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OPTIMAL DESIGN OF A SOLAR ASSISTED COOLING SYSTEM

BY

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Abstract

Rapid development around the globe is fairly associated with huge consumption of energy; regardless of the continuous attempts of exploiting renewable energy resources, further investigations in renewable energy involvement in comfort cooling appears to be interesting. District Cooling Systems (DCS) are chilled water based systems operate to provide comfort cooling. DCS consists of chilled water plant, chilled water distribution network and energy transfer station(s), where Thermal Energy Storage system (TES) might be included alongside with DCS as auxiliary components(s). Although typical DCS are fully dependent on fossil fuel as source of energy in their operation, providing comfort cooling is considered as a necessity in some regions of the globe. Such circumstances highlight the imperative of examining other sources of energy, such as renewable energy. One thinks there is no better alternative of energy resource problem than solar energy, specifically the science of converting heat into cool. Researches in the field of Solar Assisted Cooling systems (SAC) designated typical components of solar assisted cooling system to be solar collector(s) and absorption chiller(s); where TES and water boiler utilized as auxiliary components. In comparison to conventional cooling systems, SAC systems have the advantages of renewable energy utilization beside the correlation of high availability of solar energy with the high demand of comfort cooling. Yet, their relatively high investment cost introduces barriers toward their implementation; thus, the contribution of this research is realized in mathematically modeling SAC system and obtaining the optimal design of such system with the aim of minimizing the investment and operational costs. The problem is modeled as Mixed Integer Linear Problem (MILP) and the optimization of the model is implemented using CPLEX optimizer. The optimized solution specifies the optimal area of the solar collector, size of absorption chiller, size and existence of chilled and hot water storage tanks, and the auxiliary boiler.

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1. Introduction

The enormous development witnessed around the globe forced mankind to increase their consumption of energy, taking into account that considerable amounts of the used energy is coming from unsustainable energy resources. Such case raised concerns about the future existence of energy resources and the lack of wise utilization of it; alongside with the consequences related to the environment. Solar energy, a renewable energy resource, has been always a natural resource of thermal energy that is used over the years, yet it could be transformed to generate other forms of energy such as electrical energy. While solar energy is exploited in major variety of applications, its involvement in District Cooling Systems (DCS) suggests an interesting topic to be investigated.

The flow of chapters of this report begins with an introductory brief of DCS, followed by a detailed description of Solar Assisted Cooling System (SAC). Moreover, literature review is presented in a separate chapter to indicate optimization efforts of DCS and SAC. In addition, a chapter is dedicated to introduce the problem description and mathematical formulation. Finally, computational analysis chapter demonstrates the optimization results and the conducted sensitivity analysis.

2. District Cooling System

District Cooling System (DCS) is a system utilizes the technology of chilled water production to provide space cooling for residential, industrial and commercial buildings. The early development of DCS started in 1889 by the company Colorado Automatic Refrigerator [1]. Nevertheless, the technology advanced to form the current typical District Cooling System comprising central plant, distribution network and customer connection point as illustrated in Figure 1.

As DCS is a closed- loop network based systems, chilled water is produced in the central plant to be conveyed through piping distribution network to the customer connection point (referred to as 'energy transfer stations') [2]. The chilled water used in space cooling flows back into the network after dissipating its coldness to be re-chilled and re- pumped; as a result, the piping network combines pipes with water flow in both directions; from the chiller plant to the customer and from the customer to the chiller plant. A supplementary element to the system is a Thermal Energy Storage (TES) represented in cool –storage improves the performance of the system and offers benefits to the power supplier and the customer [3].

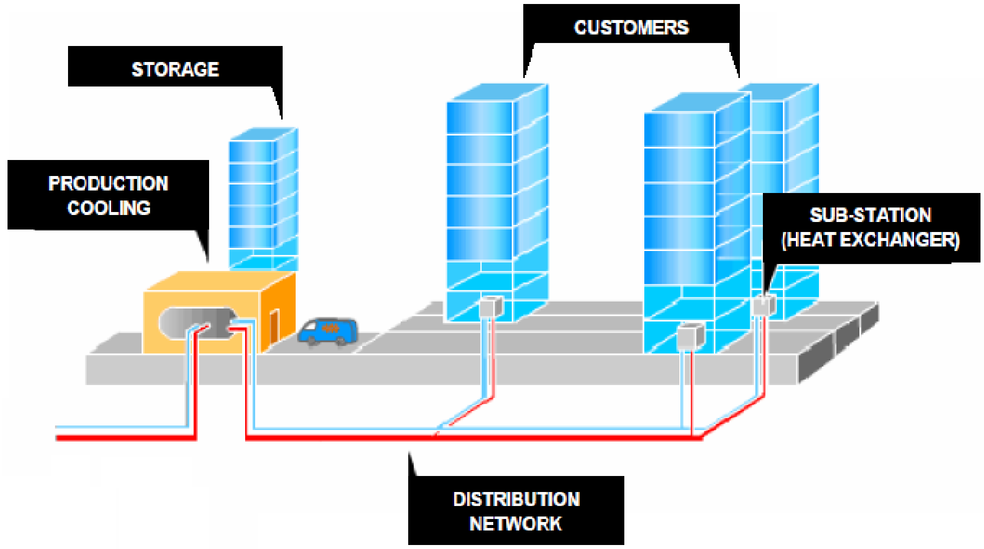

Figure 1: District Cooling System configuration

2.1 Economical DCS Benefits

District Cooling System is commonly used to provide space cooling for high density urban areas; it is noteworthy that DCS is more advantageous solution than individual chiller plants installed for each building due to its higher efficiency [3]. The benefits of DCS to the customer are realized in offering comfort through providing a reliable and high- quality source of cooling; besides the continues developments by service providers to reach optimal operation and maintenance. DCS manages to eliminate any heavy, vibrating or noisy equipment near the customer side, which achieves a quitter environment in residential and commercial areas. From facility management point of view, DCS fits the need of providing reliable space cooling with no requirements to utilize labor and material for maintaining and operating chiller system. Moreover, DCS are considered reliable than conventional cooling since the former operates with highly reliable equipment being controlled by cooling company's experts [4].

Economical perspective indicates that DCS is a cost effective solution, considering several aspects such as the optimized operation of the equipment since they are used on the most efficient levels; in addition, DCS exploits advanced technologies like TES which further reduces the peak demand power resulting savings in expenses. It is worth mentioning, that depending in the technology used in DCS it could be able to reduce power demand by 50% to 87% compared to conventional cooling. Furthermore, DCS achieves savings in capital cost of construction required for equipment's space, as well as reductions in annual cost paid for electricity, maintenance and labor required for building chiller system. From governmental point of view, DCS offers reductions in capital cost of infrastructure needed for power generation, transmission, and distribution besides power sector operating costs savings; however, total cost of power is reduced in a way of decreasing the need of power plants building [4].

2.2 Environmental DCS Benefits

District Cooling Systems have a significant impact on the reduction of CO_2 emissions due to the fact that they play a role in reducing electrical power consumption leading to an increase in energy efficiency. Its centralized based technology allows for minimization of the cooling capacity consequently less electric power consumption and better detection of leakage from equipment resulting lower emissions [5].

The annual emissions of CO_2 of a DCS supplies 100 GW of cooling energy on yearly bases counts for 5378 ton, while it reaches 32297 ton for the conventional cooling system, as DCS has the flexibility that enables the operator to select industrial equipment with better environmental profile. Efficient District Cooling System has the advantages of reduced cooling water for the cooling towers, less chemicals used for water treatment and minimal footprint for the dry coolers [5].

Indeed, refrigerants such as CFCs (chlorofluorocarbons) and HCFCs (hydro chlorofluorocarbons) utilized in conventional cooling are contributing to the depletion of the ozone layer which is linked to serious health and environmental harms; aside from its involvement in the phenomenon of global warming; on the other hand, DCS proved its effectiveness in phasing out such refrigerants [6].

With all benefits mentioned previously, District Cooling System represents an appealing solution to replace conventional cooling method. Consequently, DCS is a system gets numerous attention by researchers and scientists to develop diverse techniques and approaches exploiting it by increasing its flexibility and competency. A trend toward such achievement, suggests integrating it with other energy technologies such as renewable energy resources which would be a topic investigated in the next section.

2.3 DCS Integration with Sustainable Energy Technologies

The integration of DCS and District Heating System (DHS) with other energy technologies allows for energy efficiency improvements; typical renewable energy sources integrated to DCS/DHS are the surface water (such as the sea, river and lake), geothermal energy, solar energy, wind energy and biomass [1]. There are several benefits for coupling renewable energy resources to DCS; though, most focuses realized in taking the advantage of the sustainability of renewable energy resources. The integration of surface water into DCS /DHS seems an attractive energy resource in coastal areas; whether the source of water is ocean, river or lake water, surface water utilization proved its feasibility and reliability in DCS in different coastal cities such as Paris in France and Dalian in China [1]. Geothermal energy is the energy from aquifer or groundwater with energy conservation levels that reaches about 90-95% energy applied to DCS; one significant environmental benefit of such system is the elimination of chillers that are using a refrigerant gas has causing ozone depletion [7]. Another form of energy integrated into DCS is biomass, where waste incineration replaced landfilling to be coupled to power plant and heat is recovered and utilized in space cooling [8]. Solar energy, integrated into space cooling, is used in the form of thermal energy based on heating the water driving chillers to produce chilled water that provides space cooling. Such application of solar energy is different than the technology of solar-power generation, where the solar radiation used to generate electricity via Photovoltaic cells (PV).

In general, renewable energy resources exploited effectively in District Cooling System as well as District Heating System (DHS); beside the fact that coupling DCS to renewable energy resources offer remarkable energy savings and has an impact on decreasing Greenhouse Gases emissions (GHG) [1].

2.4 Scope of the Study

The aim of this research is to find the optimal design of a solar assisted cooling system; this implies the optimal selection of the system components to operate with in proper level of efficiencies targeting minimum investment and operating cost. The possibility of coupling an auxiliary heating unit to the system is a suggested alternative to improve the system efficiency. The integration of a renewable energy source as auxiliary system would be a sustainable alternative that contributes to the trend of greenhouse gases reduction and toward better energy efficiency. However, such integration is out of the scope of this study; instead, fuel based boiler is utilized.

3. Solar Assisted Cooling System

The insisting demand of space cooling in commercial and residential areas increases the electricity consumption, which is mainly dependent on fossil fuel consumption, in a way that requires alternatives to be introduced. One can notice that the availability of solar energy seems a very reasonable solution for mainly two reasons; sun radiation is abundantly obtainable and the peak of cooling demand coincides with the peak of solar energy availability [9]. However, the intermittent nature of the solar energy mandates the need for auxiliary units to be integrated into the system to improve the reliability of the cooling system.

The involvement of solar energy into space cooling has become a mature technology; however, improvements and enforcements of it remain to be requirements for flexibility and reliability purposes. A typical solar assisted cooling system consists of solar collectors, chiller(s), storage tank (s) and an auxiliary heating unit; each component of the system is described separately in the coming sections.

3.1 Solar Collectors

According to [10], a solar collector is a heat exchanger that uses a heat transport medium (water) to convert solar radiation into internal energy, whereas an efficient solar collector completes the energy conversion with minimum losses. Fundamentally, solar collectors fall into two categories based on their motion; stationary (non- concentrating) collector and sun tracking (concentrating) collectors. Table 1 represents the different types of solar collectors with their indicative features.

For comfort cooling application, small and medium temperature ranges collectors (60- 250°C) are utilized [11]. The two-axis tracking types of solar collectors are known in their high range of indicative temperatures beside their common contribution to power generation application. Hence, their inclusion in the solar assisted cooling system can be in the form of power generating units.

Table 1: Types of Solar Collectors [10]

Motion	Collector Type	Absorber Type	Concentration Ratio	Indicative Temperature Range (°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Stationary compound parabolic collector (CPC)	Tubular	1-5	60-240
Single-axis tracking	Compound parabolic collector (CPC)	Tubular	5-15	60-300
	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Cylindrical trough collector (CTC)	Tubular	15-50	60-300
	Parabolic trough collector (PTC)	Tubular	10-85	60-400
Two-axis tracking	Parabolic dish reflector (PDR)	Point	600-2000	100-1500
	Heliostat field collector (HFC)	Point	300-1500	150-2000

To select the proper solar collector for solar cooling system design, several aspects shall be considered such as their output temperature ranges, efficiency and cost. Stationary or non- concentrating collectors i.e. flat plate and evacuated tube collectors are characterized by their ability to collect direct and diffuse radiation at relatively low output temperature; though, the material used in ETC manufacturing allows for higher output water temperature than FPC. Moreover, evacuated tube collector has the advantage of daylong performance over the flat plate collector due to their higher efficiency at low incidence angles. In other words, the thermal efficiency of ETC is higher than FPC; consequently, ETC is considered relatively more expensive than FPC. The efficiency of stationary solar collectors is calculated according to Formula 1.

$$ŋ = \frac{Q_u}{A_c G_t} \qquad (1)$$

Where Q_u is the energy collected by the solar collector in *watts*, A_c is the area of the collector in m^2 and G_t is the irradiance in W/m^2 [10].

With regard to the concentrating collectors (single-axis), they show their ability of sun tracking with high output temperature ranges, besides their manufacturing style that allows them to minimize heat losses thus increasing the energy delivery. For similar area of flat plate collector and a concentrating collector, the transfer medium can reach higher temperatures in a concentrating collector, leading to higher thermal efficiency for the concentrating collector; moreover, in concentrating collectors materials used in manufacturing are less with simpler structure than used in FPC meaning lower cost per unit area for concentrating collectors. Nonetheless, concentrating collectors need continues cleaning because reflecting surfaces lose their reflectance with time, beside the fact that they showed inability to collect diffuse radiation [10].

Figure 2 illustrates a comparison of five solar collectors considering two different irradiation levels; the collectors are flat plat (FP), advanced flat plat (AFP), stationary compound parabolic collector (CPC), evacuated tube collectors (ETC) and parabolic trough collector (PTC) [11].

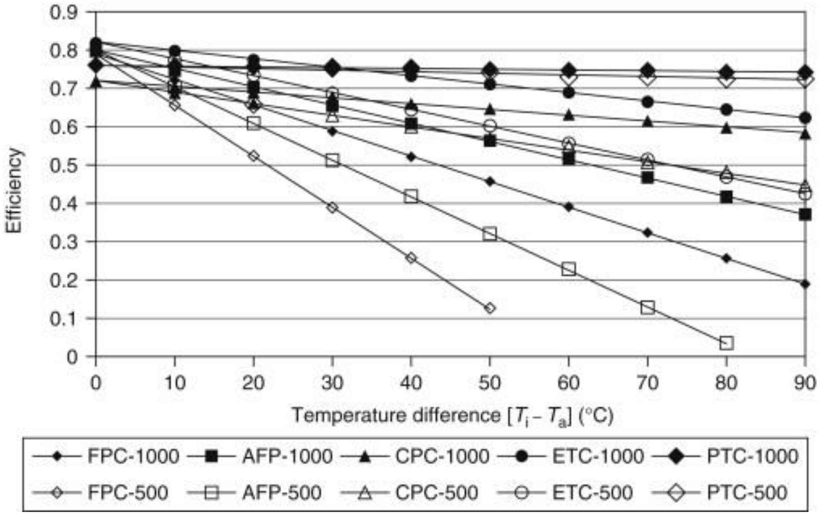

Figure 2: Comparison of the efficiency of various collectors at two irradiation levels: 500 and 1000 W/m^2 [11]

3.2 Absorption chillers

Solar sorption refrigeration technologies are classified into absorption and adsorption technologies, whereas their application encompasses comfort cooling, food storage and ice making (freezing). Broadly speaking, adsorption technology is deployed in low temperature purposes; while absorption technology is applied to comfort cooling applications. The well-known working pairs in solar absorption refrigeration are lithium bromide -water based chillers H_2O–LiBr and Water-ammonia absorption chillers NH_3–H_2O; the first is utilized in air- conditioning and the latter in refrigeration and industrial applications [12]. Thus absorption chiller using lithium bromide -water chillers are investigated in this study.

A lithium bromide -water chiller includes an absorber, evaporator, generator and a condenser as depicted in Figure 3; water vapor generated from evaporator is absorbed in the absorber by a strong lithium bromide solution causing it to become into a weak solution that is pumped and heated in the generator. The heating process produces water vapor because of water desorbed from the weak solution, the resultant vapor flows to the condenser; afterward, the condensed water passes through an expansion valve to reduce the pressure. While the strong lithium bromide solution is pumped back from the generator to the absorber, water vapor will be absorbed all over again [13].

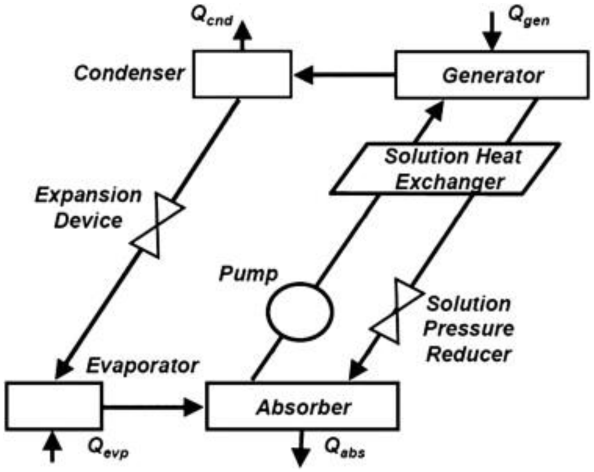

Figure 3: Lithium bromide absorption chiller diagram [13]

The different types of H_2O–LiBr chillers are distinguished by the number of generation processes of refrigerant (water) vapor; accordingly, single effect, double effect and triple effect absorption chillers developed. The differences among the three types realized in the temperature of the driving heat source (water), the cooling capacity and the coefficient of performance (COP); Table 2 demonstrates the features of the chillers [13].

Table 2: Lithium bromide-water absorption chiller types

Absorption chiller Type	Heat Source Temperature (°C)	Cooling Capacity (KW)	COP	Current Status
Single-Effect	80-120	5-7000	0.5-0.7	Commercial
Double-Effect	120-170	20-11,630	1-1.2	Commercial
Triple-Effect	200-230	530-1400	1.4-1.7	Experimental and small batch commercial

The temperature of the heat source or the hot water in the case of H_2O–LiBr chiller has a significant impact on the performance of the chiller; the higher the effect of the chiller, the higher temperature is needed to drive it. In [14], the authors discussed the fact that for each type of the chillers, the heat source temperature shall be maintained above a specific minimum value; below this value the chiller will not perform at all. However, beyond this minimum value the performance of the chiller is improved till it reaches a saturated value regardless of the increase of heat source temperature. Therefore, the single effect absorption chillers have the best performance when the temperature of water ranges from 80 to 120 Celsius degrees, as for the double effect absorption chiller the minimum temperature of the water shall be 120 °C, falling below this temperature cause a radical decrease in the performance of the chiller.

The selection of the proper size of the chillers to meet the cooling demand affects the performance of the chiller, as it is found that the rate of load connected to the chiller influences the performance of the chiller [15]. Figure 4 shows each type of the absorption chiller manufactured by the company *Kawasaki Thermal Engineering*, where different chillers have a specific coefficient of performance corresponding to a load rate.

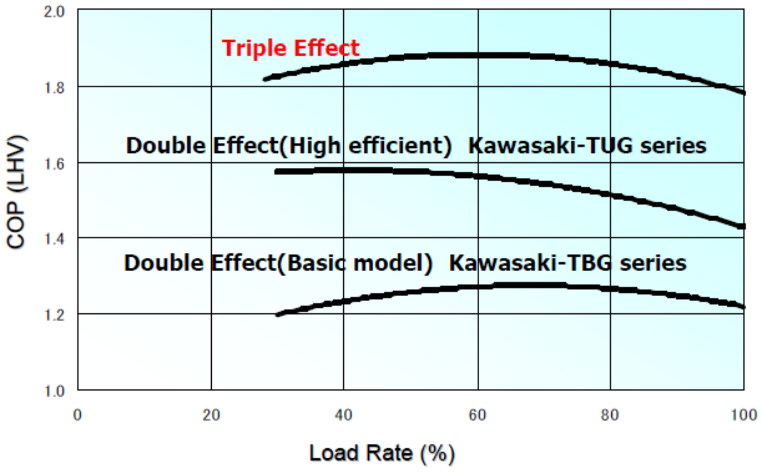

Figure 4: Characteristic of Partial Load of absorption chillers

A key characteristic of absorption chillers is the thermal coefficient of performance (COP); it is described by the ratio of refrigeration capacity to the driving thermal power required. In other words, COP represents the ratio of the thermal energy produced and consumed by the chiller; absorption chiller with higher effect attain higher COP. In literature where COP ranges from 0.5 to 0.7 for single-effect absorption chiller and 1-1.2 for double-effect absorption chiller. While triple-effect absorption chiller is still on its experimental stage, its COP is higher than single and double effect chillers where it reaches a COP of 1.7 while according to *Kawasaki*, a triple-effect absorption chiller might have a COP that reaches 1.9 approximately as shown in Figure 4. Eventually, single and double effect absorption chillers are commercially available and utilized in district cooling systems to provide comfort cooling for residential, commercial and institutional buildings [13].

3.3 Thermal Energy Storage

As in conventional cooling systems, the addition of thermal energy storage into solar assisted cooling systems improves the reliability and efficiency of the system. However, solar assisted cooling systems might integrate two forms of thermal energy storage, to both cover hot and chilled water demand. In this section, different types of Thermal Energy Storage (TES) are presented and their corresponding characteristics.

There are three known technologies of TES exploited in variety of applications to store thermal energy with temperature ranges from -40 °C to higher than 400 °C. The technologies are Sensible Thermal Energy Storage (STES), Storage in Phase Change Materials (PCM) and Thermo-chemical Energy Storage (TCS). For hot water storage, STES would be a proper solution where it proved its cost-effectiveness and appropriate level of efficiency if optimum water stratification in the tank is achieved besides efficient thermal insulation. In domestic hot water applications, STES ranges from 500 liters to quite a few cubic meters (m^3); though, for large applications their volume may serve up to thousand cubic meters (m^3). There are some weaknesses related to STES such as reduced low energy density and temperature insatiability while discharging; however, Storage in Phase Change Materials (PCM) dominate such issues justifying its relatively higher cost than STES. It is noteworthy to mention that the storage period of PCM covers both short-term (days) and long-term (seasons). Thermo-chemical Energy Storage (TCS) is based on chemical-reactions to storage cold energy that is considered to represent an appealing system due to its ability to convert heat into cold and maintaining high efficiency. Broadly speaking, the key properties related to the different TES technologies are capacity, power, efficiency, storage period, charge and discharge time and cost; some of these properties are shown in Table 3 [16].

Table 3: Properties of different TES technologies

TES Type	Sensible Thermal Energy Storage (STES)	Storage in Phase Change Materials (PCM)	Thermo-chemical Energy Storage (TCS)
Capacity (kWh/t)	10-50	50-150	120-250
Power (MW)	0.001-10	0.001-1	0.01-1
Efficiency (%)	50-90	75-90	75-100
Storage period (h, d, m)	d/m	h/m	h/d

Where capacity refers to the amount of energy stored, power indicates the power of charging and discharging, efficiency represents the ratio of the stored energy to the delivered energy and the storage period determined in hours, days and months [16].

3.4 Auxiliary heating unit

As the solar energy is obtainable at daytime and unavailable at nighttime and the fact that climatic conditions could be unstable; a necessity rises for auxiliary system to increase the reliability of the system. The integration of several auxiliary heating systems exhibited in the form of Electric Boiler, LPG-fired heating unit, and Biomass gas fired boiler. However, adding an auxiliary heating system such as Electric Boiler or LPG-fired heating unit decreases the energy efficiency of the system, where coupling a renewable energy source such as Biomass gas fired boiler serves for the sake of greenhouse gas emissions reduction [17].

3.5 Solar Assisted cooling system component integration

According to the previously discussed sections, the components of a solar cooling system are solar collectors, absorption chiller, thermal energy storage and backup boiler. Figure 5 illustrates the assembly of a typical solar assisted cooling system.

The basic principle of solar assisted cooling system starts with the water heated at the solar collector and pumped to drive the absorption chiller, which in turn produces the chilled water to flow in the distribution network and provide the comfort cooling to

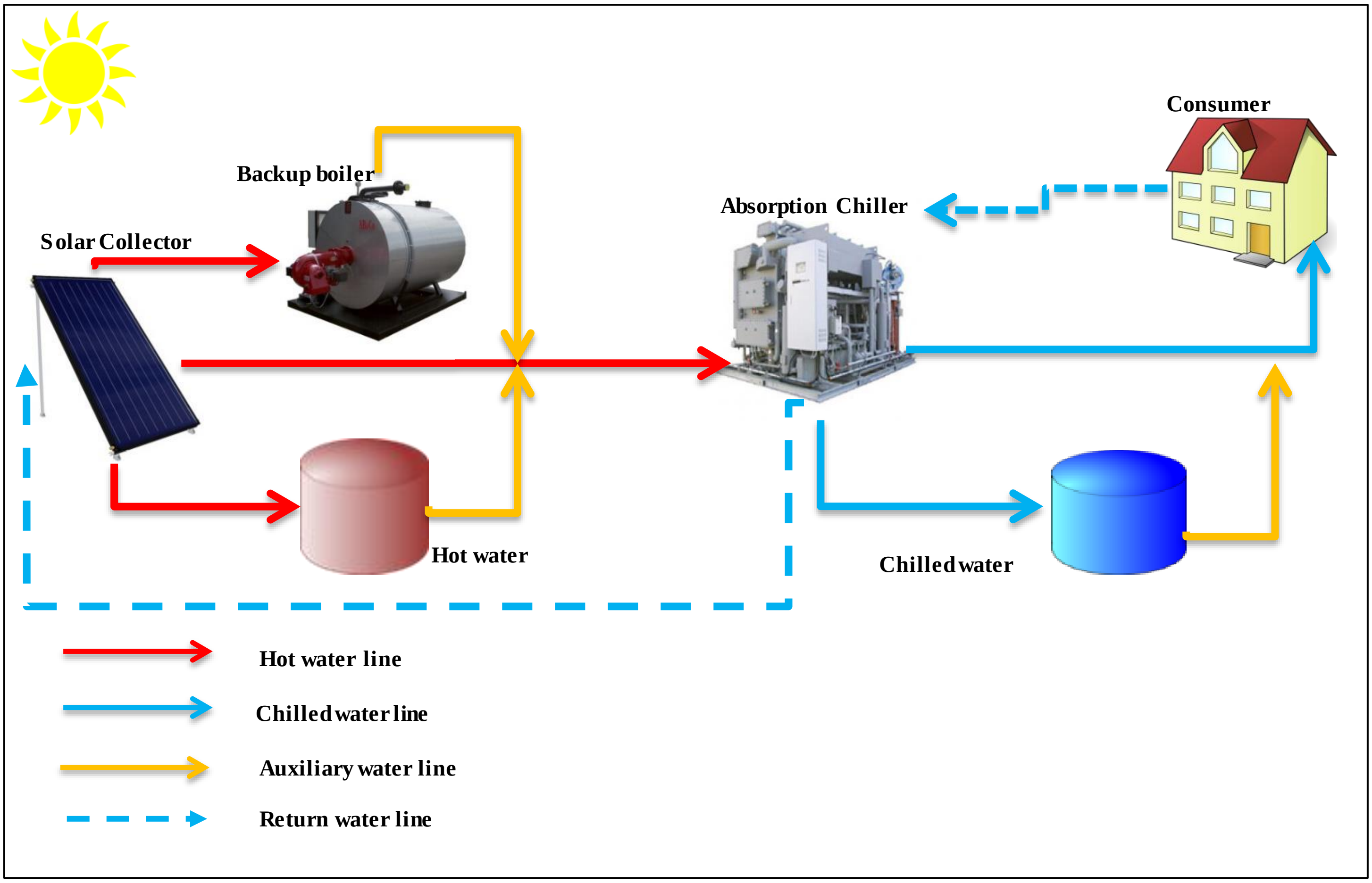

Figure 5: Schematic diagram of solar assisted cooling system

the consumers. As for the thermal-energy storage, the hot water storage tank is connected to the solar collector array, and the cold water storage tank is coupled to the absorption chiller. The efficiency of the solar collector affects the performance of the absorption chiller in a way that a proper efficiency of the collector allows the water to be heated in the range needed to drive the absorption chiller with high coefficient of performance; in contrast, poor collector efficiency causes water temperature used to drive the chiller to drop below required values preventing the absorption chiller form working properly. In the case of peak solar radiation and an absorption chiller operating with a required thermal energy less than thermal energy produced by the collector, a hot water storage tank is required to store hot water that can be used in later in scarce sun radiation times. Chilled water storage tank is integrated in the system in situations where cooling demand is less than the absorption chiller production of chilled water; as a result, chilled water is stored and used to shave the peak of cooling demand.

4. Literature Review

Literature review chapter is presented to enrich the consistency of this work; it shall start with extensive investigation of DCS in literature followed by findings in literature related to solar assisted cooling systems and their mathematical modeling.

4.1 Optimization of DCS

Spurr et al. (2008) developed an extensive investigation of DCS and its state of art; the publication included the motivation behind adapting such technology where the main elements of discussion are the benefits of DCS to customers, infrastructure and environment. In addition, the authors presented the process of design and operation of DCS and key issues related to load estimation, design temperatures, master planning and the integration of other utility infrastructure. Moreover, the study focused on the distribution system of chilled water to encompass the hydraulic design, pumping schemes and pressure control; as well as the different materials and components forming the piping system. Notwithstanding, the authors dedicated a significant chapter discussing the production technologies utilized in chilled water plants and the available alternatives of chillers such as compression chillers, natural gas chillers, absorption chillers and engine-driven chillers; alongside with other components of the chilled water plant component including thermal energy storage systems. Toward an end, the authors provided the existing alternatives of procurement and delivery of DCS projects which varied between Design/Bid/Build (DBB), Engineer/Procure/Construct (EPC) and packaged plants [4].

Gang et al. (2015) published a review paper combining the previous research of DCS and DCS projects and applications. A key element considered in their work is the integration of the sustainable energy technologies into DCS, thermal energy storage systems and cooling combined heat and power systems (CCHP). The authors reviewed the optimization of DCS from planning, design and operational approaches; from planning point of view, achieving a uniform cooling load for several types of buildings is the goal leading to an objective of finding the optimal cooling shares for each building. In the efforts of finding the optimal design of DCS, two topics have been broadly investigated; firstly is the optimization of global system design which in turn aims to find the optimal technology used for chilled water production, or to find the optimal location and capacity of chillers plant and energy storage systems where some researchers used Mixed Integer Linear Problem (MILP) models. Secondly, the optimization of subsystem design is studied to encompass the optimal layout of the chilled water distribution network and the optimal thickness of distribution pipes where Genetic Algorithm (GA) and Solver in Microsoft Excel are used respectively. With regard to the optimization of DCS operation, the objective is to minimize operational cost and consumption of energy where multi objective nonlinear programming is used. However, the authors referred to the lack of efforts in control optimization that includes both sides; the DCS and the end-user in addition to the optimization of the design with uncertainties such as the uncertainties in the estimation of cooling load, the performance components of the chiller plant and cooling load profile[1].

Feng & Long (2008) developed a mathematical model to optimize the network layout of a DCS, and the objective function is presented as the annual cost of investment, operation and maintenance. In their work, the application of Single Parent Genetic Algorithm (SPGA) is used to optimize the network layout and compared to Dijkstra algorithm; which proved better efficiency and stability for SPGA. In the discussion of the results for the examined case study, the authors selected a near optimal solution due to the incompliance of the optimal solution with the road conditions for the given case [18].

Khir & Haouari (2015) worked on an optimization problem of a single plant DCS, whereas the objective is to minimize the investment and operational costs of the designed system. Consequently, the included design variables are capacity of the chiller plant and the thermal storage tank, the layout of the chilled water distribution network and the production and inventory levels of chilled water along every period of time. The optimization problem formulated as Mixed Integer Problem (MIP), where thermal and hydraulic characteristics are incorporated which required the usage of Reformulation Linearization Technique (RLT); according to the results, authors managed to get an optimal solution with a short computational time [19].

4.2 Optimization of SAC

Solar assisted cooling system (SAC) attracted researchers' attention on several levels; some of them focused on improving the performance of the absorption chiller, while others studied the integration of solar cooling into conventional cooling systems. Moreover, research extended to investigate the practicality of combining solar cooling and heating systems to meet a certain demand along the different seasons. In fact, numerous research employed the software TRNSYS to simulate and optimize the performance of solar cooling systems.

Raja & Shanmugam (2012) published a review paper of developed solar assisting cooling systems; in their work, they stated that Lithium Bromide- Water absorption chillers are the most commonly used chiller for cooling purposes. Although, some research was done to compare different types of solar cooling technologies other than absorption cooling system, such as solar compression refrigeration and solar adsorption refrigeration. Another discussed research is the formulation of the problem of SAC as a bi-criterion nonlinear optimization to minimize the cost and the contribution to global warming. To assess solar cooling system economically two approaches are suggested, the first considers investment and operation cost and the second considers Life Cycle Cost (LCC) which in turn includes investment, operation, maintenance and energy estimation costs. The authors proposed a new design to minimize the heat transfer losses of the generator of the absorption chiller by placing it at the top of the hot water storage tank [20].

Mateus and Oliveira (2009) used TRNSYS in their work of an integrated solar absorption cooling and heating system to meet the demand of three different types of facilities (hotel, office building and a single-family housing) located in three different countries of Europe. It is worth mentioning that each type of buildings has similar area, construction material and number of floors for the three different locations. In their analysis, the authors managed to present the influence of the solar collector type, area and slope angle on the performance of the system alongside with the chiller type and the volume of the hot water tank. The results discussion included economic and energy considerations in addition to the CO_2 emission savings; whereas the investment and operating costs are taken into account with the different costs of electricity, water and gas with regard to the locations [21].

Tsoutsos et al. (2009) assessed the performance of a solar cooling and heating system composing of solar collector, a LiBr-H_2O absorption chiller, a storage tank, a backup heat unit, and a water cooling tower. The system provided comfort cooling for a Greek hospital during summer months and heating during winter with annual loads of energy reaches 123.91 kWh and 34.21 kWh respectively. The purpose of their study is to provide the optimal sizing of the system with the most benefits economically and environmentally using TRNSYS as a simulation software. Toward an optimal sizing of the system, the involved design parameters are solar collector surface, absorption chiller power, boiler power, water tank volume and cooling tower type and power; hence, the study analyzed four different scenarios based on varying the design parameters. The optimum scenario revealed a quite high investment cost yet a very attractive level of environmental benefits with high total annual savings [22].

Al-Alili et al. (2010) investigated the optimization of the performance and the cost of a solar cooling system under the climatic conditions of Abu Dhabi. The solar assisted cooling system consisted of evacuated tube collectors, 10 kW ammonia–water absorption chiller, an electric heater and a hot water storage tank. The design variables involved in the optimization are: the collector area, slope angle and flow rate, in addition to the volume of the hot water storage tank. The authors designated the coupling of MATLAB to TRNSYS to solve the multi objective optimization problem. Via MATLAB, three different algorithms are used, *fminsearch*, the Pattern Search (PS) and Genetic Algorithm (GA) to solve the optimization problem; while in TRNSYS the optimizer TRNOPT is used. Among the different optimization algorithms GA offered the optimum design, yet the authors preferred PS for being faster and providing a near optimal solution [23].

Gebreslassie et al. (2009) investigated the optimization of the cooling cycle design and operation under uncertainties of the prices of energy; in their work, they formulated a stochastic bi-criteria nonlinear optimization problem to minimize the cost of design and operation of absorption cycle and the associated risk level. The solution of the problem is presented as Pareto set of solutions expressing the tradeoff in the objectives [24].

Xu et al. (2015) studied the design of solar assisted cooling and heating system under life cycle uncertainties, the authors developed a stochastic multi-objective mathematical model to find the optimal design, where the design variables are slope and area of the solar collector and the volume of the hot and main storage tanks. In the analysis of results, they concluded that small systems has better economic performance than large systems; yet, the latter shows improved energy and environmental performance. Moreover, stochastic optimization would serve the purpose for an extreme risk-averse designer, while the deterministic optimization gives the designer the opportunity of improving the average performance of the system [25].

4.3 Literature Summary

The literature review integrated the optimization and related application of the design and operation of DCS in general and SAC specifically. Most of optimized SAC are simulated and optimized using TRNSYS software while optimization of DCS included a lot of mathematical modeling and operation research analysis. Table 4 below summarize the demonstrated literature survey.

Table 4: Literature review summary

Author	District Energy System	Cooling Technology	Optimization objective	Optimization method	Studied parameters
Feng & Long (2008)	DCS	Absorption/ Electricity chillers	Optimize network Layout	SPGA	___
Khir & Haouari (2015)	DCS	Compression chillers	Optimize investment and operation cost	MINLP/MIP Heuristics	Capacity of the chiller plant and the thermal storage tank and the production and inventory levels of chilled water
Mateus and Oliveira (2009)	SACH	Absorption/ Compression chillers	Optimize total cost and Co2 emissions reduction	TRNSYS software	Type, area and slope of Solar collector and chiller type and the volume of the hot water tank
Tsoutsos et al. (2009)	SACH	Absorption/ Compression chillers	Optimize the solar fraction for cooling, heating and overall solar fraction	TRNSYS software	collector plate area, collector plate slope angle, volume of hot water storage tank, nominal power of absorption chiller, cooling tower and backup heat source
Al-Alili et al. (2010)	SAC	Absorption chillers	Optimize system performance and its total cost	TRNSYS/ MATLAB	collector slope, the collector mass flow rate, the collector area and the storage tank volume
Gebreslassie et al. (2009)	SAC	Absorption chillers	Optimize the cost of design and operation of absorption cycle and the associated risk	stochastic bi-criteria nonlinear Programing	___
Xu et al. (2015)	SACH	Absorption chillers	Optimize life-cycle energy, economic, and environment performance	GA	Area of the solar collector, slope of the solar collectors and the volumes of the main storage tank and the heating storage tank

4.4 Contribution of Present Work

Through surveying literature, it is noted that the ability to find efforts in optimizing the design and operation of DCS are quite available, while there is lack of research that investigates SAC in the design stage where optimization of design and operation are highly recommended. Hence, the contribution of this work realized in developing a mathematical model for the SAC system as a whole and to solve a Mixed-Integer Linear Problem (MILP) aiming to find the optimal design of solar assisted cooling system. In other words, the outcome of this research shall emphasize on the global view of the design of SAC to achieve the best trade-off that combines all system components and their correlation simultaneously.

5. Problem Descriptions and Formulation

This chapter considers the formal description of the problem covering the design of the system to select the proper components with the required sizes to operate within anticipated levels of efficiency.

5.1 Design Components Selection

The selection of components comprising the system depends primarily on the selection of the absorption chiller type and size to meet the cooling demand. Another significant design component is the adoption of the solar collector type that has the capability to fit the selection of the absorption chiller, and the required area of the solar collectors to provide adequate thermal energy to drive the absorption chiller. However, integrating the thermal energy storage tank into the system may play an important role in selecting the size of the absorption chiller and the area of the solar collector; besides affecting the overall performance of the system. Likewise, incorporating auxiliary heating unit (if any) with appropriate size, efficiency and power consumption indicated influence on system performance and reliability.

Since solar assisted cooling system is driven by thermal energy, the consistency of temperatures between system components shall be achieved to operate as required. Hence, temperature of the source of heat provided by the solar collector to drive the absorption chiller shall be maintained in such levels that allow the coefficient of performance of the chiller to remain in acceptable range. As all system components are connected to each other in a way that the performance of one component affects the performance of the system as a whole.

5.2 Units Conversion

Typical cooling systems use the unit Ton of Refrigeration (TR) to measure the cooling capacity of the system, where 1 ton of cooling refers to the amount of heat needed to melt one ton of ice through the period of 24 hours. According to [26], British Thermal Unit (BTU) per hour is a unit equates RT, where 1 TR = 12000 BTU/hr. Another well-known unit that measures cooling capacity of refrigeration system is the thermal Kilo-Watt ($kW_{thermal}$) and 1 TR is equivalent to 3.52 $kW_{thermal}$; consequently, for the sake of coefficient of performance (COP) and solar collector area calculations, the unit $kW_{thermal}$ is adopted in this research as capacity measuring unit for the solar collector, absorption chiller, TES tanks and auxiliary boiler.

5.2 Scope of the problem

The previous discussion does not negate with the fact that there are solar cooling systems are operating successfully with considerably competitive coefficient of performance to conventional cooling system; yet the cost of such systems remains an issue to be focused on. Toward an end, the challenge realized in this work is to find the optimal design of a solar assisted cooling system with minimum investment and operating cost while achieving the most optimal attainable level of efficiency. Such optimal solution is realized by determination of:

1. The optimal area of solar collector.

2. The optimal capacity to be installed of the absorption chiller, thermal energy storage tank (if any), auxiliary heating unit (if any) .
3. The quantities of chilled and hot water to be produced and stored at each period of time.

5.3 Problem Formulation

Figure 6 represent the diagram of the solar assisted cooling system, it demonstrates the flow of energy in form of hot and chilled water between system components. It precisely illustrates that the flow of hot water produced in the solar collector (L_t) shall be pumped directly into the absorption chiller (L_t^c) or stored, in the case of excess production, into hot water storage tank (M_t) for later consumption (D_t^{HWT}). However, the failure of the two previously mentioned hot water sources allows the operation of an auxiliary boiler to supply hot water (B_t) to meet the chiller demand. Whereas the total amount of energy consumed by the chiller expressed as (F_t^{In}). The cooling energy produced by the chiller (F_t^o) is distributed in a way that meets the customer demand directly (S_t^{CW}), or in the case of excess production of cooling energy, the chilled water is pumped into chilled water storage tank (E_t) where it is used to meet customer demand of cooling energy in latter times (D_t^{CWT}).

5.4 Problem Assumptions:

Some assumptions shall be made to enable the mathematical modeling of the problem as listed below:

- Cooling demands are deterministic and known in predefined manner.
- Thermal energy storage tanks operate with full efficiency, counting for no losses.

- Efficiency of solar collector is constant and known in advance.
- Transient state of system operation is not considered, hence system operates in steady state.

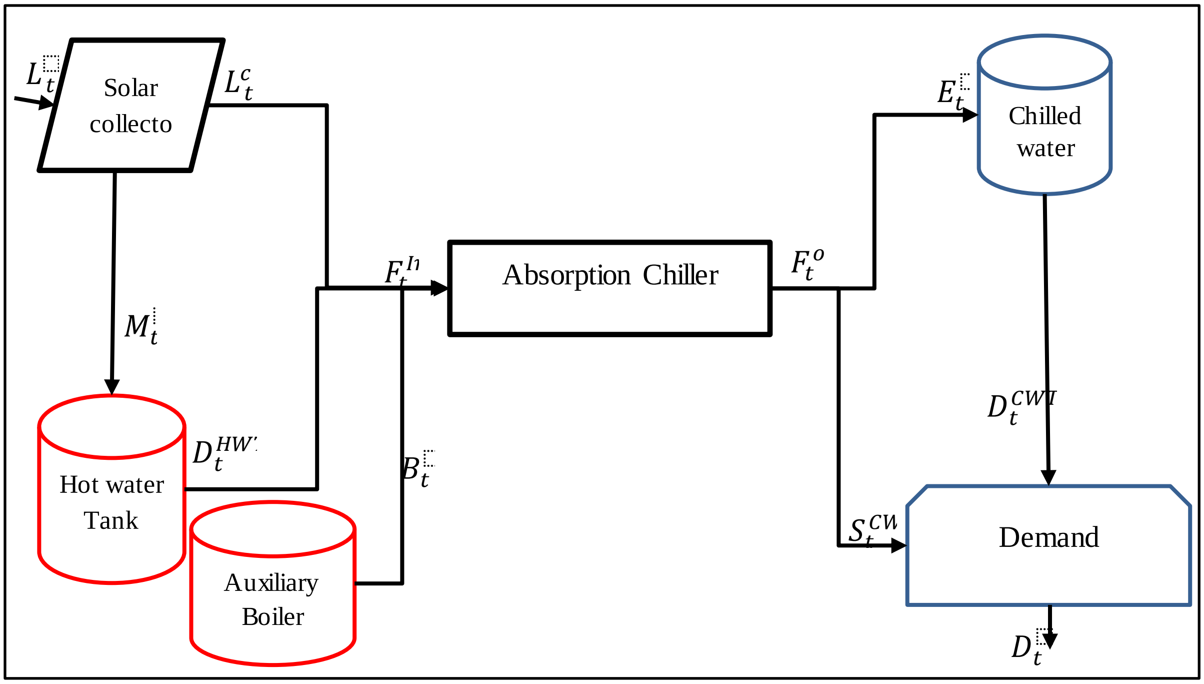

Figure 6: Diagram of SAC

Parameters

T : Number of operating time periods, t = 1,…,T.

FC_k^{Ch} : Fixed investment cost of installing chiller of capacity k ∈ K.

FC^{SC} : Fixed investment cost per unit area of installed solar collector.

FC_h^{CW} : Fixed investment cost of installing chilled water TES tank of capacity h ∈ H.

FC_j^{HW} : Fixed investment cost of installing hot water TES tank of capacity j ∈ J.

FC_q^{HW} : Fixed investment cost of installing auxiliary boiler of capacity q ∈ Q.

VC_t^{Ch} : Variable cost of producing a unit of chilled water at chiller during period t ∈ T.

VC_t^{Hsto} : Variable cost of storing a unit of hot water at TES tank during period t ∈ T.

VC_t^{Chsto} : Variable cost of storing a unit of chilled water at TES tank during period t ∈ T.

VC_t^{HW} : Variable cost of producing a unit of hot water at auxiliary boiler during period t ∈ T.

G_t : Global solar radiation during period t ∈ T expressed in (W/m^2).

η_{sc} : Efficiency of a given type of solar collector.

Q_k : kth capacity for chiller expressed in (KW), ∀ k∈ K

COP_k : Coefficient of performance of chiller of kth capacity, ∀ k∈ K

D_h : hth capacity for chilled water TES tank expressed in (KWh), ∀ h∈ H

R_j : jth capacity for hot water TES tank expressed in (KWh), ∀ j∈ J

L_q : qth capacity of auxiliary boiler expressed in (KWh), ∀ q∈ Q

D_t : Amount of customer demand of cooling during period t∈ T, expressed in (KW).

A : Maximum area of installed solar collector, expressed as (m^2).

EFF_q : Efficiency of auxiliary boiler of qth capacity, ∀ q∈ Q

τ : the duration of every time periods, expressed as an hour

Decision Variables

y_k : Binary variable that takes value 1 if chiller is installed of capacity k ∈ K.

x : Variable represents the total area of installed solar collector, expressed as (m^2).

g_h : Binary variable that takes value 1 if chilled water TES is installed of capacity h ∈ H.

z_j : Binary variable that takes value 1 if hot water TES is installed of capacity j ∈ J.

w_q : Binary variable that takes value 1 if auxiliary boiler is installed of capacity q ∈ Q.

F_t^o : Amount of cooling production by chiller during period t ∈ T, expressed as KW.

F_t^{In} : Amount of heat consumption by chiller during period t ∈ T, expressed as KW.

S_t^{CW} : Amount of customer cooling consumption met from chiller during period t ∈ T, expressed as KW.

L_t : Amount of heat production by solar collectors during period t ∈ T, expressed as KW.

L_t^c : Amount of heat production by solar collectors delivered directly to chiller during period t ∈ T, expressed as KW.

I_t^{CW} : Inventory level of cooling energy stored at TES tank at the end of period t ∈ T expressed (KWh).

I_t^{HW} : Inventory level of heating energy stored at TES tank at the end of period t ∈ T expressed (KWh).

E_t : Amount of cooling production of chiller, delivered to chilled water TES tank during period t ∈ T expressed (KW).

M_t : Amount of heat production of solar collector delivered to hot water TES tank during period t ∈ T expressed as (KW).

D_t^{CWT} : Amount of customer cooling consumption, met from chilled water TES tank during period t ∈ T expressed as (KW).

D_t^{HWT} : Amount of heat consumption of chiller, met from hot water TES tank during period t ∈ T, expressed as (KW).

B_t : Amount of heat production of auxiliary boiler during period t ∈ T, expressed as KW.

Mathematical Formulation

$$\sum_{k \in K} FC_k^{Ch}\, y_k + \sum_{t \in T} VC_t^{Ch}\, F_t^o + \sum_{i \in I} FC^{SC}\, x + \sum_{h \in H} FC_h^{CW}\, g_h + \sum_{t \in T} VC_t^{Chsto}$$

$$I_t^{CW} + \sum_{j \in J} FC_j^{HW}\, z_j + \sum_{t \in T} VC_t^{Hsto}\, I_t^{HW} + \sum_{q \in Q} FC_q^{HW}\, w_q + \sum_{t \in T} VC_t^{HW}\, B_t \qquad (1)$$

The objective function (1) minimizes the sum of the fixed costs of installing chillers, solar collectors, hot and chilled water storage tanks and auxiliary boiler along with the variable cooling and heating production and storage costs.

Existence Constraints

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

Constraint (2) enforce that only one chiller is installed with kth capacity

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

Constraint (3) enforce that if chilled water storage tank is installed it shall have only one capacity.

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

Constraints (4) enforce that if hot water storage tank is installed it shall have only one capacity.

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

Constraints (5) enforce that if auxiliary boiler is installed it shall have only one capacity.

Capacity Constraints

$$\frac{L_t}{\eta_{sc}\ G_t} \le x \ \le \mathrm{A} \qquad \forall\ t \in \mathrm{T} \tag{6}$$

Constraint (6) introduce the total area of selected solar collector

$$F_t^{o} \le \sum_{\mathrm{k} \in \mathrm{K}} Q_k\ y_k \qquad \forall\ t \in \mathrm{T} \tag{7}$$

Constraint (7) ensure that the cooling production does not exceed installed capacity of the chiller.

$$I_t^{CW} \le \sum_{\mathrm{h} \in \mathrm{H}} D_h\ g_h \qquad \forall\ t \in \mathrm{T} \tag{8}$$

Constraint (8) ensure that the amount of inventory level of chilled water tank does not exceed installed capacity of the tank.

$$I_t^{HW} \le \sum_{\mathrm{j} \in \mathrm{j}} R_j\ z_j \qquad \forall\ t \in \mathrm{T} \tag{9}$$

Constraint (9) ensure that the amount of inventory level of hot water tank does not exceed installed capacity of the tank.

$$B_t \ \le \sum_{\mathrm{q} \in \mathrm{Q}} L_q\, w_q \ * Effq \qquad \forall\ t \in \mathrm{T} \tag{10}$$

Constraint (10) ensure that the amount of heat production of auxiliary boiler does not exceed installed capacity of the boiler with certain efficiency of the boiler.

$$F_t^{o} \le COP_k\ F_t^{In} \tag{11}$$

Constraint (11) introduce the coefficient of performance of the chiller.

Balance Constraints

$$I_{t-1}^{CW} + \tau\, E_t \ = I_t^{CW} + \tau\ D_t^{CWT} \qquad \forall\ t \in \mathrm{T} \tag{12}$$

Constraint (12) impose the balance constraints for the chilled water storage tank.

$$I_{t-1}^{HW} + \tau\, M_t \ = I_t^{HW} + \tau\ D_t^{HWT} \qquad \forall\ t \in \mathrm{T} \tag{13}$$

Constraint (13) impose the balance constraints for the chilled water storage tank.

Supply Demand Constraints:

$$S_t^{CW} + D_t^{CWT} = D_t \qquad \forall\ t \in \mathrm{T} \tag{14}$$

Constraint (14) enforces that customer demand of cooling could be met by either chiller or chilled water storage tank or both of them.

$$L_t^C + D_t^{HWT} + B_t = F_t^{In} \qquad \forall\ t \in T \tag{15}$$

Constraint (15) enforces that chiller demand of heat could be met by either solar collector, hot water storage tank or auxiliary boiler.

$$L_t^C + M_t = L_t \qquad \forall\ t \in T \tag{16}$$

Constraint (16) enforces that production heat by solar collector could be pumped directly into the chiller or stored into hot water storage tank.

$$S_t^{CW} + E_t = F_t^o \qquad \forall\ t \in T \tag{17}$$

Constraint (17) enforces that cooling production by chiller could be pumped directly to meet customer demand or stored into chilled water storage tank.

Non-negativity and integrality Constraints

$$y_k\ , g_h\ , z_j\ , w_q \in \{0,\ 1\} \tag{18}$$

$$x\ \ , F_t^o, F_t^{In}, S_t^{CW}, L_t\ , L_t^c, I_t^{CW}, I_t^{HW}, E_t\ , M_t\ , D_t^{CWT}, D_t^{HWT}\ , B_t\ \geq 0 \tag{19}$$

6. Computational Experiments

This chapter presents the results of a computational study of the developed MILP model. In this context, MIP commercial solver, IBM ILOG CPLEX Optimization Studio 12.6 is used with the aim of finding optimal solution of the developed model; where all formulations are coded into Optimization Programming Language (OPL). All computational analysis were carried out on Intel® Core™ i5-4210U CPU@ 1.7 GHz Computer with 4GB RAM. The aim of these computational tests is to validate and verify the solvability of the proposed model and to examine different scenarios to focus on the impact of changing certain problem parameters on results of the optimization.

6.1 Optimization Parameters

For the sake of computational experiments, the hourly cooling load is assumed for January, which is the basis for cooling load assumption for the other 11 moths. In this framework, a ratio of the outdoor temperature for each month to the outdoor temperature of January is multiplied by the assumed cooling demand of January resulting the cooling demand for each month. The cooling load for 1 year is depicted in Figure 7.

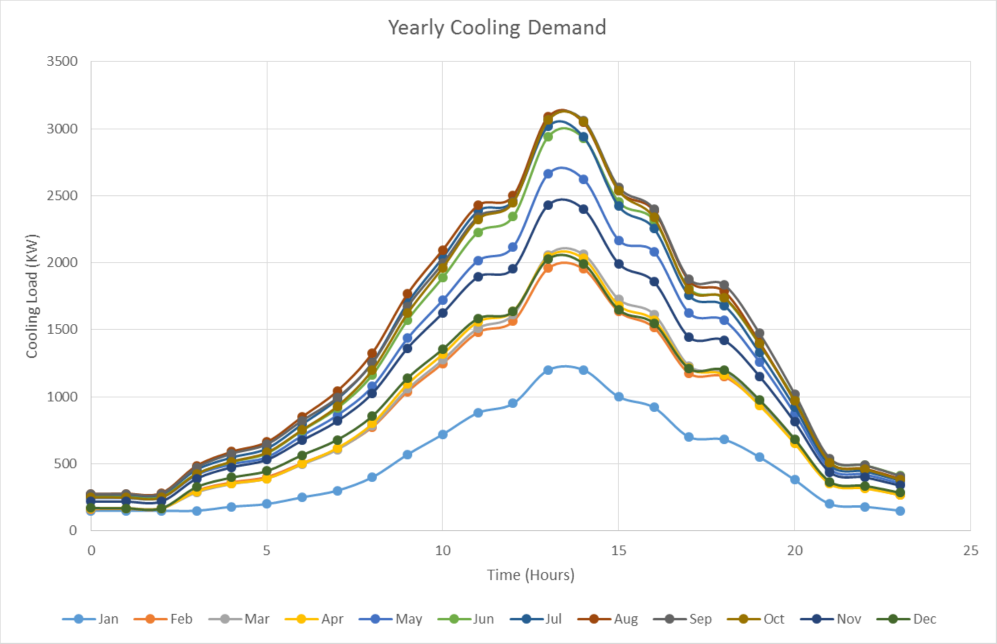

Figure 7: Yearly Cooling load

As for the global solar irradiance levels, the hourly real-life measurements are provided by Qatar General Electricity & Water Corporation (Kahramaa). A sample of the collected data illustrated in Figure 8, shows that there is a gap between the demand in very early morning hours and night hours and the available solar energy. In this case, assistance of the coupled auxiliary units such as boiler or TES tanks is required. The costs and the efficiencies of the system's components are assumed based on the study examined in [27], where some values were modified according to the analysis needs.

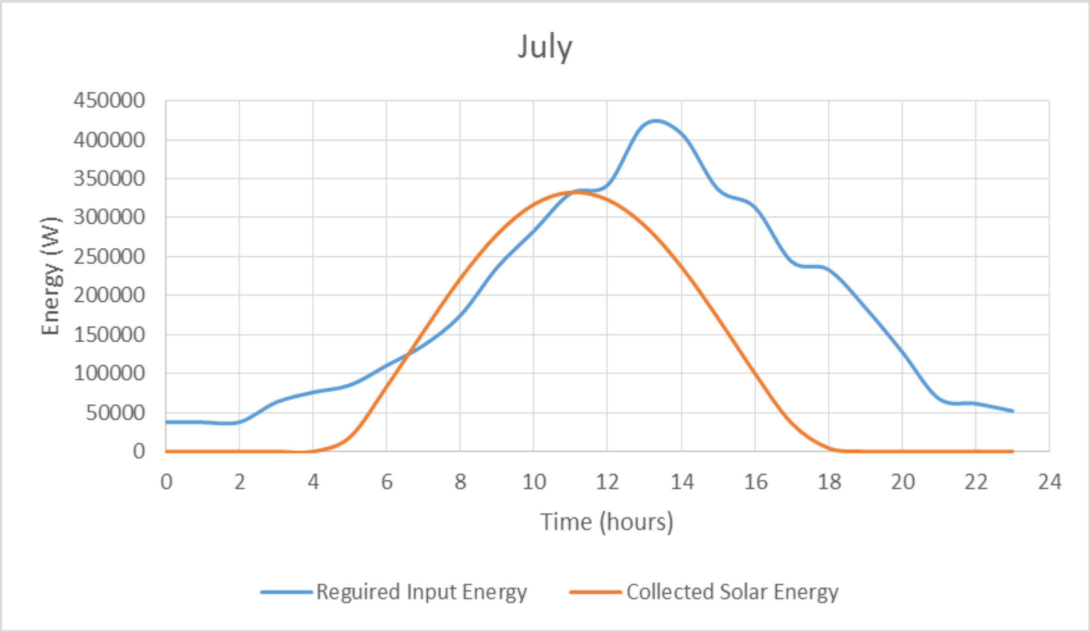

Figure 8: Sample of Collected Solar Energy and required input energy

6.2 Optimization of a solar assisted cooling system

The parameters in chapter 5 are loaded into CPLEX, with the assumed cooling demand. The number of periods of the tested proposed optimization model exceeded 8000, representing the number of hours per annum; hence all the assumed variable costs have the same length as number of periods. Table 5 demonstrates some of the parameters included in the problem such as capacities and fixed costs of alternatives of system components. Yet variable costs and solar irradiance measures are not shown in the report due to their high number of indices which is similar to the number of operating periods.

Table 5: Problem Parameters

Parameter	Alternatives		
Chiller Capacity (KW)	2792	3193	3376
Chiller COP	0.7	0.72	0.71
Chiller Fixed Cost(QR)	3,403,727	3,892,586	4,115,681
Chilled water Tank Capacity(KWh)	1500	2000	
Chilled water Tank Fixed Cost(QR)	159,000	212,000	
Hot water Tank Capacity(KWh)	400	550	
Hot water Tank Fixed Cost(QR)	71,540	94,352	
Boiler Capacity (KW)	1000	3000	
Boiler Efficiency	0.8	0.7	
Boiler Fixed Cost(QR)	44,676	134,028	
Collector cost (QR/m^2)	1700		
Maximum area of solar collector(m^2)	500		
Optimal Area of Solar Collector (m^2)	500		
Total optimal cost (QR)	66,075,143		

An optimal solution realized in the minimized investment and operational cost represented in the highlighted alternatives and the optimal total cost demonstrated in

Table 5. It is noteworthy to mention that optimal solution is obtained with all constraints satisfied in around 15 minutes of computational time.

6.3 Sensitivity Analysis

The optimized cost obtained in the computational analysis represents the initial investment cost for the system and the operational cost per annum. Therefore the Net Present Value (NPV) of the system based on an interest rate of 8% and a life cycle of 20 years is calculated. In this section sensitivity analysis is conducted to examine the impact of key parameters on the total cost of the system. In this essence; solar collector's efficiency, chiller's coefficient of performance, auxiliary boiler's efficiency and the cost of all components are varied one at a time keeping all other values fixed. Such analysis measures the sensitivity of the final solution to the changes of each parameter. The variation of the key parameters are examined according to the values shown in Table 6.

Table 6: Sensitivity analysis levels

Input Parameter	Minimum	Maximum	Base Value	Increment
Solar Collector Efficiency	0.56	0.84	0.7	0.014
Chiller COP	0.576	0.864	0.72	0.0144
Boiler Efficiency	0.56	0.84	0.7	0.014
Solar Collector Cost (QR/m^2)	1,360	2,040	1,700	34
Chiller Cost (QR)	3,114,069	4,671,103	3,892,586	77,851
Boiler Cost (QR)	107,222	160,838	134,028	26,81
Hot Water Tank Cost (QR)	75,481	113,222	94,352	1,887
Chilled Water Tank Cost (QR)	169,600	254,400	212,000	4,240

The results of the analysis are shown in Figures 9 and 10, where each base value is plotted versus to the NPV of the optimized system. The diagram in Figure 9 illustrates the impact of varying the efficiencies of the solar collector, chiller and auxiliary boiler from -20% of the base value to 20% of the base value. Clearly, the highest impact of such variation on the NPV is for the coefficient of performance of the chiller; while the efficiencies of the collector and the boiler has relatively lower impact on the NPV of the system. Similar conclusion is applied to the variation of the costs of the components of the system; where the NPV shows higher sensitivity to the changes of the cost of the chiller. Yet, the variations of the cost of solar collectors has higher impact on NPV than the changes in TES and boiler costs. Finally, Figure 11 shows the different cases examined when TES is coupled to the system or not. Excluding both TES from the system introduces an increase in the NPV by 14%

compared to the base case when TES are included in the system. In fact, the higher impact is found to be for the Chilled Water tank compared to the Hot Water tank and this is due to the fact that chilled water tank works on shaving the peak of the demand alongside with the chiller and its initial investment cost which is higher in the proposed model than hot water storage tank. Moreover, the existence of the hot water storage has lower impact on NPV because the available area for solar collectors in the proposed model is relatively sufficient to cover the demand of the chiller leading to less dependence on its production and accordingly less storage costs and the fact that any shortage of hot water is covered by the auxiliary boiler.

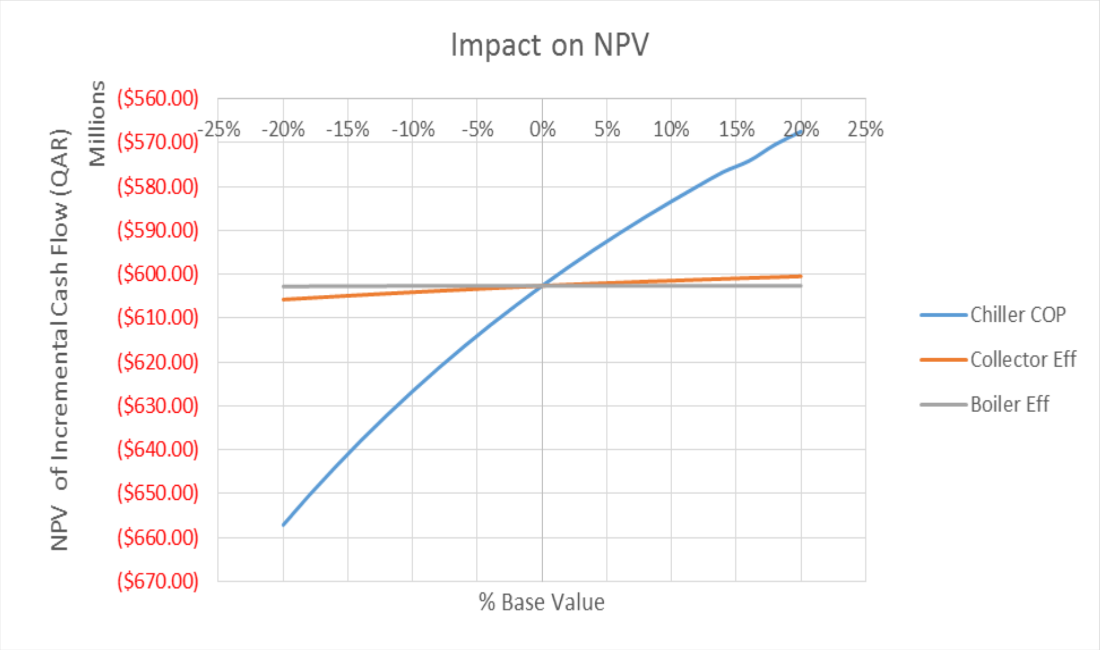

Figure 9: Spider diagram illustrating sensitivity of NPV to efficiencies

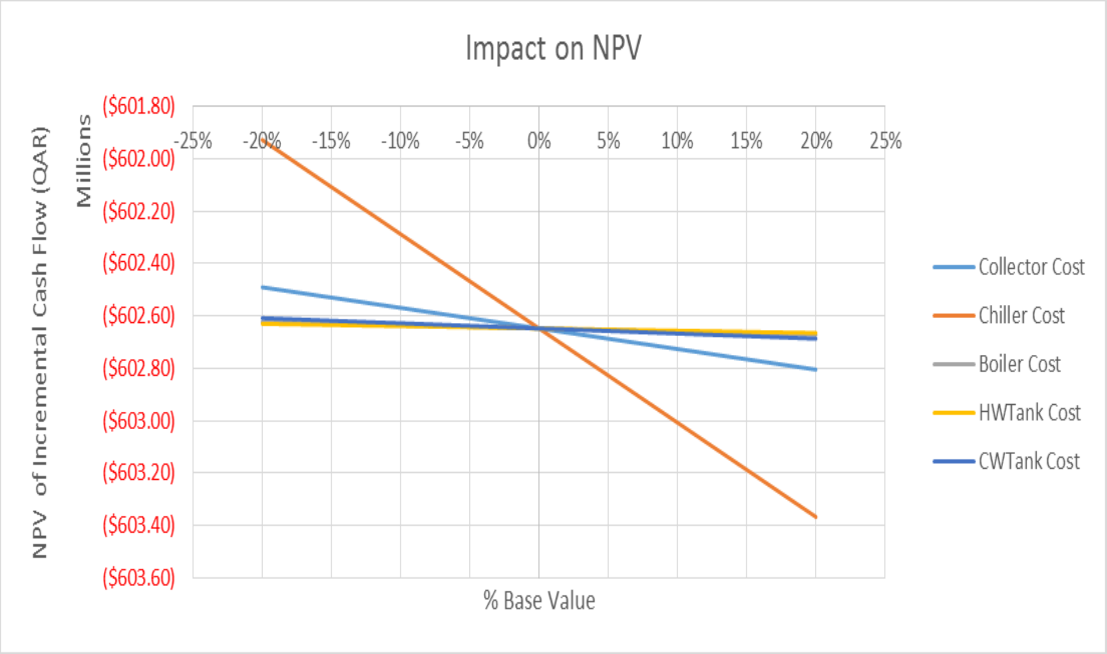

Figure 10: Spider diagram illustrating sensitivity of NPV to costs

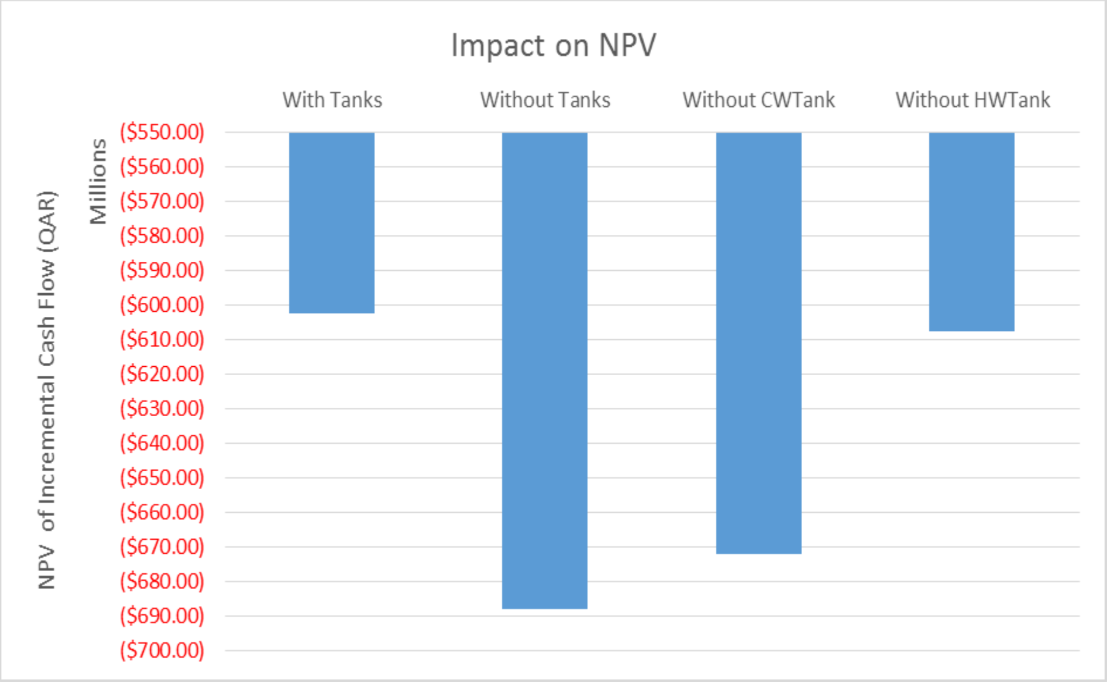

Figure 11: Impact on NPV in cases with/out TES tanks

7. Conclusion and Future Research

Solar assisted cooling technology, the science of converting heat into cool, appears to be very appealing concept where comfort cooling is a crucial demand. SAC systems have a promising future to replace conventional cooling systems due to dependency on renewable energy resource. In addition, the advantage of the correlation between availability of solar energy supply and the necessity of cooling demand assured their presence as a feasible alternative. Nevertheless, the relatively high initial investment costs made conventional cooling technology more preferable alternative to consumers. Therefore, this work is completed with the aim of minimizing the total cost of investment and operation of a SAC system, where the problem is modeled as MILP problem and optimal size and existence of system components are obtained while meeting the cooling demand using CPLEX optimizer. Toward an emphasis on the conducted computational analysis, the net present value of the system for a specific life cycle is calculated to be the base of the followed sensitivity analysis. The sensitivity of the optimal solution to key parameters such as the efficiencies and the costs of system components is examined; in addition to the existence of the TES into the system. According to the results, the performance and the cost of the chiller has the higher impact on the cost of the system, as well as, the inclusion and the elimination of the TES tanks to the system.

Toward future researches, considering maximization of SAC system performance offers great advantage and increase system's competency; such maximization suggests increase in the efficiency of the selected solar collectors and the coefficient of performance of the absorption chillers. The interim nature of solar irradiance require most of SAC system to utilize heating/cooling auxiliary units that driven by electricity; hence, considering CO_2 reduction into the problem is very much recommended to reach a zero carbon system. That goal might be achieved in several ways, one of them is the adaption of other renewable energy resources to drive auxiliary units, while another alternative would be the inclusion of some types of solar collectors that are used to generate electricity.

References

1. Gang, W., Wang, S., Xiao, L., & Gao, D.-c. (2015). District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. *Renewable and sustainable enrgy review*, 253–264.

2. Mildenstein, P. (2002). *District Heating and Cooling Connection Handbook* . Netherlands Agency for Energy and the Environment.

3. Chan, A., Chow, T.-T., Fong, S., & Lin, J. (2006). Performance evaluation of district cooling plant with ice storage. *Energy*, 2750–2762.

4. Spurr, M., Kleist, B., Miler, R., Moe, E., & Mark, F. (2008). *District cooling best practice guide.* Massachusetts: International District Energy Association.

5. (AREA), A. c. (2014). *Guidelines - How to Approach District Cooling.* AREA.

6. Euroheat, P. (2006). *District Cooling: Cooling more with less.* EUROHEAT & POWER.

7. Paksoy, H., Andersson, O., Abaci, S., Evliya, H., & Turgut, B. (2000). Heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in an aquife. *Renewable energy*, 117–122.

8. Rentizelas, A., Tatsiopoulos, I., & Tolis, A. (2009). An optimization model for multi-biomass tri-generation energy supply. *Biomass and Bioenergy*, 223–233.

9. Siddiqui, M., & Said, S. (2015). A review of solar powered absorption systems. *Renewable and Sustainable Energy Reviews*, 93–115.

10. Kalogirou, S. (2014). Solar Energy Collectors. In S. Kalogirou, *Solar Energy Engineering* (pp. 125-220). Elsevier .

11. Kalogirou, S. (2014). Performance of Solar Collectors. In S. Kalogirou, *Solar Energy Engineering* (pp. 221-256). Elsevier .

12. Fan, Y., Luo, L., & Souyri, B. (2007). Review of solar sorption refrigeration technologies:Development and applications. *Renewable and Sustainable Energy Reviews*, 1758–1775.

13. Deng, J., Wang, R., & G.Y, H. (2011). A review of thermally activated cooling technologies for combined cooling,heating and power systems. *Progress in Energy and Combustion Science*, 172-203.

14. Grossman, G. (2002). Solar-powered systems for cooling, dehumidification and air-conditioning. *Solar Energy*, 53–62.

15. Yabase, H. (2012). *Technology and Application of Absorption Chillers.* Shiga: Kawasaki Thermal Engiineeriing.

16. (IRENA), T. I. (2015). *Solar Heating and Cooling for Residential Applications.* IRENA.

17. Zhai, X., Qu, M., Li, Y., & Wang, R. (2011). A review for research and new design options of solar absorption cooling systems. *Renewable and Sustainable Energy Reviews*, 4416– 4423.

18. Feng, X., & Long, W. (2008). Applying Single Parent Genetic Algorithm to Optimize Piping Network Layout of District Cooling System. *IEEE Computer Society*.

19. Khir, R., & Haouari, M. (2015). Optimization models for a single-plant District Cooling System. *European Journal of Operational Research*, 648-658.

20. Boopathi Raja, V., & Shanmugam, V. (2012). A review and new approach to minimize the cost of solar assisted absorption. *Renewable and Sustainable Energy Reviews*, 6725–6731.

21. Mateus, T., & Oliveira, A. (2009). 6. Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates. *Applied Energy*, 949–957.

22. Tsoutsos, T., Aloumpi.E, Gkouskos, Z., & Karagiorgas, M. (2010). Design of a solar absorption cooling system in a Greek hospital. *Energy and Buildings*, 265–272.

23. Al-Alili, A., Hwang, Y., Radermacher, Y., & Kubo, I. (2010). Optimization of a solar powered absorption cycle under Abu Dhabi’s weather conditions. *Solar Energy*, 2034–2040.

24. Gebreslassie, B., Guillén-Gosálbez, G., Jiménez, L., & Boer, D. (2009). Economic performance optimization of an absorption cooling system under uncertainty. *Applied Thermal Engineering*, 3491–3500.

25. Xu, D., Qu, M., Hang, Y., & Zhao, F. (2015). Multi-objective optimal design of a solar absorption cooling and heating system under life-cycle uncertainties. *Sustainable Energy Technologies and Assessments*, 92–105.

26. *Refrigeration tons to BTU per hour conversion*. (2016, January 15). Retrieved from Rapid Tools: http://www.rapidtables.com/convert/power/ton-to-btu.html.

27. Sanaye, S., & Hajabdollahi, H. (2015). Thermo-economic optimization of solar CCHP using both genetic and particle swarm algorithms. *Journal of Solar Energy Engineering* .