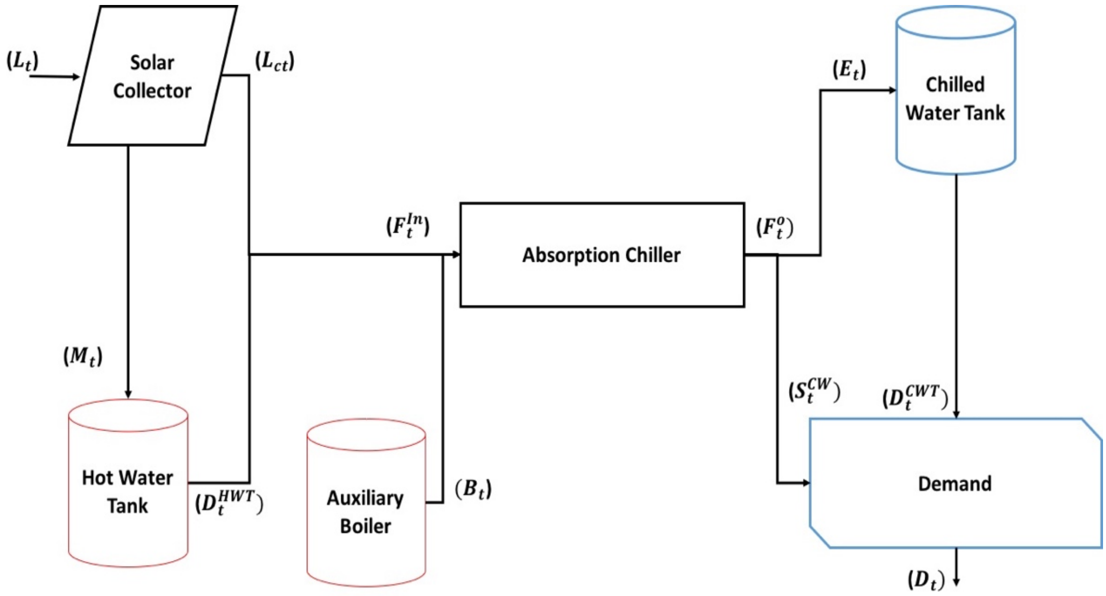

Figure 12: Solar thermal cooling system model formulation

5.5 Assumptions and Observations

The following assumptions considered during the model formulation:

- The cooling demands are known in advance and deterministic
- TES tanks function with full efficiency and no losses would happen

- The solar collector efficiency is known in advance and constant
- The system operates in a steady state
- The system's transient state is not considered

The observations made during the model formulation:

- The peak cooling hours occur from 1 pm to 4 pm according to our generated cooling demand data.

5.6 Mathematical Model

This section contains the sets, parameters, decision variables, objective function and constraints included in the proposed mathematical model.

1. Sets

The below table (14) shows the sets and indices used in the model formulation

Table 14: The Sets of The Mathematical Model

Indices	*Definition*
T	*: Set of time periods, indexed by t.*
K	*: Set of chiller capacities, indexed by k.*
H	*: Set of chilled water TES tank capacity, indexed by h.*
J	*: Set of hot water TES tank capacity, indexed by j.*
Q	*: Set of auxiliary boiler capacities, indexed by q.*

2. Parameters

The below table (15) shows the parameters used in the model formulation

Table 15: The Parameters of The Mathematical Model

Parameters	*Definition*
$\boldsymbol{FC_k^{Ch}}$	*: Fixed cost of a chiller installed of capacity, ∀k∈ K.*
$\boldsymbol{F^{SC}}$	*: Fixed cost of a unit area of solar collector installed*
$\boldsymbol{FC_h^{CW}}$	*: Fixed cost of a cold-water storage tank installed of capacity, ∀h ∈ H.*
$\boldsymbol{FC_j^{HW}}$	*: Fixed cost of a hot water storage tank installed of capacity,∀ j ∈ J.*
$\boldsymbol{FC_q^{HW}}$	*: Fixed cost of an auxiliary boiler installed of capacity, ∀q ∈ Q.*
$\boldsymbol{VC_t^{Ch}}$	*: Variable cost per unit of producing cold water at a chiller in a period, ∀t ∈ T.*
$\boldsymbol{VC_t^{Hsto}}$	*: Variable cost per unit of storing hot water at a storage tank in a period, ∀t ∈ T.*
$\boldsymbol{VC_t^{Chsto}}$	*: Variable cost per unit of storing cold water at a storage tank in a period, ∀t ∈ T.*
$\boldsymbol{VC_t^{HW}}$	*: Variable cost per unit of producing hot water at an auxiliary boiler in a period, ∀t ∈ T.*
$\boldsymbol{G_t}$	*: Global solar irradiance in a period given in W/m^2, ∀t ∈ T.*
$\boldsymbol{n_{sc}}$	*: Efficiency of the solar collector.*
$\boldsymbol{Q_k}$	*: k^{th} capacity of a chiller given in KW, ∀ k∈ K.*
$\boldsymbol{COP_k}$	*: Coefficient of performance of a chiller of k^{th} capacity, ∀ k∈ K.*
$\boldsymbol{D_h}$	*: h^{th} capacity of a cold-water storage tank given in KWh, ∀ h∈ H.*
$\boldsymbol{R_j}$	*: j^{th} capacity of a hot water storage tank given in KWh, ∀ j∈ J.*
$\boldsymbol{L_q}$	*:q^{th} capacity of an auxiliary boiler given in KW, ∀ q∈ Q.*
$\boldsymbol{D_t}$	*: Quantity of customer cooling demand in period, given in KW, t∈ T.*

Parameters	Definition
$\boldsymbol{EFF_q}$	: *Efficiency of an auxiliary boiler of q^{th} capacity, ∀ q∈ Q.*
$\boldsymbol{A}$	: *Maximum installed area of solar collectors, given in m^2.*
$\boldsymbol{\tau}$	: *The duration of time periods, given in hour (h)*

3. Decision Variables

The below table (16) shows the decision variables used in the model formulation

Table 16: The Decision Variables of The Mathematical Model

Decision Variables	Definition
$\boldsymbol{y_k}$	: *Binary variable that will take value of 1 if a chiller having capacity Q_k is installed, k∈ K.*
$\boldsymbol{X}$	: *Area of installed solar collectors, given in m^2.*
$\boldsymbol{g_h}$	: *Binary variable that will take value 1 if a cold-water storage tank having capacity of D_h is installed, h∈ H.*
$\boldsymbol{z_j}$	: *Binary variable that will take value 1 if a hot water storage tank is having capacity of R_j is installed, j∈ J.*
$\boldsymbol{w_q}$	: *Binary variable that will take value 1 if an auxiliary boiler having capacity of L_q is installed, q∈ Q.*
$\boldsymbol{F_{kt}^{In}}$	: *Quantity of power consumed by a chiller k∈ K in a period t∈ T, given in KW*
$\boldsymbol{F_t^o}$	: *Quantity of cooling produced by chiller in period t∈ T, given in KW.*

Decision Variables	*Definition*
$\boldsymbol{F_t^{In}}$	*: Quantity of power consumed by a chiller in a period t∈ T, given in KW.*
$\boldsymbol{S_t^{CW}}$	*: Quantity of customer's consumption of cooling satisfied from a chiller in a period t∈ T, given in KW.*
$\boldsymbol{L_t}$	*: Quantity of power reaching the solar collectors in a period t∈ T, given in KW.*
$\boldsymbol{L_t^{C}}$	*: Quantity of power produced by solar collectors supplied to a chiller directly in a period t∈ T, given in KW.*
$\boldsymbol{I_t^{CW}}$	*: Storage level of cooling energy stored at a storage tank at the end of a period t∈ T, given in KWh.*
$\boldsymbol{I_t^{HW}}$	*: Storage level of heating energy stored at a storage tank at the end of a period t∈ T, given in KWh.*
$\boldsymbol{E_t}$	*: Quantity of production of cooling from a chiller, supplied directly to a chilled water storage tank in a period t∈ T, given in KW.*
$\boldsymbol{M_t}$	*: Quantity of solar collector's heat production supplied directly to a hot water storage tank in a period t∈ T, given in KW.*
$\boldsymbol{D_t^{CWT}}$	*: Quantity of cooling consumption of a customer, satisfied from a cold-water storage tank in a period t∈ T, given in KW.*
$\boldsymbol{D_t^{HWT}}$	*: Quantity of power supplied from a hot water storage tank in a period t∈ T, given in KW.*
$\boldsymbol{B_t}$	*: Quantity of power supplied by an auxiliary boiler in a period t∈ T, given in KW.*

4. Objective Function

The objective function (1) minimizes the addition of the annual fixed cost of installing an absorption chiller, solar collectors, a chilled and hot water TES tank and an auxiliary boiler along with the annual variable cost of producing hot and cold water from the absorption chiller and auxiliary boiler and annual variable cost of storing hot and cold water at TES tank. The present value of the investment cost of the components is multiplied by a ratio to convert it to an annual value. The ratio has two important parameters to consider, the interest rate and the life cycle of a component. In this research, all the components are assumed to have the same interest rate and life cycle. Hence, the fixed costs of all components are multiplied by the same ratio.

Minimize $\frac{i*(i+1)^n}{(1+i)^n-1} * [\sum_{k\in K} FC_k^{Ch} y_k + FC^{SC}x + \sum_{t\in T} FC_h^{CW} g_h + \sum_{j\in J} FC_j^{HW} z_j + \sum_{q\in Q} FC_q^{HW} w_q] + \sum_{t\in T} VC_t^{Ch} F_t^o + \sum_{t\in T} VC_t^{Chsto} I_t^{CW} + \sum_{t\in T} VC_t^{Hsto} I_t^{HW} + + \sum_{t\in T} VC_i^{HW} B_t$ *(1)*

Where i:interest rate = 8% and n: life cycle = 20 years

5. Constraints

5.1 Existence Constraints

$\sum_{k\in K} y_k = 1$,*(2)*

Constraint (2) enforces the installation of only one chiller

$\sum_{h\in H} g_h \leq 1$, *(3)*

Constraint (3) enforces that the cold-water TES tank will be assigned with only one capacity if it is installed

$\sum_{z\in Z} z_j \leq 1$,*(4)*

Constraint (4) enforces that the hot water TES tank will be assigned with only one capacity if it is installed

$\sum_{q\in Q} w_q \leq 1$, *(5)*

Constraint (5) enforces that the auxiliary boiler will be assigned with only one capacity if it is installed

5.2 Capacity Constraints

$\frac{L_t}{\eta_{sc} G_t} \leq x \leq A, \forall t \in T,$ *(6)*

Constraint (6) introduces the selected solar collector's total area

$F_t^o \leq \sum_{k \in K} Q_k y_k, \forall t \in T,$*(7)*

Constraint (7) ensures that the production of cooling does not go beyond the capacity of the installed chiller

$I_t^{CW} \leq \sum_{h \in H} D_h g_h, \forall t \in T,$ *(8)*

Constraint (8) ensures that the quantity of cold-water storage level does not go beyond the capacity of the installed tank

$I_t^{HW} \leq \sum_{j \in J} R_j z_j, \forall t \in T,$ *(9)*

Constraint (9) ensures that the quantity of hot water storage level does not go beyond the capacity of the installed tank

$B_t \leq \sum_{q \in Q} L_q w_q \, EFF_q, \forall t \in T,$ *(10)*

Constraint (10) ensures that the quantity of heat produced by the auxiliary boiler does not go beyond the capacity of the installed boiler

$F_t^o = \sum_{k \epsilon K} COP_k \, F_t^{In} y_k, \forall t \in T,$ *(11)*

Constraint (11) introduces the chiller's COP. However, it needs to be linearized. This is achieved as follows:

$0 \leq F_{kt}^{In} \leq M y_k, \forall t \in T, \forall k \in K$ *(11a)*

$\sum_{k \epsilon K} F_{kt}^{In} = F_t^{In}, \forall t \in T,$*(11b)*

$F_t^o = \sum_{k \epsilon K} COP_k \, F_{kt}^{In}, \forall t \in T,$ *(11c)*

$F_{kt}^{In} \geq F_t^{In} - ((1 - y_k) M), \forall t \in T, \forall k \in K$*(11d)*

M: Is a very big number M

5.3 Balance Constraints

$I_{t-1}^{CW} + \tau E_t = I_t^{CW} + \tau D_\tau^{CWT}, \forall t \in T$, *(12)*

Constraint (12) imposes the energy balance constraint for the cold-water TES tank

$I_{t-1}^{HW} + \tau M_t = I_t^{HW} + \tau D_\tau^{HWT}, \forall t \in T$,*(13)*

Constraint (13) imposes the energy balance constraint for the hot water TES tank

5.4 Supply Demand Constraints

$S_t^{CW} + D_t^{CWT} = D_t, \forall t \in T$, *(14)*

Constraint (14) imposes that customer cooling demand could be satisfied by cold water TES tank or chiller

$L_t^C + B_t + D_t^{HWT} = F_t^{In}, \forall t \in T$, *(15)*

Constraint (15) imposes that chiller power consumption could be satisfied by hot water TES tank, solar collector or auxiliary boiler

$L_t^C + M_t = L_t, \forall t \in T$, *(16)*

Constraint (16) imposes that heat produced by solar collector could be stored into the hot water TES tank or directly pumped into the chiller

$S_t^{CW} + E_t = F_t^o, \forall t \in T$, *(17)*

Constraint (17) imposes that chiller's cooling production could be stored into the cold-water TES tank or directly pumped to meet customer demand

5.5 Non-negativity and integrality Constraints

$y_k, g_h, z_j, w_q \in \{0,1\}$ *k∈K; h∈H; j∈J; q∈Q (18)*

$x, F_t^o, F_t^{In}, S_t^{CW}, L_t, L_t^c, I_t^{CW}, I_t^{HW}, E_t, M_t, D_t^{CWT}, D_t^{HWT}, B_t, F_{kt}^{In} \geq 0$, *t∈T (19)*

5.7 Numerical Results and Discussion

5.7.1 Design of Experiments

The experiments are carried out on the same aforementioned four scenarios which are a Health Center representing low cooling demand, Texas A&M University in Qatar representing medium cooling demand, Lusail city representing high cooling demand and Qatar University campus representing very high cooling demand. For each of the following scenario, two design cases considered, main design case where all the components are presented in the system and the aforementioned mathematical model formulation is used in AIMMS to solve for the optimal solution. The other is a special design case where the auxiliary boiler component is absent from the system. So, the value of the auxiliary boiler is set to zero in the mathematical model to ensure no heat will be produced from the boiler. However, the system under study starts operating during the night-time periods and there is no heat produced from the solar collectors as there is no solar radiations. So, the demand of absorption chiller for heat can't be met. As a result, this will lead to an infeasible solution. Nonetheless to solve such infeasibility, an assumption of existence of hot water at the hot water TES in the first period is made. The assumed amount of hot water stored at the tank will ensure to feed the chiller with the required hot water during the first six periods during the absence of the sun. Regarding the mathematical model formulation, a minor alteration is made to constraint number 13, where an initial value for $\boldsymbol{I_t^{HW}}$ is given. Also, another assumption is made related to the amount of hot water delivered to the chiller in the first period from hot water tank. This assumption is to ensure that the absorption chiller satisfies its demand for the hot water in the first period. In term of mathematical model formulation, a minor alteration is made to constraint 13 as well, where an initial value for $\boldsymbol{D_t^{HW}}$ is given. The updated constraints are as follows:

$$If\ t = 1\ \ then I_t^{HW} = Hot\ water\ Demand\ needed\ for\ first\ six\ periods$$

$$Else\ I_{t-1}^{HW} + \tau M_\tau = I_t^{HW} + \tau D_\tau^{HWT} \forall t\ \in T$$

$$If\ t = 1\ \ then D_t^{HW}$$

$$= Hot\ water\ supplied\ to\ absorption\ chiller\ at\ the\ first period$$

$$Else\ I_{t-1}^{HW} + \tau M_{\tau} = I_{t}^{HW} + \tau D_{\tau}^{HWT} \forall t \ \in T$$

A. Low Cooling Demand Scenario

A health service center located in Mekkah in KSA represents the low cooling demand scenario. it has a construction area of 12,410 m^2 and one floor. The daily cooling demand of it is around 1655 TR which is equivalent to 5820.3 kW.

1. Main Design Case

The below table (17) shows the obtained results from the main design case where all the components are presented in the system.

Table 17: Results of Main Design Case of Health Center

Component	Capacity	Investment Cost	Efficiency
Absorption Chiller	5,830 kW	$1,053,280	1.36
Solar Collector (Flat Plate)	Area = 223.9 m^2	$67,170	0.75
Hot Water TES	N/A	N/A	N/A
Chilled Water TES	N/A	N/A	N/A
Auxiliary Boiler	6,156 kW	$123,096	0.85
Annual Total Cost (Annual Investment Cost + Annual Operational Cost)	$1,589,951 (126,660 + 1,463,291)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 137,081 iterations and using CPLEX 12.6.3 Solver, solving time is 1731.97 seconds, total time is 1737.36 seconds and the memory used is 1815.3 Mb

- The boiler satisfies 54% of the heat demand required by the absorption chiller while the other 46% are satisfied by the solar collector
- There is no cold or hot water TES tank installed in the system
- The annual investment cost of the components represents 8% of the annual total cost while the annual operational cost of the components represents 92% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 85% of annual total investment cost which is equivalent to 107,661$
- The annual investment cost of solar collector represents 5% of annual total investment cost which is equivalent to 6,333$
- The annual investment cost of auxiliary boiler represents 10% of annual total investment cost which is equivalent to 12,666$
- The annual operational cost to produce cold water from the absorption chiller represents 72% of the annual total operational cost which is equivalent to 1,048,739$
- The annual operational cost to produce hot water from the auxiliary boiler represents 28% of the annual total operational cost which is equivalent to 414,552$

2. **Special Design Case**

In this special design case, the heat is only produced from the solar collectors. It means there is no auxiliary boiler installed in the system. However, the existence of the other components remains the same as in the first design case. The below table (18) shows the results obtained from the special design case.

Table 18: Results of Special Design Case of Health Center

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	5,830 kW	1,053,280	1.36
Solar Collector (Flat Plate Collector)	Area = 2500.6 m^2	750,180	0.75
Hot Water Thermal Energy Storage Tank (PTES)	63,000 kWh	24,948	N/A
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Auxiliary Boiler	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	4,080,628 (186,228 + 3,894,400)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 65,684 iterations and using CPLEX 12.6.3 Solver, solving time is 356.25 seconds, total time is 386.92 seconds and the memory used is 2243.9 Mb
- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%)
- There is a hot water TES tank with a capacity of 63,000 kWh and a fixed cost of 24,948$ installed in the system

- There is no cold-water TES tank installed in the system
- The annual investment cost of the components represents 5% of the annual total cost while the annual operational cost of the components represents 95% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 58% of annual total investment cost which is equivalent to 107,279$
- The annual investment cost of solar collectors represents 41% of annual total investment cost which is equivalent 76,407$
- The annual investment cost of hot water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The annual operational cost to produce cold water from the absorption chiller represents 27% of the annual total operational cost which is equivalent to 1,048,739$
- The annual operational cost to store hot water at the hot water thermal energy storage tank represents 73% of the total annual operational cost which is equivalent to 2,845, 661$

B. Medium Cooling Demand Scenario

Texas A&M University at Qatar represents the medium cooling demand scenario. It has an academic section with an area of 30,800 m^2 and consists of 4 floors. The maximum cooling demand occurs in August with around 12,445 kW.

1. Main Design Case

The below table (19) shows the obtained results from the main design case where all the components are presented in the system.

Table 19: Results of Main Design Case of TAMUQ

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	12,000 kW	1,746,960	1.36
Solar Collector (Flat Plate Collector)	Area = 478.4 m^2	143,520	0.75
Hot Water Thermal Energy Storage Tank	N/A	N/A	N/A
Chilled Water Thermal Energy Storage Tank (PTES)	63,000 kWh	24,948	N/A
Auxiliary Boiler	10,260 kW	205,160	0.85
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	3,342,561$ (215,988 + 3,126,573)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 27,783 iterations and using CPLEX 12.6.3 Solver, solving time is 505.44 seconds, total time is 512.31 seconds and the memory used is 1770.2 Mb
- The boiler satisfies 54% of the heat demand required by the absorption chiller while the other 46% are satisfied by the solar collector
- There is a cold-water TES tank with a capacity of 63,000 kWh and a fixed cost of 24,948$ installed in the system

- There is no hot water TES tank installed in the system
- The annual investment cost of the components represents 6% of the annual total cost while the annual operational cost of the components represents 94% of the total cost of the system
- The annual investment cost of absorption chiller represents 82% of annual total investment cost which is equivalent to 177,932$
- The annual investment cost of solar collector represents 7% of annual total investment cost which is equivalent to 14,618$
- The annual investment cost of cold-water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The investment cost of auxiliary boiler represents 10% of annual total investment cost which is equivalent to 20,896$
- The annual operational cost to produce cold water from the absorption chiller represents 72% of the annual total operational cost which is equivalent to 2,240,489$
- The annual operational cost to produce hot water from the auxiliary boiler represents 28% of the annual total operational cost which is equivalent to 885,600$

2. **Special Design Case**

In this special design case, the heat is only produced from the solar collectors. It means there is no auxiliary boiler installed in the system. However, the existence of the other components remains the same as in the first design case. The below table (20) shows the results obtained from the special design case.

Table 20: Results of Special Design Case of TAMUQ

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	12,000 kW	1,746,960	1.36
Solar Collector (Flat Plate Collector)	Area = 5342.2 m^2	1,602,660	0.75
Hot Water Thermal Energy Storage Tank (PTES)	126,000 kWh	49,896	N/A
Chilled Water Thermal Energy Storage Tank (PTES)	63,000 kWh	24,948	N/A
Auxiliary Boiler	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	8,669,053 $ (348,789 + 8,320,264)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 20,096 iterations and using CPLEX 12.6.3 Solver, solving time is 237.84 seconds, total time is 255.70 seconds and the memory used is 2225.5 Mb
- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%)
- There is a hot water TES tank with a capacity of 126,000 kWh and a fixed cost of 49,896$ installed in the system

- There is a cold-water TES tank with a capacity of 63,000 kWh and a fixed cost of 24,948$
- The annual investment cost of the components represents 4% of the annual total cost while the annual operational cost of the components represents 96% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 51% of annual total investment cost which is equivalent to 177,932$
- The annual investment cost of solar collector represents 47% of total investment cost which is equivalent to 163,234$
- The annual investment cost of cold-water tank represents 1% of annual total investment cost which is equivalent to 2541$
- The annual investment cost of hot water tank represents 1% of total investment cost which is equivalent to 5,082$
- The annual operational cost to produce cold water from the absorption chiller represents 27% from the annual total operational cost which is equivalent to 2,240,489$
- The annual operational cost to store hot water at the hot water thermal energy storage tank represents 73% from the annual total operational cost which is equivalent to 6,079,344$

C. High Cooling Demand Scenario

Lusail Marina District Cooling system at Qatar represents the high cooling demand. It extends over 38 km^2 and more than 200,000 residents will live in the city and more than 170,000 people are predicted to work in the various districts of the city. The cooling demand of it is around 5000 TR currently which is equivalent to 17,590 kW.

1. Main Design Case

The below table (21) shows the obtained results from the main design case where all the components are presented in the system.

Table 21: Results of Main Design Case of Lusail District

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	17,640 kW	2,568,031	1.36
Solar Collector (Flat Plate Collector)	Area = 677.6 m^2	203,280	0.75
Hot Water Thermal Energy Storage Tank	N/A	N/A	N/A
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Auxiliary Boiler	17,850 kW	318,750	0.85
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	4,742,285 (314,730 + 4,427,555)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 20,435 iterations and using CPLEX 12.6.3 Solver, solving time is 431.00 seconds, total time is 436.36 seconds and the memory used is 1800.5 Mb
- The boiler satisfies 54% of the heat demand required by the absorption chiller

while the other 46% are satisfied by the solar collector

- There is no cold or hot water TES tank installed in the system
- The annual investment cost of the components represents 6% of the annual total cost while the annual operational cost of the components represents 94% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 83% of annual total investment cost which is equivalent to 261,560$
- The annual investment cost of solar collector represents 7% of annual total investment cost which is equivalent to 20,705$
- The annual investment cost of auxiliary boiler represents 10% of annual total investment cost which is equivalent to 32,465$
- The annual operational cost to produce cold water from the absorption chiller represents 72% of the annual total operational cost which is equivalent to 3,173,224$
- The annual operational cost to produce hot water from the auxiliary boiler represents 28% of the annual total operational cost which is equivalent to 1,254,330$

2. **Special Design Case**

In this special design case, the heat is only produced from the solar collectors. It means there is no auxiliary boiler installed in the system. However, the existence of the other components remains the same as in the first design case. The below table (22) shows the results obtained from the special design case.

Table 22: Results of Special Design Case of Lusail District

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	17,640 kW	2,568,031	1.36
Solar Collector (Flat Plate Collector)	Area = 7,566.2 m^2	2,269,860	0.75
Hot Water Thermal Energy Storage Tank (PTES)	270,000 kWh	106,920	N/A
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Auxiliary Boiler	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	12,287,125 (503,640 + 11,783,485)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 19,387 iterations and using CPLEX 12.6.3 Solver, solving time is 250.03 seconds, total time is 274.94 seconds and the memory used is 2236.5 Mb
- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%)
- There is a hot water TES tank with a capacity of 270,000 kWh and a fixed cost of 106,920$ installed in the system

- There is no cold-water TES tank installed in the system
- The annual investment cost of the components represents 4% of the annual total cost while the annual operational cost of the components represents 96% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 52% of annual total investment cost which is equivalent to 261,560$
- The annual investment cost of solar collector represents 46% of annual total investment cost which is equivalent to 231,190$
- The annual investment cost of hot water tank represents 2% of annual total investment cost which is equivalent to 10,890$
- The annual operational cost to produce cold water from the absorption chiller represents 27% of the annual total operational cost
- The annual operational cost to store hot water at the hot water thermal energy storage tank represents 73% of the annual total operational cost

D. Very High Cooling Demand Scenario

Qatar University's District Cooling Plant at Qatar represents the very high cooling demand scenario. It extends over 8.1 km^2 and the cooling demand is 6,000 TR which is equivalent to 21,101 kW.

1. Main Design Case

The below table (23) shows the obtained results from the main design case where all the components are presented in the system.

Table 23: Results of Main Design Case of QU District Cooling Plant

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	24,000 kW	3,493,920	1.36
Solar Collector (Flat Plate Collector)	Area = 809.7 m^2	242,910	0.75
Hot Water Thermal Energy Storage Tank (PTES)	63,000 kWh	24,948	N/A
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Auxiliary Boiler	17,850 kW	318,750	0.85
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	5,705,970$ (415,610 + 5,290,360)		

The main observations of the obtained results are:

- The results are obtained from AIMMS software after 97,577 iterations and using CPLEX 12.6.3 Solver, solving time is 970.31 seconds, total time is 993.84 seconds and the memory used is 1815.3 Mb
- The boiler satisfies 54% of the heat demand required by the absorption chiller while the other 46% are satisfied by the solar collector
- There is a hot water TES tank with a capacity of 63,000 kWh and a fixed cost of 24,948$ installed in the system

- There is no cold-water TES tank installed in the system
- The annual investment cost of the components represents 7% of the annual total cost while the annual operational cost of the components represents 93% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 86% of annual total investment cost which is equivalent to 355,863$
- The annual investment cost of solar collector represents 6% of annual total investment cost which is equivalent to 24,741$
- The annual investment cost of hot water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The annual investment cost of auxiliary boiler represents 8% of total investment cost which is equivalent to 32,465$
- The annual operational cost to produce cold water from the absorption chiller represents 72% of the annual total operational cost which is equivalent 3,791,596$

  The annual operational cost to produce hot water from the auxiliary boiler represents 28% of the total annual operational cost which is equivalent to 1,498,749$

2. **Special Design Case**

In this special design case, the heat is only produced from the solar collectors. It means there is no auxiliary boiler installed in the system. However, the existence of the other components remains the same as in the first design case. The below table (24) shows the results obtained from the special design case.

Table 24: Results of Special Design Case of QU District Cooling Plant

Component	Capacity	Investment Cost ($)	Efficiency
Absorption Chiller	24,000 kW	3,493,920	1.36
Solar Collector (Flat Plate Collector)	Area = 9040.6 m^2	2,712,180	0.75
Hot Water Thermal Energy Storage Tank (PTES)	270,000 kWh	106,920	N/A
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Auxiliary Boiler	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	14,722,750$ (642,996 + 14,079,754)		

The main observations of the obtained results are:

- The results are obtained from AIMMS software after 37,144 iterations and using CPLEX 12.6.3 Solver, solving time is 495.31 seconds, total time is 525.28 seconds and the memory used is 2275.9 Mb
- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%)
- There is a hot water TES tank with a capacity of 270,000 kWh and a fixed cost of 106,920$ installed in the system

- There is no cold-water TES tank installed in the system
- The annual investment cost of the components represents 4% of the annual total cost while the annual operational cost of the components represents 96% of the annual total cost of the system
- The annual investment cost of absorption chiller represents 55% of annual total investment cost which is equivalent to 355,863$
- The annual investment cost of solar collector represents 43% of annual total investment cost which is equivalent to 276,242$
- The annual investment cost of hot water tank represents 2% of annual total investment cost which is equivalent to 10,890$
- The annual operational cost to produce cold water from the absorption chiller represents 27% of the annual total operational cost which is equivalent to 3,791,596$
- The annual operational cost to store hot water at the hot water TES represents 73% of the annual total operational cost which is equivalent to 10,288,158$

The below graph (13) shows the annual investment cost, and annual operational cost of each scenario. The purpose of this graph is to show how much each annual cost contributes to the annual total cost of the system. Also, it highlights which scenario have the highest annual total cost. From the graph, we can notice that the fourth scenario which represents the very high cooling demand has the highest annual total cost including both the highest annual investment cost and the highest annual operational cost compared to other scenarios. That is reasonable, since the cooling demand of that scenario is the highest compared to other scenarios. That explained by components with high capacities must be installed to accommodate the required high cooling demand. So, these components will have a high annual investment cost and high annual operational cost associated with them.

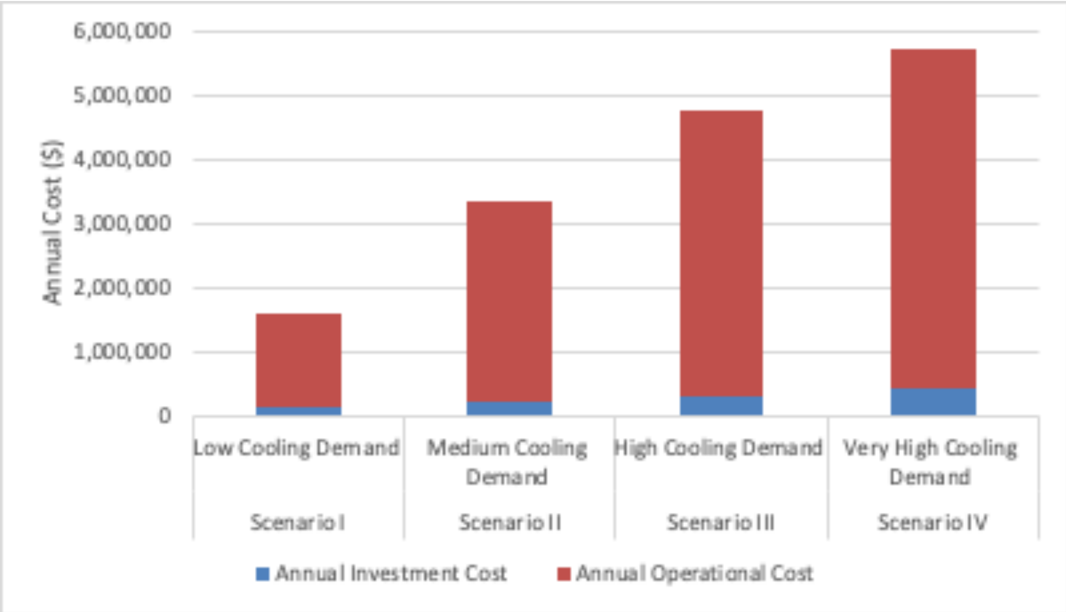

Figure 13: Summary of results of main design cases of scenarios

The below tables (25) (26) (27) (28) summarize and compare the results obtained from each design case and special design case for all the scenarios.

Low Cooling Demand Scenario

Table 25: Comparison of Results for Health Center

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost (Annual Fixed & Variable cost)
Main Design Case	5,830 kW; 1,053,280\$; COP: 1.36	223.9 m^2; 67,170\$; 0.75	N/A	N/A	6,156 kW; 123,096\$; 0.85	1,589,951\$ (126,660 + 1,463,291)
	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost (Annual Fixed & Variable cost)
Special Design Case	5,830 kW; 1,053,280\$; COP: 1.36	2500.6 m^2; 750,180\$; 0.75	63,000 kWh; 24,948\$	N/A	N/A	4,080,628 (186,228 + 3,894,400)

- The area of the solar collector has increased by 1017% compared to the main design case. Hence, the fixed cost of the solar collector has increased by 1017% compared to the main design case. The difference between the two fixed costs is around 683,010$ and between the annual fixed cost is around 69,566$

- There is an existence of hot water thermal energy storage tank with a capacity of 63,000 kWh and a fixed cost of 24,928$ where there was not a hot water tank in the main design case
- The cold-water thermal energy storage tank is absent in both of design cases
- The annual total cost of the system has increased by 157% compared to the main design case
- The annual investment cost has increased by 47% mainly due to increasing the annual fixed cost of the solar collectors by 69,566$
- The annual operational cost has increased by 166% compared to the main design case and one of the main reasons for such increasing is more water needs to be stored at the tank during the daytime period to be consumed at the nighttime period when the sun is absent. Hence, storing the hot water in the hot storage tank will consume electricity where it is considered to be one of variable costs parameters. The annual operational cost of storing the hot water at the hot thermal energy storage tank represents 73% of the annual total operational cost where there was not any annual operational cost associated with storing hot water in the main design case

Medium Cooling Demand Scenario

Table 26: Comparison of Results for TAMUQ

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost (Annual Fixed cost + Annual Variable cost)
Main Design Case	12,000 kW; 1,746,960$; COP: 1.36	478.4 m^2; 143,520$; 0.75	N/A	63,000 kWh; 24,948$	10,260 kW; 205,160$; 0.85	3,342,561$ (215,988 + 3,126,573)
Special Design Case	12,000 kW; 1,746,960$; COP: 1.36	5342.2 m^2; 1,602,660$; 0.75	126,000kWh; 49,896$	63,000 kWh; 24,948$	N/A	8,669,053 $ (348,789 + 8,320,264)

- The area of the solar collector has increased by 1017% compared to the main design case. Hence, the fixed of the solar collector has increased by 1017% compared to the main design case. The difference between the two fixed costs is around 1,459,140 $ and between the annual fixed costs is around 148,616$
- A hot water thermal energy storage tank exists in the special design case where

it was absent in the main design case with a capacity of 126,000 kWh and a fixed cost of 49,896$

- A cold-water thermal energy storage tank of the same capacity and fixed cost exists in both of the design cases
- The annual total cost of the system has increased by 159% compared to the main design case.
- The annual investment cost has increased by 61% due to the addition of a hot water storage tank with an annual fixed cost of 5,082$. Also, increasing the annual fixed cost of the solar collectors by 148,616$
- The annual operational cost has increased by 166% compared to the main design and one of the main reasons for such increasing is the addition of the hot water storage tank, where water needs to be stored at the tank during the daytime period to be consumed at the nighttime period when the sun is absent. Hence, storing the hot water in the hot storage tank will consume electricity where it is considered to be one of variable costs parameters. The annual operational cost of storing the hot water at the hot thermal energy storage tank represents 73% of the annual total operational cost in the special design case

High Cooling Demand Scenario

Table 27: Comparison of Results for Lusail District

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost (Annual Fixed cost + Annual Variable cost)
Main Design Case	17,640 kW; 2,568,031\$; COP: 1.36	677.6 m^2; 203,280\$; 0.75	N/A	N/A	17,850 kW; 318,750\$; 0.85	4,742,285\$ (314,730 + 4,427,555)
Special Design Case	17,640 kW; 2,568,031\$; COP: 1.36	7,566.2 m^2; 2,269,860\$; 0.75	270,000kWh; 106,920\$	N/A	N/A	12,287,125 (503,640 + 11,783,485)

- The area of the solar collector has increased by 1017% compared to the main design case. Hence, the fixed of the solar collector has increased by 1017% compared to the main design case. The difference between the two fixed costs is around 2,066,580\$ and the annual fixed cost is around 210,485\$
- There is an existence of hot water thermal energy storage tank in the special design case with a capacity of 270,000kWh and a cost of 106,920\$ where it was

absent in the main design case

- The cold-water thermal energy storage tank is absent in both of design cases
- The annual total cost of the system has increased by 159% compared to the main design case
- The annual investment cost has increased by 60% due to the existence of hot water TES with annual fixed cost of 10,890$. Also, increasing the annual fixed cost of the solar collectors by 210,485$
- The annual operational cost has increased by 166% compared to the main design and one of the main reasons for such increasing is the existence of a high capacity hot water storage tank, where more water needs to be stored at the tank during the daytime period to be consumed at the nighttime period when the sun is absent. Hence, storing the hot water in the hot storage tank will consume electricity which is considered to be one of variable costs parameters. The annual operational cost of storing the hot water at the hot thermal energy storage tank represents 73% from annual the total operational cost in the special design case where there was not any hot water TES in the main design case

Very High Cooling Demand Scenario

Table 28: Comparison of Results for QU Distrcit Cooling Plant

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost (Annual Fixed & Variable cost)
Main Design Case	24,000 kW; 3,493,920$; COP: 1.36	809.7 m^2; 242,910$; 0.75	63,000 kWh; 24,948$	N/A	17,850 kW; 318,750$; 0.85	5,705,970$ (415,610 + 5,290,360)
Special Design Case	24,000 kW; 3,493,920$; COP: 1.36	9040.6 m^2; 2,712,180$; 0.75	270,000kWh; 106,920$	N/A	N/A	14,722,750$ (642,996 + 14,079,754)

- The area of the solar collector has increased by 1017% compared to the main design case. Hence, the fixed of the solar collector has increased by 1017% compared to the main design case. The difference between the two fixed costs is around 2,469,270$ and the annual fixed costs is around 251,501$
- A hot water thermal energy storage tank exists in the special design case with a capacity of 270,000 kWh and a fixed cost of 106,920$. The capacity of the tank has increased by 329%. Hence, the fixed cost increased by 329% and the annual

fixed cost by 8349$ compared to the main design case

- There is no cold-water thermal energy storage tank installed in both of cases
- The annual total cost of the system has increased by 158% compared to the main design case
- The annual investment cost has increased by 55% due to increasing the capacity of a hot water storage tank by an annual fixed cost of 8,349$. Most importantly, due to increasing the annual fixed cost of the solar collectors by 251,501$ compared to main design case
- The annual operational cost has increased by 166% compared to the main design and one of the main reasons for such increasing is due to increasing the capacity of the hot water storage tank, where water needs to be stored at the tank during the daytime period to be consumed at the nighttime period when the sun is absent. Hence, storing the hot water in the hot storage tank will consume electricity which is considered to be one of variable costs parameters. The annual operational cost of storing the hot water at the hot thermal energy storage tank represents 73% of the annual total operational cost in the special case

5.7.2 Sensitivity Analysis. The sensitivity analysis is conducted on the fourth scenario Qatar University District Cooling Plant which is the very high cooling scenario. During the sensitivity analysis, one parameter is changed at a time while the other parameters are kept fixed. The sensitivity analysis is performed on the following key parameters, solar collector efficiency, boiler efficiency, chiller COP, solar collector cost, Boiler cost, chiller cost, and hot water thermal energy storage tank. Their values are varied between 20% and -20% of the base value. These values are showed on the x-axis. While the y-axis shows the percentage of Total Cost Difference (PTCD) which is calculated using the following equation:

$$PTCD = \frac{New\ Cost - Base\ Cost}{Base\ Cost}\ x\ 100$$

The purpose of this analysis is to examine and measure how the changes of each parameter are sensitive to the optimal solution. The below table (29) shows the parameters that are studied during the sensitivity analysis along with indicating the maximum and the minimum values the base value is varied by using the mentioned incremental value.

Table 29: Parameters of Senstivity Analysis

Parameter	Maximum Value (20%)	Base Value	Minimum Value (-20%)	Incremental Value
Solar Collector Efficiency	0.9	0.75	0.6	0.015
Chiller COP	1.632	1.36	1.088	0.0272
Boiler Efficiency	1.00	0.85	0.68	0.017
Solar Collector Cost $/m^2	360	300	240	6
Chiller Cost $	4,192,704	3,493,920	2,795,136	698,784
Boiler Cost $	382,500	318,750	255,000	6,375
Hot Water Storage Tank Cost $	29,937	24,948	19,958	499

Most of the trends generated from sensitivity analysis are almost straight-line trends which means a direct proportional relationship between the parameters and the annual total system cost was obtained for solar collector efficiency, chiller COP, solar collector cost, chiller cost, boiler cost, and hot water TES cost as indicated from the R^2 value. However, the trend obtained from the sensitivity analysis on the boiler efficiency parameter is the only non-linear trend. Therefore, a graph will be showed below to explain the obtained behavior.

The below table (30) summarizes the results obtained from the analysis where it highlights the parameters that have a crucial effect on the annual total system cost compared to other parameters.

Table 30: Results of Senstivity Analysis

Parameters	Maximum Annual Cost Difference Percentage (20%)	Minimum Annual System Difference Percentage (-20%)	Generated Straight Line Equation	Coefficient of Determination R^2
Solar Collector Efficiency	-0.063	0.116	$y = -0.0088x + 0.1066$	$R^2 = 0.9745$
Chiller COP	-4.431	8.372	$y = -0.5707x + 6.2243$	$R^2 = 0.974$
Boiler Efficiency	0	1.268	Non-Linear Trend	$R^2 = 0.4766$
Solar Collector Cost $/m^2	0.087	-0.087	$y = 0.0087x - 0.0954$	$R^2 = 1$
Chiller Cost $	1.247	-1.247	$y = 0.1247x - 1.3721$	$R^2 = 1$

Parameters	Maximum Annual Cost Difference Percentage (20%)	Minimum Annual System Difference Percentage (-20%)	Generated Straight Line Equation	Coefficient of Determination R^2
Boiler Cost $	0.11	-0.11	y = 0.0114x - 0.1252	$R^2 = 1$
Hot Water Storage Tank Cost $	0.0089	-0.0089	y = 0.0009x - 0.0098	$R^2 = 1$

The table (30) shows that the chiller COP parameter has the most effect on the annual total system cost, where increasing the COP by 20% will decrease the annual total system cost by -4.431%. While decreasing the COP by 20% will increase the annual total system cost by 8.372%. Hence, the focus should be on increasing the chiller COP to reduce the annual total annual cost. Nevertheless, if increasing the chiller COP is not an option due to technology unavailability or the technology price, then the focus should be directed on the chiller cost parameter as a second alternative. Decreasing the chiller cost would decrease the annual total system cost by -1.247%. However, if reducing the chiller cost is infeasible due to chiller type availability, then reducing the boiler cost parameter should be considered as a third alternative. If that is impossible due to capacity, type or technology constraints, then solar collector cost, solar collector efficiency, and hot water storage tank cost should be considered, respectively.

The graph (14) shows the behavior of the boiler efficiency parameter on the annual total system cost where it has the only non-linear trend among the other parameters.

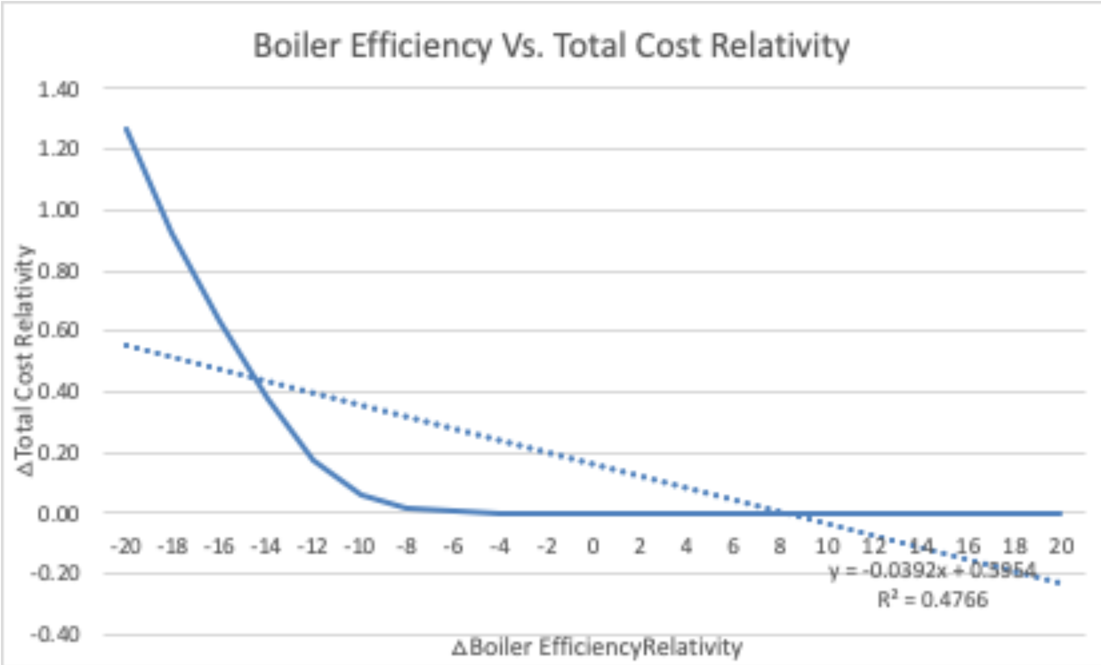

Figure 14: Auxiliary boiler parameter senstivity analysis

The graph shows the relationship between how varying the efficiency of the boiler effects on the annual total cost of the system. Increasing the efficiency of the boiler above the base value which is 0.85 doesn't affect the annual total system cost. However, once the efficiency of the boiler is dropped below 0.85, then the annual total cost of the system starts to increase slowly. The reason behind such behavior is the efficiency of the boiler is changing from one period to another according to constraint number 10 and the maximum efficiency the boiler operates at during the examined periods (8784 hours) is observed to be 0.85. This indicates that the full capacity of the boiler is being completely utilized at certain periods. Hence, selecting and installing a boiler with an efficiency of more than 0.85 would not decrease annual total cost of the system as the cost would remain the same. This information is a useful indicator to the owner of the system, where he could avoid employing a boiler with a high capacity and a high efficiency with a high fixed cost as it would not contribute in decreasing the annual total cost of the system.

The below two graphs (15) and (16) summarize the sensitivity results carried on the parameters.

Efficiency Graph

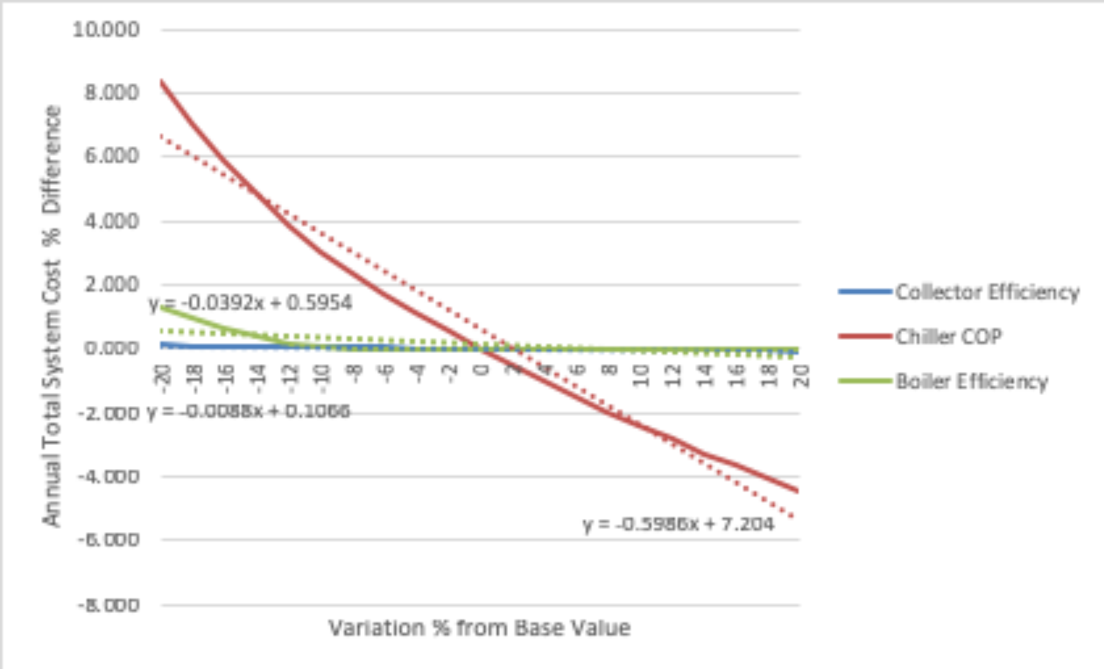

Figure 15: Efficiencies parameters senstivity analysis

The above graph (15) illustrates how different parameters impact the annual total cost of the system. This graph shows the impact of the efficiencies of different parameters which are solar collectors, chiller and boiler on the annual total cost of the system. We can notice from the graph and the generated straight-line equation that the COP of the chiller effects the most on the annual total cost of the system compared to the other efficiencies. According to the straight-line equations, the COP of the chiller impacts the annual total cost of the system by 0.5986%. While the efficiency of the boiler impacts the annual total cost of the system by 0.0393 %. However, the solar collector efficiency doesn't impact on the annual total cost of the system significantly compared to other with an impact of 0.0088%. Since, the main objective of the developed mathematical model is to obtain the optimal system configuration with the minimum annual total cost possible, then the user of the system should focus on increasing the COP of the chiller as it affects the most on the annual total cost of the system. The chiller component is the focal point of the system as it connects all other components with each other. Hence, increasing or decreasing the COP of the chiller will impact the other components in the system. For instance, increasing the COP will result in decreasing the capacity of the chiller as more chilled water will be produced for the same or less amount of hot water. That will lead to decreasing the efficiency and the required area of the solar collector, capacity of the hot water TES tank and capacity and efficiency of the boiler as less amount of hot water will be required to produce the needed chilled water. Moreover, the owner of the system could reduce the annual total cost of the system by focusing also on increasing the efficiency of the solar collector. However, the impact of the solar collector efficiency on the annual total cost of the system is way less than the impact of the COP of the chiller.

Cost Graph

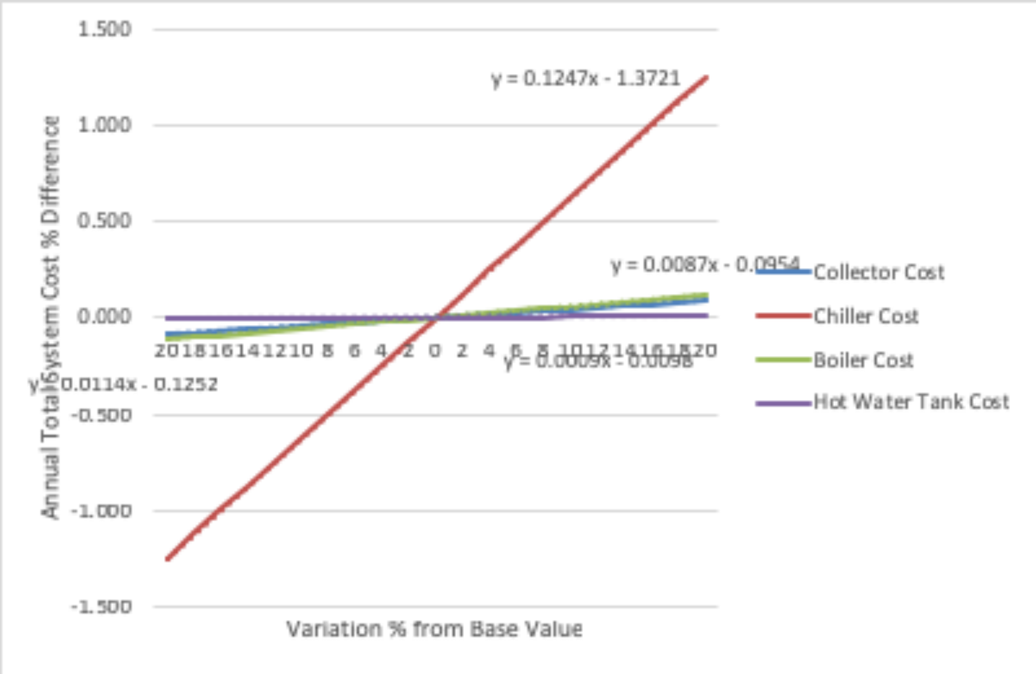

Figure 16: Fixed cost paramters senstivity analysis

The above graph (16) illustrates how different parameters impact the annual total cost of the system. This graph shows the impact of the fixed cost of different parameters which are solar collectors, chiller, boiler, and hot water storage tank on the annual total cost of the system. We can notice from the graph and the generated straight-line equations that the chiller cost has the most effect on the annual total cost of the system compared to the other fixed costs. According to the straight-line equations, the fixed costs of the chiller impacts the annual total cost of the system by 0.1247%. While the fixed cost of the boiler impacts the annual total cost of the system by 0.0114%. However, the solar collectors and the hot water storage tank fixed cost impacts the total cost of the system by 0.0087% and 0.0009% respectively. Since the main objective of the developed mathematical model is to obtain the optimal system configuration with the minimum annual total cost possible, then the user of the system should focus on decreasing the fixed cost of the chiller as it affects the most on the annual total cost of the system. Nevertheless, if the user can’t reduce the fixed cost of the chiller due to some constraints like the unavailability of a certain type of chiller at the market, then he could focus on reducing the fixed of the boiler instead. That will lead to reducing the annual total cost of the system, but it won't be a significant reduction in the annual total cost as reducing the fixed cost of the chiller. The solar collectors and the hot water storage tank fixed costs have an insignificant effect on the total annual system cost compared to others. But, it will consider a reduction in the annual total cost of the system.

Chapter 6: Solar Electric Cooling System Model

This chapter is divided into nine main sections which are problem scope, system's operation, model formulation, assumptions and observations, mathematical model, numerical results and discussion, sensitivity analysis, economical and sustainable comparison between three models. The first section identifies the model's scope in details. The second section explains how the proposed model would operate in real-life. The third section shows and explains how the proposed model is formulated. The fourth section states the assumptions and observations made during the model formulation and solving. The fifth section demonstrates the parameters, decision variables, the objective function and the constraints of the mathematical model. The sixth section shows the different scenarios along with their design cases considered for optimizing the proposed model. Also, this section discusses the results obtained from the optimized models. The seventh section carries out a sensitivity analysis on the parameters of the model. The eight section conducts an economic comparison between the three developed models. Lastly, the nine section conducts a sustainable comparison between the three developed models.

6.1 Problem Scope

The aim is to obtain the solar electric cooling system connected to the main grid optimal design. This includes finding the optimal configuration for the system components with a target to obtain the minimum annual investment and annual operational costs while obtaining the most optimal possible efficiency level. The optimal solution will specify the following:

I. The optimal capacity of the compression chiller and TES (if any)

II. The quantities of cold water to be stored and produced at each point of time

I. The optimal area of photovoltaics panels

The objective is to minimize the addition of the annual fixed cost of installing a compression chiller, photovoltaics and a cold-water TES tank along with the annual variable cost of producing cold water from the compression chiller and annual variable cost of storing cold water at TES tank.

Moreover, the scope of the research is studying and analyzing the system over 8784 hours/year to gain a better understanding on how the system would operate and behave during the different months of the year. Hence, the selection of the optimal system would be based on the cooling demand observed throughout the year.

6.2 Operation of System

The proposed solar electric cooling system connected to the main grid is composed of three main components which are a compression chiller, a cold-water TES tank, and photovoltaic panels. The below figure (17) shows the layout of the solar electric cooling system connected to the grid.

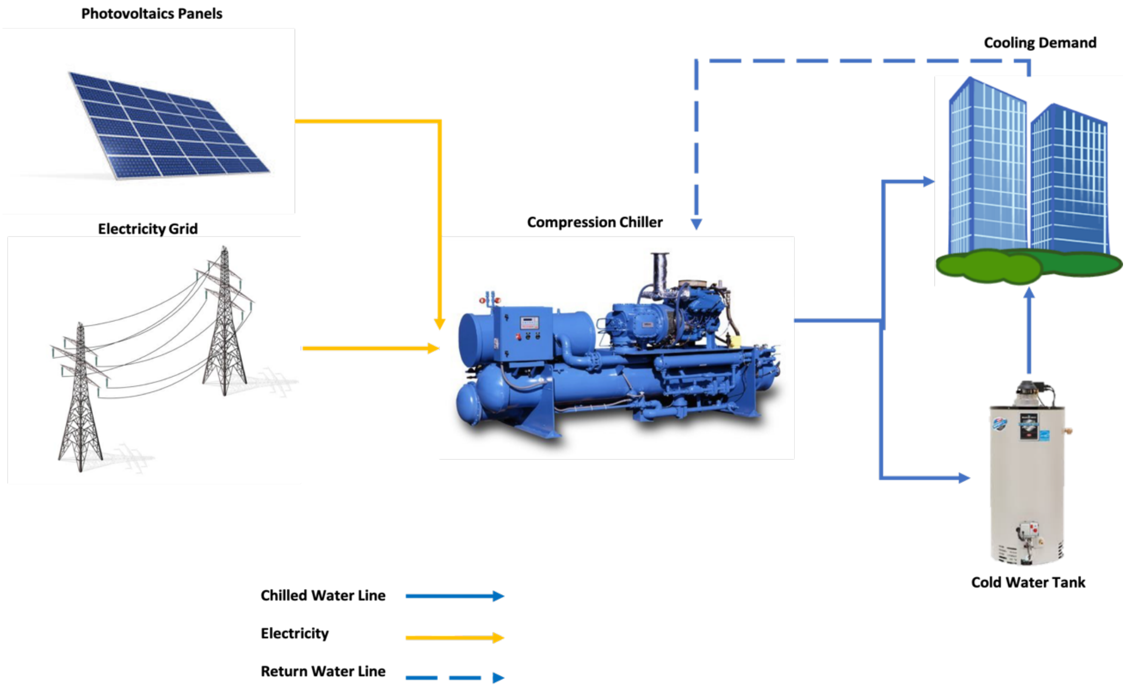

Figure 17: Solar electric cooling system layout

The operation of the proposed solar electric cooling system starts with the main grid supplying the required electricity to the compression chiller in case if the photovoltaics panels is unable to supply the required electricity to the compression chiller due to absence of solar radiance. Hence, the chiller will be powered by the electricity that is either coming from the main grid, photovoltaics or from both, and starts to produce cold water. The chiller will either produce the required cold water to satisfy the cooling demand or will produce more cold water than it is required. This additional cold water will be stored in the cold-water thermal storage tank to be used at later periods during the day to meet the cooling demand. The COP of the compression chiller is taken into consideration during the operation of the system.

6.3 Model Formulation

The below figure (18) shows the configuration of the proposed solar electric cooling system connected to the main grid. It highlights the energy flow in the form of chilled water between the system components. The photovoltaics panels will absorb the sun radiance (L_t). The amount of electricity required by the compression chiller will be supplied to the chiller from the photovoltaics panels (L_t^c). In case if the sun radiance is absence, then the required amount of electricity will be supplied from the main grid (B_t). Hence, the total amount of electricity required by the chiller will come either from the main grid, photovoltaics panels or from both is given by (F_t^{In}). The cooling energy generated by the chiller (F_t^o) will be distributed in such way to meet the customer demand directly (S_t^{CW}), or the chilled water will be stored in the chilled water TES tank (E_t), in case of excess cooling energy production, to meet the customer cooling demand at later periods (D_t^{CWT}).

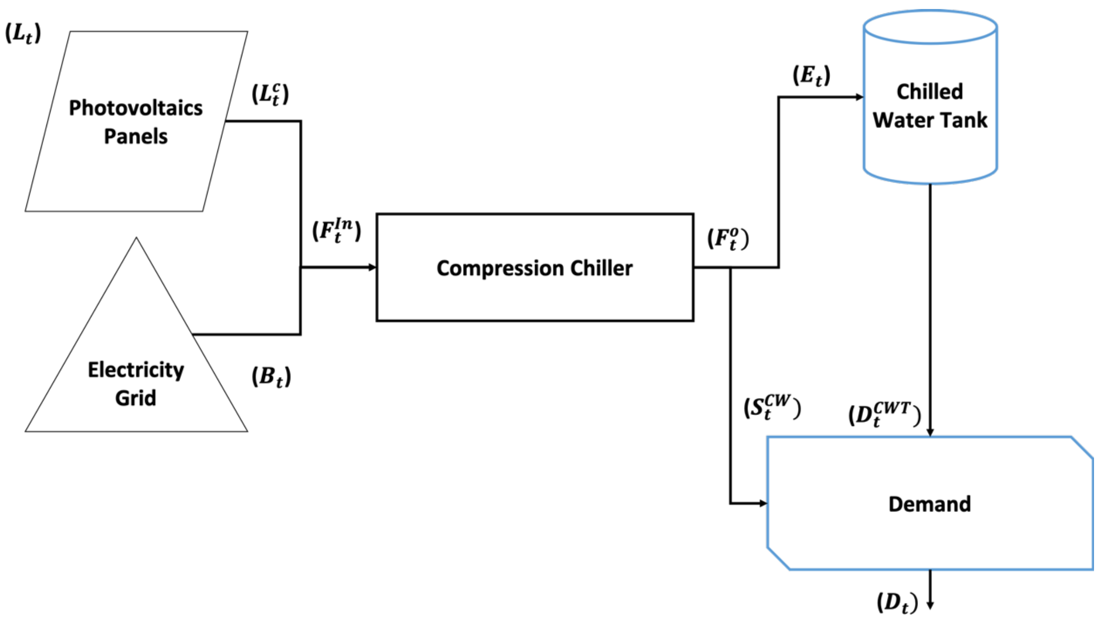

Figure 18: Solar electric cooling system model formulation

6.4 Assumptions and Observations

The following assumptions considered during the model formulation:

- The cooling demands are deterministic and known in advance

- TES tanks function with full efficiency where no losses would happen
- The system operates in a steady state
- The system's transient state is not considered
- The efficiency of photovoltaics panels is constant and known in advance

The observations made during the model formulation:

- The peak cooling hours occur from 1 pm to 4 pm according to our generated cooling demand data which is based on the

6.5 Mathematical Model

This section contains the sets, parameters, decision variables, objective functions and constraints included in the proposed mathematical model.

1. ***Sets***

The below table (31) shows the sets and indices used in the model formulation

Table 31: The Sets of The Mathematical Model

Indices	*Definition*
T	*: Set of time periods, indexed by t.*
K	*: Set of chiller capacities, indexed by k.*
H	*: Set of chilled water TES capacities, indexed by h.*

2. ***Parameters***

The below table (32) shows the parameters used in the model formulation

Table 32: The Parameters of The Mathematical Model

Parameters	*Definition*
$\boldsymbol{FC_k^{Ch}}$	*: Fixed cost of a chiller installed of capacity, ∀k∈ K.*
$\boldsymbol{F^{PV}}$	*: Fixed cost of a unit area of photovoltaics panels installed*
$\boldsymbol{FC_h^{CW}}$	*: Fixed cost of a cold-water storage tank installed of capacity, ∀h ∈ H.*
$\boldsymbol{VC_t^{Ch}}$	*: Variable cost per unit of producing cold water at chiller in a period, ∀t ∈ T.*
$\boldsymbol{VC_t^{Chsto}}$	*: Variable cost per unit of storing cold water at a storage tank in a period, ∀t ∈ T.*
$\boldsymbol{VC_t^{Gr}}$	*: Variable cost of supplying a unit of electricity from main grid in a period, ∀t ∈ T.*
$\boldsymbol{G_t}$	*: Global solar radiance in a period given in* W/m^2*, ∀t ∈ T.*
$\boldsymbol{n_{sc}}$	*: Efficiency of the photovoltaics panels*
$\boldsymbol{Q_k}$	*:* k^{th} *capacity of a chiller given in KW, ∀ k∈ K.*
$\boldsymbol{COP_k}$	*: Coefficient of performance of a chiller of* k^{th} *capacity, ∀ k∈ K.*
$\boldsymbol{D_h}$	*:* h^{th} *capacity of a cold-water storage tank given in KWh, ∀ h∈ H.*
$\boldsymbol{D_t}$	*: Quantity of cooling demand of a customer in a period, given in KW, t∈ T.*
$\boldsymbol{A}$	*: Maximum installed area of photovoltaics panels, given in* m^2*.*
$\boldsymbol{\tau}$	*: The duration of time periods, given in hour (h).*

3. Decision Variables

The below table (33) shows the decision variables used in the model formulation

Table 33: The Decision Variables of The Mathematical Model

Decision Variables	*Definition*
$\boldsymbol{y_k}$	*: Binary variable that will take value of 1 if a chiller having capacity of Q_k is installed, k∈ K.*
$\boldsymbol{X}$	*: Area of installed the photovoltaics panels, given in (m^2).*
$\boldsymbol{g_h}$	*: Binary variable that will take value 1 if a cold-water storage tank having capacity of D_h is installed, h∈ H.*
$\boldsymbol{F_{kt}^{In}}$	*: Quantity of power consumed by a chiller k∈K in a period t∈ T, given in KW*
$\boldsymbol{F_t^{o}}$	*: Quantity of cooling produced by a chiller in a period t∈ T, given in KW.*
$\boldsymbol{F_t^{In}}$	*: Quantity of power consumed by a chiller in a period t∈ T, given in KW.*
$\boldsymbol{S_t^{CW}}$	*: Quantity of customer's consumption of cooling satisfied from a chiller in a period t∈ T, given in KW.*
$\boldsymbol{L_t}$	*: Quantity of power reaching the photovoltaics panels in a period t∈ T, given in KW.*
$\boldsymbol{L_t^{C}}$	*: Quantity of power produced by photovoltaics panels in a period t∈ T, given in KW.*
$\boldsymbol{I_t^{CW}}$	*: Storage level of stored cooling energy at a storage tank at the end of a period t∈ T, given in KWh.*
$\boldsymbol{E_t}$	*: Quantity of chiller's cooling production, supplied to cold water storage tank in a period t∈ T given in KW.*

Decision Variables	*Definition*
$\boldsymbol{D_t^{CWT}}$	*: Quantity of cooling consumption of a customer, satisfied from cold water storage tank in a period t∈ T given in KW.*
$\boldsymbol{B_t}$	*: Quantity of power supplied by the main grid in a period t∈ T, given in KW.*

4. Objective Function

The objective function (1) minimizes the sum annual of the fixed cost of installing a compression chiller, photovoltaics panels, and a chilled water thermal energy storage tank along with the annual variable cost of producing cold water from the compression chiller, annual variable cost of storing cold water at thermal energy storage tank and annual variable cost of supplying electricity from the main grid. The present value of the investment cost of the components is multiplied by a ratio to convert it to an annual value. The ratio has two important parameters to consider, the interest rate and the life cycle of a component. In this research, all the components are assumed to have the same interest rate and life cycle. Hence, the fixed costs of all components are multiplied by the same ratio.

Minimize $\frac{i*(i+1)^n}{(1+i)^n-1} * [\sum_{k\in K} FC_k^{Ch} y_k + FC^{PV} x + \sum_{t\in T} FC_h^{CW} g_h] + \sum_{t\in T} VC_t^{Ch} F_t^{o} + \sum_{t\in T} VC_t^{Chsto} I_t^{CW} + \sum_{t\in T} VC_i^{Grid} B_t$ *(1)*

Where i:interest rate = 8% and n: life cycle = 20 years

5. Constraints

5.1 Existence Constraints

$\sum_{k\in K} y_k = 1$,*(2)*

Constraint (2) enforces the installation of only one chiller

$\sum_{h\in H} g_h \leq 1$, *(3)*

Constraint (3) enforces that the cold-water storage tank will be assigned with only one capacity if it is installed

5.2 Capacity Constraints

$\frac{L_t}{\eta_{sc} G_t} \leq x \leq A, \forall t \in T$, *(4)*

Constraint (4) introduces the selected photovoltaics panel's total area

$F_t^o \leq \sum_{k\in K} Q_k y_k, \forall t \in T$,*(5)*

Constraint (5) ensures that the production of cooling does not go beyond the capacity of the installed chiller

$I_t^{CW} \leq \sum_{h\in H} D_h g_h, \forall t \in T$, *(6)*

Constraint (6) ensures that the amount of cold-water storage level does not go beyond the capacity of the installed tank

$F_t^o = \sum_{k\epsilon K} COP_k F_t^{In} y_k, \forall t \in T$,*(7)*

Constraint (7) introduces the chiller's COP. However, it needs to be linearized. This is achieved as follows:

$0 \leq F_{kt}^{In} \leq M y_k, \forall t \in T, \forall k \in K$ *(7a)*

$\sum_{k\epsilon K} F_{kt}^{In} = F_t^{In}, \forall t \in T$, *(7b)*

$F_t^o = \sum_{k\epsilon K} COP_k F_{kt}^{In}, \forall t \in T$, *(7c)*

$F_{kt}^{In} \geq F_t^{In} - \left((1-y_k)\, M\right), \forall t \in T, \forall k \in K$*(7d)*

M: Is a very big number M

5.3 Balance Constraints

$I_{t-1}^{CW} + \tau E_t = I_t^{CW} + \tau D_\tau^{CWT}, \forall t \in T$, *(8)*

Constraint (8) imposes the energy balance constraint for the cold storage tank.

5.4 Supply Demand Constraints

$S_t^{CW} + D_t^{CWT} = D_t, \forall t \in T$ *(9)*

Constraint (9) imposes that customer cooling demand could be satisfied by either cold water storage tank or the chiller

$L_t^C + B_t = F_t^{In}, \forall t \in T,$ *(10)*

Constraint (10) enforces that chiller power consumption could be met by photovoltaics panels, or main grid

$L_t^C = L_t, \forall t \in T,$ *(11)*

Constraint (11) enforces that electricity produced by photovoltaics panels is pumped directly into the chiller

$S_t^{CW} + E_t = F_t^o, \forall t \in T,$*(12)*

Constraint (12) enforces that chiller's cooling production could be stored into the cold-water storage tank or pumped directly to satisfy customer demand

5.5 Non-negativity and integrality Constraints

$y_k, g_h \in \{0,1\}$ *k∈K; h∈H;(13)*

$x, F_t^o, F_t^{In}, S_t^{CW}, L_t, L_t^c, I_t^{CW}, E_t, D_t^{CWT}, B_t, F_{kt}^{In} \geq 0,$ *t∈T (14)*

6.6 Experimentation and Numerical Result

The experiments are carried out on the same aforementioned four scenarios which are a Health Center representing low cooling demand, Texas A&M University in Qatar representing medium cooling demand, Lusail city representing high cooling demand and Qatar University campus representing very high cooling demand.

A. Low Cooling Demand

A health service center located in Mekkah in KSA represents the low cooling demand scenario. It has a construction area of 12,410 m^2 and one floor. The daily cooling demand of it is around 1655 TR which is equivalent to 5820.3 kW.

The below table (34) shows the obtained results from the main design case where all the components are presented in the system.

Table 34: Results of Main Design Case of Health Center

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	5,300 kW	903,409	6.7
Photovoltaics Panels (Mono-Crystalline)	Areal = 118.8 m^2	21,978	0.20
Chilled Water Thermal Energy Storage Tank (PTES Type)	63,000 kWh	24,948	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	1,233,924 (96,794 + 1,137,130)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 329,603 iterations and using CPLEX 12.6.3 Solver, solving time is 11689.25 seconds, total time is 11701.66 seconds and the memory used is 2266.8Mb
- There is a chilled water TES installed in the system with a capacity of 63,000 kWh and a cost of 24,948$
- The grid covers 54% of the electricity demand of the chiller while the

photovoltaics panels system covers 46% of the demand

- The annual investment cost of the components represents 8% of the annual total cost while the annual operational cost of the components represents 92% of the annual total cost of the system
- The annual investment cost of compression chiller represents 95% of annual total investment cost which is equivalent to 92,014$
- The annual investment cost of cold-water tank represents 3% of annual total investment cost which is equivalent to 2,541$
- The annual investment cost of Photovoltaics Panels represents 2% of annual total investment cost which is equivalent to 2,239$
- The annual operational cost to produce cold water from the compression chiller represents 92% from the annual total operational cost which is equivalent to 1,048,739$
- The annual operational cost to supply electricity from the grid to the chiller represents 7% from the annual total operation cost which is equivalent to 84,785$
- The solar Photovoltaics Panels system covers the electricity demand of the compression chiller during the day time while the demand is met through the grid in the night time

B. Medium Cooling Demand

Texas A&M University at Qatar represents the medium cooling demand scenario. It has an academic section with an area of 30,800 m^2 and consists of 4 floors. The maximum cooling demand is occurring in August with around 12,445 kW.

The below table (35) shows the obtained results from the main design case where all the components are presented in the system.

Table 35: Results of Main Design Case of Texas A&M University at Qatar

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	12,300kW	2,096,591	6.7
Photovoltaics Panels (Mono-Crystalline)	Area = 253.8 m^2	46,953	0.20
Chilled Water Thermal Energy Storage Tank (PTES Type)	63,000 kWh	24,948	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	2,642,578 (220,865 + 2,421,713)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 202,595 iterations and using CPLEX 12.6.3 Solver, solving time is 3118.20 seconds, total time is 3129.41 seconds and the memory used is 2305.8 Mb
- There is a chilled water TES installed in the system with a capacity of 63,000 kWh and a cost of 24,948$
- The grid covers 54% of the electricity demand of the chiller while the photovoltaics panels system covers 46% of the demand
- The annual investment cost of the components represents 8% of the annual total

cost while the annual operational cost of the components represents 92% of the annual total cost of the system

- The annual investment cost of compression chiller represents 97% of annual total investment cost which is equivalent to 213,542$
- The annual investment cost of cold-water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The annual investment cost of Photovoltaics Panels represents 2% of annual total investment cost which is equivalent to 4,782$
- The annual operational cost to produce cold water from the compression chiller represents 93% from the annual total operational cost which is equivalent to 2,240,489$
- The annual operational cost to supply electricity from the grid to the chiller represents 7% from the annual total operation cost which is equivalent to 181,184$
- The solar Photovoltaics Panels system covers the electricity demand of the compression chiller during the day time while the demand is met through the grid in the night time

C. High Cooling Demand

Lusail Marina District Cooling system at Qatar represents the high cooling demand. It extends over 38 km^2 and more than 200,000 residents will live in the city. The cooling demand of it is around 5000 TR currently which is equivalent to 17,590 kW.

The below table (36) shows the obtained results from the main design case where all the components are presented in the system.

Table 36: Results of Main Design Case of Lusail District

Component	Capacity	Investment Cost ($)	Efficiency
Compression Chiller (Centrifugal Type)	19,350 kW	3,298,295	6.7
Photovoltaics Panels (Mono-Crystalline)	Area = 359.4 m^2	66,489	0.20
Chilled Water Thermal Energy Storage Tank	N/A	N/A	N/A
Annual Total Cost of the System ($) (Annual Investment Cost + Annual Operational Cost)	3,772,549 (342,711 + 3,429,838)		

The main observations of the obtained results are:

- The results obtained from AIMMS software after 137,208 iterations and using CPLEX 12.6.3 Solver, solving time is 1227.84 seconds, total time is 1238.73 seconds and the memory used is 2295.4 Mb
- There is no chilled water TES installed in the system
- The grid covers 54% of the electricity demand of the chiller while the photovoltaics panels system covers 46% of the demand
- The annual investment cost of the components represents 9% of the annual total cost while the annual operational cost of the components represents 91% of the annual total cost of the system

- The annual investment cost of compression chiller represents 98% of annual total investment cost which is equivalent to 335,939$
- The annual investment cost of Photovoltaics Panels represents 2% of annual total investment cost which is equivalent to 6,772$
- The annual operational cost to produce cold water from the compression chiller represents 93% from the annual total operational cost which is equivalent to 3,173,224$
- The annual operational cost to supply electricity from the grid to the chiller represents 7% from the annual total operation cost which is equivalent to 256,614$
- The solar Photovoltaics Panels system covers the electricity demand of the compression chiller during the day time while the demand is met through the grid in the night time

D. Very High Cooling Demand

Qatar University's District Cooling Plant at Qatar represents the very high cooling demand scenario. It extends over 8.1 km^2. And the cooling demand is 6,000 TR which is equivalent to 21,101 kW.

The below table (37) shows the obtained results from the main design case where all the components are presented in the system.

Table 37: Results of Main Design Case of QU District Cooling Plant

Component	Capacity	Investment Cost	Efficiency
Compression Chiller (Centrifugal)	19,350 kW	$3,298,295	6.7
Photovoltaics Panels (Mono-Crystalline)	Area = 429.5 m^2	$79,458	0.20

Component	Capacity	Investment Cost	Efficiency
Chilled Water TES (PTES Type)	63,000 kWh	$24,948	N/A
Total Cost of the System ($) (Investment Cost + Operating Cost)		4,453,115 (346,572 + 4,106,543)	

The main observations of the obtained results are:

- The results obtained from AIMMS software after 55,129 iterations and using CPLEX 12.6.3 Solver, solving time is 484.73 seconds, total time is 494.11 seconds and the memory used is 2303.5 Mb
- There is a chilled water TES installed in the system with a capacity of 63,000 kWh and a cost of 24,948$
- The grid covers 54% of the electricity demand of the chiller while the photovoltaics panels system covers 46% of the demand
- The annual investment cost of the components represents 8% of the annual total cost while the annual operational cost of the components represents 92% of the annual total cost of the system
- The annual investment cost of compression chiller represents 97% of annual total investment cost which is equivalent to 335,939$
- The annual investment cost of cold-water tank represents 1% of annual total investment cost which is equivalent to 2,541$
- The annual investment cost of Photovoltaics Panels represents 2% of annual total investment cost which is equivalent to 8,093$
- The annual operational cost to produce cold water from the compression chiller

represents 92% from the annual total operational cost which is equivalent to 3,791,596$

- The annual operational cost to supply electricity from the grid to the chiller represents 7% from the annual total operation cost which is equivalent to 306,561$
- The solar Photovoltaics Panels system covers the electricity demand of the compression chiller during the day time while the demand is met through the grid in the night time

To conclude this section, we can notice from the results generated, that design case 3 representing the high cooling demand scenario is the only design case where no chilled water thermal energy storage tank is installed. The reason is a compression chiller with a high capacity exceeds the maximum cooling demand of the application is installed in the optimized system. Hence, it eliminates the need to install a chilled water tank in the system. Another observation to highlight is the type and the capacity of chilled water thermal energy storage installed for the other design cases is the same which is PTES type with a capacity of 63,000 kWh and a cost of 24,948$.

6.7 Sensitivity Analysis

The sensitivity analysis is conducted on the fourth scenario which is very high cooling scenario. During the sensitivity analysis, one parameter is varied at a time while the other parameters are kept fixed. The sensitivity analysis is performed on the following key parameters, unit price of the photovoltaics panels and their efficiency. Their values are varied between 20% and -20% of the base value. These values are showed on the x-axis. While the y-axis shows the percentage of Total Cost Difference (PTCD) calculated using the following equation:

$$PTCD = \frac{New\ Cost - Base\ Cost}{Base\ Cost}\ x\ 100$$

The purpose of this analysis is to examine and measure how the changes of each parameter are sensitive to the optimal solution. The below table (38) shows the parameters studied during the sensitivity analysis along with the maximum and the minimum values that the base value is varied at using the incremental values.

Table 38: Parameters Studied During Senstivity Analysis

Parameter	Maximum Value (20%)	Base Value	Minimum Value (-20%)	Incremental Value
Photovoltaics Panels Unit Cost ($\$/m^2$)	222	185	148	3.7
Photovoltaic Panels Efficiency	0.16	0.20	0.24	0.004

Most of the trends generated from sensitivity analysis are almost straight-line trends which means a direct proportional relationship between the parameters and the annual total system cost was obtained for Photovoltaics panels unit cost and their efficiencies as indicated from the R^2 value. The below table (39) summarizes the results obtained from the analysis as it highlights the parameters that have a significant effect on the annual total system cost compared to other parameters.

Table 39: Results of Senstivity Analysis

Parameters	Maximum Annual Cost Difference Percentage (20%)	Minimum Annual Cost Difference Percentage (-20%)	Generated Straight Line Equation	Coefficient of Determination R^2
Photovoltaics Panels Unit Cost ($\$/m^2$)	0.0363	-0.0364	y = 0.0036x - 0.04	$R^2 = 1$
Photovoltaic Panels Efficiency	-0.0301	0.0436	y = -0.0036x + 0.0422	$R^2 = 0.9901$

The table (39) shows that both of the parameters have almost the same effect on the annual total system cost based on the generated straight-line equation. However, the PV unit cost parameter exhibits a linear relationship between varying the unit cost parameter and annual total system based on R^2 value which is more than R^2 obtained from varying the PV efficiency parameter. If the PV unit cost decreases by 20%, the annual total system cost will decrease by -0.0364% and the new annual total system cost will be 4,451,496$. While if the PV efficiency increases by 20%, the annual total system cost will decrease by -0.0301% and the new annual total system cost will be 4,451,774$. Hence, the focus should be on decreasing the PV unit cost parameter as it will decrease the annual total system cost by a percentage a little bit more than the percentage obtained from increasing the PV efficiency. The difference between the two percentages is around 0.0063% and it is an insignificant difference. So, if decreasing the PV unit cost parameter is not an option due to reasons related to the technology unavailability, then the user should focus on increasing the PV efficiency parameter.

The below graph (19) shows the behavior, straight line equations and coefficient of determination of the two parameters.

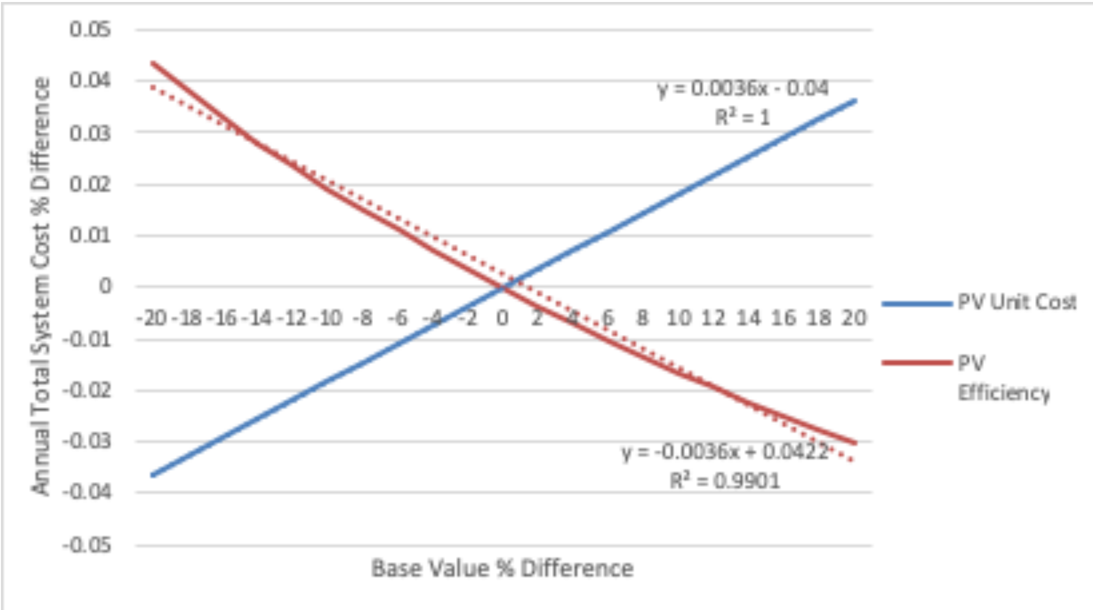

Figure 19: Senstivity analysis of parameters

6.8 Economical Comparison Between Three Models

6.8.1 Design Cases Comparison. This section compares the results obtained from the main design cases of the three developed models.

- **Low Cooling Demand Design Case**

The below table (40) shows and compares annual costs obtained from the three models.

Table 40: Comparison between Three Models on First Design Case

Component	Solar Thermal System	Conventional System	Solar Electric System
Chiller	1,053,280 $	903,409 $	903,409 $
Hot Water Tank	N/A	N/A	N/A
Chilled Water Tank	N/A	24,948 $	24,948 $
Solar Collectors	67,170 $	N/A	N/A
Photovoltaics Panels	N/A	N/A	21,978 $
Auxiliary Boiler	123,096 $	N/A	N/A
Annual Total Cost of System (Annual Investment Cost + Annual Operational Cost)	1,589,951 $ (126,660 + 1,463,291)	1,303,429 $ (94,555 + 1,208,874)	1,233,924 $ (96,794 + 1,137,130)

From the above table (40), we can notice the annual total cost of solar electric system is the cheapest cooling system by 69,505$ (6%) compared to conventional system and by 356,027$ (29%) compared to solar thermal system. To give more insights on this difference, the annual operational cost of the solar electric system is cheaper than conventional and solar thermal system by 6% and 29% respectively. This is explained by almost half of the electricity demand of the compression chiller in the solar electric system is covered by the solar photovoltaics system where in the conventional system all the electricity demand of the chiller is covered by the main grid. Moreover, in comparison with the solar thermal cooling system, the solar electric system doesn't have an auxiliary boiler installed in the system as it depends on the PV during daytime and the grid in the night time. Whereas, the boiler in the solar thermal system works during daytime and nighttime. Thus, that reduces the annual operational cost of the solar electric system. Regarding the annual investment cost, the solar electric system lies between the two systems, where it is cheaper than the solar thermal system by 31% as it has less expensive components installed in the system. However, its more expensive than the conventional system by 2% only due to more components installed in the system such as the existence of the PV system.

- **Medium Cooling Demand Design Case**

The below table (41) shows and compares annual costs obtained from the three models.

Table 41: Comparison between Three Models on Second Design Case

Component	Solar Thermal System	Conventional System	Solar Electric System
Chiller	1,746,960 $	2,096,591 $	2,096,591 $
Hot Water TES	N/A	N/A	N/A
Chilled Water TES	24,948 $	24,948 $	24,948 $
Solar Collectors	143,520 $	N/A	N/A
Photovoltaics Panels	N/A	N/A	46,953 $
Auxiliary Boiler	205,160 $	N/A	N/A

Component	Solar Thermal System	Conventional System	Solar Electric System
Annual Total Cost (Annual Investment & Operational Cost)	3,342,561$ (215,988 + 3,126,573)	2,791,014$ (216,084 + 2,574,930)	2,642,578$ (220,865 + 2,421,713)

From the above table (41), we can notice the annual total cost of solar electric system is the cheapest cooling system by 148,436$ (6%) compared to conventional system and by 699,983$ (26%) compared to solar thermal system. To give more insights on this difference, the annual operational cost of the solar electric system is cheaper than conventional and solar thermal system by %6 and 29% respectively. This is explained by almost half of the electricity demand of the compression chiller in the solar electric system is covered by the solar photovoltaics system where in the conventional system all the electricity demand of the chiller is covered by the main grid. Moreover, in comparison with the solar thermal systems, the solar electric system doesn't have an auxiliary boiler installed in the system as it depends on the PV during daytime and the grid in the nighttime. Whereas, the boiler works daytime and nighttime in the solar thermal cooling system. Thus, that reduces the annual operational cost of the solar electric system. Regarding the annual investment cost, the solar electric system is the most expensive compared to other systems. It is expensive than the solar thermal system and conventional system by 2%, as more expensive components such chillers and more components installed in the system.

- **High Cooling Demand Design Case**

The below table (42) shows and compares annual costs obtained from the three models.

Table 42: Comparison between Three Models on Third Design Case

Component	Solar Thermal System	Conventional System	Solar Electric System
Chiller	2,568,031$	3,298,295 $	3,298,295 $
Hot Water Tank	N/A	N/A	N/A
Chilled Water Tank	N/A	N/A	N/A
Solar Collectors	203,280$	N/A	N/A
Photovoltaics Panels	N/A	N/A	66,489 $
Auxiliary Boiler	318,750$	N/A	N/A
Annual Total Cost of System (Annual Investment Cost + Annual Operational Cost)	4,742,285$ (314,730 + 4,427,555)	3,982,778$ (335,939 + 3,646,840)	3,772,549$ (342,711 + 3,429,838)

From the above table (42), we can notice the annual total cost of solar electric system is the cheapest cooling system by 210,229$ (6%) compared to conventional system and by 969,736$ (26%) compared to solar thermal system. To give more insights on this difference, the annual operational cost of the solar electric system is cheaper than conventional and solar thermal system by %6 and 29% respectively. This is explained by almost half of the electricity demand of the compression chiller in the solar electric system is covered by the solar photovoltaics system where in the conventional system all the electricity demand of the chiller is covered by the main grid. Moreover, in comparison with the solar thermal systems, the solar electric system doesn't have an auxiliary boiler installed in the system as it depends on the PV during daytime and the grid in the nighttime. Whereas, the boiler works daytime and nighttime in the solar thermal cooling system. Thus, that reduces the annual operational cost of the solar electric system. Regarding the annual investment cost, the solar electric system is the most expensive compared to other systems. It its expensive than the solar thermal system and conventional system by 8% and 2%, respectively, since more expensive components such chillers and more components installed in the system.

- **Very High Cooling Demand Design Case**

The below table (43) shows and compares annual costs obtained from the three models.

Table 43: Comparison between Three Models on Fourth Design Case

Component	Solar Thermal System	Conventional System	Solar Electric System
Chiller	3,493,920$	3,298,295$	3,298,295$
Hot Water Tank	24,948$	N/A	N/A
Chilled Water Tank	N/A	24,948$	24,948$
Solar Collectors	242,910$	N/A	N/A
Photovoltaics Panels	N/A	N/A	79,458$
Auxiliary Boiler	318,750$	N/A	N/A
Annual Total Cost of System (Annual Investment Cost + Annual Operational Cost)	5,705,970$ (415,610 + 5,290,360)	4,704,371$ (338,479 + 4,365,892)	4,453,115$ (346,572 + 4,106,543)

From the above table (43), we can notice the annual total cost of solar electric system is the cheapest cooling system by 251,256$ (6%) compared to conventional system and by 1,252,855$ (28%) compared to solar thermal system. To give more insights on this difference, the annual operational cost of the solar electric system is cheaper than conventional and solar thermal system by %6 and 29% respectively. This is explained by almost half of the electricity demand of the compression chiller in the solar electric system is covered by the solar photovoltaics system where in the conventional system all the electricity demand of the chiller is covered by the main grid. Moreover, in comparison with the solar thermal systems, the solar electric system doesn't have an auxiliary boiler installed in the system as it depends on the PV during daytime and the grid in the nighttime. Whereas, the boiler works daytime and nighttime in the solar thermal cooling system. Thus, that reduces the annual operational cost of the solar electric system. Regarding the annual investment cost, the solar electric system lies between the two systems, where it is cheaper than the solar thermal system by 20% since it has less expensive and less components installed in the system. However, its more expensive than the conventional system by 2% where more components installed in the system such as the existence of PV system.

To conclude this section, from the generated results on the four design cases, we can notice the following:

- The solar electric cooling system is always the cheapest system in terms of annual total system cost by an average of 6% compared to conventional system and by 27% compared to solar thermal system
- The annual operational cost of the solar electric system is always the cheapest by 6% compared to conventional system and by 29% compared to solar thermal system

- The annual investment cost of the solar electric system is never the cheapest where either it lies between the two other systems or it is the most expensive. In the first and fourth design case, the annual investment cost of the solar electric lies between the two systems as its cheaper than solar thermal on an average of 26% and more expensive than conventional system by 2%. However, in the second and third design case, the annual investment cost of the solar electric system is the most expensive by 2% compared to conventional system and by an average of 5% compared to solar thermal system

6.8.2 Sensitivity Analysis on Electricity Prices. The sensitivity analysis is performed on the fourth scenario which is the very high cooling demand. The analysis is carried out on the electricity prices which are reflected on the following parameters, the variable cost per unit of producing chilled water from the compression chiller, the variable cost per unit of storing chilled water in the chilled water thermal energy storage tank, the variable cost per unit of storing hot water in the hot water thermal energy storage tank, and the variable cost of supplying electricity from the main grid to the chiller. Currently the price of the electricity is around 0.055 $/kW according to kahramma website. The price of the electricity is varied from this base value to a maximum value of 20% of the base value, since the electricity prices always increases and never decreases. The purpose of this analysis is to examine and measure how the changes of these parameters are sensitive to the optimal solution. The sensitivity analysis is performed on the annual total system cost of the three models (Solar thermal Cooling System, Conventional Cooling System and Solar Electric Cooling System). The graph is generated using the below equation:

$$PTCD = \frac{New\ Cost - Base\ Cost}{Base\ Cost}\ x\ 100$$

The below table (44) shows the parameters studied during the sensitivity analysis along with the maximum values the base value varied at using the incremental values.

Table 44: Parameters Studied During Senstivity Analysis

Parameter	Base Value	Maximum Value	Incremental Value
Variable cost per unit of producing chilled water	0.055	0.066	0.00055
Variable cost per unit of storing chilled water	0.055	0.066	0.00055
Variable cost per unit of storing hot water	0.055	0.066	0.00055
Variable cost of supplying electricity from main grid to the chiller	0.055	0.066	0.00055

The below table (45) shows the results obtained from the sensitivity analysis conducted on three models.

Table 45: Results of Senstivity Analysis

Model	Maximum Annual Cost Difference Percentage (20%)	Generated Straight Line Equation	Coefficient of Determination R^2
Solar Thermal System	18.54%	$y = 0.9272x - 0.9272$	$R^2 = 1$

Model	Maximum Annual Cost Difference Percentage (20%)	Generated Straight Line Equation	Coefficient of Determination R2
Conventional System	18.56%	y = 0.9281x - 0.928	$R^2 = 1$
Solar Electric System	18.44%	y = 0.9222x - 0.9222	$R^2 = 1$

The table (45) and below graph (20) show the three models exhibit a linear relationship between varying the electricity prices and the annual total system cost as indicated by the generated R^2 value which is equal to 1. However, in terms of the generated straight-line equations, the three models have very close slope values, but the solar electric system has the lowest slope among them. The slope indicates the solar electric system will have the least annual system cost compared to other systems when the electricity prices vary. So, if the electricity prices increase by 20%, the annual total system cost of solar thermal system will increase by 18.54% and the annual total cost will reach to 6,764,042$, conventional system will increase by 18.56% and it is equivalent to 5,577,549$ and solar electric system will increase by 18.44% and it is equivalent to 5,274,423$. The difference between these values and their respected base values are 1,058,072$, 873,178$ and 821,308$ for solar thermal, conventional and solar electric cooling system respectively. So, the solar electric system will have the least annual total system cost compared to other systems which makes it the most economical system.

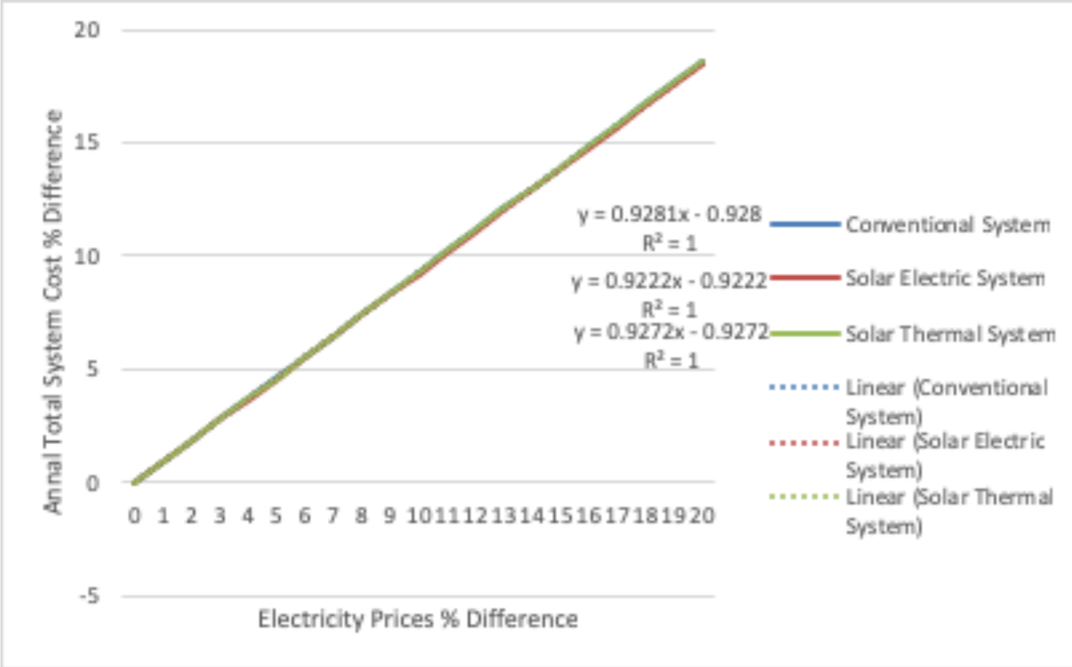

Figure 20: Senstivity analysis on parameters

6.9 Sustainable Comparison Between Three Models

This section briefly compares the three developed models in terms of the contribution of the solar energy to satisfy the chiller demand for heat or electricity in the system.

First Model: Solar Thermal Cooling System

In this system, on an average the solar collectors satisfy 46% of heat demand of the absorption chiller. While the other 54% are satisfied by the installed auxiliary boiler.

Second Model: Conventional Cooling System

In this system, no renewable energy is used to power the compression chiller. Hence, the electricity demand of the compression chiller is satisfied by the electricity grid.

Third Model: Solar Electric Cooling System connected to grid

On an average the photovoltaics panels satisfy 46% of electricity demand of the compression chiller. While the other 54% are satisfied by the main electricity grid.

Chapter 7: Research Conclusion and Future Work

This chapter summarizes the results obtained from the three developed models. (the solar thermal system, the conventional system, and the solar electric cooling system system). Lastly, the future work and extensions that can be carried out in this area of research are discussed in the last section.

7.2 Model 1: Conventional Cooling System

This section summarizes the results obtained from the second model of the conventional cooling system. The main components of the system were compression chiller, and cold-water TES. This system was connected to the main grid to supply electricity to the compression chiller. The objective function of the developed MILP was to minimize the sum of the annual investment costs of the aforementioned components along with their corresponding annual operational costs. Four scenarios were solved using the developed model; a health center at KSA, Texas A&M University at Qatar, Lusail city and QU District Cooling Plant. From the generated results, it was noticed as the application size increases, the annual total system cost increases. The annual total system cost increased from 1,303,429$ for the low cooling demand scenario to 4,704,371$ for the very high cooling demand scenario. Moreover, the results obtained indicated on an average the annual investment and annual operational cost represented 7% and 93%, respectively of the annual total system cost. Another observation to highlight the high cooling demand scenario was the only design case where no cold-water TES was installed due to the capacity of the compression chiller exceeded the maximum cooling demand of the application. While the rest scenarios had a cold-water TES of the same capacity. Furthermore, the results showed on an average the annual operational cost to produce chilled water from the chiller was around 87% while the remaining 13% are related to operational cost to supply electricity from the main grid to the chiller.

Finally, a sensitivity analysis was carried out on the parameters related to electricity variable costs of the fourth scenario. The variable costs were varied from their base value to a maximum value of 20% of base value. The results indicated that the annual total system cost increases by 873,178$ if the electricity prices increase by 20%.

7.2 Model 2: Solar Thermal Cooling System

This section summarizes the results obtained from the first model of the solar thermal cooling system. The main components of the system were absorption chiller, auxiliary boiler, hot water TES, cold water TES and solar collectors. The objective function of the developed MILP was to minimize the sum of the annual investment costs of the aforementioned components along with their corresponding annual operational costs. Four scenarios were solved using the developed model; a health center at KSA, Texas A&M University at Qatar, Lusail city and QU District Cooling Plant. In this section, two design cases were solved for each scenario, a main design case where all the components existed in the system and a special design case where the auxiliary boiler was absent from the system.

First, comparing between the results of main design cases of four scenarios, it was noticed as the application size increases, the annual total system cost increases. The annual total system cost increased from 1,589,951$ for the low cooling demand scenario to 5,705,970$ for the very high cooling demand scenario. Another observation to highlight on an average the solar collectors and auxiliary boiler covered 46% and 54%, respectively of the heat demand required by the absorption chiller. Moreover, the results obtained indicated on an average the annual investment and annual operational cost represented 7% and 93%, respectively of the annual total system cost. Also, the results highlighted in the low and high cooling demand scenario, no hot or cold-water

TES were installed. That was explained by the capacity of the absorption chiller exceeded the maximum cooling demand of the application. However, in the medium cooling demand scenario, a chilled water TES was installed due to the capacity of the absorption chiller was smaller than the maximum cooling demand of the application hence, cold water with large quantities needed to be stored at cold water TES tank for consumptions at later times. In the very high cooling demand scenario, no cold-water TES was installed as the capacity of the absorption chiller was larger than the maximum cooling demand of the application. Hence, no cold water was required to be stored for peak demand consumptions.

Second, comparing between the results of special cases of four scenarios, it was noticed for the scenarios that didn't have a hot water TES in their main design, in this case there was an existence of hot water TES tank. And for the scenarios which already had a hot water TES tank in their main design case, in this case the capacity of the hot water TES increased to store more hot water during daytime to be consumed in the nighttime as solar collectors were the only source to meet the chiller demand for hot water during daytime.

Moving on to comparing between the results of main and special design case for each scenario, its noteworthy to mention in the special design case, the total annual system cost increased by 159% compared to the main design case where the annual investment cost increased by 60% due to area of solar collectors increased by 1017% and the existence or the increasing capacity of hot water TES compared to main design case. The annual operational cost increased by 166% compared to the main design case and one of the main reasons was due to more hot water needed to be stored at the tank during daytime to be consumed at nighttime when the sun was absent.

Finally, a sensitivity analysis was carried out on parameters related to the system components of the fourth scenario. The results indicated that COP of the chiller had the highest and most significant impact on the annual total system cost as indicated by the slope of the straight-line equation and other indicators. And the fixed cost of the chiller had the second most effect.

7.3 Model 3: Solar Electric Cooling System

This section summarizes the results obtained from the third model of the solar electric cooling system. The main components of the system were compression chiller, cold water TES and photovoltaics panels. This system was connected to the main grid to supply electricity to the compression chiller during nighttime. The objective function of the developed MILP was to minimize the sum of the annual investment costs of the aforementioned components along with their corresponding annual operational costs. Four scenarios were solved using the developed model; a health center at KSA, Texas A&M University at Qatar, Lusail city and QU District Cooling Plant. From the generated results, it was noticed as the application size increases, the annual total system cost increases. The annual total system cost increased from 1,233,924$ for the low cooling demand scenario to 4,453,115$ for the very high cooling demand scenario. An interesting point to highlight 54% of the electricity demand of the chiller was satisfied by the grid while the remaining 46% was satisfied by the photovoltaics panels. Moreover, the results indicated on an average the annual investment and annual operational cost represented 8% and 92%, respectively of the annual total system cost. Another observation to point out the high cooling demand scenario was the only design case where no cold-water TES was installed due to the capacity of the compression chiller exceeded the peak cooling demand of the application. While the rest scenarios had a cold-water TES of the same capacity. Furthermore, the results showed on an average the annual operational cost to produce chilled water from the chiller was around

93% while the remaining 7% are related to operational cost to supply electricity from the main grid to the chiller.

A sensitivity analysis was carried out on parameters related to system components. The values of the parameters varied between -20% to 20% of their base values. The results indicated the fixed cost of PV panels and its efficiency had almost the same effect on the annual total system cost. However, the unit cost of the PV panels had a little bit more effect on the annual total system cost compared to the other parameter. So, the focus should be on reducing the unit cost of PV panels to reduce the annual total system cost significantly.

At the end of this section, a comparison between the three developed models was conducted. The comparison was made on each of four scenarios of three models based on the objective function. In all of scenarios, the solar electric cooling system had the minimum annual total system cost (most economical system) where on an average it was cheaper than the conventional system and solar thermal cooling system by 6% and 27% respectively. This was explained by the annual operational cost of the solar electric cooling system was cheaper by 6% compared to conventional cooling system and by 29% compared to solar thermal cooling system. Therefore, the solar electric system was the most economical system. Also, the comparison included performing a sensitivity analysis on the electricity prices. The sensitivity analysis was conducted on the fourth scenario of each of the three models. The electricity prices were varied from their base value to a maximum value of 20% of base value. The results showed the three models had almost the same effect when the electricity prices increased. Nonetheless, the solar electric cooling system model had the smallest percentage difference which indicated as the electricity prices increase, the annual total system cost increases by the smallest percentage compared to percentages of the other two models. This was another indication the solar electric cooling system was the most economical system.

7.4 Future Work

One of the areas that has great importance is to focus on the reduction of CO_2 to reach a zero-carbon system, since the interim nature of solar irradiance requires the solar assisted cooling system to use cooling/ heating auxiliary components driven by electricity. This can be accomplished in various ways, either through the adaption of other sustainable energy resources to operate the auxiliary components or by including solar photovoltaics panels to produce electricity.

Moreover, extensions to the current developed models can be part of the future work such as considering the individual variable costs for each different type of system's components separately in the objective function, this will create more parameters, hence more data to collect. In addition, the objective function will become a non-linear that must be linearized before solving. Another possible extension to be considered is building a hybrid solar cooling system where all components including solar collectors, photovoltaics panels, compression chillers, absorption chillers and hot and cold water TES are integrated simultaneously in the system. The system to be optimized through developing and solving a MILP to obtain the minimum annual total system cost while achieving the optimal system configuration.

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Appendices

Appendix A: Data Collected on Absorption Chiller Components

New Fixed Cost ($)	New Capacity (kW)	COP
8120	35	0.6
16704000	12000	0.8
2784000	6000	0.75
5568000	12000	0.75
5846400	12600	0.75
8352000	18000	0.75
153335.76	150	0.7
116998.76	50	0.7
128598.76	100	0.7
145998.76	200	0.7
151798.76	250	0.7
163398.76	300	0.7
174998.76	350	0.7
184990.15	400	0.7
198198.76	450	0.7
600000	176	0.7
2024000	1547	0.74
4752000	4642	0.79
1980000	1161	1.42
5808000	4642	1.42
2178000	1161	1.35

4000000	3517	1.38
124120	233	1.36
229680	582	1.36
283040	872	1.36
338720	1163	1.36
399040	1454	1.36
443120	1745	1.36
559120	2326	1.36
650760	2908	1.36
737760	3489	1.36
892040	4652	1.36
1053280	5830	1.36
1195960	7000	1.36
1512640	9304	1.36
3493920	24000	1.36
5240880	36000	1.36
6987840	48000	1.36
8734800	60000	1.36
1746960	12000	1.36
80000	100	0.5
2150000	5000	1.3
1228000	2000	1.2
737000	1000	1.1
460500	500	0.8
2568031.2	17640	1.36

Appendix B: Data Collected on Solar Collector Components

Solar collector	Fixed Cost ($/m2)	Efficiency
SWH, flat plate and evacuated tube	162$/m2	0.70
Flat collector FK250		0.802
Flat collector FK500		0.811
Flat Collector GK3000		0.82
Flat Collector	300 $/m2	0.75
	300 $/m2	0.75
	300 $/m2	0.75
	300 $/m2	0.75
	300 $/m2	0.75
	500 $/m2	0.75
	500 $/m2	0.75
	500 $/m2	0.75
	500 $/m2	0.75
	500 $/m2	0.75
	700 $/m2	0.75
	700 $/m2	0.75
	700 $/m2	0.75
	700 $/m2	0.75
	700 $/m2	0.75
	900 $/m2	0.75
	900 $/m2	0.75
	900 $/m2	0.75

900 $/m2	0.75
900 $/m2	0.75
1100 $/m2	0.75
1100 $/m2	0.75
1100 $/m2	0.75
1100 $/m2	0.75
34.19 - 56.98 $/m2	
102.56 - 170.93 $/m2	
650 $/m2	0.40
429.61 $/m2	0.40
859.23 $/ m2	0.40
1287.70 $/m2	0.40
533 $/m2	0.21
505 $/m2	
159 $/m2	
339 $/m2	0.38
360 $/m2	0.43
333.33 $/m2	0.45
346 $/m2	0.36
310 $/m2	0.35
827.32 $/m2	0.327
747.55 $/m2	0.268
708.80 $/m2	0.212
1220.46 $/m2	0.316

	731.59 $/m2	0.371
	711.08 $/m2	0.356
	920.76 $/m2	0.345
	589.15 $/m2	0.346
	1125 $/m2	0.70
Vacuum Tube	847 $/m2	0.49
	621 $/m2	0.36
Evacuated Tube	1,154$/m2	0.44
	858 $/m2	0.63
	827$/m2	0.54
	576 $/m2	0.39
	815 $/m2	0.52
	1148 $/m2	0.57
	740 $/m2	0.42
	2,000$/m2	
	1,095 $/m2	
Parabolic	411 $/m2	

Appendix C: Data Collected on Hot and Cold Water Thermal Energy Storage

Thermal Energy Storage Type (TES)	New Capacity (kWh)	New Investment Cost ($)
Water Tank (TTSE)	1230898	360294
	8616289	2522059
	1195730	350000
	8370110	2450000
	2285954	455000
	2180449	434000
	3165168	630000
	6330335	1260000
	18991005	3780000
	703371	500000
	50	580
	14	488.4
	4	1069
	375000	495000
	938	237600
	1278	308880
	1440000	1900800
	8640000	11404800
	855000	1128600
	156900	740305
	261621	1105887
	600966	1398353

Hot Water Tank (PTES)	12000000	4752000
	4500000	1782000
	3600000	1425600
	7200000	2851200
	84000	33264
	270000	106920
	63000	24948
	75663	29963
	126000	49896
	90000	35640
	58106	462690.63
	40758	196500
	307246	726595
	579710	913956
	4330985	3513021
Hot Water Tank (BTES)	285000	150480
	562000	297000
	504855	266563
	900000	475200
	949500	501336
	140250	73920
	290322	514100
	261627	257050
	619008	855692
Hot water tank	576000	5220000

	2556	617760
	1876	475200
	2814	712800
	500	58000
	750	87000
	1000	116000
	1250	145000
	1500	174000
	1750	203000
	2000	232000
	2250	261000
	2500	290000
	17482	163369
	34865	311887.76
Chilled water tank	998786	626600
	2707977	913000

Appendix D: Data Collected on Auxiliary Boiler Components

Type	Fixed Cost ($)	New Capacity (kW)	Efficiency
Gas Boiler	4640000	50000	0.55
Oil Boiler	4640000	50000	0.8
	1392000	10000	0.8
	4176000	30000	0.8
	5568000	40000	0.8
	6960000	50000	0.8
	2784000	20000	0.8
Liquid Fuel Boiler	2250000	60	0.6
	4230000	120	0.6
	9900000	300	0.6
	18900000	600	0.65
	36900000	1200	0.65
	74250000	3000	0.7
	148500000	6000	0.7
	222750000	9000	0.7
	297000000	12000	0.7
Coal Boiler	2250000	60	0.5
	4230000	120	0.5
	9900000	300	0.5
	18900000	600	0.55
	36900000	1200	0.55
	74250000	3000	0.6
	41032	2052	0.85

	182438	733	0.8
	1459504	5861	0.8
	103010	733	0.8
	486156	440	0.8
	101278	733	0.8
	180674	440	0.8
	95125	733	0.8
	88475	586	0.8
Electric boilers (EU-27)	7047	25	0.96
Electric Boiler (EU-27)	24000	100	0.96
	57000	250	1
	1328100	5875	1
Electric Boiler	11750	165	0.98
Gas Boiler	32450	234	0.85
Oil Boiler	31500	234	0.82
	82064	4104	0.85
	123096	6156	0.85
	164128	8208	0.85
	205160	10260	0.85
	246192	12312	0.85
	125000	7000	0.85
	254398.4	12722	0.85
	318750	17850	0.85

Appendix E: Data Collected on Global Solar Radiation

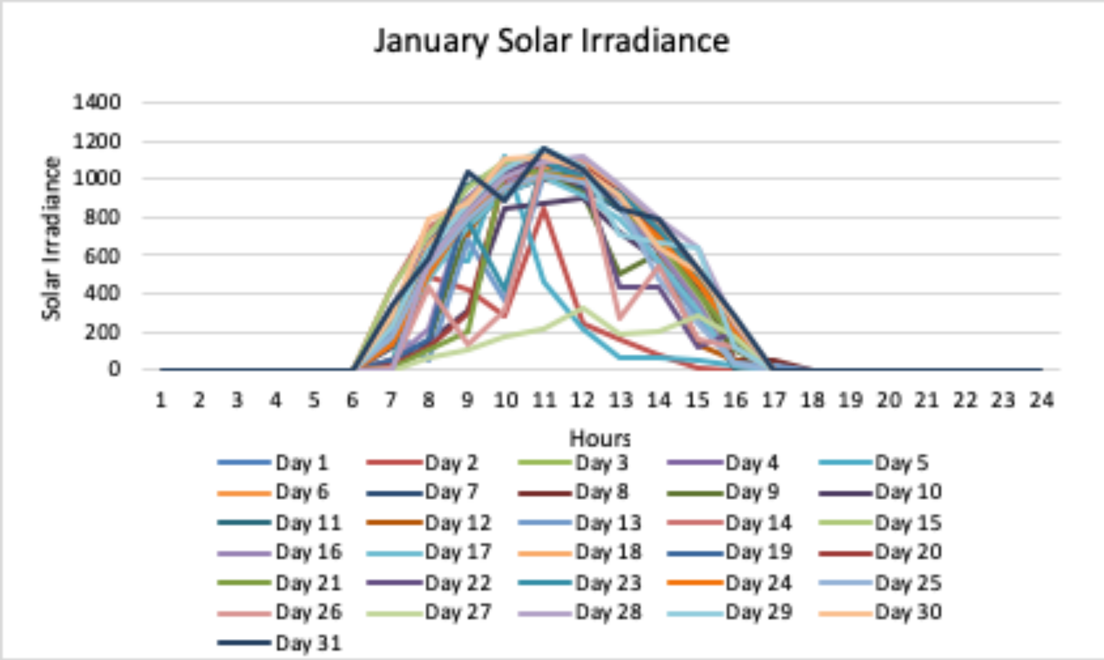

Figure 21: January solar global solar irradiance

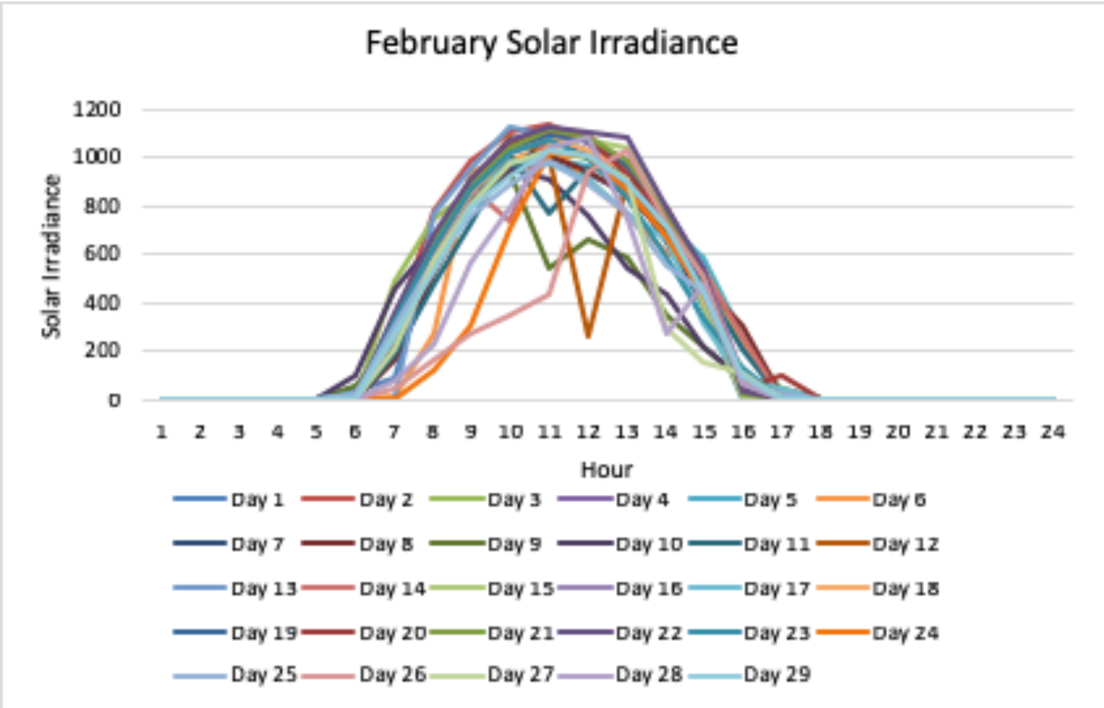

Figure 22: February solar global solar irradiance

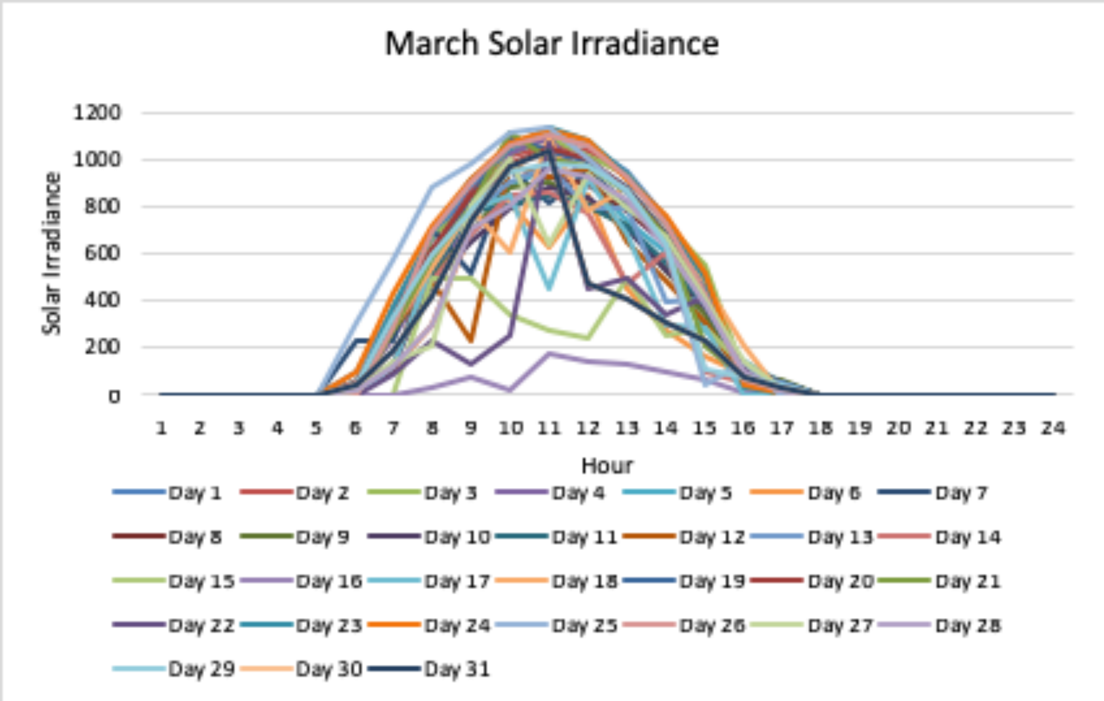

Figure 23: March solar global solar irradiance

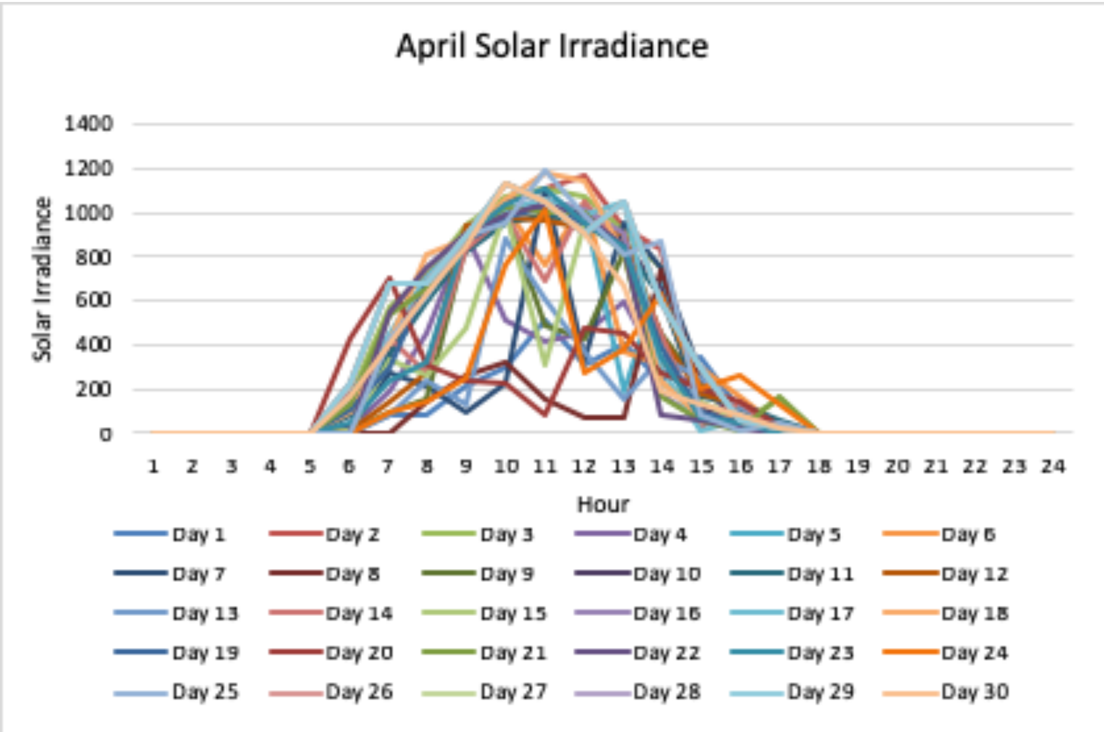

Figure 24: April global solar irradiance

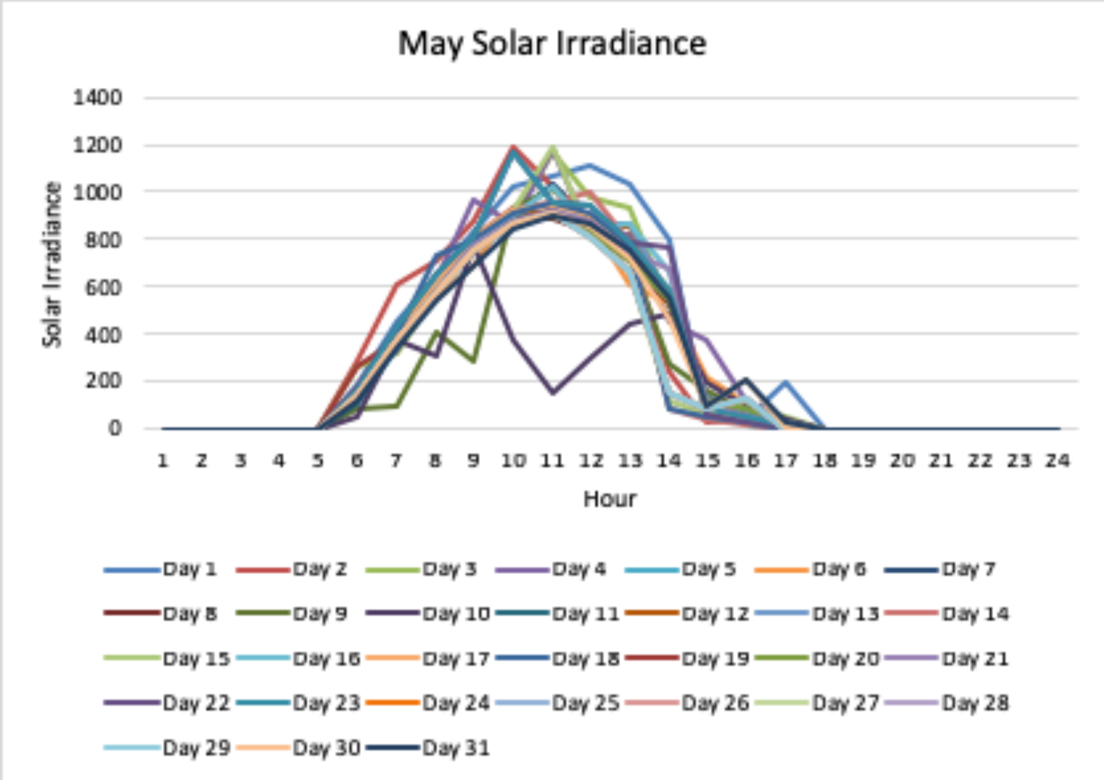

Figure 25: May global solar irradiance

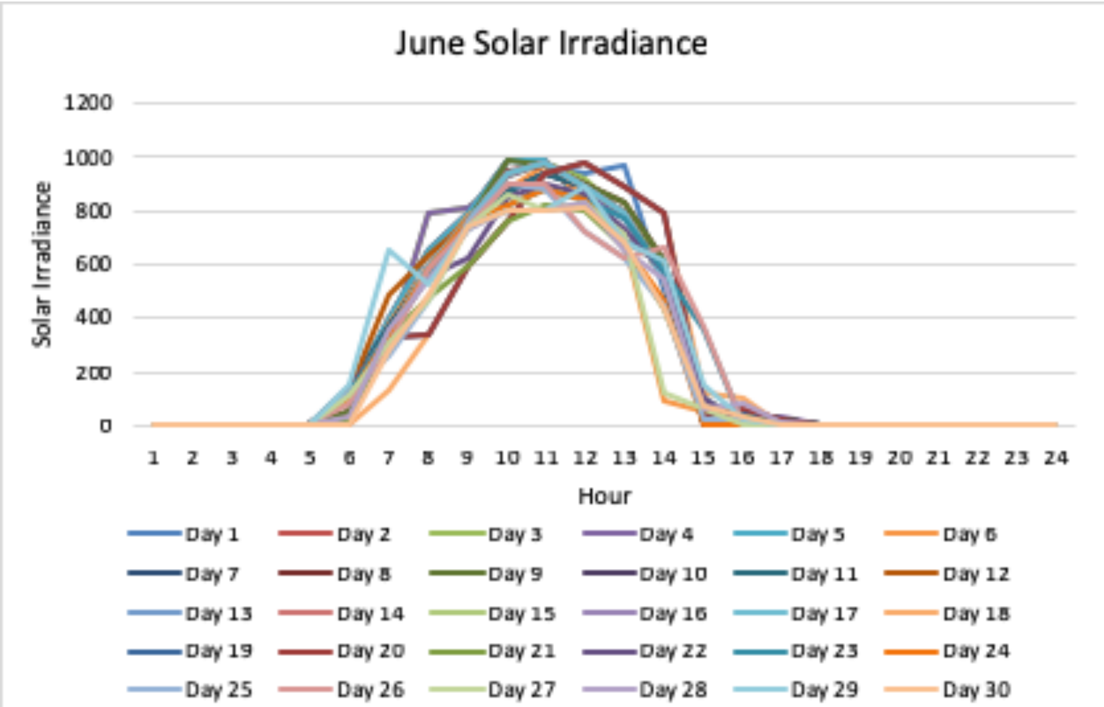

Figure 26: June global solar irradiance

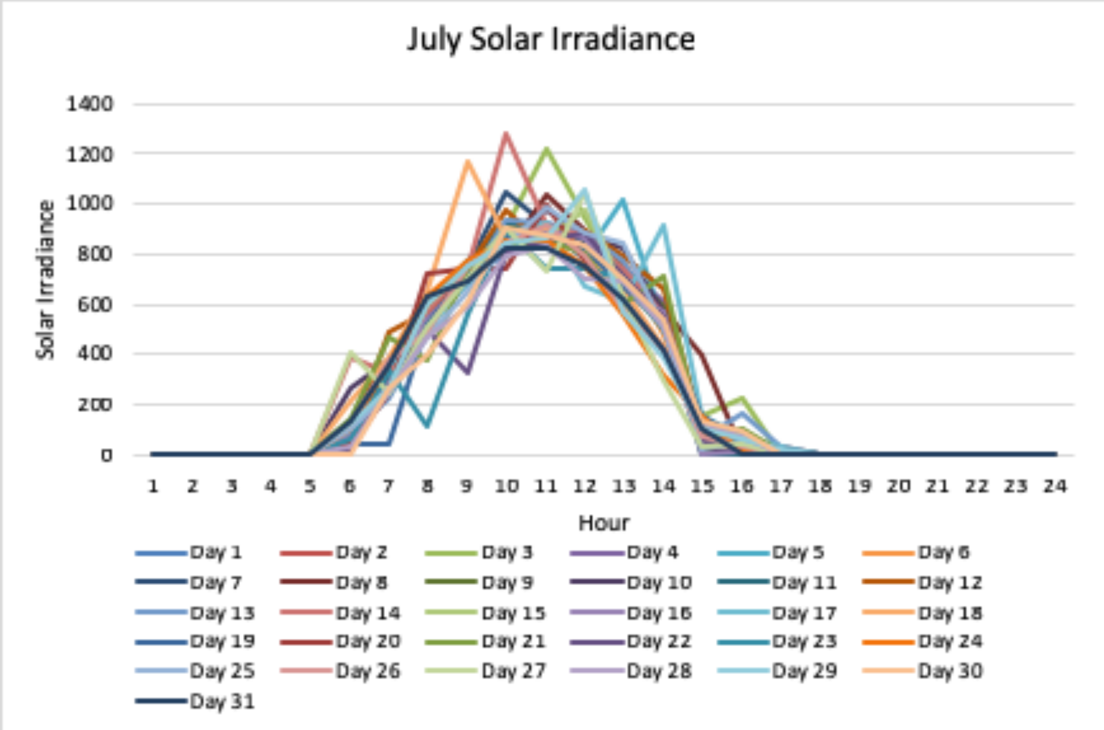

Figure 27: July global solar irradiance

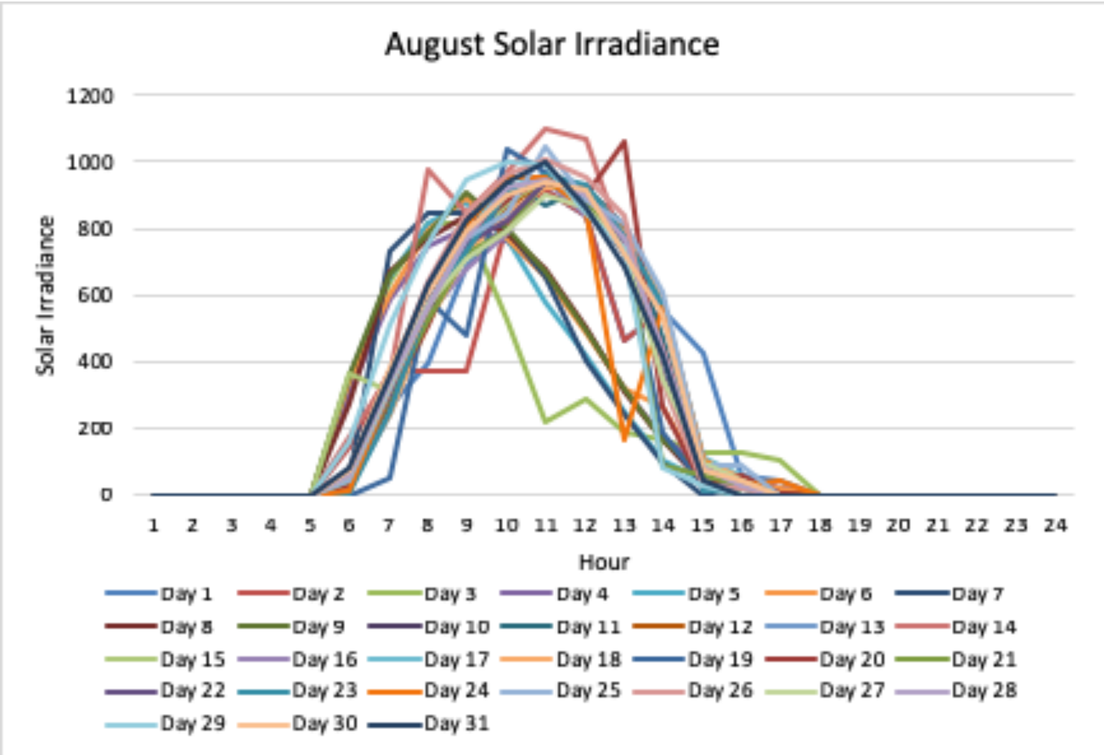

Figure 28: August global solar irradiance

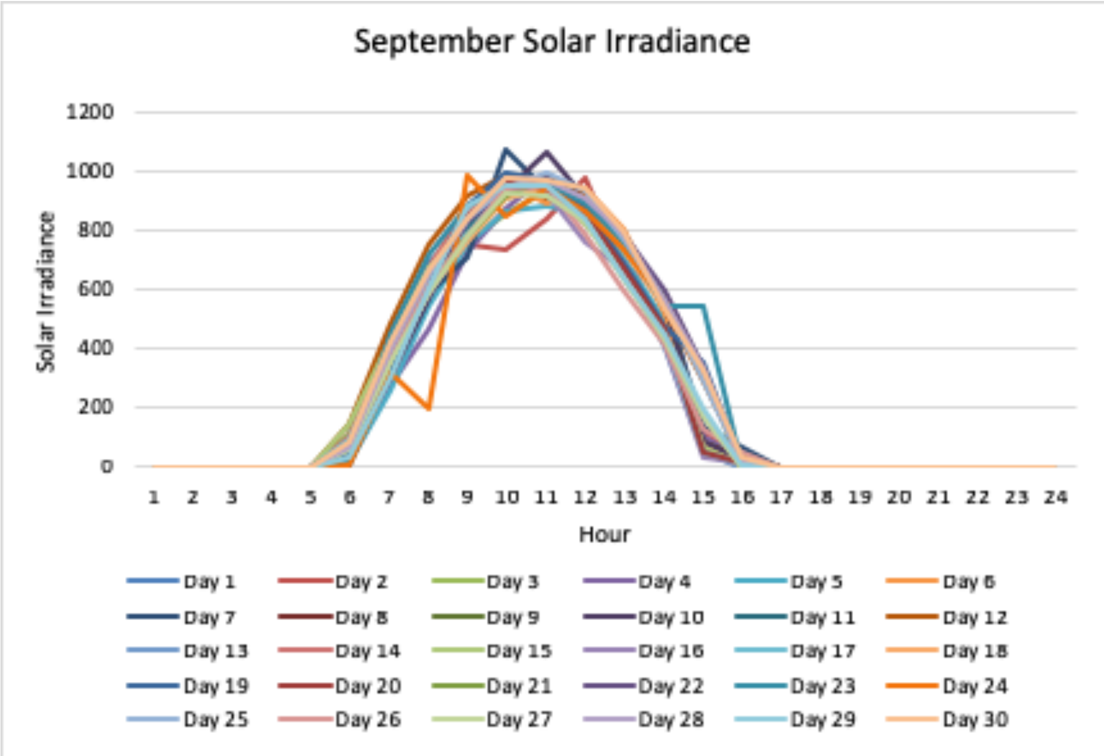

Figure 29: September global solar irradiance

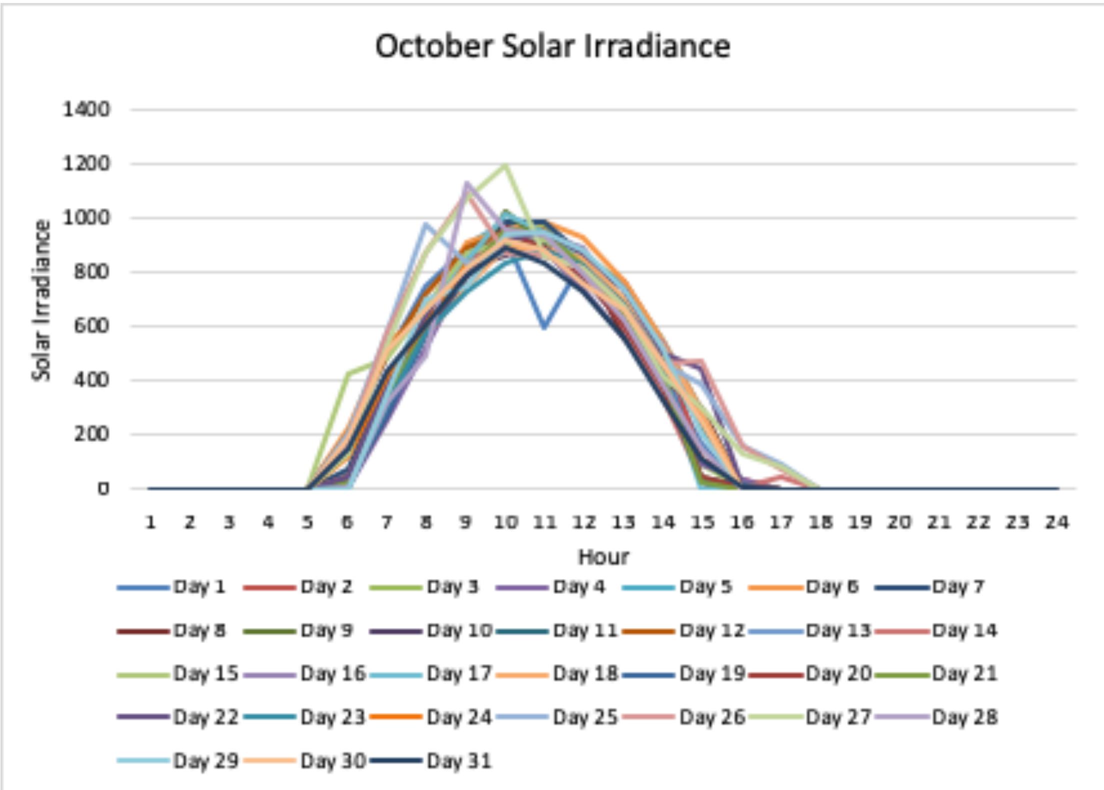

Figure 30: October global solar irradiance

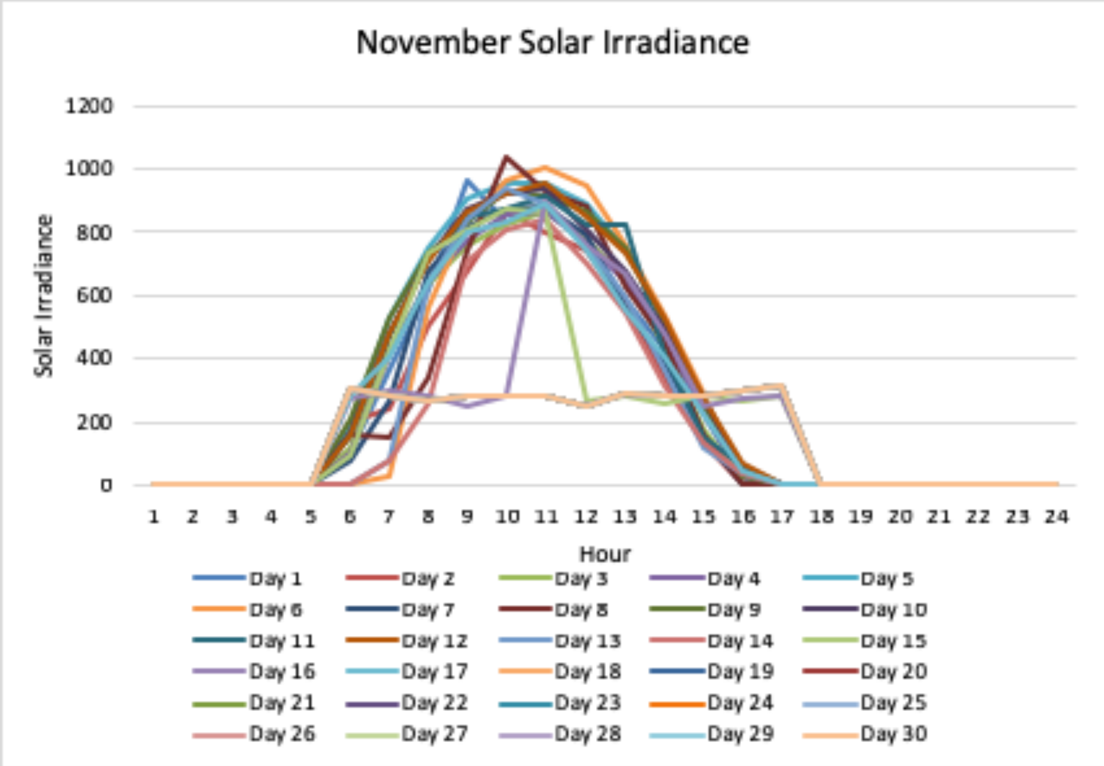

Figure 31: November global solar irradiance

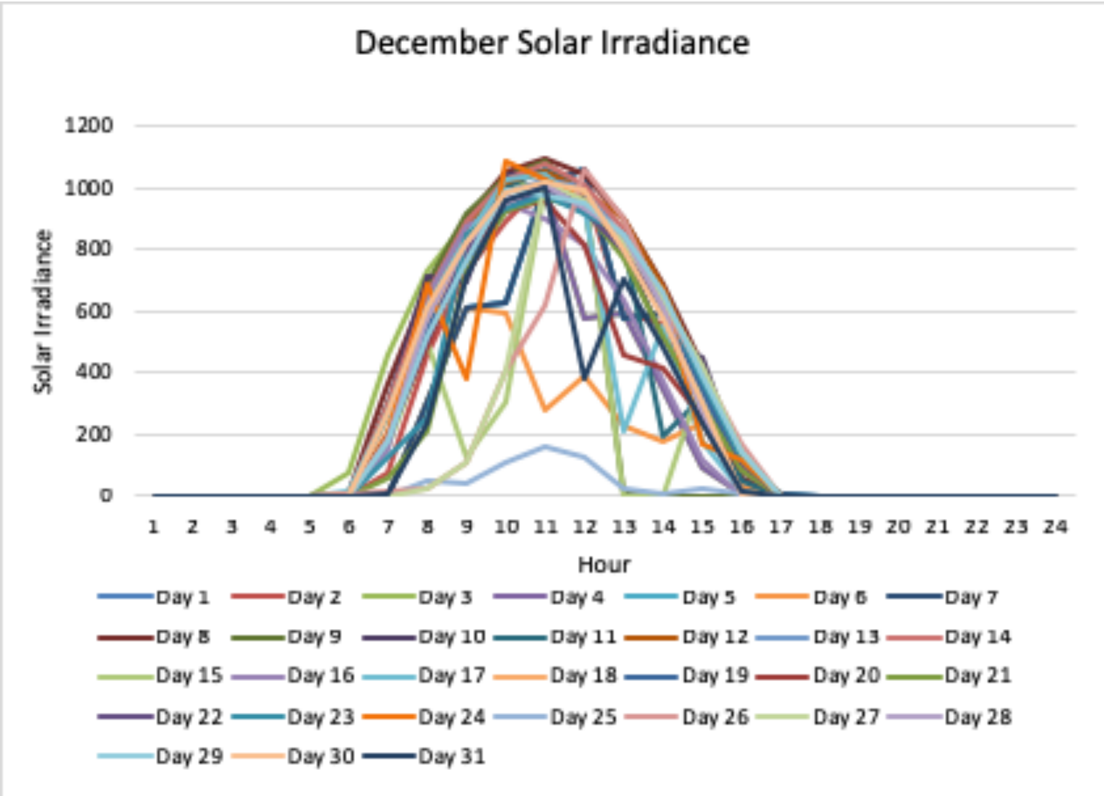

Figure 32: December global solar irradiance

Appendix F: Data Collected on Cooling of Qatar

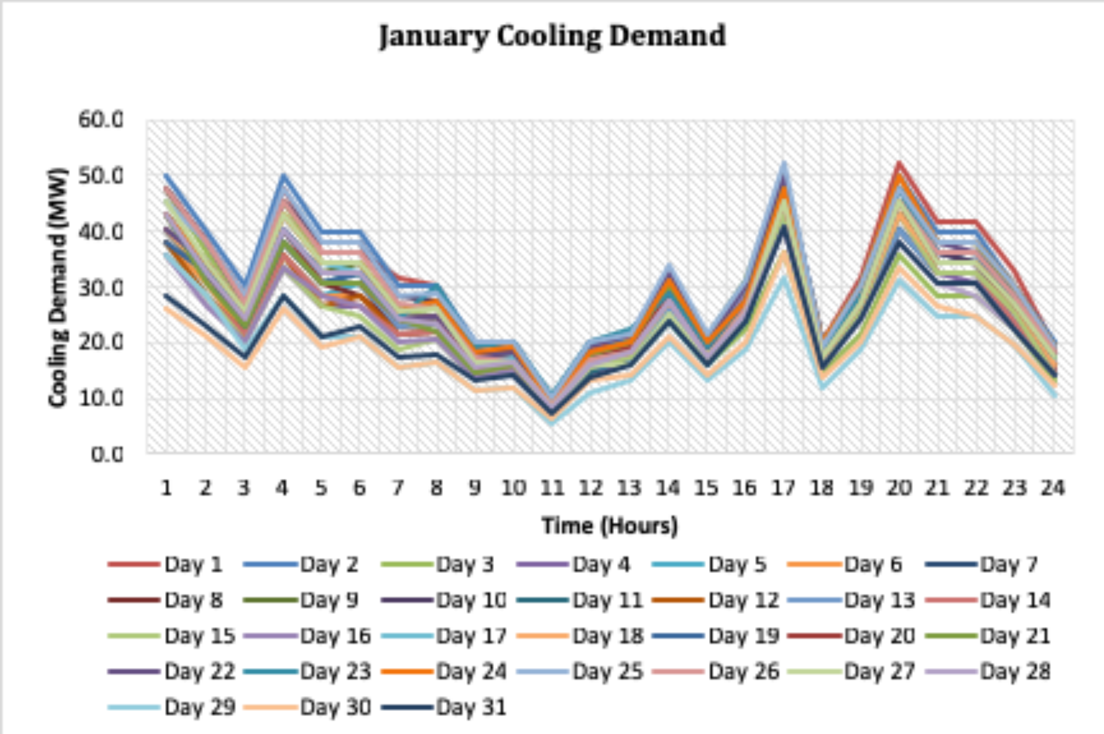

Figure 33: Monthly cooling demand of january

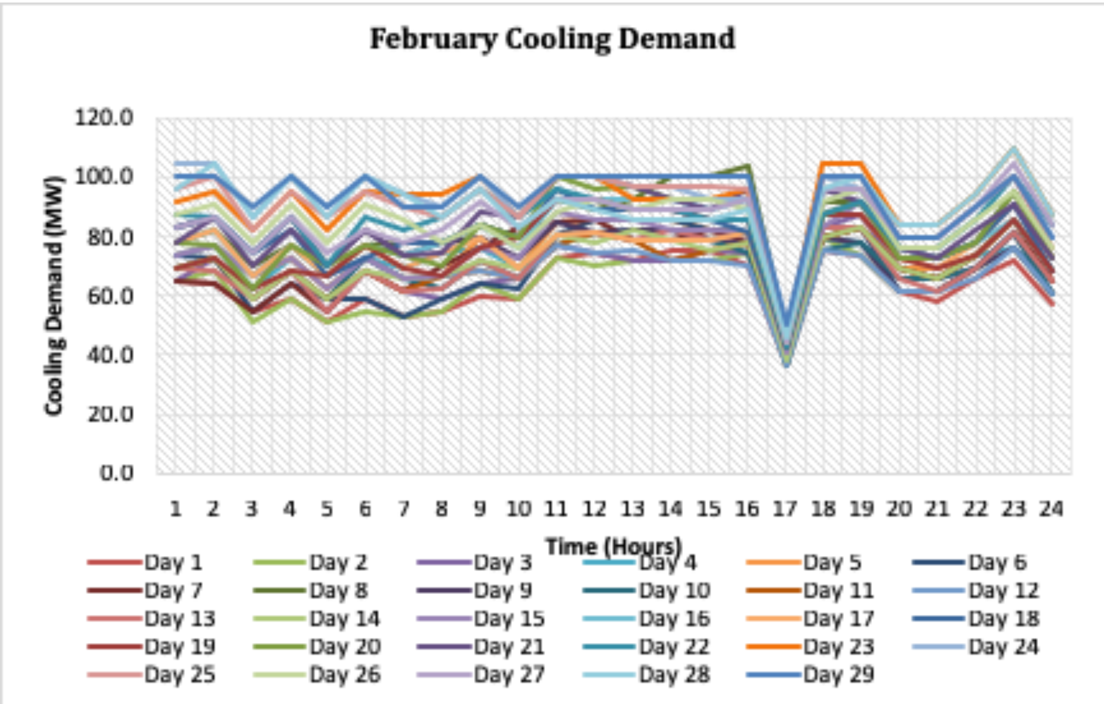

Figure 34: Monthly cooling demand of february

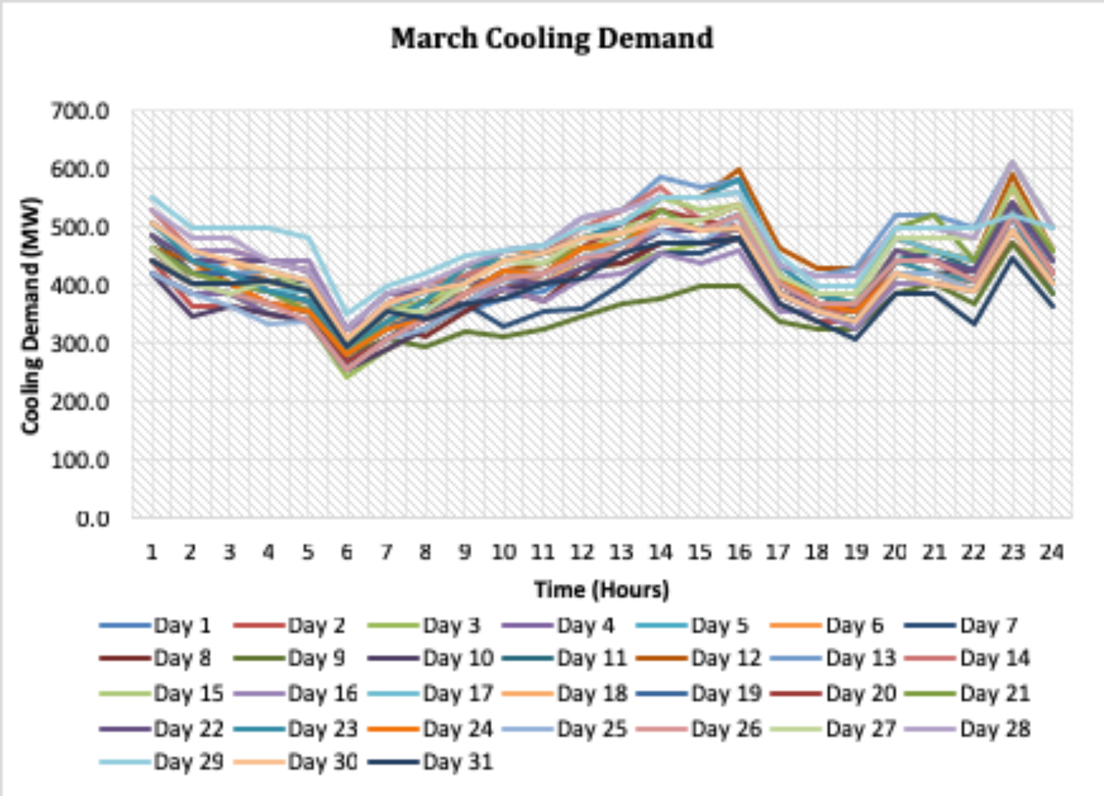

Figure 35: Monthly cooling demand of march

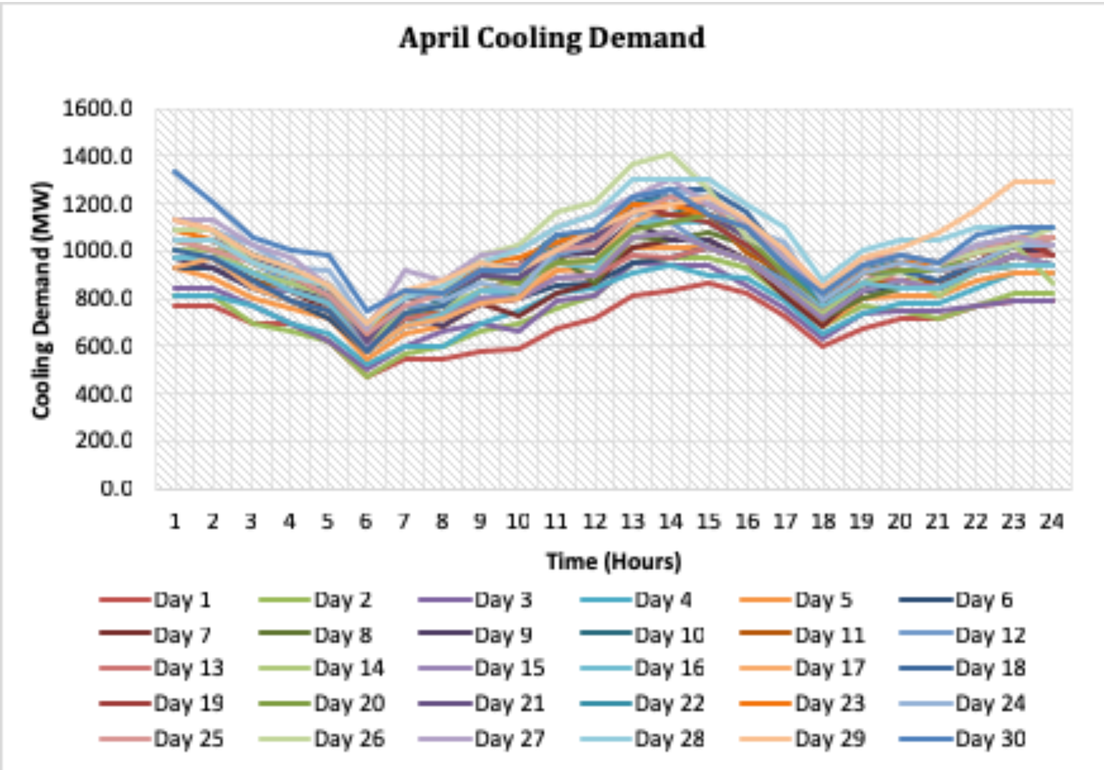

Figure 36: Monthly cooling demand of april

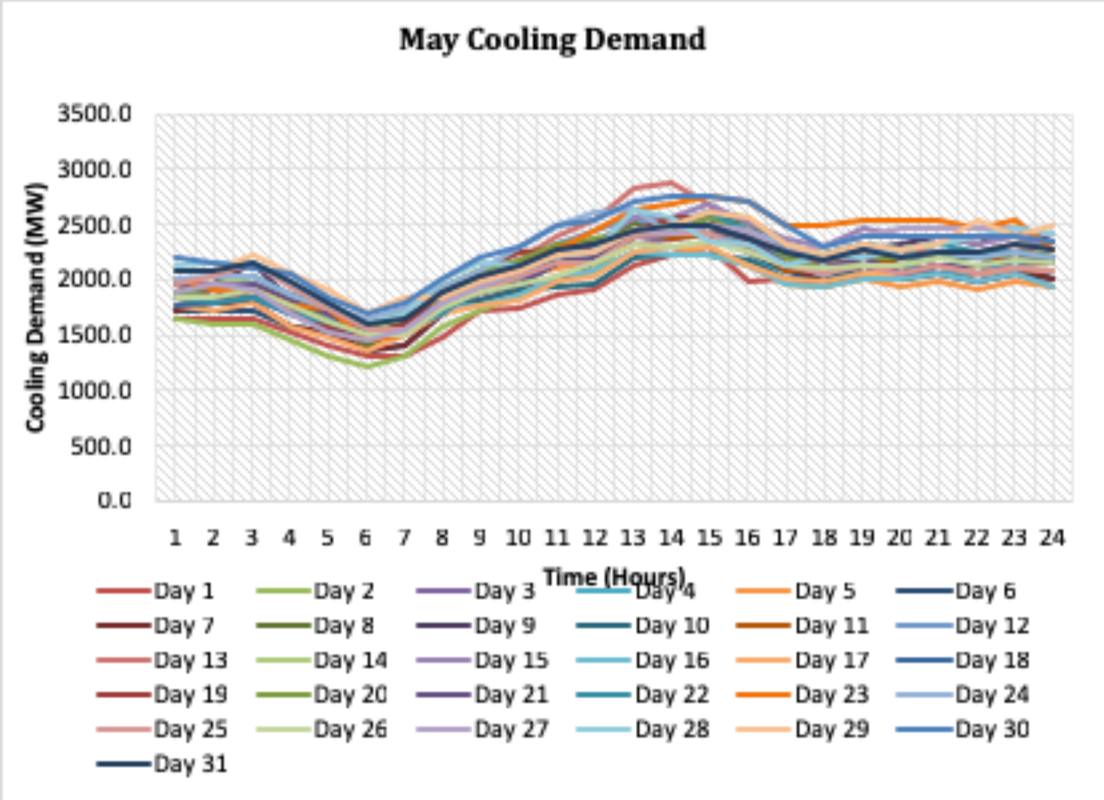

Figure 37: Monthly cooling demand of may

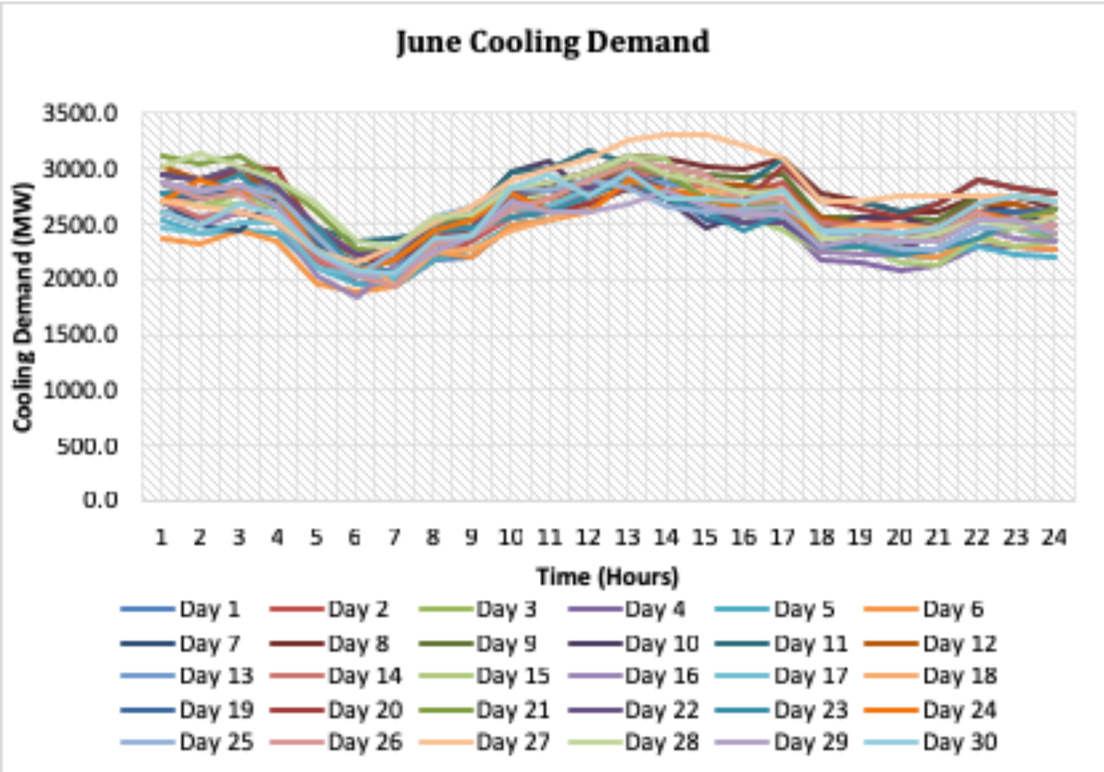

Figure 38: Monthly cooling demand of june

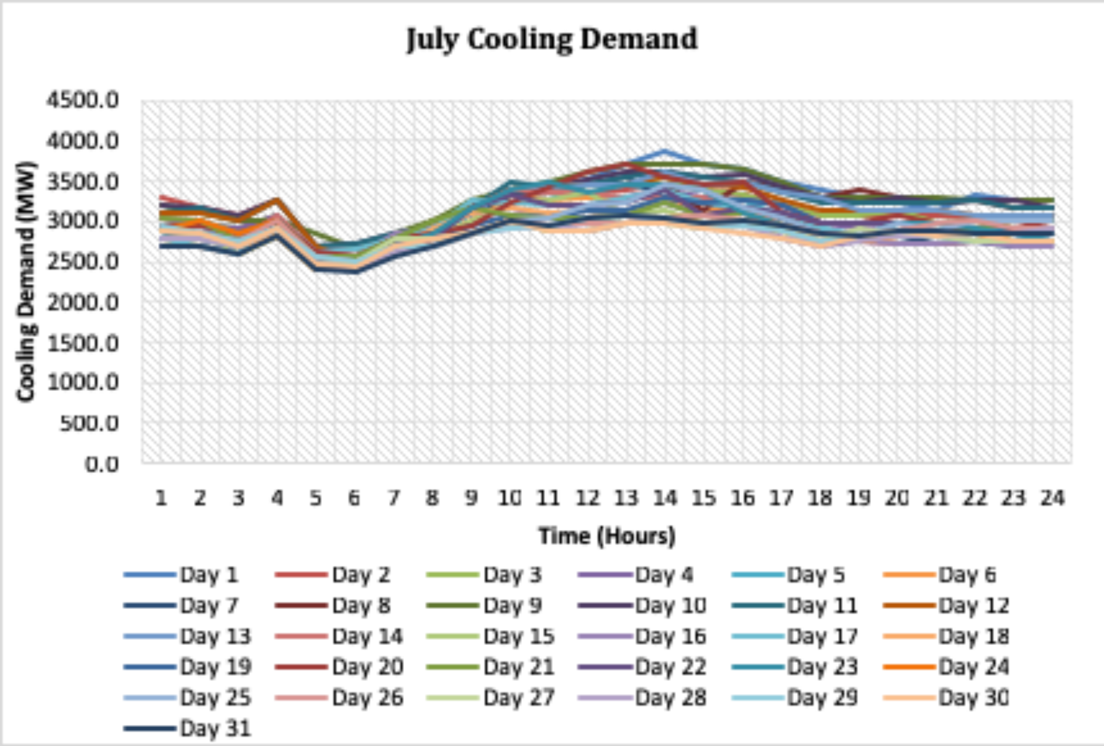

Figure 39: Monthly cooling demand of july

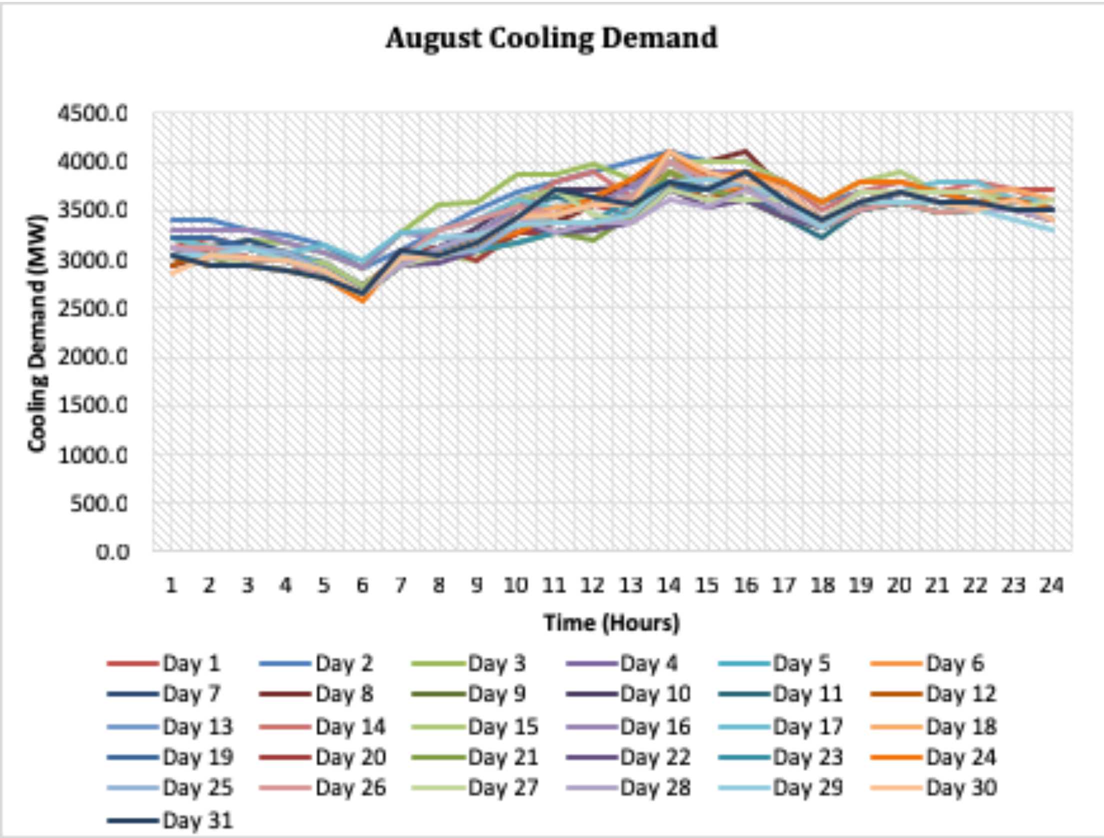

Figure 40: Monthly cooling demand of august

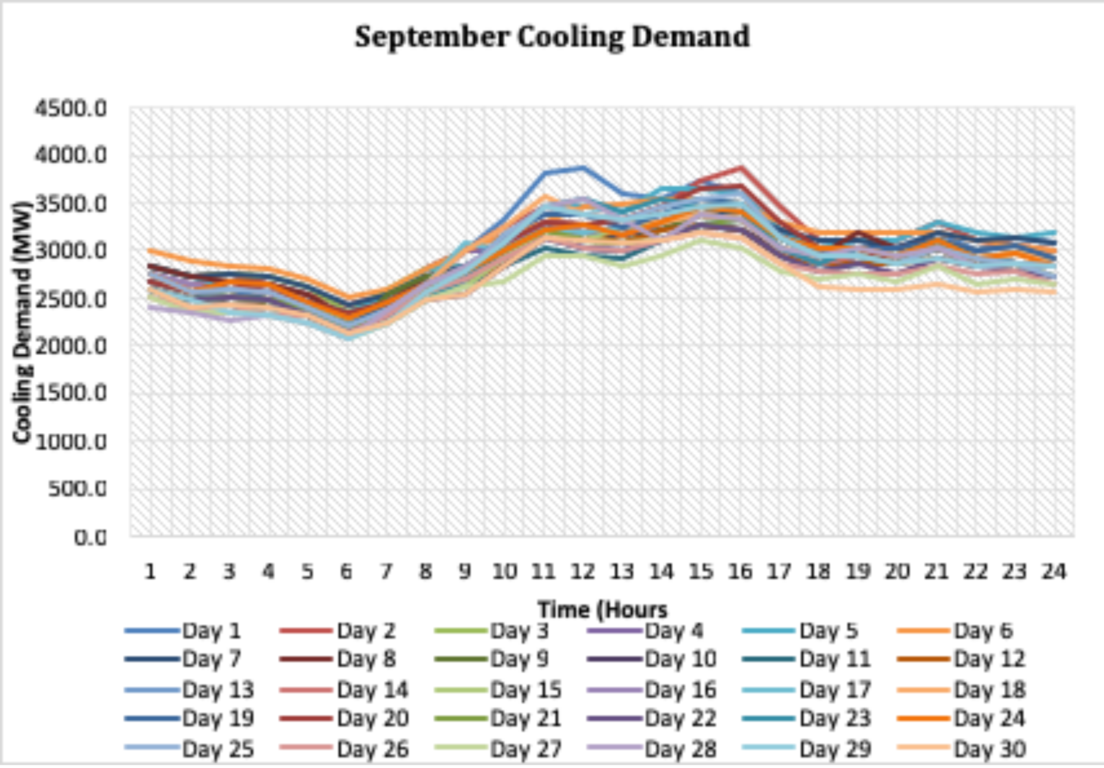

Figure 41:Monthly cooling demand of september

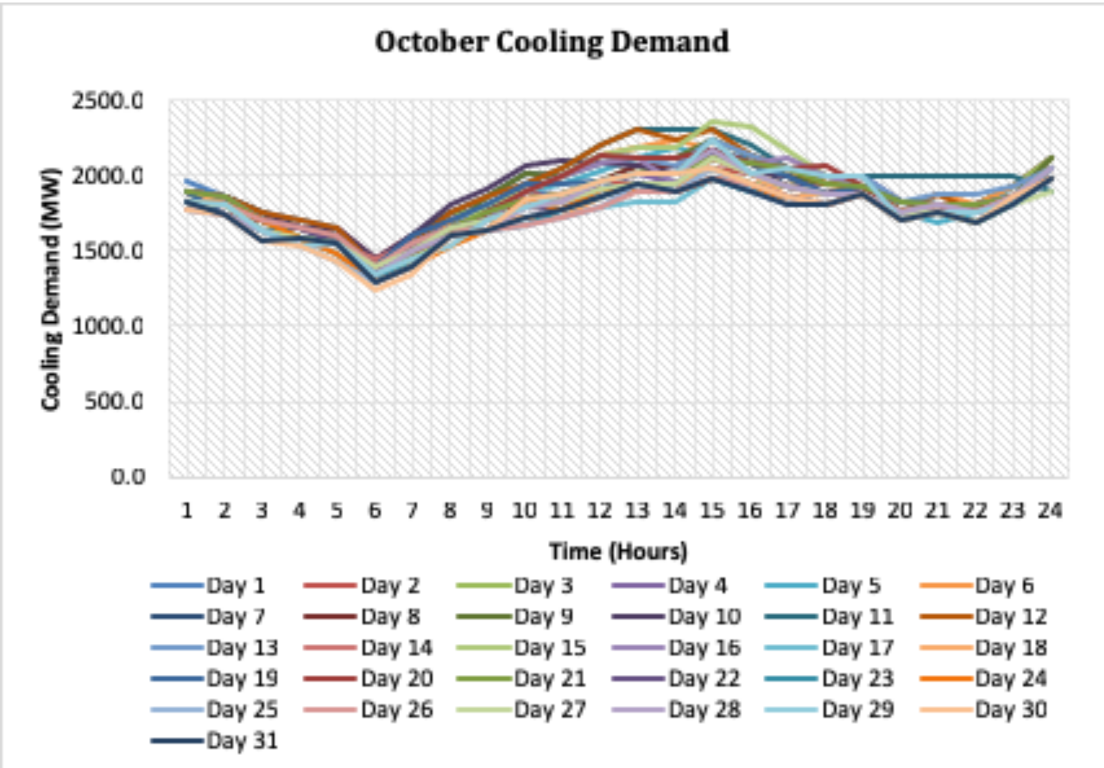

Figure 42: Monthly cooling demand of october

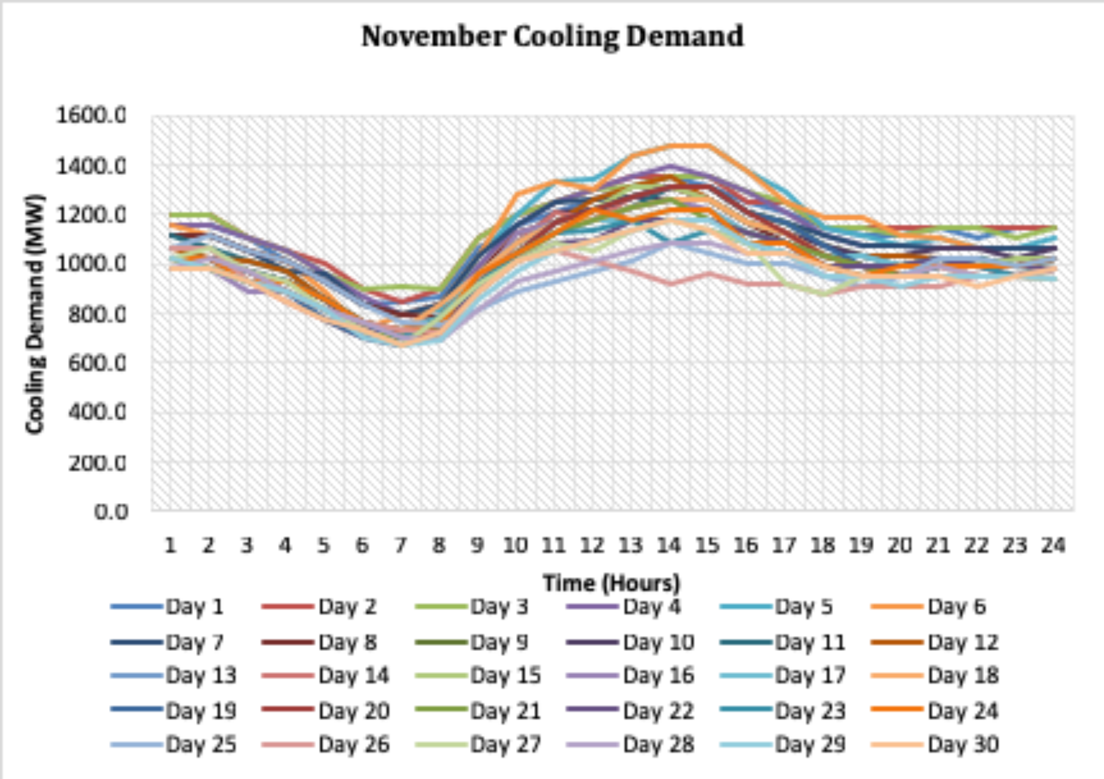

Figure 43: Monthly cooling demand of november

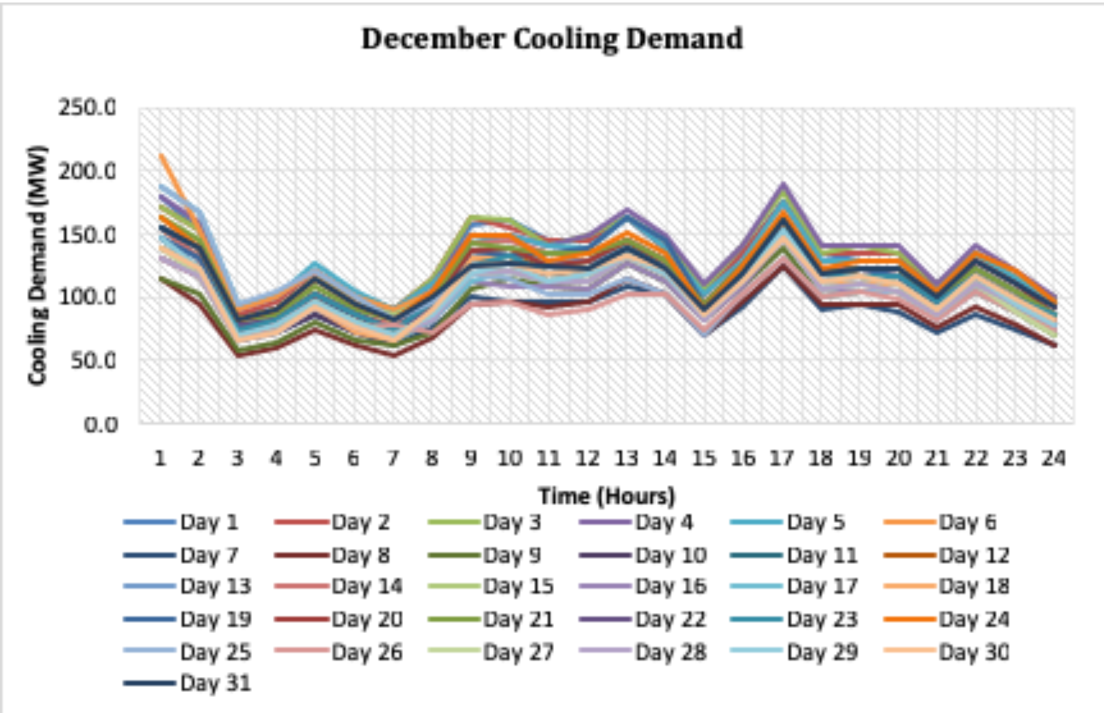

Figure 44: Monthly cooling demand of december

Appendix G: Literature Review Summary

Author	District Energy System	Cooling Technology	Optimization Objective	Optimization Method	Studied Parameters
Magori et al. (2000)	DCS	Compression Chiller	Minimize components fixed cost, construction costs and operating costs	non-linear combinational model and (DP)	-
Powell et al. (2013)	DCS	Compression Chiller	Minimize energy consumption	thermodynamic semi-empirical model, MINLP, and QP	Capacity of multiple chiller, and TES
Söderman (2007)	DCS	Compression Chiller	Minimize total cost includes the annualized	MILP	Location and capacity of cooling plants,

			operating and investment cost of all the components		andcold storage and the routing of distribution of pipelines
Gang et al. (2015)	DCS	Compression Chiller	Minimize the operational cost and consumption energy	MILP and MONLP	Chillers plant and energy storage systems location and capacity
Khir and Haouari (2015)	DCS	Compression Chiller	Minimize investment and operational cost	MINLP/ MIP Heuristics	The chiller and the thermal energy storage capacities and the storage levels and the production of cold water

Raja and Shanmugam (2012)	Solar Thermal System	Absorption Chiller	Minimize operational costs and capital costs	General Approach	Absorption chiller capacity, area of flat plate and evacuated solar collectors, hot water TES size and three electrical equipment
Prasartkaew and Kumar (2010). And Sun et al. (2015)	Solar Thermal System	Absorption Chiller	Assess the performance of cooling system	Simulation Approach	Absorption chiller capacity, solar collectors area, hot water TES size, and auxiliary boiler size
Tsoutsos et al. (2010)	Solar Thermal	Absorption Chiller	Minimize system's cost and increase the	TRNSYS	Collector area and slope, back-up heater,

	System		environmental benefits		size of storage tank and capacity of absorption chiller
Qu et al. (2010)	Solar Thermal System	Absorption Chiller	Assess the performance of cooling system	TRNSYS	Area and orientation of solar collectors and TES and pipe diameter and length
Ortiz et al. (2010)	Solar Thermal System	Absorption Chiller	Optimize the parameters and performance of the system.	TRNSYS	Area of flat and evacuated solar collectors, absorption chiller capacity, and hot water TES size
Parane et al. (2011)	Solar Thermal	Absorption Chiller	Develop a cost effective solar absorption cooling	TRNSYS	Area of flat, PTC, vacuum tube solar

	System		system		collectors, absorption chiller capacity , size of hot and cold water TES
Martinez et al. (2012	Solar Thermal System	Absorption Chiller	Optimize energy savings	TRNSYS	Hot water storage tank volume, collector area, and absorption chiller capacity
Vasta et al. (2015)	Solar Thermal System	Absorption Chiller	Optimize performance of the system	TRNSYS	TES size, flat solar collectors area and number, absorption chiller capacity and auxiliary boiler

					existence
Sokhansefat et al. (2017)	Solar Thermal System	Absorption Chiller	Optimize performance of the system	TRNSYS	Storage tank volume, collector slop, auxiliary boiler set point temperature, collector area and mass flow rate
Soussi et al. (2017)	Solar Thermal System	Absorption Chiller	Optimize performance of the system	TRNSYS	Parabolic trough collector area, hot water TES volume, and absorption chiller capacity
Khan et al, (2018)	Solar Thermal	Absorption Chiller	Optimize performance of the system	TRNSYS	Solar collector tilt, type and size and

	System				TES storage volume, and absorption chiller capacity
Molero et al. (2012)	Solar Thermal System	Absorption Chiller	Optimize performance of the system	TRNSYS	Hot and cold water TES volume, solar collectors area and efficiency, COP and temperature set point of chiller
Hang and Qu (2011),	Solar Thermal System	Absorption Chiller	Optimize performance of the system	TRNSYS	Hot and cold water TES volume, chiller capacity, solar collector area
Balghouthi et al.	Solar	Absorption	Optimize performance	TRNSYS and ESS	Chiller capacity, solar

(2008)	Thermal System	Chiller	of the system by taking climatic conditions into consideration		collectors area and slope, hot water TES volume and auxiliary boiler capacity
Marc et al. (2012)	Solar Thermal System	Absorption Chiller	Optimize performance of the system by taking climatic conditions into consideration	TRNSYS	Solar collectors area, chiller capacity, hot and cold water TES volume and cooling tower capacity
Sim (2014)	Solar Thermal System	Absorption Chiller	Optimize performance of the system by taking climatic conditions into consideration	TRNSYS	Solar collector scope and area, tank volume, heat exchanger effectiveness and

					water flow rate, chiller capacity
Asaee et al. (2014)	Solar Thermal System	Absorption Chiller	Optimize performance of the system by taking climatic conditions into consideration	TRNSYS	Solar collector area, and storage capacity
Pongtornkulpanich et al. (2008)	Solar Thermal System	Absorption Chiller	Optimize performance of the system using maximum cooling demand	TRNSYS	Evacuate tube solar collector area, chiller capacity, hot water TES volume, and LPG back-up heating unit
Agyenim et al. (2010)	Solar Thermal	Absorption Chiller	Optimize performance of the system using	TRNSYS	Evacuated tube solar collector area and

	System		maximum cooling demand		slope, chiller capacity, cold water TES volume
Hang et al. (2010)	Solar Thermal System	Absorption Chiller	Optimize economic, environmental and energetic performances of the system	TRNSYS	Chiller capacity, solar collector type and area, auxiliary heater power and storage tank volume
Shirazi et al. (2016)	Solar Thermal System	Absorption and Compression chiller	Optimize energy savings	TRNSYS	Chiller capacity and COP, solar collector area and slope, gas fired heater and storage tank volume
Calise et al. (2011)	Solar	Absorption	Optimize economic	TRNOPT	-

	Thermal System	Chiller	performance		
Hang et al. (2011)	Solar Thermal System	Absorption Chiller	Maximize solar fraction of solar cooling system	TRNSYS, CCD, and DE	Solar collector slope and area, hot and cold water volume
Arsalis et al. (2015)	Solar Thermal System	Absorption Chiller	Optimize economic performance	MATLAB	Collector area and slope, and hot water TES volume
Hang et al. (2013)	Solar Thermal System	Absorption Chiller	Maximize economic, energy and environmental benefits	CCD, regression and multi-objective optimization	-
Xu et al. (2015)	Solar Thermal System	Absorption Chiller	Minimize present worth cost, LCE consumption and LCCO$_2$ emission	Stochastic multi-objective optimization model	Solar collector area and slope, hot water TES volume

				(SMOO) and Genetic Algorithm	
Gebreslassie et al. (2010)	Solar Thermal System	Absorption Chiller	Optimize environmental impact and economic performance	Bi- criteria MILNP	Natural gas boiler, solar collectors, and absorption chiller
Iranmanesh and Mehrabian (2014)	Solar Thermal System	Absorption Chiller	Optimize auxiliary energy consumption and net profit	Multi-objective optimization model	Storage tank volume, and solar collectors area, and mass flow rates
Shirazi et al. (2017)	Solar Thermal System	Absorption and Compression Chiller	Minimize the primary energy consumption and total annual cost	Multi-objective optimization model	Gas fired heater, chillers, solar collectors area and slope, TES volume, solar pump nominal

					flow rate and collector set point temperature
Fong et al. (2010)	Solar Electric System	Compression Chiller	Optimize performance of the system	TRNSYS	PV panels, and vapor compressions chiller and grid
Hartmann et al. (2011)	Solar Electric and Thermal System	Absorption and Compression Chiller	Optimize energy savings and system cost	TRNSYS	PV panels, vapor compressions chiller and grid
Eicker et al. (2014)	Solar Electric and Thermal System and	Absorption and Compression Chiller	Optimize energy savings	TRANSOL and TRNSYS	PV panels and solar collector area, vapor compressions and absorption chiller

	DCS				capacity, and cold water TES
Noro and Lazzarin (2014)	Solar Electric and Thermal System	Absorption and Compression Chiller	Optimize economic performance of the system	TRNSYS	PV panels and solar collector area, vapor compressions and absorption chiller capacity and COP,
Mokhtar et al. (2010)	Solar Electric and Thermal System	Absorption and Compression Chiller	Optimize economic performance of the system by considering weather and cooling demand	General Approach	PV panels and solar collector area, vapor compressions and absorption chiller capacity and COP
Otanicar et al. (2012)	Solar Electric and	Absorption and	Optimize economic and environmental	General Approach	PV panels and solar collector, vapor

	Thermal System	Compression Chiller	performance of the system		compressions and absorption chiller capacity, TES and heat exchanger unit
Fumo et al. (2013)	Solar Electric and Thermal System and DCS	Absorption and Compression Chiller	Optimize performance of the system	General Approach	PV panels and solar collector area, vapor compressions and absorption chiller capacity
Eicker (2014)	Solar Electric and Thermal System	Absorption and Compression Chiller	Optimize economic performance of the system	General Approach	PV panels and solar collector area, vapor compressions and absorption chiller capacity and TES

Porumb et al. (2016)	Electric and Thermal System	Absorption and Compression Chiller	Optimize economic performance of the system	General Approach	PV panels and solar collector slope, vapor compressions and absorption chiller capacity
Al-Ugla et al. (2016)	Electric and Thermal System and DCS	Absorption and Compression Chiller	Optimize economic performance of the system	General Approach	PV panels and solar collector slope and power, vapor compressions and absorption chiller capacity and COP
Papoutsis et al. (2017)	Electric and Thermal System and	Absorption and Compression	Optimize performance of the system	General Approach	PV panels power, and vapor compressions chiller capacity and

	hybrid system	Chiller			COP
Bilgili (2011)	Electric System	Compression Chiller	Optimize performance of the system	General Approach	PV panels area, and vapor compressions chiller COP
Abdollahi	Hybrid system	Absorption and Compression Chiller	Optimize exergetic efficiency, economic and environmental impact	Multi-objective Genetic Algorithm (GA) optimization	chiller, micro turbine power generation, auxiliary boiler, electrical chiller and HRSG capacity
Brandoni et al. (2015)	Hybrid system	Absorption and Compression Chiller	Optimize economic performance of the system	Linear programming Model	PV panels area and efficiency, chiller COP, auxiliary boiler, TES, grid and CHP