QATAR UNIVERSITY

COLLEGE OF ENGINEERING

MODELING AND OPTIMIZATION OF DISTRICT COOLING SYSTEM

BY

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ABSTRACT

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Title: Modelling and Optimization of District Cooling System

Supervisor of Thesis: Tarek El Mekkawy - Shaligram Pokharel .

This research focuses on modeling and optimization of the design and operation of a district cooling system (DCS). The research investigates two solution paths: (1) the system transformation leading to re-organizing the conventional system (powered by the grid electricity) to achieve better economic and energy performance, and (2) the system integration of solar cooling technologies to enhance sustainable development for decreasing CO_2 emissions.

The multi-chillers district cooling plant is modeled by using algebraic modeling language (AML). The mathematical model is developed as a mixed-integer linear programming (MILP) problem. Frameworks are proposed to ease the DCS understanding and bridge the system modeling and optimization gap. A Model-Based System Engineering (MBSE) driven by the stakeholders and system requirements is developed. The DCS model includes the design, operation, and control by considering the interconnectivity of its components. The chiller short cycling requirement is modeled as system sequencing control. The optimization leads to reducing the total cost, including the design and operation. Consequently, it becomes cost-effective and reduces energy consumption; hence, decreasing carbon emission. Results show that the change of requirements improves the system performance.

Renewable energy is considered an add-on to cooling technologies. Multiple configurations of solar-cooling systems are analyzed through a generalized model by considering the energy prices and the available installation area. The results show that the electricity tariff and the available installation area have an impact on the cost competitiveness of the solar energy integration. The results show that when the electricity tariff is subsided (low), the conventional Grid-based DCS is the most competitive. However, the photovoltaic-DCS configuration is more competitive than the thermal and hybrid systems and reduces the pollution up to 58.3%. The hybrid-DCS configuration has the lowest operation cost and the highest environmental performance as it decreases pollution up to 89.5%. The thermal-DCS configuration becomes economically attractive only at high electricity tariff and medium to high available installation area, and decreases the pollution up to 43.76%.

The two developed models are useful for the conceptual design phase of the DCS, where the front end engineering design (FEED) phase requires such information (optimal design and operation) for further detail development

DEDICATION

I dedicated this thesis to all people who supported me and did not give up on finishing my doctorate, especially to

My wife Echraf Cherif

For her patience, support, and encouragement during these years of study.

May she find here the testimony of my deep gratitude,

To my daughter Sandra and my son Bedyss

Their encouragement helped me to continue my work to bring it to this stage after losing about a year.

I never thought of coming back again.

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LIST OF ACRONYMS AND ABBREVIATIONS

Ab	Absorption chiller
Bld	building
Bo	Auxiliary boiler
Col	Type of solar collector (T, PV, PVT)
CRF	Capital recovery factor
Cwt	Chilled water storage tank
DCS	District cooling system
Elec	Electricity
ETS	Energy transfer station
Gas	Fuel (natural gas)
Grid	Electric grid
Hwt	Hot water storage tank
Ma	Maintenance
Net	Net
PLR	Partial load ratio (%)
TES	Thermal energy storage
Ther	Thermal
Vc	Vapor compression chiller

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Chapter 1: Introduction

The building sector represents almost one-third of total energy consumption, where cooling accounts for almost 10% worldwide and 15% in the Middle East region. It is estimated that the space cooling energy consumption uses electricity which accounts for more than 2,000 TWh annually and has tripled between 1990 and 2016 [2]. Due to its benefits, the district cooling system (DCS) is widely used, mainly in hot regions, such as in the Middle East and this trend is increasing. For example, up to 2018, the state of Qatar has installed more than 41 district cooling plants with a total capacity of 794,062 TR. Additionally, 61 projects are under construction and design phases with a total capacity of 876,070 TR [3]. The design and operation of these systems is challenging due to diverse stakeholders' requirements and during integration with new technology

1.1 District Cooling System (DCS)

The DCS is a centralized plant that produces and distributes thermal energy in the form of chilled water to meet the cooling demand of an aggregated set of customers [4]. The system comprises a central plant, including the heat rejection unit, pumps and chillers, underground insulated distribution network, and customer's interconnection (energy transfer station, ETS). These systems provide a cooling load to a range of buildings (residential, commercial, industrial, and office buildings). The chilled water is pumped from the centralized plant to the end-user and then back to the DC plant through the network. The heat exchanger transfers the thermal energy of the chilled water to the building system. The returned warm water is chilled again and re-pumped. Based on the system requirements, other components can be added to the system, such as thermal energy storage (TES) and water treatment units [5].

1.2 Benefits of DCSs

In contrast to the conventional decentralized cooling system, DCS has advantages in environmental and economic aspects. The principle of mass production and higher technology performance classifies the DCS as more efficient than conventional cooling. The ability of chillers staging to satisfy the aggregate cooling load and its flexibility allowed the DCS to be more efficient, and thus the environmental impacts are reduced. The DCS can take advantage of other equipment such as TES that further shaves the peak demand and reduce energy consumption and CO_2 emissions.

The DCS can be integrated with renewable energy (solar and free cooling), waste heat (from industrial processes, incineration, and co-generation plants), and waste cooling (liquefied natural gas re-gasification). The central production and the underground network enhance the building aesthetic and improve the local environment by decreasing the noise. The used chemicals and refrigerants at the central plant are controlled and monitored to avoid hazards. From the economic perspective, the DCS provides a secured supply of cooling demand. It avoids the extra investment in the cooling system and electricity infrastructure for both customers and the government.

Furthermore, it significantly reduces the operation cost [6]. The Planning and Statistics Authority (PSA) report concerning the DCS in Qatar shows that DCS saved around 16,334,588 MWh during 2018 compared to the conventional cooling and contributed to emissions reduction by 7,350,564 thousand tons of CO_2-equivalent. Moreover, 3,466,573 m^3 of freshwater was saved using the treated wastewater in makeup cooling towers [3].

1.3 Challenges of DCS

The DCS is considered a complex system for many reasons; the system is composed of interacting parts [8], and these parts include products (hardware, software, and firmware), processes, people, information, techniques, facilities, and services [9]. Different technology may be used to develop the system (for example, for cooling, pumping, and energy). Each technology has its cost, behavior, efficiency, and requirement characteristics. There is no unique configuration to design and operate DCS that satisfies the cooling demand. The DCS is mainly powered by electricity, but many other energy sources can be the candidates to drive the DCS. The system component and behavior work under the thermodynamics and heat transfer laws. The system behavior in terms of energy consumption is not linear. The environment interacts heavily with the DCS (building and climate). These later have an uncertain behavior. Many parameters must be controlled during the cooling process (temperature, pressure, flow rate, energy efficiency, cooling load, outside temperature, and moisture) towards energy efficiency and cooling satisfaction. Stakeholders intervene in the design and the operation of DCS (regulatory authority, developer, operator, customers, and component supplier). Thus, stakeholders generate multiple requirements to be considered during the DCS design, operation, and control. A set of key indicators are commonly used to assess economic, energy, and environmental-related performance.

1.4 Research objectives

The following are the main objectives of the research:

- To develop a modeling framework to bridge the gap between the DCS complexity and the optimization process.
    - The framework integrates the holistic view of DCS, enhances the system knowledge, and draws the link between the system's components.

- To develop a model based on stakeholders' requirements for optimizing the design and the operation of DCS.
    - The proposed model aims to consider the main regulatory authority, developer, and systems' requirements for the optimal design and operation of multi-chillers district cooling plant. Energy efficiency is the keyword for the developed model and thus for selecting and operating chillers.
- To study the integration of solar energy technology with the DCS, in terms of economics and environmental benefits.
    - The proposed model aims to generalize the design and the operation optimization of solar cooling configurations by considering the electricity tariff and the availability of installation area and to compare the different configurations based on the economic, energy use, and environmental performance.

1.5 Research questions

The design, the operation, and the performance of DCS reflects the statement of the stakeholder's and system requirements. Therefore, their impacts should be analyzed to improve the cost and the energy consumption for the DCS.

1. What is the impact of stakeholders and system requirements on the DCS performance?

Solar energy has a great potential for the sustainable development of DCS in hot region. The diversity in solar and cooling technologies generates a variety of possible configurations to meet the cooling demand. Decision-makers struggle to select the appropriate configuration.

2. What are the most effective solar cooling configurations for sustainable DCS based on energy price and availability of installation area?

Different models are required during the DCS development stages (pre-conceptual, conceptual, preliminary, and final design). During the project planning period the DCS modeling is crucial for decision gate. The project approval is tributary to the design, the operation performance (efficiency), and the overall DCS cost.

3. What modeling methodology can be formulated for efficient design and operation of DCS?

Project related energy system can be described as a succession of phases and decisions (gates). During earlier stage (planning), the pre-conceptual and conceptual design are critical phases, where the development focus on selecting the appropriate technology and system configuration by considering the main system functionality (technical feasibility), which is in our case the satisfaction of the cooling demand and by estimating certain system performance such as cost, renewable energy use, and emissions. Data regarding the system performance is used in addition to other criteria (risk) to make decision for further continuing the project development or declining. During conceptual design, the modeling framework is essential to capture the main system structure, behaviors, and to optimize the considered performances without the need of a deep investigation of all the system operational parameters and by considering hypothesis. However, if the project is selected, a comprehensive system model is constructed during the detailed design by using domain analysis approach.

1.6 Thesis Contributions

As DCS is designed by understanding the total supply, demand and processing requirements for cooling, this thesis contributes it by assessing the total cooling system by using a systemic approach through a Model-based System Engineering

(MBSE) concept. The following are the main contributions made in this thesis

- This thesis utilizes model-based system engineering (MBSE) method to provide a holistic understanding and analysis of the DCS. The focus of the method is not only on the design but also on the behavior (operation) of the DCS.
- The second contribution is made by developing optimization models to analyze the design and operation and the DCS and extending it to the integration of solar technology to analyze the cost, the use of renewable energy based on the available area covered by the solar installation, and the environmental benefits of such an integration.

1.7 Thesis outline

The thesis is divided into seven chapters. After introducing the topic in Chapter 1, theoretical background on systems engineering, district cooling, solar technologies, and optimization methods are given in Chapter 2. In Chapter 3, the literature review is provided, and research gaps are mentioned. Chapter 4 presents the proposed framework for DCS modeling and optimization to bridge the gap between the DCS complexity and optimization practices. A model-based system requirement is developed to optimize multi-chillers district cooling plants. A set of system and stakeholders' requirements drives the model, mainly the regulatory authority and the DC developer. The formulation and analyses are given in Chapter 5. In Chapter 6, the optimal integration of solar energy and DCS by considering the cooling and solar technologies is investigated. A generalized model is developed to optimize and analyze different configurations by considering the energy price and the available installation area. In addition to the economic assessment and comparison of these configurations, key performance indicators are used to assess the renewable energy use and environmental-related performances. The conclusions and future research are given in Chapter 7.

1.8 Thesis outcomes

Two journal papers were published as outcomes of this dissertation:

- The content of the chapter 4 and 5 was published in Energy journal (Elsevier): Ismaen, R., El Mekkawy, T. Y., Pokharel, S., & Al-Salem, M. (2022). System requirements and optimization of multi-chillers district cooling plants. Energy, 246 doi:10.1016/j.energy.2022.123349
- The content of the chapter 6 was published in Energies journal (MDPI): Ismaen, R., Elmekkawy, T. Y., Pokharel, S., Elomri, A., & Al-Salem, M. (2022). Solar technology and district cooling system in a hot climate regions: Optimal configuration and technology selection. Energies, 15(7) doi:10.3390/en15072657

Chapter 2: Theoretical Concepts

As shown in figure 1, this chapter is composed of three sections, and it provides the fundamental aspects on which this research is built. In Section 1, the system approach is introduced. In Section 2, the district cooling is presented. In Section 3, the modeling and optimization methodology is detailed.

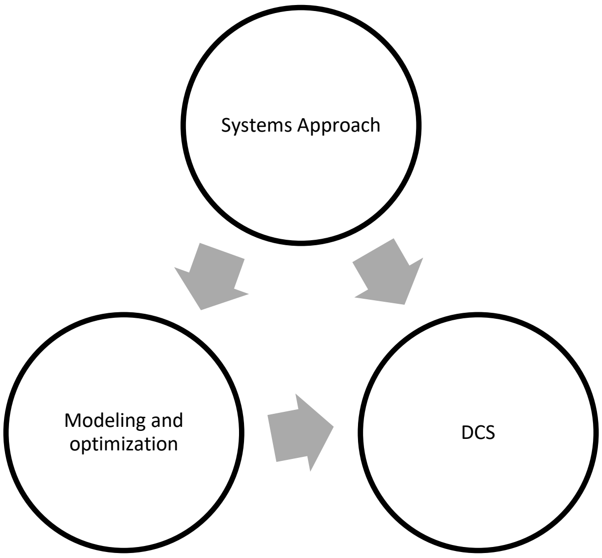

Figure 1. Thesis foundations

2.1 System approach

In this section, the essential of systems engineering (SE) concepts and methods are presented, where systems science (foundations, theories, and representations), thinking, and approaches are involved in a praxis framework [10].

2.1.1 System science

The idea behind the system science is to provide common aspects of the system regarding identifying goals, exploring, and understanding the patterns of complexity along with discipline and areas of application, which gives a theoretical foundation of all types of systems regardless of their types, constituent elements, and application. The systems science concepts are valuable to the development of systems approach and then systems engineering to examine the whole process under consideration. In systems engineering, the requirements of all stakeholders are assessed to develop an optimal solution for the given problem context [17-18]. Different definitions for systems are given by ([8], [11-12]).

The international council of system engineering (INCOSE) [13] defines a system as "an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements."

The system complexity, such as structure complexity (system elements and interactions) and behavior complexity (interaction in the short term and long term), has been considered [14-16] to express the understanding difficulties of the system behavior and the prediction of change.

2.1.2 Systems thinking

One of the most shared ideas of system thinking is pattern identification, which represents similarity in a set of systems, problems, or solutions. These patterns become valuable tools for standards, references, and templates edition. The systems thinking is enriched over time. Now it contains a set of aspects such as:

- Understanding of the holistic view (big or rich picture)
- Studying the behavior of a certain system structure
- Considering the circular aspect of cause and effects and time delay
- Identifying the system structure elements that may impact the solution

The systems sciences and systems thinking have more practical considerations:

- The system context (environment) is considered an extension of the system under consideration.

- The interaction between the systems' components and between the system and its environment are considered.
- The system-level properties are considered as the whole system properties.
- The system has a life cycle, function, structure including parts, interaction between the systems' components, and its boundary.
- The system has a behavior.
- The system has a performance associated with functions and behavior.
- The cause-and-effect relationships may be difficult to detect immediately in a system where feedback loops are used.

2.1.3 Stakeholders' requirements and technical process.

Technical processes are executed during the life cycle stages of the system. The requirements' establishment is considered the foundation of the system creation, development, verification, and validation. These processes allow SE to coordinate all the system's stakeholders (specialists, users, operators, manufacturers).

The purpose of stakeholders' requirements definition is to negotiate, elicit, document, and maintain stakeholders' requirements, including end-user, regulatory bodies, decision-makers. Activities related to stakeholders' definition process are:

- Identification of stakeholders who have an interest in the system
- Elicitation requirements regarding the system capabilities (what and how well)
- Analyzing the clarity, consistency, and completeness of requirements.
- Establish the systems' desired performance, threshold, objectives, and critical and second-order parameters.
- Establish effectiveness measures that reflect the degree of satisfaction, such as safety, reliability, availability, and maintainability.

- Identify constraints that agreements or interfaces may impose.
- Resolve problems related to requirements
- Confirmation and record of requirements
- Establish and maintain requirements traceability.

2.2 Chiller and solar technologies

3 The DCS comprises three interconnected sub-systems; the district cooling plant, the distribution network, and the building connection (collectively called ETS). The cooling effect in the form of chilled water is produced in the central plant then pumped via the underground insulated pipes to buildings. The cooling energy is transferred to the building system via the ETS. The warm water is returned to the plant to be re-cooled and re-pumped. The district cooling plant contains two main water loops. The first is the chilled water loop (chillers' evaporator – building), and the second is the condenser water loop (chillers' condenser– cooling tower). From an efficiency perspective, the key equipment of the cooling plant are chillers and TES.

2.2.1 Chiller technology

A wide range of chillers capacity with two main technologies exists in the market. The most efficient and used are centrifugal chillers. Its functioning is based on the vapor compression cycle (Appendix A). The four main components of a centrifugal chiller are evaporator, compressor, condenser, and expansion device. The evaporator is composed of a shell and tube heat exchanger. The entering water temperature is lowered, and the heat is transferred to the refrigerant. The refrigerant boils and its phase changes from liquid to gas. The pressure and temperature of the refrigerant are raised under the compressor's kinetic energy. The condenser plays a similar role as the evaporator, and the heat is removed from the refrigerant to the condenser water, and the refrigerant becomes liquid. The refrigerant's pressure further decreases in the expansion device, and the refrigerant returns to the evaporator. The heat collected by the condenser water is transferred to the atmosphere in the cooling towers. The prime mover of the compressor is generally an electric motor. Other compressor technologies exist, such as reciprocating, rotary screw, and scroll.

The second cooling technology is the absorption chiller, known as a thermally activated chiller. The working principle is based on the separation and recombination of fluids to create the cooling effect, where refrigerant, absorbent, and four components form the absorption chiller. The used heat source changes the state of the refrigerant (liquid to vapor) in the generator. After dehydration, the high-pressure refrigerant is condensed in the condenser, then the cooled refrigerant's pressure and temperature are reduced through the expansion valve. The refrigerant absorbs the heat in the evaporator and leaves it in saturated vapor forms. The weak solution in the absorber is transformed to a strong and pumped to the generator. The most common known absorption chillers are based on the ammonia-water cycle (NH_3/H_2O – ammonia is refrigerant) and lithium bromide cycle (H_2O/LiBr – water is refrigerant). The heat sources used in the generator can be obtained from different energy sources such as boiler, heat recovery from a process, or solar thermal. Each technology has its pros and cons. The vapor compression chiller has a high capacity, high efficiency, and reduced acquisition cost. However, the maintenance and operating costs are high. The absorption chiller's operating cost and GHG emission are low. On the contrary, the acquisition cost is high, and its related capacity and efficiency are low.

Afram et al. [85] and other authors ([28-30]) classify the modeling methods for district energy systems into three main categories: data-driven models (black box), physics-based models (white box) and hybrid (grey box) model.

- The data-driven model requires data collection for regular operations or a specific condition (which can be for a test condition). Data is analyzed through mathematical techniques such as an artificial neural network (ANN) and statistical regression.
- The physics-based model is based on the laws of physics, particularly the first and the second laws of thermodynamics.
- The hybrid model is a mix of the data-driven and the physics-based model. In this case, the structure of the model is formed by the physical meaning of the system. The parameters needed for the model are collected from the system or through a data-generated algorithm.

The chiller performance depends on many variables, such as evaporator's water inlet and outlet temperature, condenser's water inlet and outlet temperature, and wet bulb temperature. All relevant variables are not usually considered in Physics-based models for chillers. Data-driven models considering relevant variables are better [87]. The centrifugal chillers' energy consumption is commonly considered as a function of its part load ratio (PLR) for a given wet-bulb temperature [43,86]:

$$E = a + b.PLR + c.PLR^2 + d.PLR^3$$

Where *a, b, c,* and *d* are the coefficient of the electricity consumption curve.

2.2.2 Thermal energy storage technology

Thermal energy storage plays an essential role in increasing system efficiency by reducing energy use, increasing system flexibility by delivering stored energy, and reducing peak energy by shifting the load production. Furthermore, it reduces the chiller's capacity to meet the peak load and stored surplus cooling when renewable energy is available. There are two main categories used in DCS applications (Appendix B):

- Sensible heat storage (chilled water) is the most commonly used in district cooling systems. The stratified tanks allow the cooler water to be at the bottom (higher density). However, the warm water at the top. Other technologies exist, such as membrane separation or labyrinth tank
- Latent heat (ice storage) is based on the storage of frozen water (ice). The ice absorbs heat during the phase change. Ice storage technologies exist in different forms; Ice-on-coil internal melt technology forms ice at submerged tank tubes' exterior surface. During off-peak periods the water-glycol cools the pipes, and during the on-peak periods, the warm water-glycol melts the ice. In contrast to the first technology, the ice-on coil external melt works principle is opposite to the first case. For the ice harvester technology, the formed ice is dropped into the tank, the cold water flows from the tank, and the warm water returns to the evaporator.

2.2.3 Solar technology

Solar technology transforms solar irradiance into other sources of energy. There are three technologies: solar thermal, photovoltaic, and hybrid.

Solar thermal collectors transform solar irradiance into thermal energy, where water is used as a medium. Solar collectors are classified based on the collector type (flat plate, evacuated tube, parabolic, linear Fresnel, cylindrical, heliostat field collector, parabolic dish reflector), their motion (stationary, single and double axis tracking), concentration rate, and the operational temperature range. The efficiency and the cost of such collectors vary accordingly. Alobaid et al. [80] reviewed solar-driven cooling technology. The authors stated that the solar thermal collector is the most driven power for thermally activated chillers. Flat plate (FPC) and evacuated tube (ETC) are commonly used in cooling applications.

Photovoltaic solar panel transforms solar energy into electricity. The semiconductor material's forming photovoltaic cells convert the sunlight into a direct current. Other devices (inverters and batteries) are needed for the application. The silicon-based PV cells are the most mature technology and constitute the first generation. The second is the thin film. The perovskite and organic-based cells are the last generations. PV panels can be classified based on the used material, the manufacturing process, the temperature level, and efficiency [84].

A hybrid solar system (PVT) is an integrated photovoltaic and solar thermal collector. This integration leads to producing electricity and heat simultaneously. The combination of both technologies can be achieved differently by varying the PVT system constituents: working fluids (air, water, or other coolants), fluid flow (natural or forced), photovoltaic cell type (monocrystalline, polycrystalline, amorphous, perovskite), collector type (flat plate, concentrator), and glaze type (glazed or unglazed). The PVT efficiency and operating temperature depend heavily on the PVT design parameters (collector type, ratio between thermal and electrical yield) [55].

3.1 Modeling and Optimization you have to strengthen this part.. this is a bit generic description

Decision-makers need modeling and optimization during the system life stages to optimize the design, the operation, and the control of the district cooling system. The modeling and mathematical approaches depend on the system stage, the problem scope, and the model's final intent. Models can be classified based on various criteria (linearity, convexity, breadth, depth, single or multi-objective, discrete or continuous, decision variables, and constraints type). Mixed-integer linear programming is widely used when design and operation optimization is required. The binary decision variables are used when equipment selection or the state machine is involved in the model. Continuous variables are used to represent system activities, such as cooling production, storage, or energy consumption. The numerical solution approach (algorithm) depends on the problems' size and formulation. Three main solution approaches are used in optimization, deterministic programming (branch and bound, branch and cut), heuristic (problem decomposition), and metaheuristic or nature-based algorithm such as genetic and particle swarm optimization algorithms.

2.4 Summary

The operation research discipline contributed to the development of the system thinking concepts. The rigorous optimization methodology, the quantitative analysis, and the implementation of the system engineering process such as stakeholders' requirements provide valuable support for decisions makers for selecting the appropriate technology, designing and operation systems, and developing control strategy while increasing stakeholders' satisfaction and reducing costs, energy consumption, and environmental impacts

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Chapter 3: Literature Review

3.1 Introduction

Sustainable energy development should cut anthropogenic greenhouse gas (GHG) emissions over the coming years and tackle the climate impact [19]. Based on the International Energy Agency (IEA) baseline scenario, the global energy demand is expected to grow by over 25% between 2017 and 2040. This trend can be doubled if the energy efficiency issue is not tackled correctly. The highest growth occurs in the Asian region; India's energy demand will increase by 100%, and China's energy use will rise significantly. The electricity demand growth is considered the fastest and follows the same tendency for the next 25 years and reaches 60% growth. The building sector is the primary source of electricity consumption and accounts for 32% of building energy demand [1]. The energy consumption for space cooling has increased considerably, and the related carbon dioxide emissions tripled between 1990 and 2016. By 2050, the trend will remain the same and reaches 6,200 TWh [1].

Today, cooling contributes almost 10% of the total electricity consumption in the building sector worldwide, and it is considered as the primary source of energy increase in buildings [1]. The increase of the cooling load directly impacts the power generation and distribution and the need to satisfy the peak demand that generates supplement stress on the electricity grid. The average worldwide cooling space impacts 14% of the peak demand (2016) and reaches 70% of peak residential electricity demand in some hot countries such as the Middle East. This tendency is expected to be accentuated in the future, given that the economic and the demographic growth and urbanization are of particular emphasis in hot countries (India, China, the Middle East, and North Africa). The need for cooling for thermal comfort and economic development will stress the overall energy demand, particularly the electricity grid, and causes real challenges of peak demand satisfaction [2]. The improvement of cooling efficiency will impact positively by decreasing the need for new generation capacity to meet peak demand. Hence, minimizing related investment and operation costs. The coupling energy efficiency and renewable energy reduce significantly cooling-related CO_2 emissions [20].

Today, DCS is considered one of the most efficient ways to produce cooling energy for vast buildings types, including residential, commercial, hotels, and sports facilities. Its rapid growth is linked to the environmental policies and growing demand for thermal comfort and its contribution to reducing the peak electricity demand and its higher customer value compared to the conventional on-site cooling system [21]. Air conditioning system (AC) exist in different shapes and sizes, from small to large-scale, and it provides thermal comfort from single room to entire building and district energy network. The conventional cooling system under its different form (packaged AC, split system, and chillers) is operated at the building level, and the cooling energy is delivered on-site only. In contrast to the DCS, the cooling energy is produced in a centralized plant using the economy of scale. Then, the chilled water is pumped via the distribution network (DN) using underground pipelines to different customers. The ETS ensures the connection to the building side, composed of a cooling coil that acts as a heat exchanger. The DCS plant consists mainly of chillers, cooling towers, pumps, and other devices and sensors that allow metering and controlling the cooling process, such as pressure, temperature, flow rate, electrical energy consumption, and cooling energy produced. DCS benefits are far from the conventional onsite cooling system installed in an individual building. These benefits positively impact the customer, the infrastructure, and the environment.

From a customer perspective, DCS provides more: (i) comfort and convenience; the industrial level of DCS equipment provides high cooling quality. The centralized production in a remote plant and the continuous distribution of cooling energy avoid the noise, vibration, and cooling unit operation at the building level. (ii) flexibility and reliability – The load diversity can be easily satisfied cost-effectively even if the demand of a particular building is low. The higher ramification of the distribution network, the storage tank, and the redundancy give DCS the required flexibility. The long equipment lifespan and the specialization of DCS staff avoid any service disruption (reliability exceeds 99.94%). (iii) aesthetic and space-saving - the absence of cooling unit installation at the façade makes the building more aesthetic. The existing space in the building can be reserved for other activities rather than for cooling heavy equipment. (iv) cost-effective - The load diversity and operation at the district level are more efficient during a long period per year than the conventional cooling system. Furthermore, the building does not invest initially in cooling equipment and related construction.

From the infrastructure side: (v) peak power load reduction. Based on the peak load profile, the integration of TES contributes to shaving the cooling load, further decreasing the peak power consumption that can reach 20%. (vi) reduction in power generation investment. As a result of peak load reduction, less power generation and distribution infrastructure are needed.

The environmental benefits lie in (vii) energy efficiency. Compared to conventional cooling systems, the superior efficiency of DCS results in fuel consumption reduction, thus decreasing CO_2 emissions and contributing positively to the environment. Gang et al. [22] investigated the performance of cooling systems at the planning stage in Hong Kong. The authors concluded that DCS could save 13% of electricity consumption than individual cooling at the building level. Furthermore, the operation cost is lower by 10% than the locally cooling building. (viii) use of renewable energy and waste heat. The successful integration of DCS and renewable energy such as solar, free cooling, and the possibility of waste heat recovery gives great potential for a sustainable district energy system [23].

Qatar's Planning and Statistics Authority report (PSA) [3] shows that up to 2018, there were 41 district cooling plants under operation phase, 40 projects under construction, and 21 projects under design with a total capacity of 1,670,132 TR. The electrical energy saving by the operational cooling capacity is estimated to be 16,334,588 MWh compared to the conventional cooling system. Also, the operational DCS contributed to reducing more than 7,350,564 (10^3 tons) of CO_2-equivalent.

3.2 Electric powered DCS

The district cooling is a technological-open system; it interacts with the environment, and the structure’s components are interconnected. The automated cooling process transforms the used energy sources into cooling energy, the system's behaviors are controlled to achieve the required performance. The system passes by different stages during its life cycle. Modeling, simulation, and optimization are conjunctively used to validate the design, analyze the trade-off, assess the system's performance during case scenarios, and verify the requirement's compliance. The consequent initial investment costs, the system complexity in terms of structure and behavior, and requirements require optimization to size, operate, and control the system optimally [24].

In order to develop such a model, the system approach, the complexity of DCS becomes essential. The systems approach here refers to considering factors that impact the design, operation, and control of the DCS. The use of a systemic approach for integrating renewable energy systems and central power networks is mentioned by Hache et al. [25]. The need to integrate internal and external factors for the design of a complete DCS system is discussed by Vakiloroaya et al. [26]. The need for a systems approach for an energy-efficient design is also mentioned by Chua et al. [27]. The use of life cycle assessment (LCA) is also considered a systemic method for the economic evaluation of air conditioning [28]. Other authors ([29], [30]) have also recommended the use of a systemic approach for the study of district energy systems or the energy performance analysis in a district or a building. Therefore, it is necessary to have systems perspectives while developing decision models for a complex system like a DCS where multiple stakeholders, components and sub-systems, energy types, and technology are involved.

The complexity in a DCS could be due to different aspects. For example, the cooling process is considered a thermal energy chain formed by a set of loops [31]; and DCS itself is considered part of a more extensive district energy system [29]. Keirstead et al. [32] mention that complexity also comes through various aspects of design that need to be considered in a DCS, for example, technology design, building design, urban climate, system design, and policy assessment. This requires a multi-disciplinary approach that adds to the complexity dimension of DCS. The complexity level also increases when there is an integration of renewable energy sources or when there is a combined cooling, heating, and power system is considered [22], the technology used in a DCS [33], or different thermodynamic behavior of the cooling system [34]. The spatial and temporal dimensions also bring complexity in a DCS. The inclusion of buildings, neighborhood, district, city, and country give spatial complexity [35] and the consideration of operation lifetime and load distributions gives the temporal complexity perspectives to a DCS [36]. The DCS complexity is also explained by the system variety

[31].

Therefore, integrating all these factors will provide a holistic view of the DCS and result in a model framework that eases the system complexity understanding and supports the system analysis.

From the system engineering perspective, the system can be interpreted first as the set of requirements that drive the design, the operation, and the control for a given context. These requirements express the stakeholders' statement of the cooling process and represent an additional dimension to the DCS. Therefore, they constrain the system space and shape the newly developed DCS feasibility region. The system performance can be assessed from different perspectives. The economic and environmental indicators (energy efficiency, renewable energy use, and CO_2 emissions) are the most considered assessment criteria.

DCS is mainly studied by using optimization and simulation methodologies. Coelho et al. [36] proposed a differential cuckoo search to optimize the energy consumption of chillers plant. In order to formulate the optimal chiller loading problem (OCL), the authors formulated constraints that translate the system behaviors and requirements in terms of electricity consumption and cooling demand satisfaction. Thangavelu et al. [37] explore reducing energy consumption in a commercial building in a tropical climate. The model integrates the thermal behavior and the energy consumption of the system components (chillers, cooling towers, and pumps). These behaviors translate the system requirement to satisfy the cooling demand efficiently. Powell et al. [38] study the impact of thermal energy storage on the flexibility of poly-generation district energy systems. The authors used dynamic optimization; their model aims to optimize the charging and discharge schedule of the excess energy. In addition to the energy balance, Heat recovery steam generation, gas turbine, auxiliary boiler, and steam turbine requirements, other equipment requirements were considered in the model, such as the thermal energy storage and chillers. Li et al. [39] used the cooling intensity of commercial building operations (in addition to other energy demands such as heating) to investigate the carbon intensity in China province. Carotenuto et al. [40] investigated the integration of renewable energy sources (geothermal, solar, and biomass) for the co-generation of heat and cooling by using TRNSYS software on a case of Monterusciello area (Italy). The authors implemented the Italian standard requirement regarding transmittance (walls, roof, floor, and transparent surfaces) to analyze the cooling requirements. Zheng et al. [41] reviewed the flexibility for district heating systems in the context of smart technologies integration and energy building flexibility. The absence of stakeholders’ requirements to develop this aspect further forced survey conduction to evaluate the stakeholders' perceptions.

The implication of requirements on system performance is not widely considered in the literature. The sequencing control is generally coded outside the optimization tool using MATLAB and interfaced with the optimization or the simulation software “the sequencing control was coded using MATLAB and communicated with TRNSYS 17 through the interface Type 155” [42].

The district cooling plant typically has multi-chillers to meet the cooling demand by adopting redundancy. The system design and configuration give sufficient freedom to satisfy the demand by different combinations of chillers loading. In comparison to equal ratio chiller loading, optimization provides the optimal chillers loading and sequencing by improving the energy efficiency. In order to formulate such an optimization problem, an equipment efficiency model and load calculation or prediction are necessary. The problem to be solved is the minimization of the total energy consumption. The focus is on chiller energy efficiency, and the problem is known as optimal chiller loading (OCL) and optimal chiller sequencing (OCS). The finality is the development of a control strategy for the multi-chillers plant based on the analysis of each chiller state and its loading ratio. The OCL and OCS are extensively studied by researchers using different optimization techniques (algorithms). Lee and Lin [43] formulated an OCL problem for a district cooling plant that contains three centrifugal chillers. The authors used a particle swarm algorithm to develop an optimization model for the OCL and compared results with the genetic algorithm and Lagrange multipliers method. Beghit et al. [44] studied a multi-chillers plant equipped with multi-scroll and twin compressors on the same circuit. The authors mentioned that the commonly used strategy consists of on/off chillers sequentially to satisfy the variation in cooling demand without assessing the system's energy consumption. The authors formulated the problem as OCL and OCS. The first problem is finding the chiller load fraction, whereas the second problem is searching the chiller sequencing (ON/OFF). The two problems are solved simultaneously. Sun et al. [46] mentioned that the control strategies are built on the process parameters and measurement devices, particularly on the adopted method for measuring or estimating instantaneous building cooling load. Huang et al. [47] proposed the measurement fusion strategy to further improve the sequencing control of multi-chillers and decrease the impact of measurements uncertainties (noise, outliers, and bias). That allows the elimination of outliers using a calibrated model, the elimination of noise using redundant measurements, the calibration of the bias via the merged measurements.

3.3 DCS and renewable energy integration

Eveloy and Ayou [50] reviewed DCS focusing on the hot region in the Middle East. They classified the literature based on sustainable energy sources cooling and storage technologies focusing on the heat-driven cooling process. Gang et al. [22]

studied the integration of renewable energy technology, CCHP systems, and thermal storage with DC. Inayat and Raza [51] reviewed DCS from renewable energy sources such as geothermal, biomass, surface water, solar photovoltaic, and waste heat recovery that can be exploited at the DC level. They mentioned that all these forms of renewable energy could be cost-effective compared to conventional systems (grid electricity) and present a great potential to supply clean cooling demand with sustainable effect. Gupta et al. [35] reviewed the thermodynamic and economic aspects of the different cooling systems by focusing on the controlled parameters that can be used to optimize the performance. They concluded that renewable energy is most adapted for cooling given the suitability of their operational parameters. Indicators such as capital recovery factor (CRF), net present worth (NPW), and discounted payback (DPB) are helpful for the economic feasibility study. Alsagri et al. [52] review is focused on the concentrating solar collectors in absorption cooling cycles. They studied the literature based on the used methodology, obtained results, and performed analysis. They concluded that solar absorption technology is more competitive than conventional cooling if the collector, subsystems, and working fluid are well selected.

Solar energy has been applied for diverse applications. The continuous reduction in costs, ease of accessibility, and carbon neutrality have driven its increased adoption. Research on solar-assisted cooling applications has been initiated for more than four decades (after the energy crisis in the 1970s). During the last decade, the number of research on solar energy for cooling applications has doubled due to the increasing need for cooling and the availability of improved solar cooling technologies. The bibliometric analysis on solar cooling technology shows that the most studied systems are solar thermal cooling systems using the thermal collector and thermal activated chiller (mainly absorption), solar combined power/cooling, and photovoltaic

(PV) compression chillers [53].

Researchers have focused in photovoltaic-thermal (PVT) technology [54-58] and their applications [59-61] with the main current applications on building operations, for example, water heating [62], heating and cooling [63], drying [64], in addition to desalination [65], and industrial application [66]. This research gap (PVT application in district cooling system) is aligned with the International Energy Agency (IEA) solar heating and cooling program (IEA SHC task 60) [67-70], which recommends further investigation concerning the use of solar hybrid technology in cooling applications, the interaction of local electricity use versus grid injection, the use and combination of cold water and hot water TES.

Simulation is the most used methodology (TRNSYS) in studying solar cooling technology, where the predefined components' model in the tool library is used to construct the system. The focus of the analysis is on the optimization of the process parameter to improve system efficiency once the design is fixed. Abid et al. [71] analyzed and compared the thermodynamics behavior of different absorption cycles (single, double, triple, and quadruple effect), evacuated solar tube collectors, and hybrid nanofluids. They concluded that the collector efficiency is higher when using hybrid nanofluids. Asadi et al. [72] used the thermo-economic analysis to evaluate an integrated 10 kW single-effect ammonia-water absorption chiller with diverse solar collectors. They concluded that the economical solution is obtained by integrating the evacuated tube collectors. Weber et al. [73] studied integrated water ammonia absorption chillers and concentrating solar collectors and analyzed the performance of the different control and operation strategies. Bellos and Tzivanidis [74] investigated the performance of a solar cooling system that comprises an absorption chiller and nanofluids using plate collectors; they found that nanofluids improve the thermal efficiency by 2.5%, the exegetic performance by 4%, and increase in refrigeration by 0.84%. The same authors [75] studied the parametric analysis and the optimization of a combined ejector-absorption chiller and parabolic collector system. They concluded that the ejector increased the system COP, and the optimized system achieved a performance enhancement of 60.9% for the respective evaporating and condenser temperature of 12.5 °C and 30°C. Shehadi [76] simulated different absorption chiller components for a range temperature to optimize the COP. The author finds that the optimum COP of the system is 0.776 with the evaporator, condenser (and absorber), and generator temperatures, respectively equal to 10°C, 30°C, and more than 70°C. Saleh and Mosa [77] optimize the solar absorption chiller in a hot climate by using a flat plate solar collector with a single-effect water-lithium bromide absorption chiller. Results show that a coating of solar collector is necessary to produce the required operating temperature (70-80°C) of the chiller. The authors show that their system improved the COP beyond 0.8. Alghool et al. [78] developed mixed-integer linear programming to optimize integrated solar-assisted DCS, the optimal solution that provides the design and operational variables of the system. The system assessment is from an economic perspective. Iranmanesh and Mehrabian [79] used a genetic algorithm to optimize an integrated double-effect bromide water absorption chiller and evacuated tube collector system. They concluded that the reduction of auxiliary energy could be achieved by optimizing mass flow rates of hot water passing through the generator and collector. Alobaid et al. [80] reviewed the solar-driven absorption cooling with photovoltaic thermal systems. The authors mentioned that the solar absorption chiller saved 50% of primary energy with electrical PVT efficiency in the range 10–35%, the solar-assisted cooling COP in the range 0.1–0.91, the thermal collector efficiency in the range 0.06–0.64.

Different models are needed during the development phases of the solar cooling systems. The appropriate approach depends on the system phase (planning, design, operation, trade-off analysis) and the model scope. The optimization approach for adjusting the system configurations with the energy prices supports decision-makers to optimize the system design, including the technology and the system sizing that continuously satisfies the cooling demand cost-effectively.

The literature review shows that cost analysis is the most used approach when optimizing solar cooling technologies. The environmental analysis is recommended by the sustainable district cooling guidelines (IEA 2019) [6]. which is lacking in the literature review.

These guidelines emphasize analyzing the environmental benefits of alternative energy production systems, reducing the emission of greenhouse gasses (GHG), and increasing the use of renewable energy with continuity and reliability of energy supply. Hence, a set of key performance indicators are defined and could be used to assess the system based on the energy use and environmental perspective [77].

Selecting the appropriate technology among different alternatives in a given context, such as the local energy prices and available installation area, is essential for decision-makers. Modeling and assessing these alternatives becomes a necessity. This requires using multi-models to assess the different configurations, which is time-consuming.

3.4 Research gaps

- The literature review shows that the modeling and the optimization of district cooling systems is a subject of interest for many fields such as building, energy, and operational research. However, most of the research is focused on a particular aspect of district cooling rather than the entire system. Therefore, enumerating and interconnecting these factors will provide a holistic view for the DCS with a net image (systemic approach).

- The research also shows that there is no uniform framework to support the holistic analysis of design and operation. The consideration of stakeholder perspectives, both in the design and operation is important.
- The system control aspect is commonly referred to the adopted strategy to decreasing the energy consumption. The consideration of the system predefined control such as chiller short cycling is lacking which may results in conflict with the chiller safe operation.
- Most of researchers have focused on electricity based cooling system. The use of hybrid system (thermal-photovoltaic) have been discussed but there is a lack of literature that shows the applications in district cooling.

Chapter 4: Frameworks for DCS Modeling and Optimization

DCS contains different elements; related to the system, such as structure (sub-systems and components), configuration, behaviors (activities), and control, and; related to the DCS interaction with its boundary (building, climate, energy source, and other systems) and the life cycle phases. The combinations of the features provide a rich picture of the DCS system.

In Section 2, the system approach framework is introduced to define the rich picture. In Section 3, the solution framework is presented. In Section 4, the modeling framework to optimize the DCS is presented.

4.1 System approach: DCS rich picture

The system approach here refers to the set of elements involved in the system. The holistic view is drowned by assembling these puzzles. Figure (2) shows the rich picture of the DCS. It demonstrates the dimensional complexity of the system. Each of these dimensions is discussed as follow.

- Stakeholders provide the requirements for the design of the system and they are further developed in terms of specifications , such as system requirements (business and mission analysis), system validation and final acceptance (V model activities), integration and verification, and communication between the different contributors.
- Building: The building system is an essential part of the DCS, given that it represents the end-user of the product. The buildings are defined by the cooling demands and other requirements concerning the energy transfer station that connect the distribution network sub-system and the building (pressure, flow rate,

temperature). The cooling load calculation represents the foundation of the DCS design. The estimation of the cooling loads impacts the design, operation, and cost-effectiveness of the DCS in many ways; it ensures the suitability between the demand and the installed cooling production and distribution capacities. It provides the ability to meet the daily and seasonal range of load cost-effectively. For new buildings, the most common methods for the cooling load calculation are the HVAC rule of thumb or the building modeling software. The main factors that affect the cooling load are the weather condition (climate), the building structure (orientation, the material used, windows, etc.), the appliance (lighting, computer), and the activity inside the building. Benchmark with similar buildings in the same climate is useful in this case.

- Climate: The weather condition (temperature and humidity) impacts not only the cooling load but also the DCS operation; the heat recuperated from the building will be transferred to the returned chilled water, then to the refrigerant, then to the cooled water, then to the atmosphere via the cooling tower. Hence, the energy efficiency of the chiller is related to the weather condition.
- Energy: One of the fundamental ideas of DCS is based on its capability to integrate other energy sources than the primary fossil energy. The use of local energy sources represents an opportunity to provide high energy efficiency and competitive cooling. The use of wasted heat and renewable energy sources represents the challenging perspectives of the DCS. At least, five categories of energy sources can operate the DCS.
    - Free cooling such as deep lake, deep see, and rivers
    - Waste heat: some industrial process generates waste heat (co-generation plant, incineration) that can be used by operating absorption chillers.

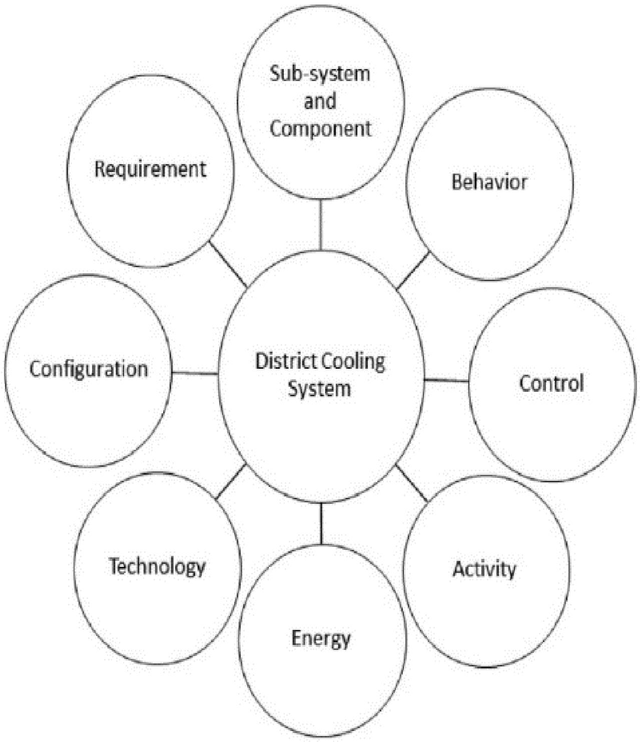
- LNG re-gasification: opposite to the waste heat, the waste cooling is generated by re-gasification of the liquid natural gas (LNG) that produces a residual cooling.
- Renewable energy, particularly solar energy with its different technology, can operate both cooling technologies (vapor compression and absorption chillers)
- Fossil energy: The driven motor of chillers' compressor can be powered by diverse energy forms (electricity, gas, fuel)

- Technologies: the cooling production at a district level can be achieved via two main technologies—the vapor compression chillers (electricity driven), and absorption chillers (thermal driven). Each technology has different operation principles and requirements. It is important to mention that the refrigerants used are different. The technology level is not restricted to the cooling production (chillers) but also to the type of compressor (centrifugal, screw, scroll, rotary), type of pumps (constant speed, variable frequency device (VSD)), type of thermal energy storage (ice thermal energy storage, low-temperature fluid thermal energy storage) and so one.
- Other systems: The integration of DCS with other systems is meaningful to take advantage of existing synergy. Generally, this integration occurs in a more extensive energy system, such as combined heating and power. The interest also lies in reducing water consumption by integrating the water treatment process for the sewage in the central plant.
- Structure and spatial aspect: the system structure is defined by all physical elements that constitute the DCS in terms of a sub-system (plant, distribution network, energy transfer station) and components (such as, chillers, compressors, pumps, pipes,

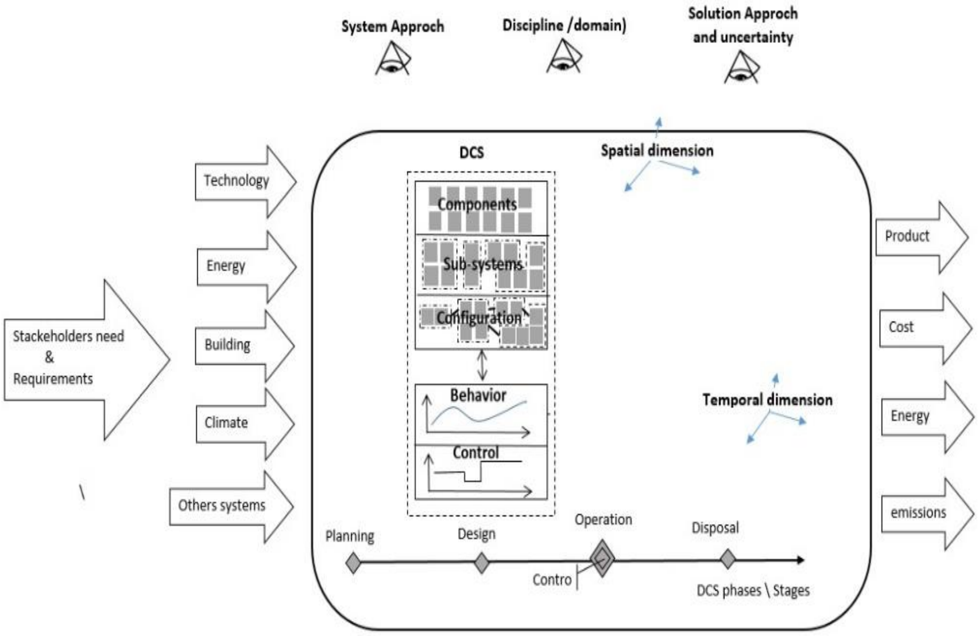
storage tank, and water filtration). Depending on the geographic coverage area of the DCS (block of building, district, city), the DCS can be implemented in one site or many geographic positions to form a network.

- Configuration: the system configuration of DCS is not unique. It may be different from one plant to another (plant layout: variable primary flow, primary-secondary pumping)
- Behavior: the thermo-hydraulic aspect of DCS forms the principal behavior of the system, where the temperature, pressure, and flow rate are the main parameter to be controlled during the process to achieve its main functionality. Others (activities) are derived from these parameters, such as chilled water production, pumping, flow regulation, storage, electricity consumption etc.
- Control: The DCS is an automated process where the programming logic controller (PLC) plays a central role in executing and controlling plant activities. The control leads to obtaining the requested system output safely and efficiently. The chiller staging and activities sequencing is the most used method for plant control.
- DCS life cycle and temporal aspect: The DCS has a different stage or phase of development from the planning to retirement. The time scale may (resolution and horizon) change during the DCS study and varies from seconds (control), hour and days (operation), and month and years (planning).

The rich picture of a DCS, as depicted in Figure 2, is helpful to improve the system's understanding by delimiting the system boundary, which leads to defining the inside (structure and behavior) and the interaction with the environment.



(a)



(b)

Figure 2. (a) Schematic illustration of the DCS rich picture (unstrcutred) (b) Schematic illustration of the DCS rich picture (strcutred)

4.2 Framework for solution approach

The rich picture is considered a starting point for the system development process, which helps to provide a framework for the solution, as depicted in Figure 3.

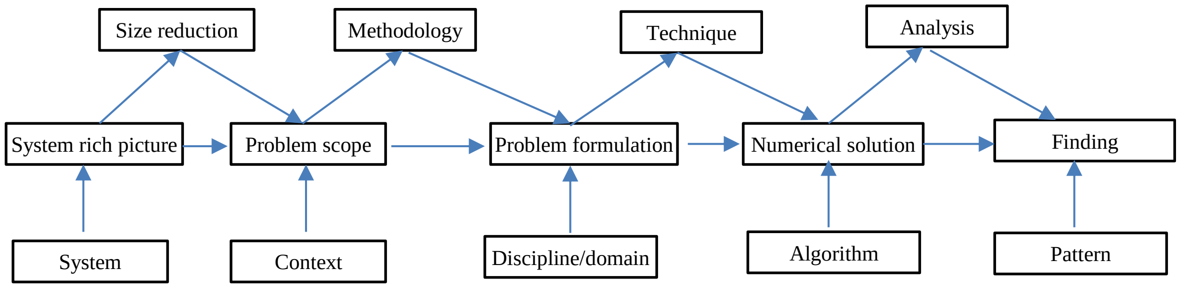


Figure 3. Framework for the solution approach

The step 1 of Figure 3 shows that the system approach allows the rich picture's definition, which is characterized by a high dimension. In step 2, the problem approach considers the system context (global, local, and specific), and the defined objective provides the problem's scope. The data availability may further reduce the dimensionality. Therefore, the first transformation reduces the rich picture dimension and gives the objective of the system exploration.

Diverse disciplines and domains may be interested in the problem. Each of them has its methodology and techniques. For the third step, the discipline/domain approach leads to formulating the problem in a specific way using a well-defined methodology and techniques. Diverse fields commonly use optimization and simulation methodologies.

In the case of optimization, the numerical solution of the formulated problem is the result of a given algorithm. The appropriate choice is often based on the problem's size and characteristics. Solution and patterns analysis contribute to justify the finding.

4.3 Framework for optimization modeling approach

The developed model should be structured given the DCS complexity, the problem formulation, and the optimization process. Therefore, the proposed framework, as shown in Figure 4 maps (i) the mathematical programming framework (input, process, and output), (ii) the DCS complexity dimensions (requirement, sub-system, and component, technology, energy, configuration, activity, behavior, and control), and (iii) the system modeling language framework (SysML), which is based on the modeling-based system engineering (MBSE) method. The model is composed of three parts as followed.

- The inputs contain stakeholder requirements, other data such as load, equipment technical sheet information, costs, and the system's use conditions (use cases or scenarios). This latter represents the analysis to be executed by the model to test the system's performance.
- The process is driven by a mathematical model, expressed as an objective function, constraints, and decision variables. Constraints are clustered based on the SysML framework. Different blocks embedded in the central core are given as followed.
    - Definition block represents the system structure as sub-system and components, physical (chillers, pumps, pipes, cooling towers). The proposed model includes chillers and storage tanks.
    - Internal block represents how the system components (like chillers and storage tanks) are interconnected (layout). It describes the configuration of the system and expresses the energy balance.
    - Activity block represents the system activities and interconnection, such as chilled water production, storage, and energy consumption.
    - Control block represents the system's control and is expressed in sequencing

and state machine.

- Outputs represent the optimal design and operation of the system.

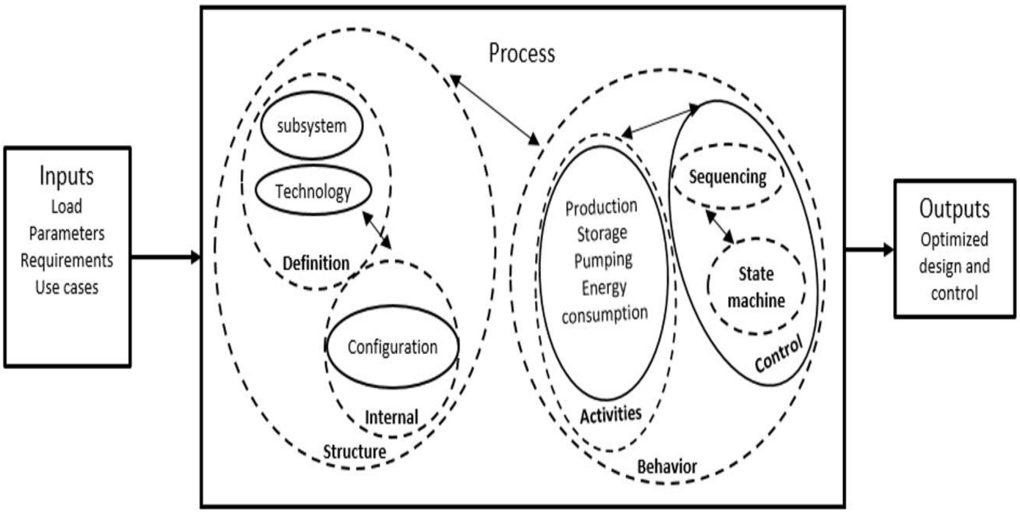


Figure 4. DCS modeling framework based on the systemic approach Pokharel (2022) [93]

The proposed framework is based on the BLOC-ICE approach [93]. It bridges the gap between operation research, SE practices, and system complexity. The formulation of the models based on the proposed framework enhances the model's understanding and the system behind it.

4.4 Summary

The modeling, the analaysis, and the optimization of the DCS requires the knwoldge of the system components and their interaction. The holistic view summarizes the DCS. The investigation of newly developed DCS using algebraic modeling language, requires the knowledge of different aspects such as structure, system configuration, behavior, and control which reflects the system complexity. In addition, the transition from the system knowledge to the solution requires a pathway. The implementation of model's necessities a clear framework to imitate these aspects. Therefore, the rich picture provides a support for the investigator to ease understanding the system by identifying these components and dimensions . Once the problem is identified, and the model scope and finality are clarified, a framework reflecting the system becomes helpful for the model implementation

Chapter 5: System Requirements and Optimization of Multi-Chillers District Cooling Plants

This chapter is divided into five main sections. In the first section, the context of the studied system is introduced. The second section explains the problem scope. In section three, the stakeholder's requirements are detailed. The mathematical formulation is developed in the fourth section. In the fifth section, the designed analysis and results are presented.

5.1 System context and stakeholders' identification

Qatar is located in the Middle East, a peninsula bordering the Persian Gulf and Saudi Arabia. It has an arid climate with a long summer (April to October) characterized by intense humid heat almost all year round, and the temperature can reach above 45°C. The cooling degree days (CDD) are widely used to simplify the representation of air temperature and their effects on the building cooling need. CDD expresses how much and how long the outside air temperature is higher than a specific base temperature in terms of degree and days. The simulation of Qatar climate shows the intense need for cooling around the year (www.degreedays.net – Figure 5)

Qatar had a significant population increase during the last two decades. The population reached almost 3 million in 2020, contrary to about 0.5 million in 2000 (https://worldpopulationreview.com), and it has prompted a significant urbanization of the country. Qatar has high GDP per capita of $ 61,791 (International Monetary Fund 2021), and its economic activities have increased significantly [88]. The climate condition, urbanization, economic growth, and the World Cup hosting (FIFA 2022) have contributed to Qatar's increasing cooling need and district cooling has been adopted in the country to a greater extent. Nowadays, more than 41 district cooling plants are operational, and 61 projects are under design and construction with a total capacity of 1,670,132 Tons of refrigerant (TR) (Tables 1 and 2).

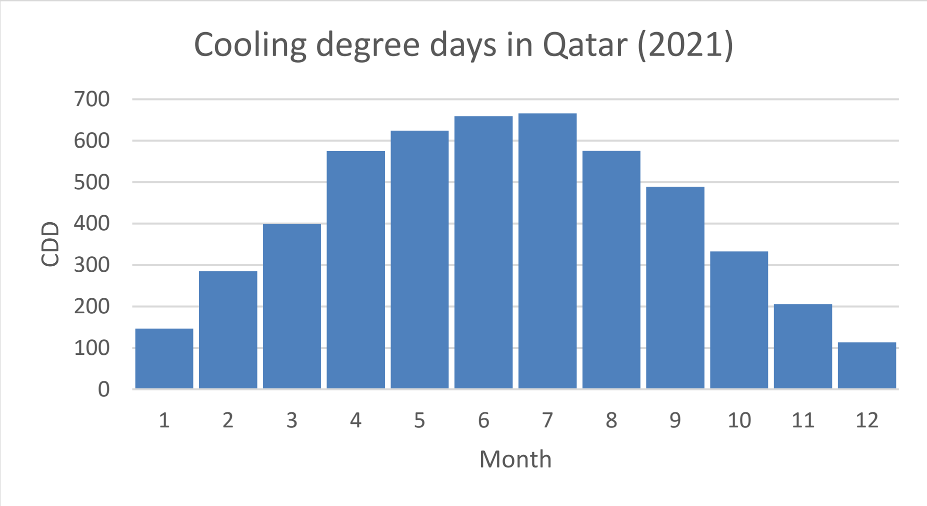


Figure 5. Cooling degree days in Qatar (2021)

Table 1. District cooling systems statistics in Qatar (PSA 2018)

	5	4	3	Cooling projects operational phase	
Economic Activity	Total (Colling projects) (1+3+4)	Cooling projects Under Design	Cooling projects Under Construction	2 No. of plants	1 No of projects
District cooling Service Provider	1			4	1
Commercial	16	1	10	5	5
Hotels	7	2	1	4	4
Education	8		5	9	3
Transport	7	6		3	1
Health	7	3		4	4
Cultural	3		1	2	2
Sport	18	4	10	4	4
Real estate development	6	3		5	3
Industrial	8		7	1	1
Other	8	2	3		
Total	**89**	**21**	**40**	**41**	**28**

Table 2. The designed capacity of DCS in Qatar (PSA 2018)

Economic Activity	Total	Cooling projects Under Design	Cooling projects Under Construction	Cooling projects operational phase
District cooling Service Provider	237,000			237,000
Commercial	121,400		58,350	63,050
Hotels	110,850	75,000	12,000	23,850
Education	225,000		57,000	168,000
Transport	93,800	48,800		45,000
Health	86,500	40,500		46,000
Cultural	43,600		13,000	30,600
Sport	346,320	101,000	169,920	75,400
Real estate development	268,872	167,000		101,872
Industrial	65,290		62,000	3,290
Other	71,500	20,000	51,500	
Total	**1,670,132**	**452,300**	**423,770**	**794,062**

Lusail city is an example of urbanization in Doha-Qatar (Figure 6). Located in the north of the Doha center, it is considered one of the most elaborated sustainable developments being undertaken worldwide. It is planned to serve 200 thousand people, and the land use consists of mixed residential, commercial, retail, school, and medical and sports facilities that cover an area of 35 square kilometers. Sustainability is one of the building criteria in Lusail city. The adoption of green buildings has impacted many aspects, such as urban connectivity, waste management, water consumption, and energy efficiency (Qatar Sustainability Assessment System).

The city master plan shows that district cooling systems to be envisaged in Lusail city are composed of four interconnected plants with an integrated network for a total capacity of 336,000 TR, through 173 km of pre-insulated piping (supply and return). These plants were planned to be constructed in multiple phases to provide the requested cooling demand during the city development, and they will serve about one thousand buildings. It was estimated that the developed DCSs would save more than 30% of energy compared to conventional cooling systems, resulting in a decrease in power consumption and CO_2 emissions (500,000 to 700,000 MWh/year and 240,000 metric tons/year).

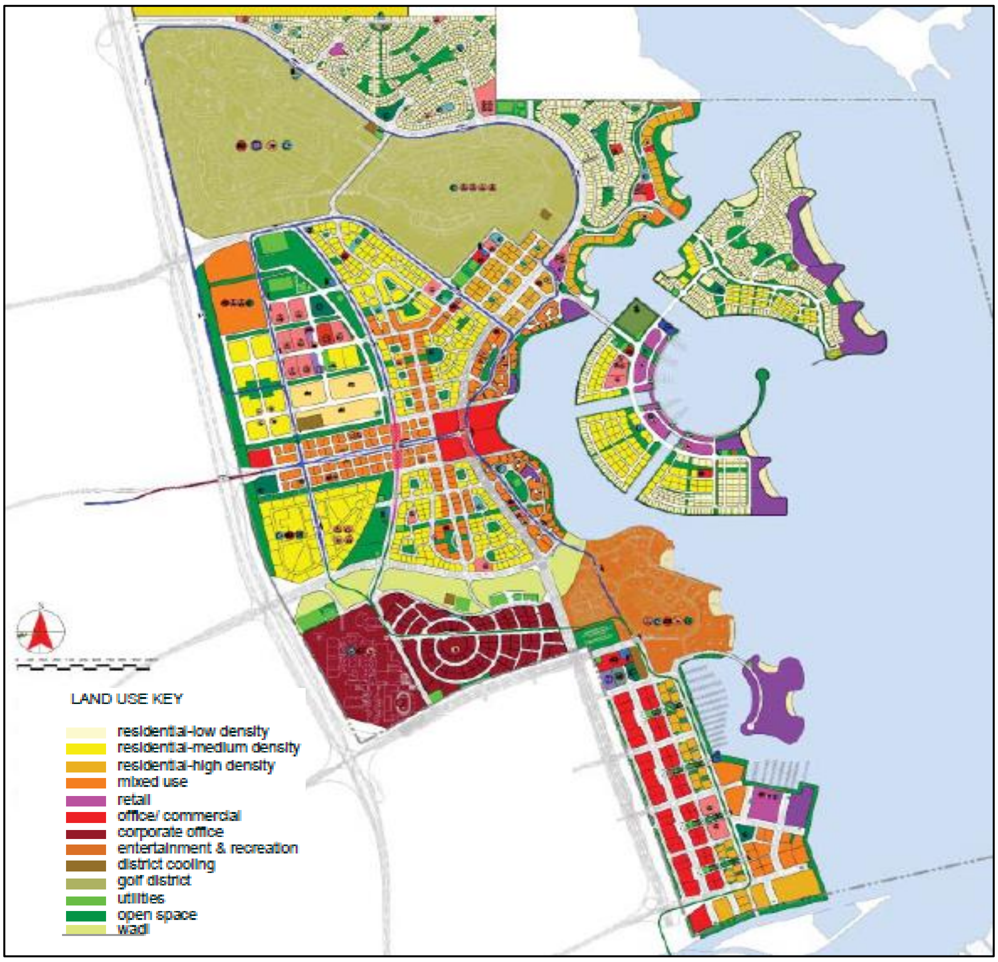


Figure 6. Lusail city master plan (Qatar - Doha)

The context of the present DCS model is a multi-chillers district cooling plant that serves medium and large cooling loads for a newly developed Marina district/ Lusail city. Marina district hosts 102 towers within 15 to 40 stories. The distribution network already exists and is integrated with the city infrastructure and is compliant with the city master plan. Different stakeholders intervene in the development of the DCS. The main stakeholders that affect the system are:

- Ashghal (Public Works Authority) owns and operates ground and surface water (distribution network).

- Marafeq Qatar, one of the leading utility development, operation, and maintenance companies that own the district cooling plant, is our industrial partner of this study.
- The customer is the owning of the building and the energy transfer stations.
- KAHRAMAA (Qatar General Electricity & Water Corporation), represented by the district cooling department as the regulatory authority.

Figure (7) illustrates the multi-chillers district cooling plant diagram. It is composed of *n* centrifugal vapor compression chillers and a TES. Chillers are configured in parallel and driven by the grid electricity. The set of chillers and the TES are interconnected. Each chiller is characterized by its capacity, energy efficiency curve, fixed acquisition cost, fixed preventive maintenance cost, unloading condition, and time threshold between two startups. Each thermal storage tank is characterized by its capacity, fixed acquisition, and variable operating costs. The grid electricity and the building are identified via the electricity tariff and the cooling demand.

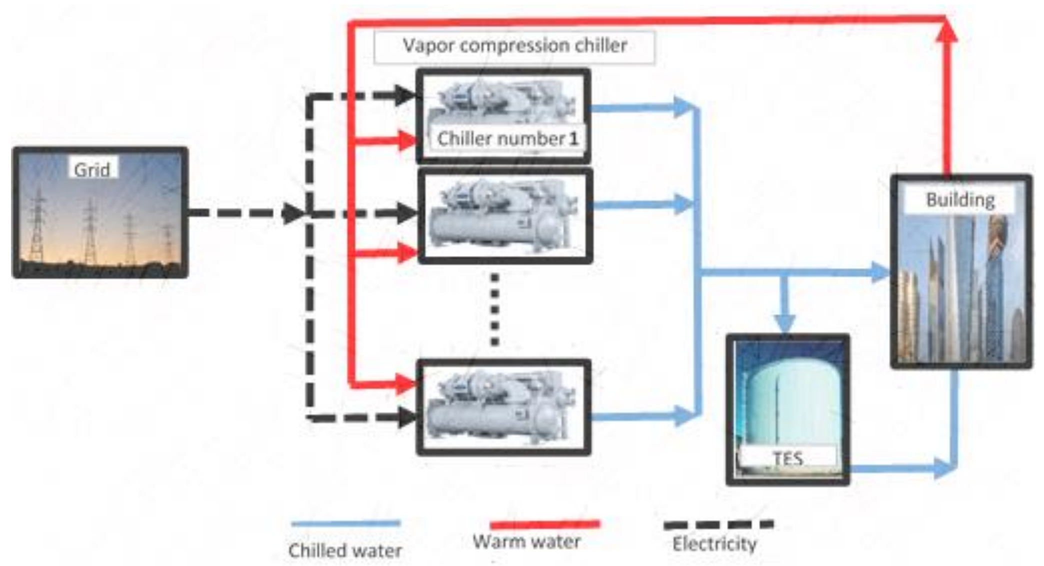


Figure 7. Multi-chillers district cooling plant diagram

5.2 Problem scope

The study aims to obtain the optimal design and operation of the MC-DCP in the presence of different stakeholders' requirements. The work is supported by Marafeq Qatar company, one of Qatar's major providers of district cooling services. Hence, the practical aspects of integrating the stakeholders (investor, users, customers, operators, and regulators) requirements with the modeling of the DCS have been considered in the proposed model. Such integration will significantly reduce the design and operation costs of the DCS and higher energy consumption efficiency. Furthermore, the impact analysis of the requirement on the energy efficiency becomes possible. The following requirements are considered to achieve this type of integration.

- The requirement of the main stakeholders was identified and classified, including the regulatory authority.
- In addition to the system functionality, other non-functional requirements are included (structure, efficiency, reliability).
- A control requirement is imposed to protect the chiller against the short cycling

5.3 MC-DCP requirements

Figure (8) illustrates the stakeholder requirements: The general requirement (R1) includes the system-functionality and the energy efficiency objectives. And three non-functional requirements that describe the expected system qualities in terms of design (R2), reliability (R3), and chiller operation (R4). The assumptions made for these requirements are as followed.

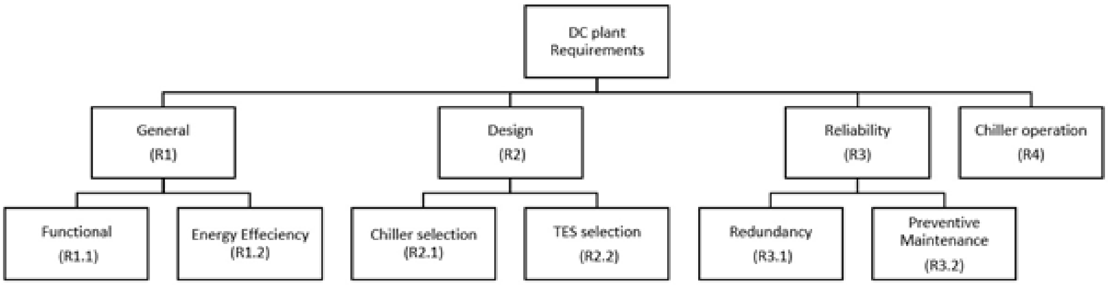


Figure 8. The multi-chillers district plant requirement diagram

- General requirement (R1): the design, the installation, and the operation of the DCS shall ensure the delivery of the design cooling load and energy efficiency.
    - Cooling load satisfaction (R1.1:functional requirement): all customers cooling load requirements can be fully met (up to maximum contracted) at all times. The proposed model denotes the cooling load by the parameter d_t.
    - Energy efficiency (R1.2): energy consumption shall be optimized. The plant operation shall avoid chiller running under a certain percentage of its total capacity (unloading condition (%)), affecting energy efficiency and cooling stability. In the presented model, the energy consumption curve function of the load ratio and the unloading condition are represented respectively by the parameters $Y_{(k,b)}$ and α.
- Design (R2): the design should mitigate the risk of technology integration and its complexity in terms of structure and consider the load profile.
    - Chiller selection (R2.1): the system shall be composed of multi-chillers of identical capacity. This requirement contributes to decreasing the control and integration complexity of the plant.
    - TES selection (R2.2): all new plants with a capacity equal to or greater than 10,000 TR shall include a TES system.

- Reliability (R3): Interruption of services shall be minimized. MC-DCP system reliability shall be compliant with a key performance indicator (KPI = 99.5%)".
    - Redundancy (R3.1): The plant chillers design shall be with redundancy ($N+1$), where N is the optimal number of chillers.
    - Maintainability (R3.2): The preventive maintenance shall be planned according to the recommendation of the fabricator. This requirement is represented by the parameters $PMP_{(k,i,t)}$ in the presented model.
- Chiller operation (R4): The chiller sequencing shall ovoid the short cycling that represents a risk for the chiller (the time between two consecutive startups should be greater than the fabricator threshold). In the presented model, it is represented by the parameter γ.

The regular authority imposes requirements R1, R2.2, and R3.1 (KAHRAMAA [82]), the developer states the other requirements. In the next section, the details of the mathematical model are given.

The stakeholders' requirement implies considering decisions to be made at different system stages. Regardless of the MC-DCP context (studied system), the integration of the stakeholder requirements and the MC-DCP involves sub-models related to design, operation, and control problems. Figure (9) illustrates the interaction of abstract requirements and the sub-models. From this perspective, it is evident that the proposed model has the potential for general use while maintaining the possibility of customization based on specific stakeholder requirements.

- The design leads to the best sizing of the plant by selecting the equipment that simultaneously satisfies the general system requirement (functional requirements and energy efficiency) and the design requirement. This is achieved by the assessment of different alternatives based on long time periods.

- The successful operation of the MC-DCP leads to the best scheduling of activities related to chilled water production and storage that satisfies the cooling load demand and minimizes the energy consumption. Furthermore, considering preventive maintenance plans concurrently with the operations process. Hence, the chillers should be at an OFF state during maintenance work; this reduces the availability and may affect the cooling load satisfaction.
- The cooling process is highly automated; hence, the interaction between the operators and the system is achieved using the user interface of the system control. The control is performed via a programmable logic controller (PLC) and supervisory control and data acquisition system (SCADA). Hence, the control strategy to be implemented should simultaneously consider the cooling load satisfaction, the energy efficiency, and the sequencing requirement of the process.

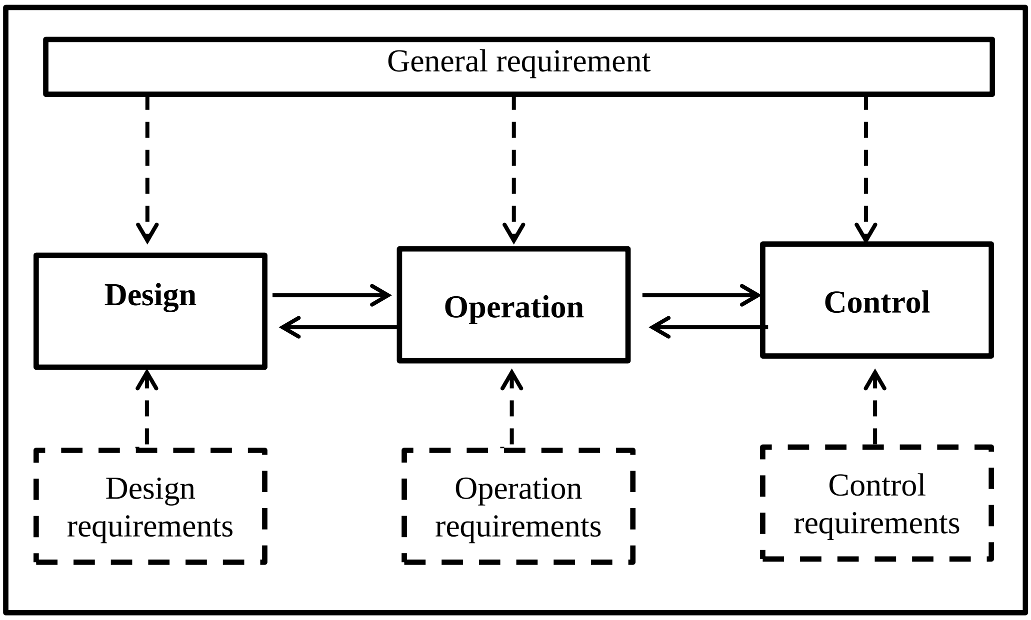


Figure 9. MC-DCP sub-problems interaction

5.4 Load approximation

The Lusail City Marina district (Figure 10) master plan illustrates the land use and utility plan. The type of buildings (residential, commercial, mix-use, and entertainment) and the building orientation are provided in the plan.

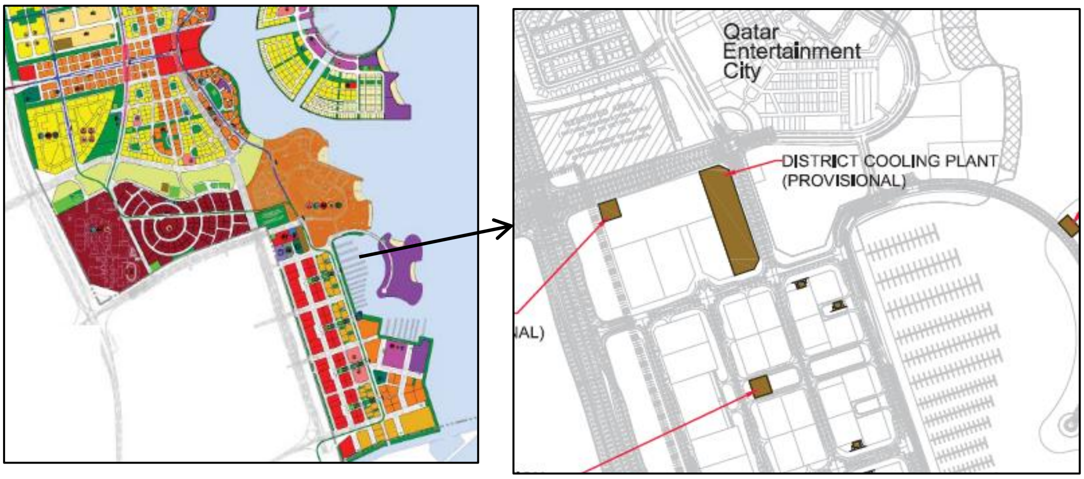


Figure 10. Lusail city master plan - Doha, Qatar

KAHRAMAA collects the hourly cooling demand for typical buildings, which serves as a basis for benchmarking cooling load for buildings. Therefore, the annual hourly cooling load is approximated based on the reference day and the annual hourly temperature of the same region, as shown in Figures (11,12).

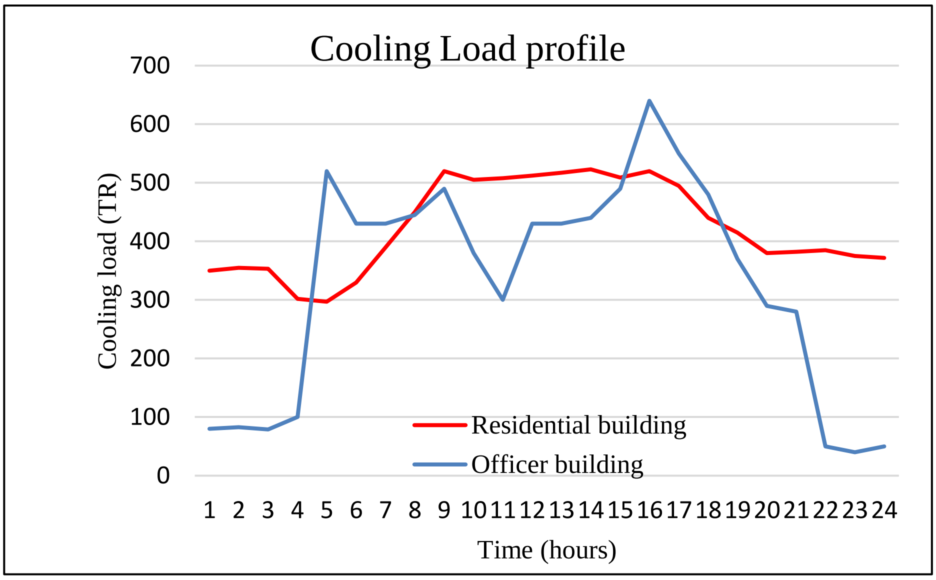


Figure 11. Hourly cooling demand (KAHRAMAA June 18th; 2014)

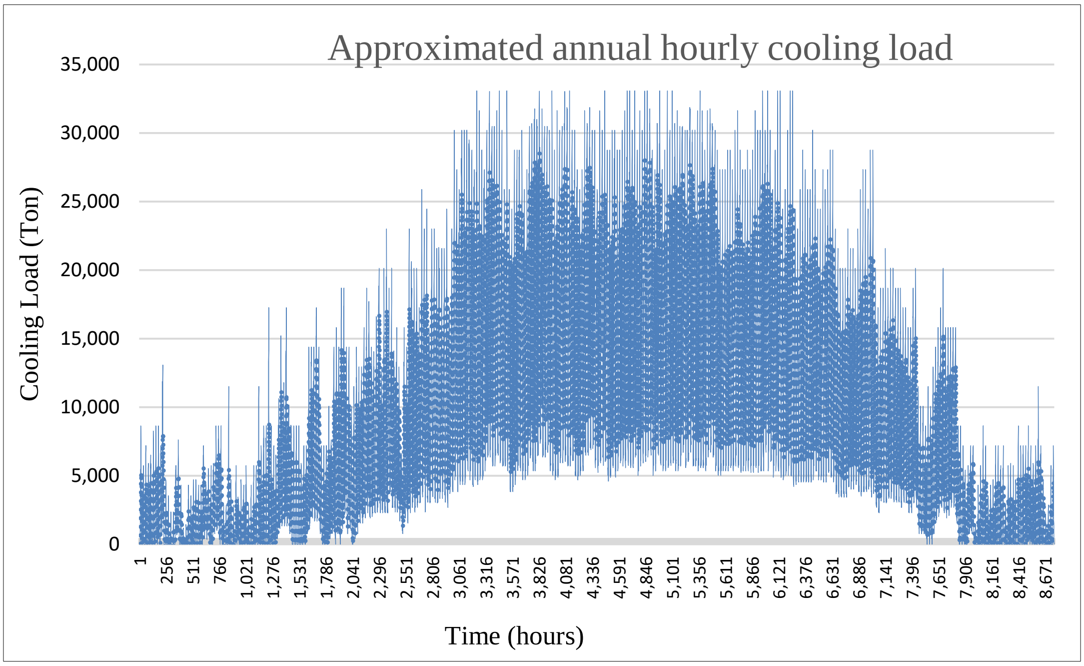


Figure 12. Estimated annual cooling load

5.5 Mathematical model

To analyze optimality of design and operation, a mathematical model is proposed. The nomenclature, parameters, and decision variables used in the model are given in Table 3 and the following assumptions are made for the development of the model.

- The cooling demands are known in advance and deterministic
- The TES function with full efficiency.
- The system operates in a steady state, and the system's transient state is not considered

Table 3. Nomenclature

Indices and sets	
K	Set of available chiller sizes.
I	Set of an available number of chillers for each chiller size.
H	Set of available storage tank sizes.
T	The schedule horizon is formed of n unit times periods of equal duration.
B	Set of the energy consumption curve breakpoints.
C	Set of the mapping function (G) value`
Parameters	
α	Unloading condition (% partial load ratio)
γ	Time threshold between two startups.
r	Interest rate.
n	Number of annuities.
$\boldsymbol{d_t}$	Total cooling demand of customers during period, t ϵ T (TR)
N	Optimal number of chillers.
$\boldsymbol{Q_k}$	Capacity associated with every chiller of size k, k ϵ K.
$\boldsymbol{D_h}$	Capacity associated with every storage tank of size h, h ϵ H.
$\boldsymbol{Fc_k^{Vc}}$	Fixed acquisition cost for vapor compression chiller of capacity Q_k, k ϵ K.
$\boldsymbol{Fc_h^{Cwt}}$	Fixed acquisition cost for chilled water storage tank of capacity Dh, h ϵ H.
$\boldsymbol{Fc_k^{Ma}}$	Fixed preventive maintenance cost for vapor compression chiller of capacity Q_k, k ϵ K
$\boldsymbol{Vc_t^{Elec}}$	Variable cost for unit energy consumed during the period t, t ϵ T.
$\boldsymbol{Vc_t^{Cwt}}$	Variable cost for storing a unit of chilled water during the period t, t ϵ T
$\boldsymbol{Y_{(k,b)}}$	Ordinate of the energy consumption curve of chiller of capacity Q_k, k ϵ K
$\boldsymbol{X_b}$	Abscissa of the energy consumption curve, representing the load ratio (%)
$\boldsymbol{PMP_{(k,i,t)}}$	Binary parameter that indicates that the i^{th} chiller of capacity Q_k is available (PMP(k,i.t) = 0) during the period t or under preventive maintenance, not available (PMP(k,i.t) = 1)
$\boldsymbol{F_c}$	{-1,0,1}, Value of the mapping function G, G (z(k,i,t) = z(k,i,t+1)-z(k,i,t)
Decisions variables	
$\boldsymbol{x_{(k,i)}}$	Binary variable that takes value one if the i^{th} chiller having capacity Qk is selected and zero otherwise,
$\boldsymbol{g_h}$	Binary variable that takes value one if the tank of capacity Dh is selected to be installed and zero otherwise
$\boldsymbol{z_{(k,i,t)}}$	Binary variable that represents the state of i^{th} chiller having capacity Q_k at the period t. It takes the value one if the chiller is in operation mode (ON) and zero others wise (OFF)

Decisions variables	
$\boldsymbol{\delta}_{(\boldsymbol{k},\boldsymbol{i},\boldsymbol{t},\boldsymbol{c})}$	Binary variable that represents the transition type of ith chiller having capacity Qk between the period *t* and *t+1*. It takes the value 1 if the transition is of *c* and zero otherwise
$\boldsymbol{P}_{(\boldsymbol{k},\boldsymbol{i},\boldsymbol{t})}$	Amount of chilled water produced by the i^{th} chiller having capacity Q_k at the period *t*
$\boldsymbol{E}_{(\boldsymbol{k},\boldsymbol{i},\boldsymbol{t})}$	The energy consumed by the compressor of the i^{th} chiller having capacity Q_k at the period *t*
$\boldsymbol{S}_{\boldsymbol{t}}$	The stock level of chilled water in the storage tank at the end of period *t*
$\boldsymbol{\lambda}_{(\boldsymbol{k},\boldsymbol{i},\boldsymbol{t},\boldsymbol{b})}$	weighting variable (special ordered set type two variables) to generate the linear approximation of the energy consumption curve

The objective function (Eq. 1) minimizes the total annualized costs and includes three terms. It comprises capital and investment, operating, and preventive maintenance costs.

$$C_{Total} = C_{inv} + C_{op} + C_{ma} \tag{1}$$

The capital cost includes the cost for the chillers and storage tank to be installed and represented by the parameters Fc_k^{Vc} and Fc_h^{Cwt}. The investment cost is obtained by multiplying the capital cost of each equipment type by the amount to be installed and the CRF. The variables $x_{(k,i)}$ and g_h represent respectively, the optimal number of chillers of capacity Q_k and storage tank of capacity D_h to be designed.

$$C_{inv} = \frac{r(1+r)^n}{(1+r)^n-1}\left(\sum_k \sum_i Fc_k^{Vc}\, x_{(k,i)} + \sum_h Fc_h^{Cwt} g_h\right) \tag{2}$$

The operating cost is the sum of the electricity cost used to run the chillers and the storage cost for three summer months. The electricity cost is obtained by multiplying the sum of electricity consumption for all selected chillers with the corresponding price. The storage cost is obtained by multiplying the amount of the stored chilled water with its corresponding price. $E_{(k,i,t)}$ represents the electricity consumption for i^{th} chiller of capacity Q_k in the period t. S_t represents the stock level of the stored chilled water during the period t.

$$C_{op} = \sum_k \sum_i \sum_t Vc_t^{Elec} E_{(k,i,t)} + \sum_t Vc_t^{Cwt} S_t \tag{3}$$

The annual preventive maintenance cost consists of the expenses related to working hours and the spare part. It is obtained by multiplying the sum of selected chillers with the corresponding preventive maintenance price Fc_k^{Ma}.

$$C_{ma} = \sum_k \sum_i Fc_k^{Ma} x_{(k,i)} \tag{4}$$

5.5.1 Definition block (Figure 6)

The definition block represents the different system components. The proposed model considers two components: the chillers and the storage tank. They are represented respectively by the binary variable $x_{(k,i)}$ and g_h.

$$\sum_k \sum_i x_{(k,i)} \geq 1 \tag{5}$$

$$\sum_k x_{(k,i)} \leq 1 \qquad \forall i \tag{6}$$

$$x_{(k,i+1)} \leq x_{(k,i)} \qquad \forall (k,i) \tag{7}$$

$$\sum_h g_h = 1 \tag{8}$$

Constraint (5) ensures that at minimum one chiller is selected for the chiller plant to satisfy the requirement $R3.1$. Constraint (6) enforces that the selected chillers are identical. Constraint (7) enforces to remain the last chiller number equal to the total number of chillers. Hence, each selected chiller will be identified via its index i. Constraint (8) dictates that a single tank of size h is selected and hence, installed. Constraints (5-8) satisfy design requirements $R2$.

5.5.2 Internal block (Figure 6)

Constraint (9) represents the needed activities (cooling water production and storage) to satisfy the cooling load and gives at the same time information about the plant layout. It indicates that the chiller and the storage tank are physically interconnected, the cooling demand is satisfied by the amount of chilled water provided by the chillers and the storage tank.

$$\sum_k \sum_i P_{(k,i,t)} + S_{(t-1)} - S_t = + d_t \qquad \forall t \qquad (9)$$

5.5.3 Activity block (Figure 6)

The activity block considers activities in the system and their interconnection. It describes the cooling process and its operation. Three types of activities are included in the proposed model: the production of chilled water $P_{(k,i,t)}$, the storage of chilled water S_t and the energy consumption $E_{(k,i,t)}$. The technical constraints related to the energy consumption curve linearization are integrated in this section for model clarity.

$$P_{(k,i,t)} = Q_k \sum_b X_b \lambda_{(k,i,t,b)}) \qquad \forall (k,i,t) \qquad (10)$$

$$E_{(k,i,t)} = \sum_b Y_{(k,b)} \lambda_{(k,i,t,b)}) \qquad \forall (k,i,t) \qquad (11)$$

$$\sum_b \lambda_{(k,i,t,b)}) = 1 \qquad \forall (k,i,t) \qquad (12)$$

The set of constraints (10-12) reflects the linearization formulation of the energy consumption ($E_{(k,i,t)}$) curve function of the load ratio ($LR_{(k,i,t)}$) by a piecewise function (Figure 15). consumption ($E_{(k,i,t)}$) curve function of the load ratio ($LR_{(k,i,t)}$) by a piecewise function (Figure 15). This type of linearization is also mentioned in [94-95]. Constraint (10) express the amount of chilled water produced within each interval $[b, b+1]$, where b represents the curve breakpoints. Constraint (11) expresses the convexity constraint. Constraint (12) is a special order set of order 2 (SOS2) constraints. It expresses that out of a set of variables $\lambda_{(k,i,t,b)}$, at most two variables can be nonzero. Besides, the two variables must be adjacent to each other.

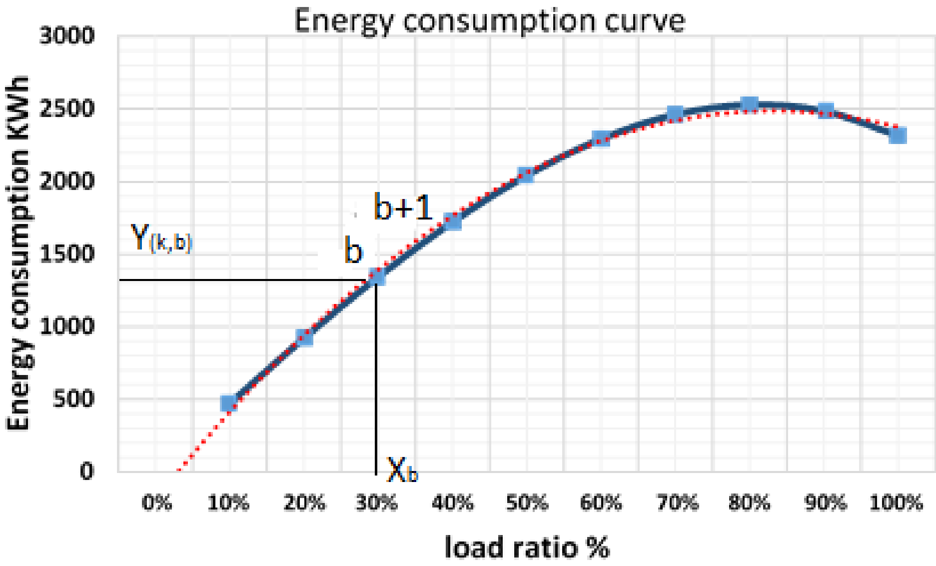


Figure 13. The linearization of the energy consumption curve

$$\alpha Q_k z_{(k,i,t)} \leq P_{(k,i,t)} \tag{13}$$

$$P_{(k,i,t)} \leq Q_k x_{(k,i)} \tag{14}$$

$$P_{(k,i,t)} \leq Q_k z_{(k,i,t)} \tag{15}$$

$$S_t \leq \sum_h D_h g_h \tag{16}$$

$$S_0 = S_T \tag{17}$$

Constraint (13) enforces that chiller cannot be loaded under $\alpha\%$ of its capacity. Constraints (11,13) satisfy the requirement $R1.2$. The constraint (14) ensures that the produced chilled water amount of the i^{th} installed chiller having capacity Q_k at any period t does not exceed its installed capacity. Constraint (15) ensures that the chiller in an OFF state does not produce chilled water. Constraint (16) ensures that the amount of chilled water served from the storage tank does not exceed its capacityD_h. Constraint (17) represents the steady-state modeling of the storage tank. It assumes that the level of chilled water stored before the first period is equal to the level of the last period.

The functional requirement $R1.1$ is satisfied by the set of constraints expressed in the definition block (5-8), internal block (9), and activity block (10, 14-17). This means that the cooling load demand satisfaction is achieved simultaneously by adapted design and operation.

5.5.4 Sequencing block (Figure 6)

The requirement $R4$ considers the short cycling problem of the chillers. This is a severe issue that may increase the risk of failure, shorten its life and lead to poor performance. It is recommended to impose a time threshold between two consecutive startups. For the formulation purpose, we introduce the definition of target sequence ($Tseq$), and the mapping function (G) used here.

- A target sequence is a particular sequencing of the machine state over the horizon (T). It is defined by its occurrence domain (specific domain) as a subset of (T). The specific domain can be consecutive or distanced periods. The target sequence ($Tseq$) has an operational meaning, such as the startup of a machine. It occurs between two consecutive periods. The $Tseq$ can be identified among other sequence types using an evaluation function (G).
- A mapping function is a linear function that is defined as an arithmetic operation applied to the machine state variable (argument). The function (G) evaluates the set of all possible sequences over the specific domain and differentiates $Tseq$ among others. In our present case $G(z_{(k,i,t)}) = z_{(k,i,t)} - z_{(k,i,t+1)}$.

The function G allows identifying chiller transition types (startup, shutdown, idle, or work in progress) as detailed in the following (Table 4) and figure (14-a).

Table 4. Different transition types

$G(z_{(k,i,t)})$	*Transition type*	*c*	*Remark*
-1	*Startup*	*1*	*Tseq1*
0	*Idle or working in progress*	*2*	*No transition*
1	*shutdown*	*3*	

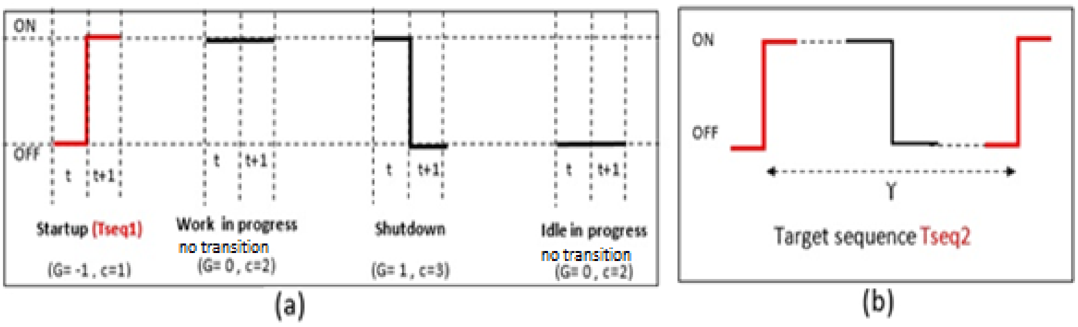


Figure 14. (a) The different transition types (b) short cycling sequence (Tseq2) identified as two consecutive startup sequences (Tseq1) distanced by γ

Figure (14-b) illustrates the chiller short cycling, namely $Tseq2$ as two $Tseq1$ (startup) distanced by the threshold γ. The chiller control (sequencing) should mitigate the scenario outlined in the figure (14-b) when γ is less than the threshold, which dedicates the short cycling formula. The formulation of $Tseq2$ is detailed as follows.

$$G\left(z_{(k,i,t)}\right) = \sum_c F_c \delta_{(k,i,t,c)} \qquad (18)$$

$$\sum_c \delta_{(k,i,t,c)} = 1 \qquad (19)$$

$$\sum_{\substack{t=t1 \\ t1 \leq n-\gamma}}^{t=t1+\gamma} \delta_{(k,i,t,1)} \leq 1 \qquad (20)$$

- First, the different transition types of sequences are identified using the mapping function G. The startup between two consecutive periods represents the $Tseq1$ which is equivalent to $\delta_{(k,i,t,1)} = 1$. In fact, the constraints (18-19) translate the transition type identification. The mapping function G represents the left-hand side of the constraint (18); constraints (18-19) express that the discrete function G can take only one of the three values (Table 4) weighted by the binary variables $\delta_{(k,i,t,c)}$ of which only one can be non-zero.

- Second, the specific domain of the sequence $Tseq2$ is formed by $1 + \gamma$ consecutive periods. $Tseq2$ occurs if the sum of startups (variable $\delta_{(k,i,t,1)}$ is greater or equal to 2 along with the specific domain. The non-occurrence of the $Tseq2$ is equivalent to imposing the sum of startups less or equal to 1. This is illustrated via the constraint (20). Hence, it satisfies the requirement $R4.2$.

5.5.5 State machine block (Figure 6)

The state machine (ON-OFF) is an aspect of the system control. The chillers state is modeled via the binary variable $z_{(k,i,t)}$.

$$z_{(k,i,t)} \leq x_{(k,i)} - PMP_{(k,i,t)} \tag{21}$$

$$z_{(k,i+1,t)} \leq z_{(k,i,t)} \tag{22}$$

$$z_{(k,i,t)} \leq 1 - \lambda_{(k,i,t,0)} \tag{23}$$

Constraint (21) demonstrates that the state of the selected chiller can be ON or OFF. Furthermore, it enforces the selected chiller to be in an OFF state during the preventive maintenance. Constraint (21) satisfies requirement $R3.2$. Constraint (22) states that chiller starting is ordered by its numerous i (the first chiller ($i = 1$) is a leader). Constraint (23) enhances the model and translates the formulation of the machine state variable ($z_{(k,i,t)}$) as a function of the variable $\lambda_{(k,i,t,0)}$. It enforces that $z_{(k,i,t)} = 0$ when the machine is OFF and $z_{(k,i,t)} = 1$ otherwise. Finally, the resulting model is a MILP model composed of constraints (1-23).

5.6 Numerical Analysis and Results

This section presents the computational studies and numerical analysis of the proposed model. It aims to demonstrate the practical usefulness of the developed model, the system assessment, analysis of the system use cases, and the possibility of design improvement.

The proposed MILP model was coded, implemented, and tested for solvability using AIMMS 4.81.4.4 software that incorporates mixed integer programing (MIP) CPLEX 20.1 solver. Four classes representing different problem sizes were generated to evaluate the effectiveness of the developed model in solving diversified-sized problems and determine its impact on the solution time. Three instances representing an increasing peak load (small, medium, large) were generated and tested for optimality. The main characteristics of each class and instance are summarized in Table (5).

Notably, the requirements used in the proposed model were collected from project stakeholders and chiller characteristics. More precisely, some of the requirements are expressed in the code 2016 (district cooling design and water management) of the regulatory authority (KAHRAMAA), which is considered mandatory. The economic data (cost parameters) were used similarly to real-life data [48]

Five objectives guided the computational analysis:

- To test and validate the solvability of the proposed model.
- To assess the system compliance against the requirements.
- To verify the system behavior during the preventive maintenance concerning the reliability objective's compliance.
- To analyze the impact of sequencing control on energy consumption.
- To review the design requirement and possibility of improvement towards energy efficiency.

5.6.1 Model test and validation

The developed MILP model was coded and solved optimally on Intel(R) Core(TM) i7-4600 CPU@2.10 GHz with 8 GB DDR3 RAM. Table (5) gives an overview of the different classes and instances, the number of constraints, variables, and binary variables for each class, and the solving time (CPU in seconds) for each instance. Interestingly, we observe that all instances were solved optimally. The solution time varied slightly between classes, depending on their size and complexity from second to a few minutes.

Additionally, Table (6) summarized the mean, minimum and maximum CPU time for solving each class. The average time for solving the 12 instances is 56.22 seconds. As noticed, the small instance is solved in 0.63 seconds, and the largest instance is solved in a reasonable time within 4 minutes 17 seconds.

Table 5. Characteristics of the problem classes and instances

Problem	**|K|**	**|I|**	**|H|**	**|B|**	**|T|**	**Number of constraints**	**Number of variables**	**Number of binaries**	**Inst ance**	**Peak cooling load (TR)**	**CPU (second)**
Class 1	3	6	3	5	24	5188	4744	453	1.1	10.000	2.55
									1.2	20.000	2.06
									1.3	30.000	0.63
Class 2	4	7	4	5	24	8039	7365	704	2.1	10.000	5.23
									2.2	20.000	8.78
									2.3	30.000	8.39
Class 3	5	8	5	5	24	11460	10510	1005	3.1	10.000	15.78
									3.2	20.000	18.23
									3.3	30.000	24.92
Class 4	5	9	6	5	48	25894	23725	2211	4.1	10.000	62.75
									4.2	20.000	243.16
									4.3	30.000	257.73

Table 6. CPU time for solving to optimality for every class

Problem	|K|	|I|	|H|	|B|	|T|	CPU (second)		
						Average	Minimum	Maximum
Class 1	3	6	3	5	24	1.75	0.63	2.55
Class 2	4	7	4	5	24	7.47	5.23	8.78
Class 3	5	8	5	5	24	19.64	15.78	24.92
Class 4	5	9	6	5	48	187.88	62.75	257.73

5.6.2 Assessment of system compliance against requirements

The objective of this analysis is to verify the system's compliance with the stakeholders' requirements. Table (5) shows that all instances are optimally solved. For discussion of the solution, instance 3.2 is selected..

The chillers and storage tank selection (|K|=5, |I|=8, and |H|=5) represents diverse capacity (chillers range between 4,000 TR and 5,000 TR and storage tank capacity range between 2,000 TR and 16,000 TR) that can be provided by the same or different manufacturers. For the energy consumption curve, five breakpoints |B|= 5) that represent the load ratio of 0%, 25%, 50%, 75% and 100% are considered. The unloading condition is fixed to 20% (α) of the chiller capacity. The threshold between two startups is fixed to 2 periods (γ). The two capital recovery parameters are 6% for the interest rate (r) and 25 years for the number of annuities (n).

The optimal medium cooling load design satisfies simultaneous requirements concerning the system functionality (cooling load satisfaction $R1.1$), energy efficiency ($R1.2$), design ($R2$), and redundancy ($R3.1$). The optimal design in terms of the number of chillers (N) is four chillers of capacity Q_3 (4,750 TR) in addition to a supplement one with the same capacity (redundancy requirement). Hence, the chillers plant is composed of five chillers of capacity Q_3 and one storage tank of capacity D_1 (2.000 TR).

Figure (15) shows the pattern of cooling load demand for a peak day. The best operation of the designed MC-DCP satisfies the customer cooling load demand, the energy efficiency, the chiller sequencing requirement ($R4$), and the preventive maintenance ($R3.2$) simultaneously. Figures (16-19) illustrate different operation decisions variables and state machines related to chillers and show respectively the optimal quantity of chilled water produced by each designed chiller ($P_{(k,i,t)}$), its energy consumption ($E_{(k,i,t)}$) the chiller state ($z_{(k,i,t)}$) and the chilled water to be stored during each period (S_t).

Figure (18) demonstrates that chiller number 5 is not needed to be operated to satisfy the cooling load demand and remains on standby in normal operating conditions. Therefore, the connection of the redundant chiller does not reduce energy consumption. The following analysis explains the utility of the designed redundant chiller.

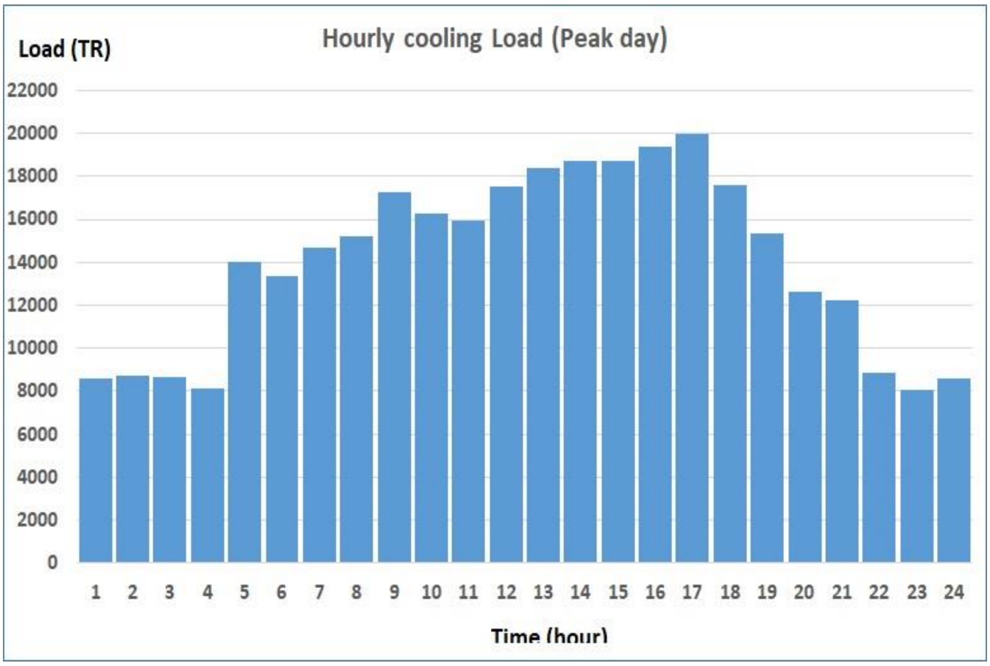


Figure 15. Medium cooling load for the peak day

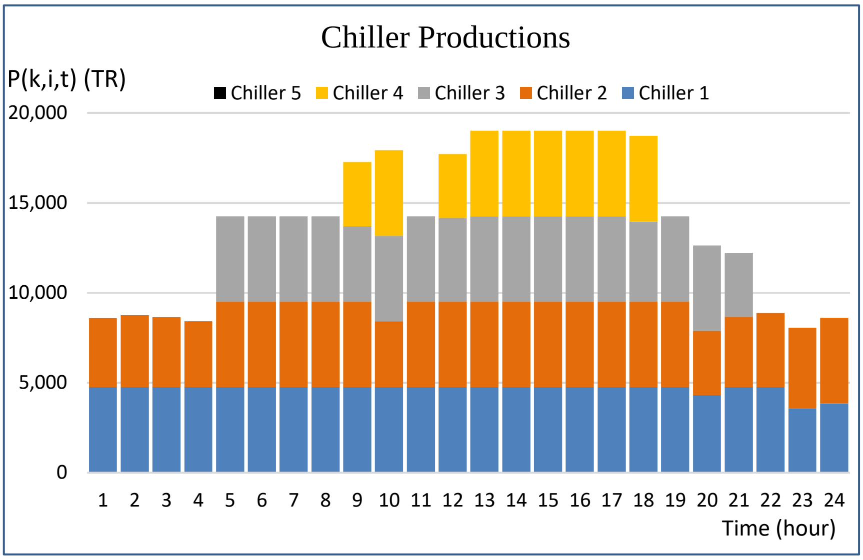


Figure 16.: Chillers operation decision variables (production)

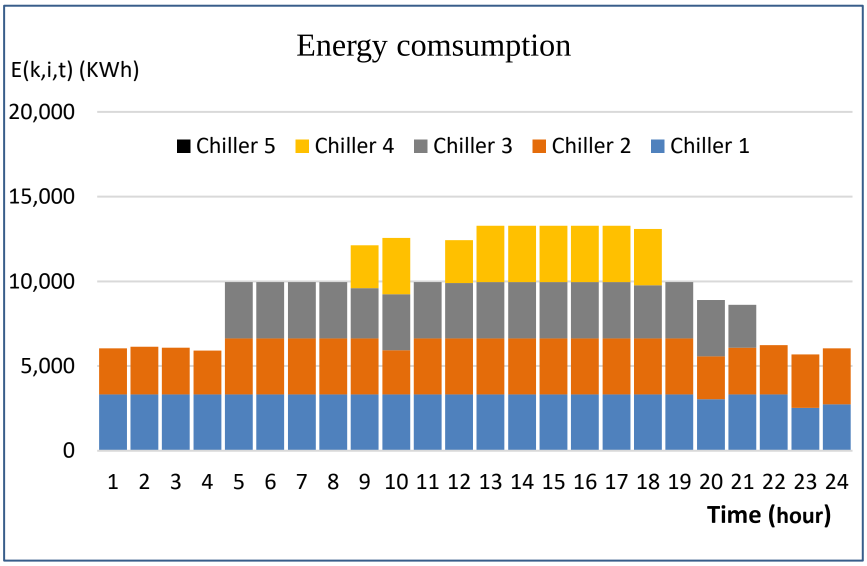


Figure 17. Chillers operation decision variables (energy consumption)

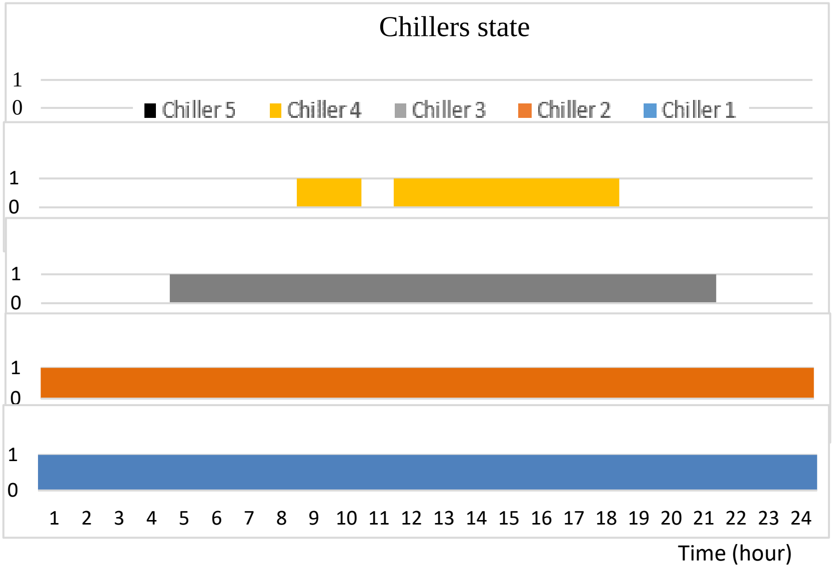


Figure 18. Chillers operation decision variables (chillers state)

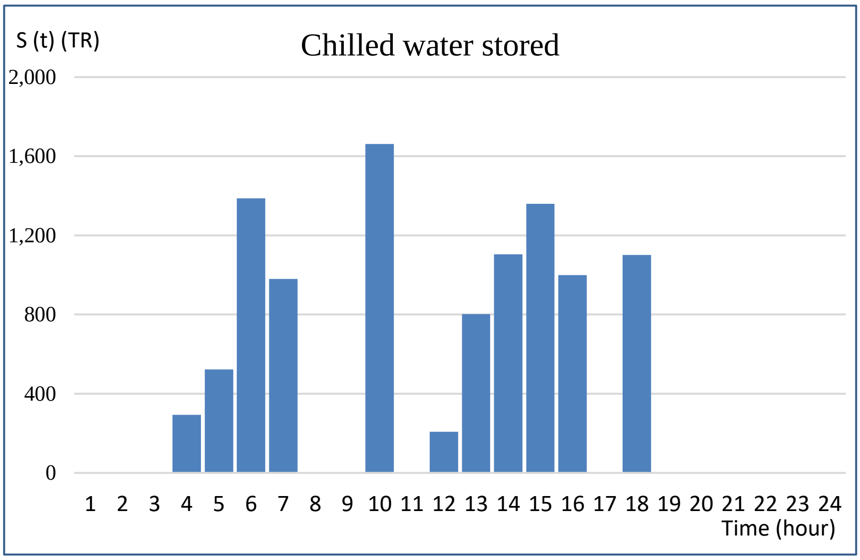


Figure 19. Chilled water storage decision variable

5.6.3 System maintainability analysis

The model integrates parameter $PMP_{(k,i,t)}$ that represents a scheduled shutdown of the chillers to execute the preventive maintenance or an unscheduled event such as chiller failure. During these maintenance periods, the chiller is in the OFF state. This numerical analysis aims to assess the system reliability in this kind of situation by ensuring the satisfaction of the cooling load demand. To simulate this kind of event, the parameter $PMP_{(3,1,t)}$ is assigned to one from period one to twelve. Hence, the chiller number 1 of capacity Q_3 is in OFF state during the twelve first periods.

Figures (20-23) represent the new operation decisions variables in the scenario of chiller number 1 is under preventive maintenance for 12 time periods. Figure (20) represents the chiller state and shows that chiller number 1(blue color) is in OFF state during the first twelve periods as scheduled. This is enforced via the constraint (21). The state of chillers 3 and 4 differs from Figure (16). Chillers 3 and 4 start respectively at periods 1 and 5 instead of 5 and 9 to satisfy the cooling load demand during the unavailability of chiller 1. The redundant chiller (chiller 5, black color) is operated from the ninth period to supply the remaining needed capacity to satisfy the cooling load demand. The redundant chiller shutdowns when chiller 1 is in operation condition (t=13). The sequencing change of chillers number 3 and 4 is explained by constraint (22) that imposes an ordered startup. Given that the redundant chiller has the same capacity and characteristics as the rest of the chillers, the total energy consumption remains unchanged, and the quantity of chilled water stored.

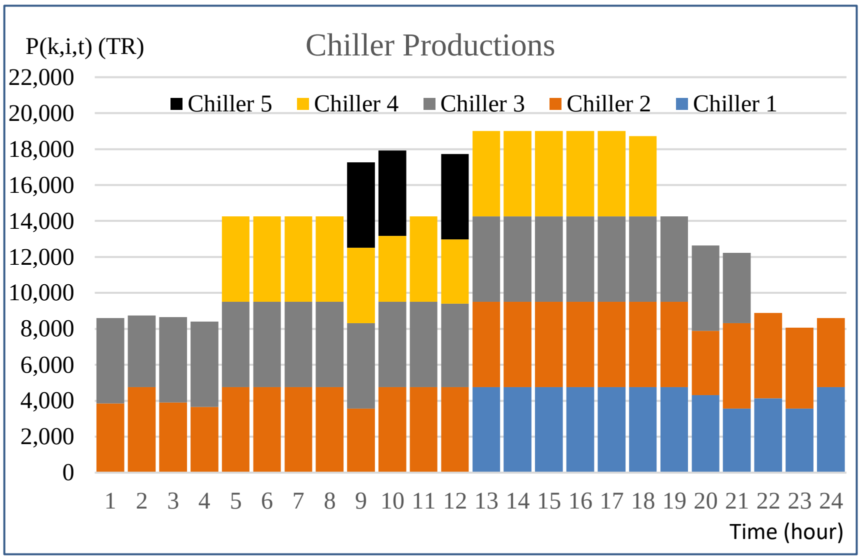


Figure 20. Operation decision variables in the case of chiller 1 under preventive maintenance (production)

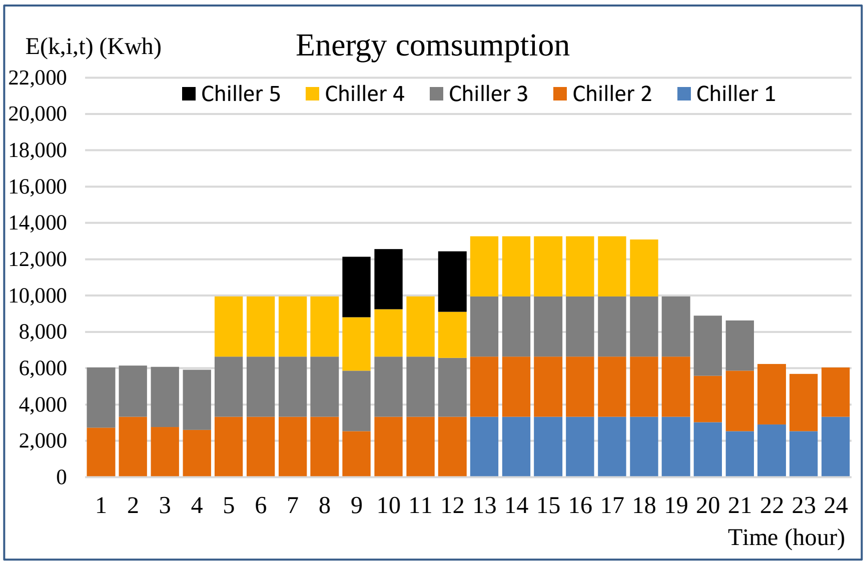


Figure 21. Operation decision variables in the case of chiller 1 under preventive maintenance (energy consumption)

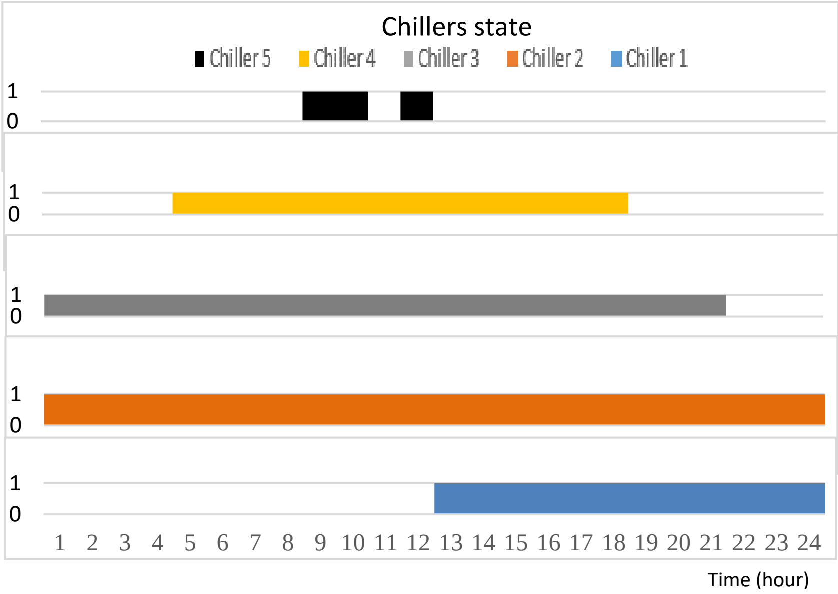


Figure 22. Operation decision variables in the case of chiller 1 under preventive maintenance (chiller state)

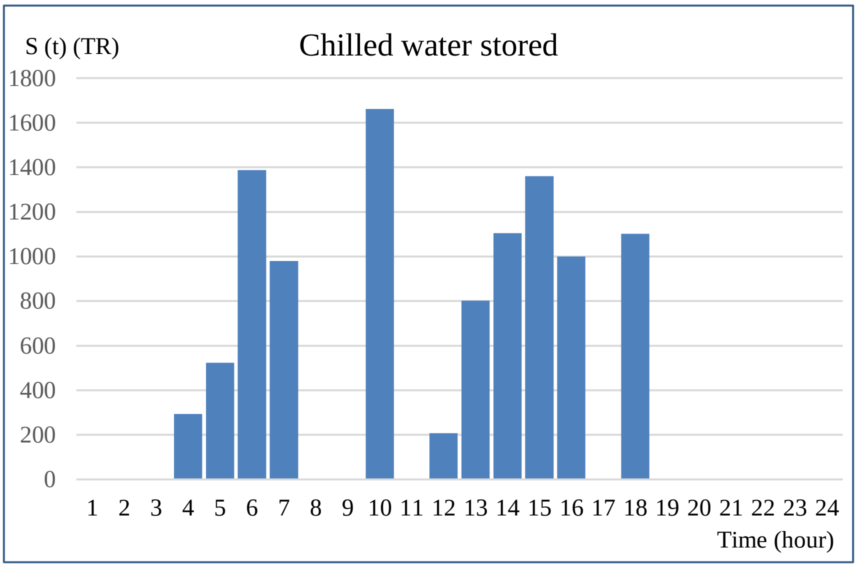


Figure 23.Chilled water storage decision variable in the case of chiller 1 under preventive maintenance

5.6.4 System sequencing and impact on operational decision variables analysis

The sequencing of chillers is a part of system control. It is used to realize the desired system output and objectives. In DCS processing, sequencing is used for different objectives such as; decreasing energy consumption, increasing safety, and extending equipment life. In the proposed model, the sequencing imposed by the technology provider is for the chiller protection and the improvement of chilling process stability. This subsection explores the impact of such sequencing (time threshold between two startups) on the system operational decision variables and its impact on system performance. Instance 3.2 was solved optimally in three scenarios by varying the time threshold between two startups from 2 time periods to 4 time periods.

Figure (24) demonstrates the sequencing formulation effectiveness of requirement 4.2 and via the concept of target sequence ($Tseq$) and mapping function (G) that impose a time threshold between two startups. The analysis shows the variation of chiller sequencing number 4 to satisfy this constraint. The remaining chillers state machine (chillers 1, 2, and 3) were unchanged since the cooling load satisfaction imposed to be operated continuously without interruption from the starting period.

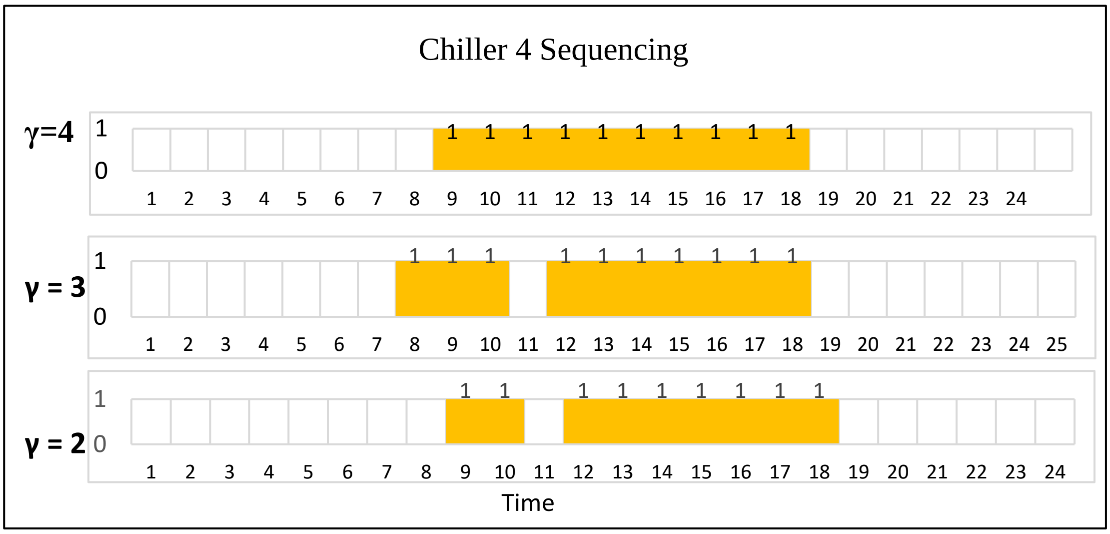


Figure 24. Chiller 4 state machine for γ∈ {2,3,4}

Figures (25-30) show the variation of the chilled water production, stored, and the energy consumption under different types of sequencing. Figure (30) illustrates that energy consumption increased slightly by 0.08% compared to the base case ($\gamma = 2$), and the chilled water stored (Figure 27) fluctuates in comparison to the base case. Imposing any sequencing on the chiller is equivalent to decreasing its degree of freedom to meet the cooling load demand optimally, consequently restricting the system's ability to adjust the operational decision variables instantaneously. On the other hand, sequencing is mandatory to operate chillers safely and reliably. Hence, the only adapted and necessary sequencing should be involved to decrease energy consumption. The less threshold time between two startups, the better energy consumption is. The chiller specifications, such as the time threshold between two startups, may impact the activities, including energy consumption. Considering this type of requirement offers more comprehension of the system behavior and allows the realistic system performance prediction.

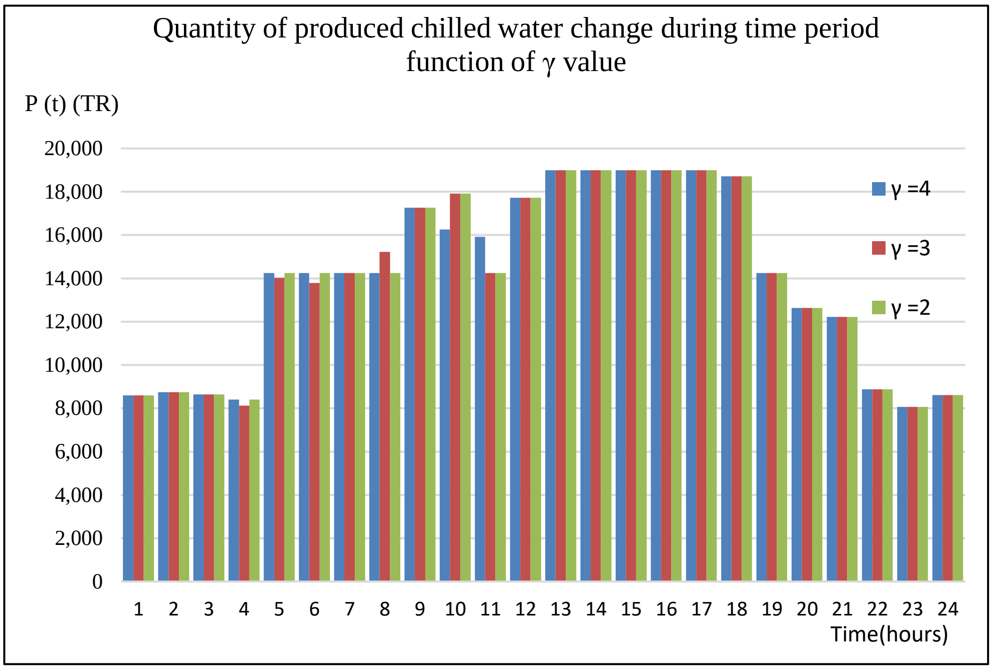


Figure 25. : Chilled water production changes under different sequencing types $\gamma \in \{2,3,4\}$

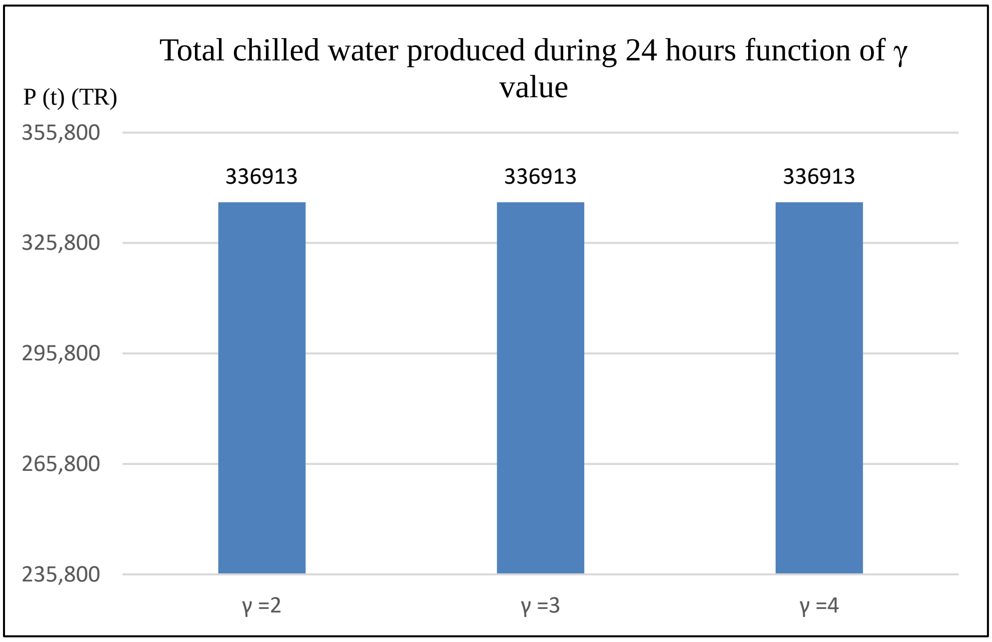


Figure 26. Amount of chilled water produced during 24 hr under different sequencing types

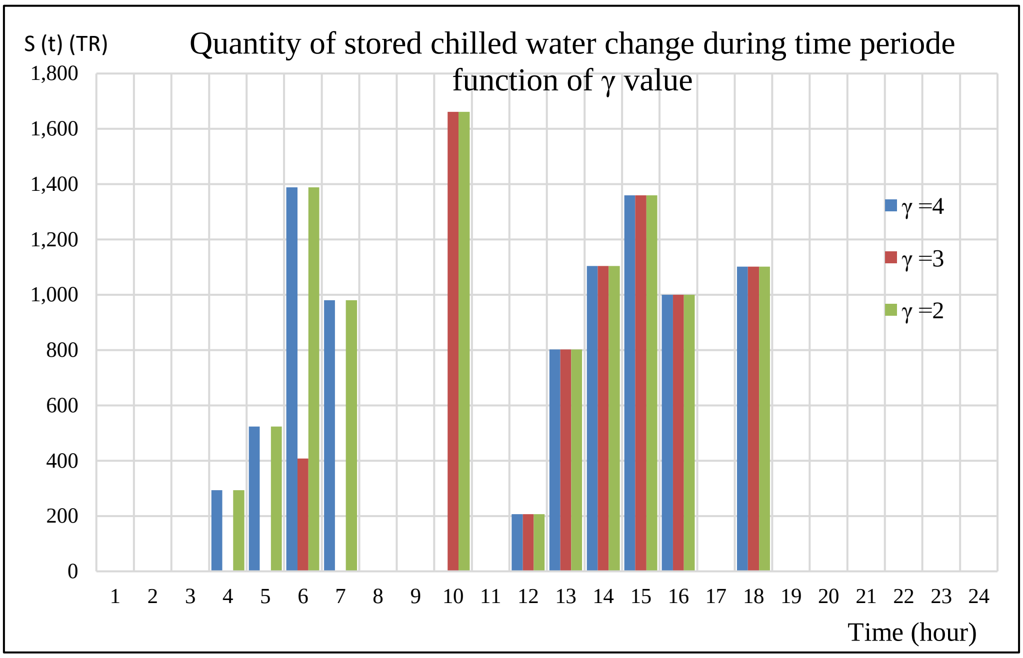


Figure 27. Chilled water stored changes under different sequencing types $\gamma \in \{2,3,4\}$

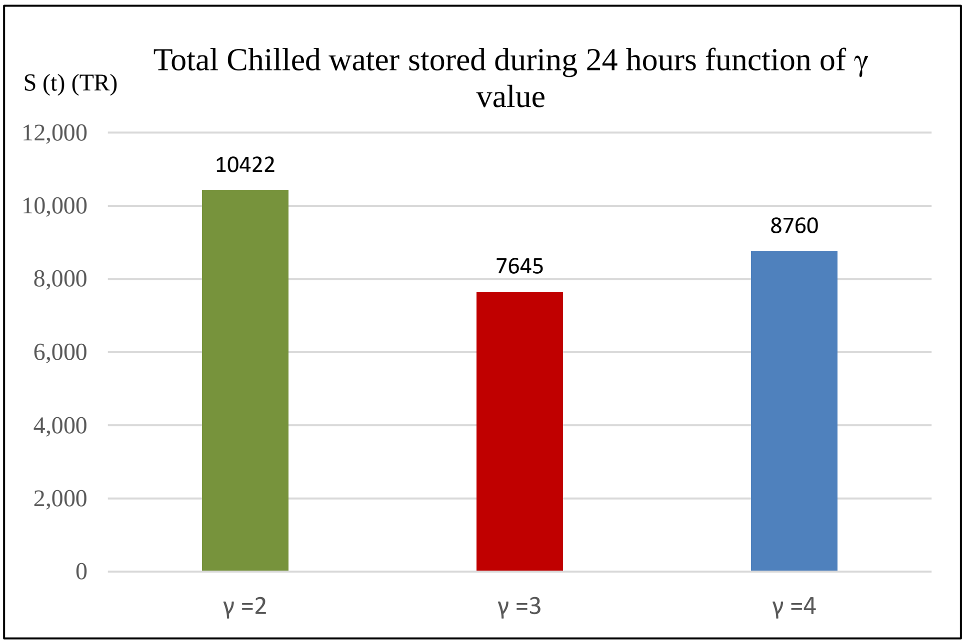


Figure 28. Chilled water stored change during 24 hr for different sequencing types

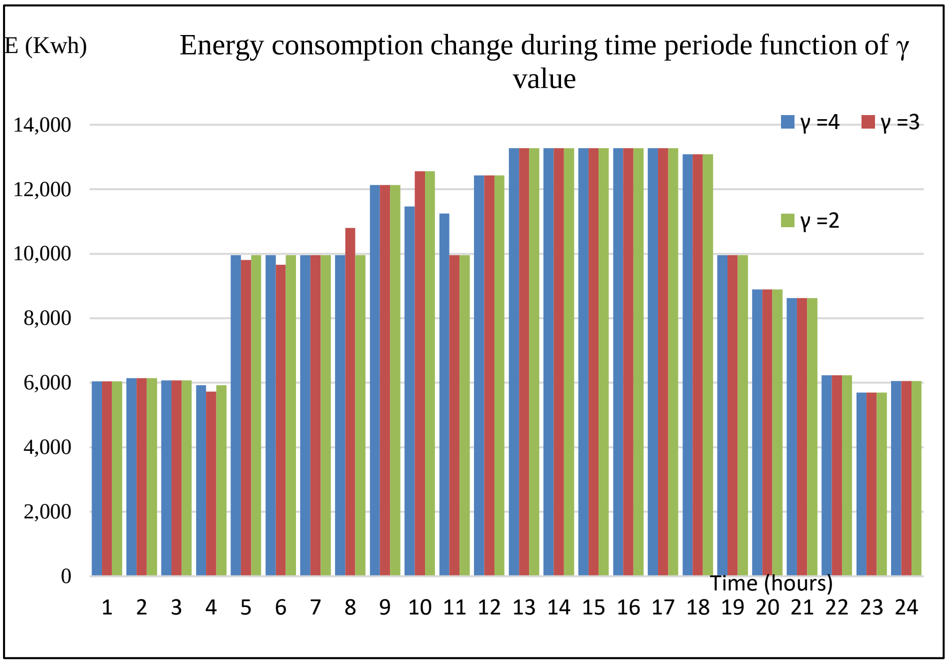


Figure 29. Energy consumption changes under different sequencing types γ∈ {2,3,4}

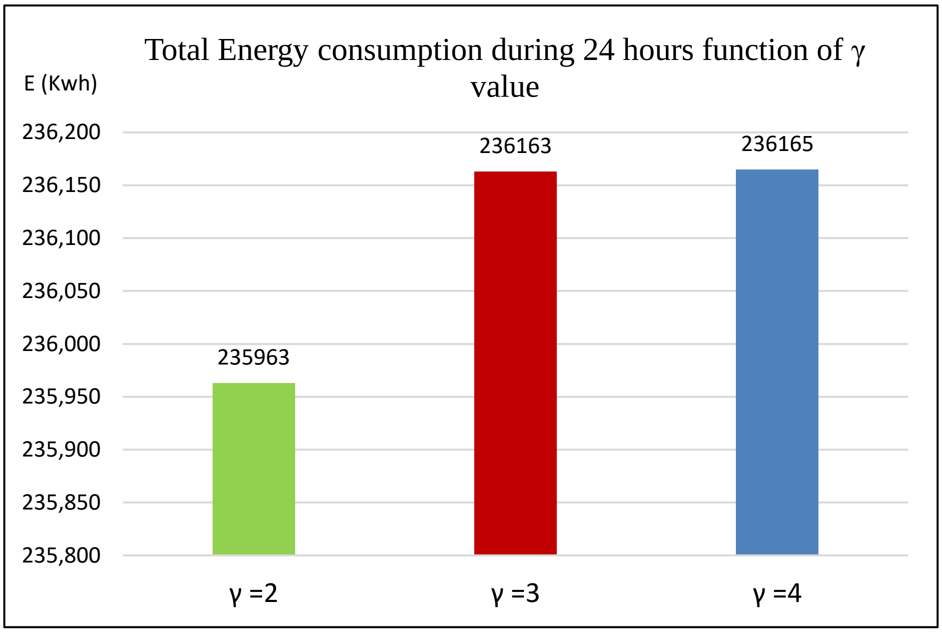


Figure 30. Total energy cunsumed during 24 hrs for different sequencing types

5.6.5 Design review towards energy efficiency

The chillers' efficiency is maximized when chillers are operated at full load. The analysis of the partial load ratio (PRL) of chillers during one running month (744 hourly periods) shows that chillers are fully loaded on average at only 61% of the operating time (Figure 31). In the remaining 39%, the chillers are operated at partial load. Hence, the unit energy consumption is higher during these periods that during the full load, degrading the global system coefficient of performance (COP). In order to explore this issue, the initial design requirement $R2.1$ (that stipulates that all selected chillers shall be of identical capacity) is reviewed for modification. Instead, the new design requirement allows the diversity of chillers capacity (maximum 2 capacities are selected).

The new optimal design is composed of 3 chillers of capacity Q_3(4750 TR) and one chiller of capacity Q_1(4000 TR) instead of 4 identical chillers of capacity Q_3 in the case of initial design (design 1). Moreover, the capacity of the storage tank is changed to D_2

(4000 TR) contrary to D_1(2000 TR) in the initial design. In the case of the new design, the total cooling capacity is decreased by 750 TR in contrast to the storage capacity, which is increased by 2000 TR. The final new design integrates a redundant chiller of capacity Q_3(to satisfy the requirement $R3.1$.

Figure (32) visualizes the partial load ratio of the newly designed chillers (design 2). Chillers 1, 2, and 3 are of capacity 4750 TR each and chiller 4 is of capacity 4000 TR. It demonstrates that the chillers' partial loading is decreased in favor of the full loading. The average of full loading becomes 87%, with only 13% partial loading. Therefore, a real improvement of the chillers' performance. Figure (33-a) shows the evolution of the COP for the two design alternatives during one running month. We observe that for most of the periods, design 2 COP is better than design 1. The global COP (33-b) demonstrates that design 2 is more efficient in energy consumption.

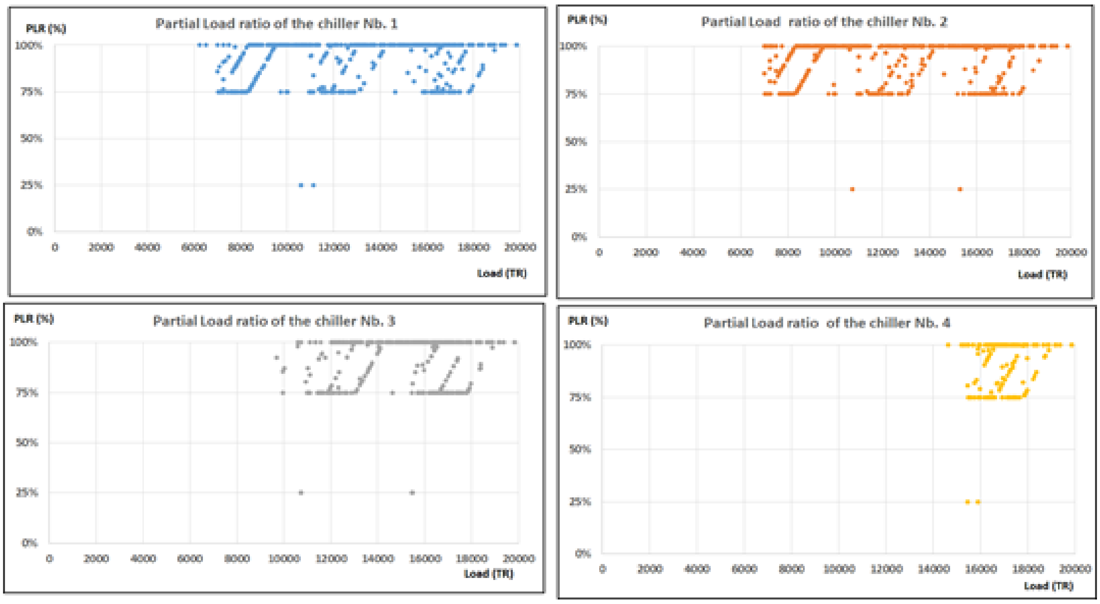


Figure 31. Partial load ratio (PRL) of the initially designed chillers

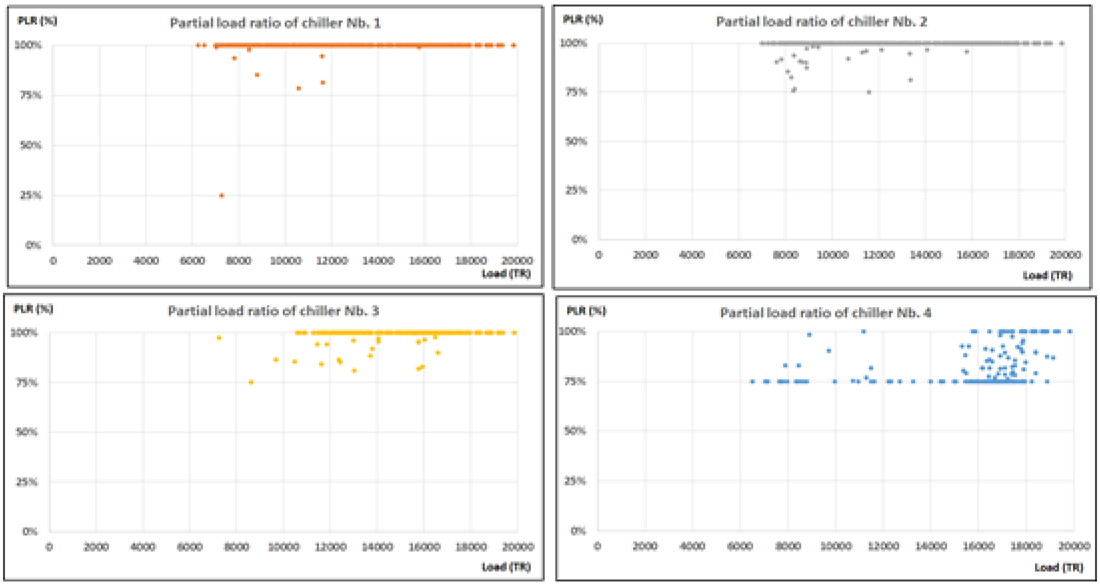
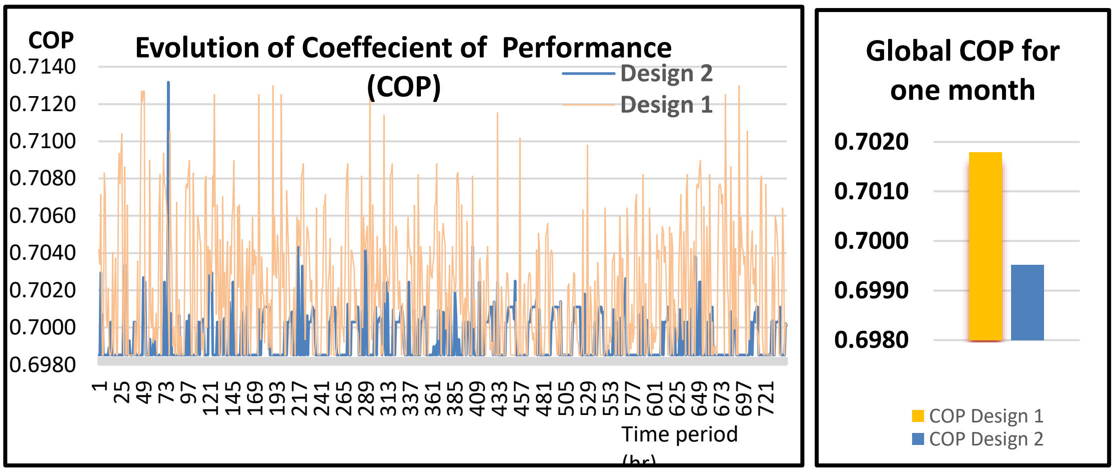


Figure 32.: Partial load ratio (PRL) of the newly designed chillers



(a) (b)

Figure 33.(a) Variation of the coefficient of performance for the initial and new design during one month - (b) the global COP for the two design alternative

The design requirement and the preselected chillers' range influence the energy consumption of the district cooling system and its energy performance. The model capability and the analysis should support the design review towards energy efficiency.

5.7 Summary

This chapter summarizes the demand requirement as a prerequisite for the development and testing of the proposed mixed integer linear programming model for the district cooling system. The model optimizes the total DCS total cost, considers energy efficiency of chillers, and provides DCS sizing, number of chillers, storage tank, and related capacity. The solution to the model shows that optimal operation can be realized by obtaining the optimal chilled produced and stored at each period time of the scheduled horizon. The optimal control is obtained by considering chiller short-cycling and the unloading conditions. The concept of the target sequence and mapping function used in the proposed model supports the formulation of predefined chiller sequencing (short cycling). Hence, the used approach allows tracing the link between the requirements and the system performance.

The results also show that the variation of the requirements, more specifically, the time threshold between two startups of the chiller (which represents technology specification) impacts the system behavior and performance regarding the chilled water produced, stored, and energy consumption. This requirement is implemented at the system control level. For the base case ($\gamma = 2$), the chilled water production is anticipated by two-time periods. A more significant amount of chilled water is stored from time-period four to seven in comparison with ($\gamma = 3$). The chilled water storage is anticipated by one time-period (at $t=10$) with consequent quantity (1662 TR) compared to ($\gamma = 4$). Hence, the system is more reactive, efficiently interacting with the cooling demand change by decreasing the energy consumption (200 KWh daily).

The analysis presented show that for a cost-effective and energy-efficient DCS design, it is necessary to understand the structure of DCS and the expected demand and the utilization of chillers, fluctuations in chiller capacities. In addition, it is also necessary to develop a control mechanism to sequence chiller operations in different periods. The analysis shows a significant relation between chilled water storage and energy consumption and the implications of operating different capacity chillers. Therefore, the designers and the system operators should develop a chiller sequencing mechanism to address fluctuating cooling demand. This might require considering alternative chiller designs. The current research is focused mainly on energy efficiency and system analysis based on a case example of district cooling.

The model was compared with other published models using simulation. Similar results were concluded by Chen et al. [90], “The results indicate that it is essential to control the chiller plant hourly” (sequencing). “It is not good to select the chillers with all the same capacity”. “The design of the chiller combination is essential in the design stage”

Chapter 6: Integration of Solar Cooling Technologies

In this chapter multiple configurations of solar technologies as shown in Table 7 for cooling are considered.. The research in this chapter aims to:

- Develop a generalized model to optimize the design and operation of each configuration
- Develop and implement the performance indicators of the system based on the numerical results of the proposed model.
- Compare the configurations performances (economic, renewable energy use, and environmental) by considering the local context (energy price and available installation area).

Table 7. Solar-cooling configurations

Configuration	Integration
Configuration 1	Integrated Photovoltaic Thermal (PVT) solar collector- district cooling system
Configuration 2	Integrated Photovoltaic (PV) solar collector – district cooling system
Configuration 3	Integrated Thermal (T) solar collector – district cooling system
Base configuration	Conventional district cooling system powered with grid electricity

This chapter is composed of 4 sections. The problem description and formulation are introduced, respectively, in Sections 1 and 2. The numerical results are presented in Section 3. The summary is provided in Section 4.

6.1 Problem description

Figure (34) shows the proposed integrated system diagram. It is composed of (i) solar collector representing a given technology (photovoltaic, thermal, and hybrid), (ii) vapor compression chiller, (iii) absorption chiller, (iv) chilled water storage tank, (v) hot water storage tank, and (vi) an auxiliary boiler. The system is connected to the electricity grid. It is worth noting that the inclusion of hot water and chilled water thermal energy storage and the auxiliary boiler is not mandatory in the system. However, their inclusion contributes to lowering the total system cost.

Figure (34) also shows the energy flow, hot water, chilled water, gas, and electricity between the different system components. Based on the used collector technology (photovoltaic, thermal, hybrid), the collected solar irradiance is transformed into electricity, hot water, or both. The generated electricity drives the vapor compression chiller. In the case of extra-generation during the peak sunlight, the surplus electricity is sold back to the grid. If the generated electricity by the solar collector is insufficient, the grid feeds the system with the needed electricity. The hot water generated feeds the absorption chiller. The surplus heat generated during the peak irradiance will be stored in a hot water storage tank to be used by the absorption chiller during limited irradiance periods; for example, when the generated hot water by the solar collector plus the inventory level of the hot water storage tank is insufficient to run the absorption chiller, or when the hot water temperature is under the operating temperature of the absorption chiller (80°C). In these cases, the auxiliary boiler is activated. The chilled water produced by the vapor-compression and absorption chillers feeds the building to satisfy the cooling demand. Extra chilled water is produced and stored in the chilled water storage tank during peak irradiance.

The integration of these components forms an interconnected system with intertwined behaviors. The proposed model captures all these interdependencies and provides an optimal solution based on an approximated annual hourly cooling demand and solar irradiance (8760 hours).

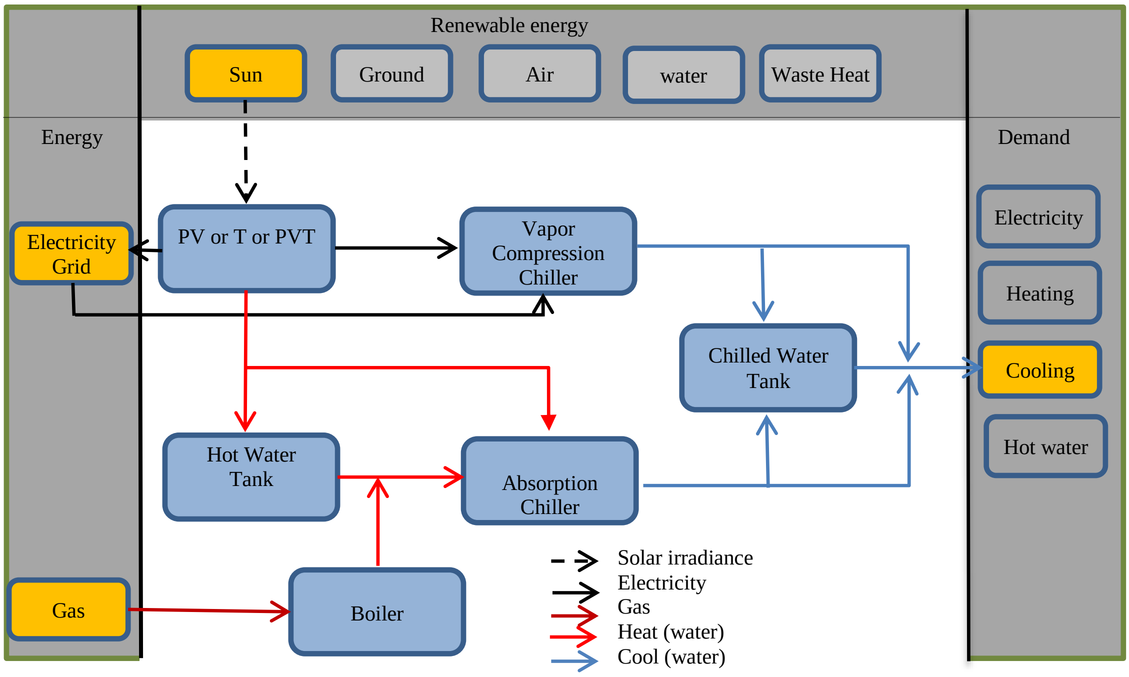


Figure 34.: Integrated solar collector and mix-technologies DCS diagram

6.2 Problem formulation

The proposed model assumes that the cooling load is deterministic, the solar collector efficiency is constant, the system operates in a steady-state, and the cool-losses are negligible. The efficiencies of the auxiliary boiler, vapor compression, and absorption chiller are assumed as constant. It is worth noting that chiller performance depends on the parameters such as the partial load ratio and the weather conditions. Integrating these aspects in the model requires additional decision variables and constraints. Such an addition increases problem complexity in terms of total numbers of binary variables, non-integers variables, and constraints, making it unlikely that the real life-size problem of the solar energy-DCS integrated system could be optimally solved. Therefore, the developed model is based on a trade-off between the model breadth (number of components, operational decisions, and time horizon length) and model depth (degree of fidelity of component model in terms of efficiency) that aims at providing a solution in a reasonable computational time. Hence, it can support decision-makers to ensure the feasibility of such an integrated system and select the appropriate configuration in the context of energy prices and available installation areas for the solar collector. The detailed proposed model nomenclature is given in Table (8).

Table 8. Nomenclature

Indices and set	
$\boldsymbol{t}$	Time period (hour)
$\boldsymbol{i}$	Type of vapor compression chiller
$\boldsymbol{j}$	Type of absorption chiller
$\boldsymbol{k}$	Type of hot water tank
$\boldsymbol{m}$	Type of chilled water tank
$\boldsymbol{n}$	Type of auxiliary boiler
Parameters	
$\boldsymbol{d}$	Cooling load demand (KW)
$\boldsymbol{S}$	Solar radiation (KW/m2)
A	Maximum solar collector area (m^2)
r	Interest rate (%)
n	Economic life (year)
$\boldsymbol{Q}$	Maximum Capacity (KW)
$\boldsymbol{EER}$	Energy Efficiency Ratio (%)
$\boldsymbol{Fc}$	Fixed investment cost per installed unit ($)
$\boldsymbol{Fm}$	Fixed maintenance cost per installed unit ($)
$\boldsymbol{P}$	Price of energy career ($/KW)
$\boldsymbol{\eta}$	Efficiency
α	Feed in tariff coefficient
Decisions variables	
$\boldsymbol{y}_i$	Binary variable for vapor compression chiller

Decisions variables	
$\boldsymbol{z}_j$	Binary variable for absorption chiller
$\boldsymbol{u}_k$	Binary variable for hot water tank
$\boldsymbol{v}_m$	Binary variable for chilled water
$\boldsymbol{w}_n$	Binary variable for auxiliary boiler
$\boldsymbol{x}$	Variable for solar collector installed area (m^2)
$\boldsymbol{E}_t$	Variable for electricity flow (KW)
$\boldsymbol{G}_t$	Variable for gas flow (KW)
$\boldsymbol{H}_t$	Variable for heat flow (KW)
$\boldsymbol{HI}_t$	Variable for heat inventory (KW)
$\boldsymbol{C_t}$	Variable for cool flow (KW)
$\boldsymbol{CI_t}$	Variable for cool inventory (KW)

Figure (35) shows the organization of the proposed model. The model is fed with solar irradiance, cooling demand, energy tariff, and component attributes (capacity, cost, efficiency). The core of the optimization process is composed of the structure and the behavior. The structure refers to the design, including the definition block (components) and internal block reflecting the interconnection between the components (Figure 34). The behavior (operation) refers to the system activities related to energy (*E, G, H, C*) production, consumption, and storage (*CI, HI*). The model's output is the optimal design and operation that minimizes the objective function, which represents the configuration's economic performance. The renewable energy use and environmental performance are obtained after the post-treatment of the numerical value of the optimal solution for each configuration.

The optimal design seeks to find the required components and their interactions. Each component is presented by a design variable (binary or non-integer). For example, if the vapor compression chiller (i) is selected, the related design variable (y_i) takes the value one and zero otherwise, which is similar for the absorption chiller (z_j), hot water tank (u_k), chiller water tank (v_m), and the auxiliary boiler (w_n). However, the design variable (x) represents the area to be installed for solar collector technology. If the variable (x > 0), the considered configuration (1 or 2 or 3) is economically competitive than the base configuration (grid-DCS). Otherwise, when (x=0), the base configuration is optimal.

The optimal operation seeks to find the quantity of chilled water (*C*), hot water (*H*), and electricity (*E*) to be produced, consumed, and stored (*CI*, *HI*) for each period to satisfy the cooling demand. It is worth noting that every component has attributes (constant parameters in the proposed model) such as capacity, efficiency, and costs (acquisition and maintenance). Some of these parameters are used in the model constraints to define the feasible region. Others (cost parameters) are used in the objective function to evaluate the solution's fitness.

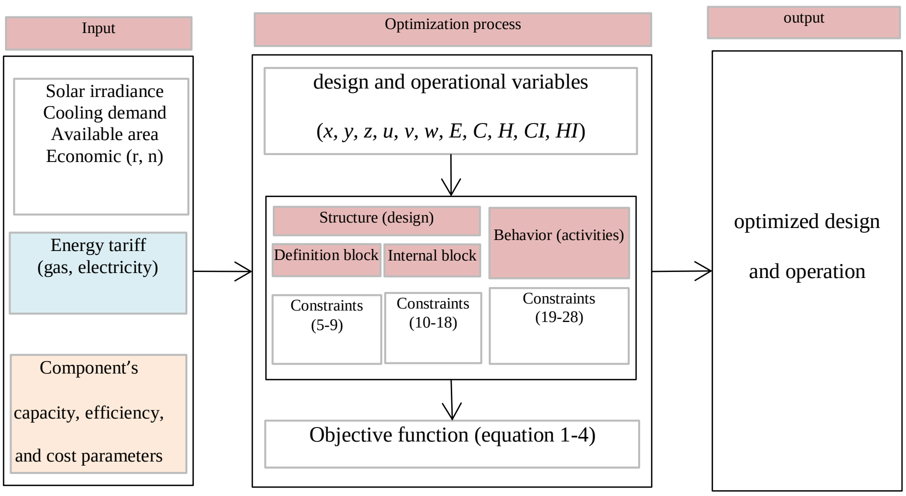


Figure 35. Framework of the developed model

The objective function (Eq. 24) minimizes the total annualized cost and includes three terms:

the first term is for the capital cost for all implemented equipment; the second term is the operating cost of the running equipment (boiler and vapor compression chiller) that is required energy from outside the system, and the third term is for the maintenance cost.

Minimize $C_{total} = C_{inv} + C_{opr} + C_{ma}$ (24)

The investment cost (Eq. 25) includes all installed equipment (solar collector, vapor compression chiller, absorption chiller, hot water storage tank, chilled water storage tank, and auxiliary boiler). The annualized investment cost is obtained by summing the product of each selected equipment's fixed cost (Fc) by its amount to be installed and the capital recovery factor (CRF = $\frac{r(1+r)^n}{(1+r)^n-1}$). The area to be installed for the solar collector (thermal, photovoltaic, or hybrid) is represented by the variable (x). For the remaining, each piece of equipment is represented by its design binary variable (y , z , u, v, w). Each technology is represented by a set of elements and identified by its index in the summation (Eq. 25). For example, index (i) represents various vapor compression chillers candidates, and each one is characterized by its attributes such as capacity, acquisition and maintenance costs, and efficiency. Table (11) contains the number of elements in each set. For the vapor compression chiller, five different types are considered.

$$c_{inv} = (CRF)(Fc^{Col}x + \sum_i Fc_i^{Vc}\, y_i + \sum_j Fc_j^{Ab} z_j + \sum_k Fc_k^{Hwt}\, u_k + \sum_m Fc_m^{Cwt} v_m + \sum_n Fc_n^{Bo} w_n) \quad (25)$$

The operating cost (Eq. 26) represents the yearly (8760 hours) sum of the running cost for all implemented equipment in the district cooling and requiring energy from outside the system, which are the boiler and the vapor compression chiller [46]. The first term in equation (26) is the cost for running the auxiliary boiler. It is equal to the product of the gas price (P^{Gas}) and the amount of gas consumed by the boiler (G^{Bo}). The second term in Eq. 26 represents the cost related to the net electricity of the system. The net electrify cost is equal to the product of the electricity cost (P^{Elec}) and the difference between the amount of electricity purchased ($E^{Grid\rightarrow Vc}$) and sold to the grid ($E^{Col\rightarrow Grid}$). If the purchase and selling costs are different, the feed-in tariff coefficient (α) is used as a correction factor. If the solar panel electricity yield is more than the need of the electric chiller, the extra generated electricity is sold to the grid and will be counted as an income. Consequently, the overall system cost will be decreased. Contrary, if the solar collector generated electricity is insufficient, the system will purchase electricity from the grid, and the overall system cost increases.

$$C_{opr} = \sum_t P^{Gas} G_t^{Bo} + \sum_t P^{Elec} (E_t^{Grid\rightarrow Vc} - \alpha . E_t^{Col\rightarrow Grid}) \quad (26)$$

The annual maintenance cost (Eq. 27) equals the sum of the annual cost of maintaining all the system components. The maintenance cost of each element is equal to the product of its maintenance cost (Fm) and the installed amount. The installed amount for the vapor compression, absorption chiller, hot and chilled water tanks, and the auxiliary boiler is equal to its design binary variable (y, z, u, v, w). For the solar panel installed area is equal to the variable (x).

$$c_{ma} = Fm^{Col} x + \sum_i Fm_i^{Vc} y_i + \sum_j Fm_j^{Ab} z_j + \sum_k Fm_k^{Hwt} u_k + \sum_m Fm_m^{Cwt} v_m + \sum_n Fm_n^{Bo} w_n \quad (27)$$

The constraints for the model are classified into three blocks. The definition block describes the system in terms of structure (components). The internal block describes the system layout or components interconnection and translates the energy balance. The activities block describes the system's elements behavior in terms of consumed, generated, and stored energy.

6.2.1 Definition Block

Constraints (28-32) define the system structure in terms of components. Six components are integrated into the proposed system: solar collector, vapor compression chiller, absorption chiller, hot water storage tank, chilled water storage tank, and auxiliary boiler.

$$x \leq A \tag{28}$$

Constraint (28) ensures that the total installed area of the solar collector does not exceed the available area (A). The available area for installing solar collectors depends on the building type. In the urban region, government institutions like universities and hospitals cover a great area and generally have more available space than commercial and residential buildings.

$$\sum_i y_i + \sum_j z_j \geq 1 \tag{29}$$

Constraint (29) ensures that two technologies of the chilling process (vapor compression and absorption) are a candidate to produce the chilled water to satisfy the cooling demand, and at least one technology should be selected. Therefore, the system structure may contain an absorption chiller, electric chiller, or both.

$$\sum_k u_k \leq 1 \tag{30}$$

$$\sum_m v_m \leq 1 \tag{31}$$

$$\sum_n w_n \leq 1 \tag{32}$$

Constraints (30,31,32) ensure that selecting the hot water storage tank, chilled water storage tank, and the auxiliary boiler is optional. Their selection contributes to decreasing the total cost.

6.2.2 Internal block

The constraints (33-41) describe the interconnection between the system components (the system layout). Hence, they describe the energy balance (arrow in Figure 1).

$$H_t^{Col} = H_t^{Col\to Hwt} + H_t^{Col\to Ab} \tag{33}$$

$$E_t^{Col} = E_t^{Col\to Grid} + E_t^{Col\to Vc} \tag{34}$$

Constraint (33) imposes the solar collector (Col) thermal energy balance (*H*). It shows that the hot water produced (*H*) by the solar collector (*col*) is delivered to the hot water storage tank ($Col \to Hwt$) and the absorption chiller ($Col \to Ab$). Constraint (34) imposes the electric energy balance (E) for the solar collector (Col), ensuring that the produced electricity (E)equals the amount delivered to the grid ($Col \to Grid$) and vapor compression chiller ($Col \to Vc$).

$$H_t^{Col\to Hwt} + HI_{(t-1)}^{Hwt} = H_t^{Hwt\to Ab} + HI_{(t)}^{Hwt} \tag{35}$$

Constraint (35) imposes the energy balance for the hot water storage tank (Hwt). It imposes that the sum of hot water received from the solar collector ($Col \to Hwt$) and the inventory level (HI) at the period (*t-1*) equals the sum delivered to the absorption chiller ($Hwt \to Ab$) and the inventory level (HI) at the period *t*.

$$C_t^{Vc\to Cwt} + C_t^{Ab\to Cwt} + CI_{(t-1)}^{Cwt} = C_t^{Cwt\to Bld} + CI_t^{Cwt} \tag{36}$$

Like constraint (35), constraint (36) imposes the energy balance for the chilled water storage tank (Cwt). It imposes that the sum of chilled water (C) received from the absorption ($Ab \to Cwt$) and vapor compression chillers ($Vc \to Cwt$) plus the inventory level (CI) at the period (t-1) equals the amount delivered to the building ($Cwt \to Bld$) plus the inventory level (CI) at the period *t*.

$$H_t^{Ab} = H_t^{Col\to Ab} + H_t^{Hwt\to Ab} + H_t^{Bo\to Ab} \tag{37}$$

$$C_t^{Ab} = C_t^{Ab\to Bld} + C_t^{Ab\to Cwt} \tag{38}$$

Constraints (37,38) represent the absorption chiller's (Ab) hot water (H) and chilled water (C) balances. The left-hand side of constraint (37) reflects the needed hot water to operate the absorption chiller as the sum of hot water provided by the solar collector ($Col \rightarrow Ab$), the hot water storage tank ($Hwt \rightarrow Ab$), and the auxiliary boiler ($Bo \rightarrow Ab$). However, constraint (38) defines that the produced chilled water by the absorption chiller equals the quantity delivered to the building ($b \rightarrow Bld$) and the chilled water storage tank ($Ab \rightarrow Cwt$).

$$E_t^{Vc} = E_t^{Col \rightarrow Vc} + E_t^{Grid \rightarrow Vc} \quad (39)$$

$$C_t^{Vc} = C_t^{Vc \rightarrow Bld} + C_t^{Vc \rightarrow Cwt} \quad (40)$$

Constraints (39,40) impose the vapor compression chiller's (Vc) electricity (E) and chilled water (C) balances. The left-hand side of constraint (39) reflects the needed electricity to operate the vapor compression chiller, and the right-hand side represents the electricity delivered from the solar collector ($Col \rightarrow Vc$) and the grid ($Grid \rightarrow Vc$). Constraint (40) represents the balance of chilled water (C); the chilled water produced equals the amount delivered to the building ($Vc \rightarrow Bld$) and the chilled water storage tank ($Vc \rightarrow Cwt$).

$$C_t^{Vc \rightarrow Bld} + C_t^{Ab \rightarrow Bld} + C_t^{Cwt \rightarrow Bld} = d_t \quad (41)$$

Constraint (41) imposes the thermal energy balance (C) for the building cooling demand satisfaction (d). It enforces that the cooling demand is assumed by the amount of chilled water delivered from the vapor compression chiller ($Vc \rightarrow Bld$), the absorption chiller ($Ab \rightarrow Bld$), and the chilled water storage tank ($Cwt \rightarrow Bld$).

6.2.3 Activities block

The constraints (42-51) describe the behavior of each system-components in terms of activities, which are energy generation (electricity (E), cooling (C), heat (H)), consumption (electricity and heat), and storage (chilled (CI) and hot water (HI)).

$$E_t^{Col} \leq S_t \, x \, \eta_{elec}^{Col} \quad (42)$$

$$H_t^{Col} \leq S_t \, x \, \eta_{ther}^{Col} \quad (43)$$

Constraints (42, 43) ensure that the amount of electricity (E) and the amount of hot water (H) produced by the solar collector (*Col*) do not exceed the capacity of the installed area (x). The solar irradiance, electric and thermal efficiency of the solar collector are respectively S, η_{elec} , and η_{ther}.

$$HI_t^{Hwt} \leq \sum_k Q_k^{Hwt} u_k \quad (44)$$

$$CI_t^{Cwt} \leq \sum_m Q_m^{Cwt} v_m \quad (45)$$

Constraints (44-45) ensure that the inventory level of hot water (HI) and chilled water (CI) does not exceed respectively, the installed capacity (Q) of the hot water tank (*Hwt*) and chilled water tank (*Cwt*).

$$H_t^{Bo \rightarrow Ab} \leq \sum_n Q_n^{Bo} w_n \quad (46)$$

$$H_t^{Bo \rightarrow Ab} = \sum_n w_n \, G_{(n,t)}^{Bo} \, \eta_n^{Bo} \quad (47)$$

Constraint (46) ensures that heat production (H) of the auxiliary boiler (*Bo*) does not exceed its installed capacity (Q). Constraint (47) ensures that the relationship between the heat generated (H) and the required amount of gas (G) in the boiler can be expressed as a linear expression using the efficiency (η^{Bo}). The efficiency is considered constant during heat production.

$$C_t^{Ab} \leq \sum_j Q_j^{Ab} z_j \quad (48)$$

$$C_t^{Ab} = \sum_j z_j H_{(j,t)}^{Ab} \, EER_j^{Ab} \quad (49)$$

Constraint (48) ensures that the amount of chilled water (C) produced by the installed absorption chiller (*Ab*) does not exceed the chiller capacity (Q). Constraint (49) expresses the linear relationship between the cooling energy and the required heat in the absorption chiller by using the energy efficiency ratio (*EER*) which is considered as a constant.

$$C_t^{Vc} \leq \sum_j Q_i^{Vc} y_i \quad (50)$$

$$C_t^{Vc} = \sum_i y_i E_{(i,t)}^{Vc} EER_i^{Vc} \quad (51)$$

Similar to constraints (48, 49), constraint (50) ensures that the amount of chilled water (C) produced by the installed vapor compression chiller (Vc) does not exceed the chiller capacity (Q). The energy efficiency ratio (EER) of the vapor compression chiller defines the linear relationship between the cooling energy (C) produced and the required electricity (constraint 51).

6.2.4 Linearization:

The right-hand side of constraints 47, 49, and 51 contain a product of binary and non-integers variables $w_n G_{(n,t)}^{Bo}$, $z_j\ H_{(j,t)}^{Ab}$, and $y_i\ E_{(i,t)}^{Vc}$, can be linearized by performing a introducing a new variable and using the BigM method [96].

- Linearization of the product $w_n G_{(n,t)}^{Bo}$:

BigM is the upper pound of the continuous variable $G_{(n,t)}^{Bo}$ and $\omega_{(n,t)} = w_n G_{(n,t)}^{Bo}$

$$\omega_{(n,t)} \leq w_n BigM \quad (52)$$

$$\omega_{(n,t)} \leq G_{(n,t)}^{Bo} \quad (53)$$

$$G_{(n,t)}^{Bo} - (1 - w_n) BigM \leq \omega_{(n,t)} \quad (54)$$

$$0 \leq \omega_{(n,t)} \quad (55)$$

- Linearization of the product $z_j\ H_{(j,t)}^{Ab}$:

BigM is the upper pound of the continuous variable $H_{(j,t)}^{Ab}$ and $\psi_{(j,t)} = z_j\ H_{(j,t)}^{Ab}$

$$\psi_{(j,t)} \leq z_j\ H_{(j,t)}^{Ab} \quad (56)$$

$$\psi_{(j,t)} \leq H_{(j,t)}^{Ab} \quad (57)$$

$$H_{(j,t)}^{Ab} - (1 - z_j) BigM \leq \psi_{(j,t)} \quad (58)$$

$$0 \leq \psi_{(j,t)} \tag{59}$$

- Linearization of the product $y_i\ E^{Vc}_{(i,t)}$:
- BigM is the upper pound of the continuous variable $E^{Vc}_{(i,t)}$ and $\chi_{(i,t)} = y_i\ E^{Vc}_{(i,t)}$

$$\chi_{(i,t)} \leq y_i BigM \tag{60}$$

$$\chi_{(i,t)} \leq E^{Vc}_{(i,t)} \tag{61}$$

$$E^{Vc}_{(i,t)} - (1 - y_i) BigM \leq \chi_{(i,t)} \tag{62}$$

$$0 \leq \chi_{(i,t)} \tag{63}$$

6.2.5 Assessment indicators

The performance indicators for integrated solar systems and their definition are introduced in SHC Task60\Report D1. They are classified into three sub-categories: economic, energy, and environmental. These indicators allow the assessment of the system over a certain period. The numerical results obtained from the proposed model allow the calculation of these indicators and the assessment of configurations over one running year (8760 hours).

6.2.5.1 Economic indicators

The model objective function represents the economic indicator and includes the annualized capital, operational, and maintenance costs.

6.2.5.2 Energy indicators

The energy indicators assess the system based on renewable energy use and saving.

- The solar electrical fraction is expressed as the ratio of the yield of electricity and electric chiller consumption :

$$f_{PVT,elec} = \frac{\sum_t E^{Col}_t}{\sum_t E^{Vc}_t} \tag{64}$$

- The solar thermal fraction is expressed as the yield heat and the absorption chiller consumption:

$$f_{PVT,ther} = \frac{\sum_t H_t^{Col}}{\sum_t H_t^{Ab}} \quad (65)$$

- The renewable energy fraction is expressed as the ratio of the sum of the heat and electricity yield and the sum of absorption and electric chillers consumption:

$$f_{ren} = \frac{\sum_t (E_t^{Col} + H_t^{Col})}{\sum_t (E_t^{Vc} + H_t^{Ab})} \quad (66)$$

- The system's final energy saving for gas is expressed as the ratio of the heat yield and the efficiency of the selected boiler. If the optimal system design does not include boiler, an efficiency reference of 0.85 is considered :

$$FE_{sav,gas}^{sys} = \sum_t \frac{H_t^{Col}}{\eta^{Bo}} \quad (67)$$

- The system's final energy-saving for electricity equals the electricity yield:

$$FE_{sav,elec}^{sys} = \sum_t E_t^{Col} \quad (68)$$

6.2.5.3 Environment indicators

The environmental indicators assess the system based on the non-renewable use and its impact on global warming.

- The non-renewable primary energy consumption (KWh oil-equivalents) is expressed as the sum of the primary energy of the gas and net electricity consumption. The primary energy consumption for gas is equal to the product of the quantity consumed and its cumulated energy demand (CED = 1.06). The primary energy consumption for electricity is equal to the product of the net quantity consumed and the cumulated energy demand for electricity (CED=2.89)

$$PE^{sys} = \sum_t CED^{Gas}\, G_t^{Bo} + \sum_t CED^{Elec}(E_t^{Grid\rightarrow Vc} - E_t^{Col\rightarrow Grid}) \quad (69)$$

- The global warming potential (Kg CO_2-equivalents) is expressed as the sum of the global warming potential for each nonrenewable energy consumed. Similar to the calculation of the PE^{sys} in the GWP^{sys}, the CED is replaced by the GWP factor for each type of non-renewable energy. ($GWP^{Gas} = 0.228$ and $GWP^{Elec} = 0.524$)

$$GWP^{sys} = \sum_t GWP^{Gas} G_t^{Bo} + \sum_t GWP^{Elec} (E_t^{Grid \to Vc} - E_t^{Col \to Grid}) \quad (70)$$

6.3 Numerical results

The proposed MILP model is coded and implemented using AIMMS 4.82.6.10 software, solved with CPLEX 20.1 branch and bound algorithm on Intel(R) Core(TM) i7-1165G7 CPU@2.80 GHz with 48 GB RAM. The MILP model is generalized to represent four system configurations: each configuration represents an integrated energy source for DCS. The model parameters setting of the solar collector efficiency η_{ther} and η_{elec} allow the selection of the desired system. Therefore, the proposed model imitates the integration of all solar technology with a district cooling system in addition to the grid-powered DCS without the need for multi-models. Table (9) illustrates the setting parameters for each configuration. For example, to optimize configuration (2), which represents a photovoltaic integrated district cooling system, the thermal efficiency parameter of the model should be set to zero. Similarly, to optimize the base configuration (Grid-DCS), the thermal and electric efficiency should be set to zero.

Table 9. Model's features

	Parameter		
System	$\boldsymbol{\eta^{THER}}$	$\boldsymbol{\eta^{ELEC}}$	**Integration**
Configuration 1	$\eta_{ther} \succ 0$	$\eta_{elec} \succ 0$	Integrated Photovoltaic Thermal (PVT) - DCS
Configuration 2	$\eta_{ther} = 0$	$\eta_{elec} \succ 0$	Integrated Photovoltaic (PV) – DCS
Configuration 3	$\eta_{ther} \succ 0$	$\eta_{elec} = 0$	Integrated Thermal (T) – DCS
Base configuration	($\eta_{ther} = 0$ and $\eta_{elec} = 0$) or A =0		Conventional district cooling system Grid-DCS

The optimal selection of the cooling technology is performed (i) via the presence of constraint (28), where both technologies (absorption and electric chillers) are a candidate for the system design without forcing a specific one, (ii) the objective function, which includes the investment, maintenance, and operation costs. This latter considers the energy costs (electricity and gas) for running the system. It is worth noting that the integrated system is connected to the grid, and both cooling technologies are the candidates. Therefore, the optimal solution of configurations 1, 2, and 3 may lead to configuration 4, which refers to us as the base system (Grid-DCS), which means that the integration of the solar technology is not competitive compared to the Grid-DCS

Figure (36) summarizes the structure of the used data in the model. The solar collector cost and efficiency are collected from IEA. SHC TASK 60 report and solar collector providers. The remaining system components (absorption chiller, vapor compression chiller, hot water, chiller water TES, and auxiliary boiler) data such as capacity, fixed cost, coefficient of performance, and the cooling load estimation are taken from the data paper [48]. The electricity cost is collected from the energy provider KAHRAMAA [49]. The electricity tariff in Qatar is subsidized, and there is a plan to remove these subsidies by employing the time of use or dynamic pricing schemes [7]. Currently, the electricity price (P^{Elec}) depends on the customer category (productive farms, residential, industrial, hotel, commercial, and government). The average tariff is \$0.055/kWh, and the feed-in-tariff coefficient (α) is set to one. The gas cost fluctuates over time; therefore, an average tariff of \$0.017 KWh is considered [90]. The life span (n) considered of the study system is 25 years, and the interest rate (r) is 6%. The maximum allowed area (A) for the solar collector installation is set to 6,000 m^2. The solar irradiance represents the typical meteorological year 2016 (TMY) of

Doha/Qatar. The peak cooling load considered is 10,000 KW. The objective function is obtained by running the system for one year, equivalent to an 8760 hourly period. Table (10) details the solar collector used parameters values. Table (11) represents the number of elements for each set.

In research, hybrid solar technology (PVT) is less investigated in district cooling applications than the others. Therefore, configuration (1) detailed optimal solution is presented for illustration in the following section.

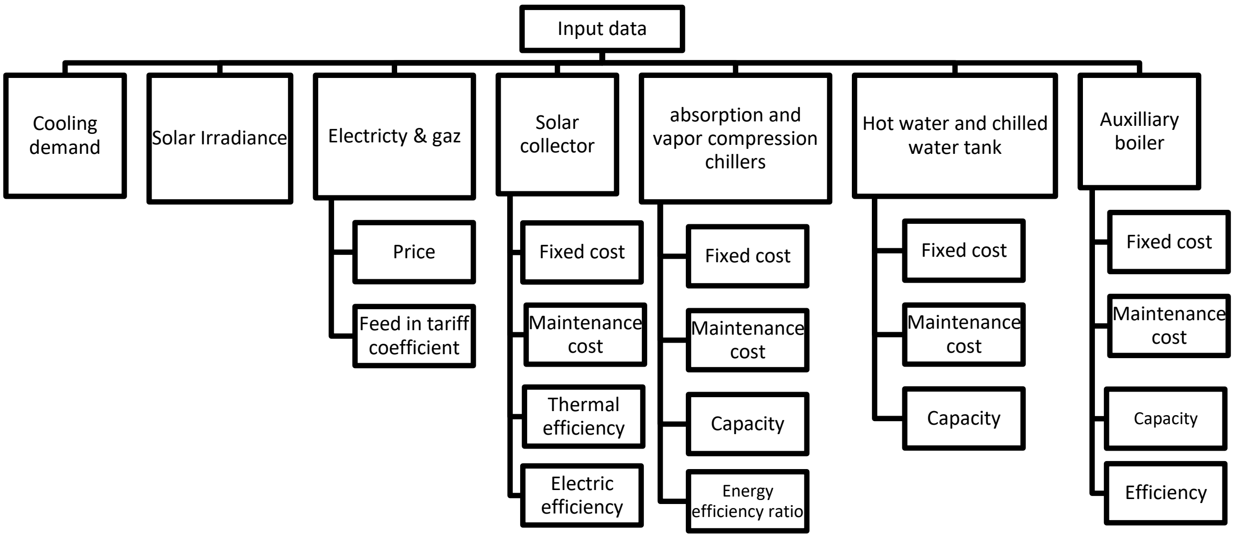


Figure 36. Strcture of used data

Table 10. Solar collectors' parameters

Configuration	Solar collector		
	η_{ther}	η_{elec}	Fc^{Col}
Configuration 1 (PVT – DCS)	0.70	0.18	300$/m^2
Configuration 2 (PV – DCS)	0.00	0.20	100$/m^2
Configuration 3 (T-DCS)	0.75	0.00	250$/m^2
Base configuration (Grid – DCS)	0	0	-

Table 11. Set size

I	J	K	M	N	I
5	6	7	7	4	5

6.3.1 Integration of hybrid solar collector and DCS

Figure (37) shows the cooling load and the solar irradiance patterns for a typical summer day. The cooling demand is over the whole day with an important load from 11 AM to 10 PM. The solar irradiance is present from 6 AM to 6 PM, with a peak at 1 PM. The storage becomes essential to profit from extra energy (hot water and electricity) during the peak irradiance. The connection to the grid allows for selling the surplus generated electricity and purchasing when needed.

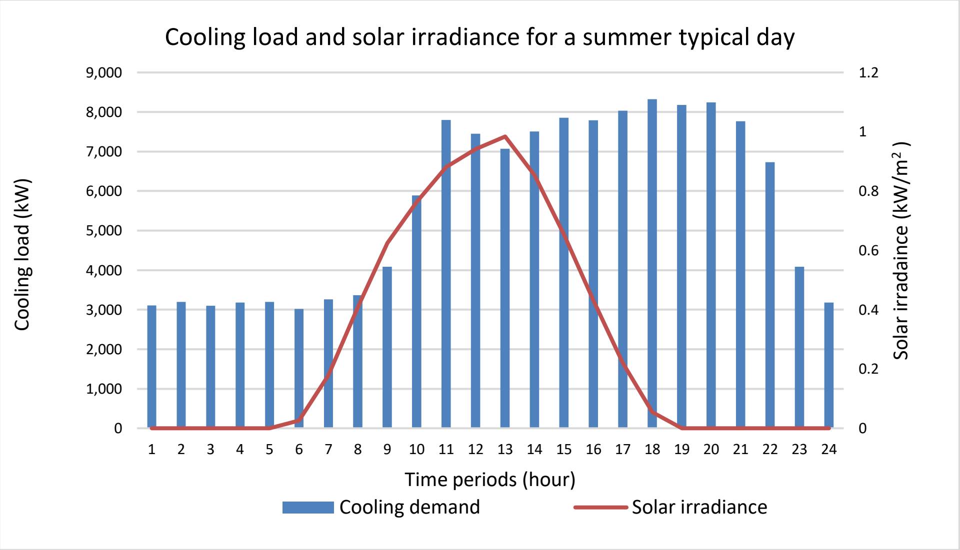


Figure 37. Cooling load and solar for a typical summer day

The optimal design of the integrated system is analyzed in terms of design, cost, electricity flow, heat flow, and cooling flow. The detailed energy and environmental characteristics of the system are calculated based on the numerical results of the model. The implementation of these indicators allowed us to further compare the different configurations from an energy and environmental perspective.

Table (12) shows the optimal design for configuration (1). The optimal installed area is equal to the maximum allowed (6,000 m²). Both cooling technologies (vapor compression and absorption) are selected, with capacities of 5,300 and 1,454 KW. Two storage tanks for hot and chilled water are selected with the same capacity of 63,000 KW. However, the auxiliary boiler is not selected in the optimal design. The investment and maintenance cost of configuration (1) is higher by 416% compared to the base configuration. However, the total cost is lower by 5.25%. This is due to the low operation cost (129,363$) in comparison with the base configuration (321,286$), which is equivalent to decreasing the energy bill by more than 59%

Table 12. Optimal design characteristics and costs for base configuration and configuration 1

	Base configuration (Grid)		Configuration 1 (PVT)	
	Capacity/amount	Efficiency	Capacity/amount	Efficiency
PVT	-	-	6,000 m2	0.7 and 0.18
electric chiller	6,330 KW	6.7	5,300 KW	6.7
Absorption chiller	-	-	1,454 KW	1.36
Hot water TES	-	-	63,000 KW	-
Chilled water TES	63,000 KW	-	63,000 KW	-
Boiler	-	-	-	-
Total cost	362,822		343,758	
Investment & maintenance costs	41,535		214,395	
Operation cost	321,286		129,363	

Figure (38) shows the system electricity flow. The generated electricity feeds the electric chiller during the daytime, and the excess is transmitted to the grid. During the absence of solar irradiance, the grid supplies the chiller. The installed area covers 45.07% of the annual DCS electricity consumption. The annual generated electricity equals 1,930,012 KWh, which is considered energy saved.

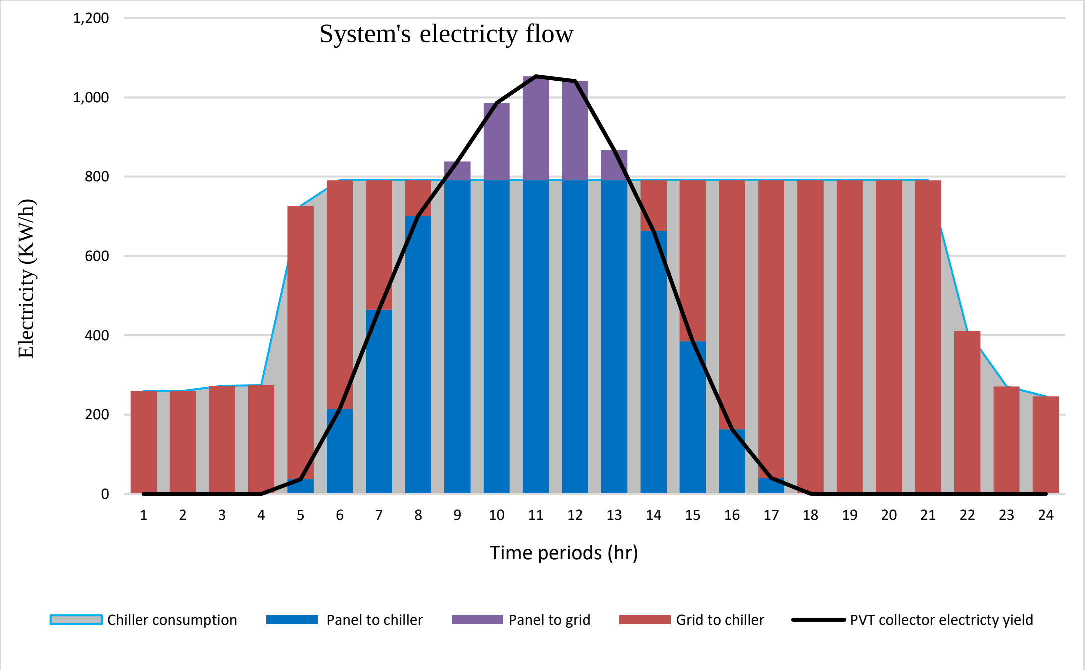


Figure 38. System's electricity flow for a typical August day

Figure (39) shows the system heat flow. The generated solar heat feeds the absorption chiller during the peak solar irradiance. The excess heat is stored in the hot water tank; during the absence of solar irradiance, the stored hot water operates the absorption chiller. In contrast to electricity, the heat generated covers 100% of the absorption chiller need and saves the equivalent of 9,055,221KWh of natural gas. Considering the electricity and the heat generated, renewable energy covers 80.36% of the total energy to operate the district cooling. The yearly primary energy consumption and the global warming potential are 6,797,412 kWh oil-equivalent and 1,232,472 Kg CO2-equivalent, which contributes to decreasing the environmental impact of the Grid-DCS configuration by 59.74% (Table 13).

Figure (40) shows the system cooling flow. Absorption and electric chiller contribute to satisfying the cooling load demand. The absorption chiller is running all day hours with its total capacity. However, the electric chiller production is adjusted to supply the complement. The surplus production during the morning hours (5 AM to 9 AM) is stored in the chilled water tank and used during the peak hours (Figure 7). The absorption chiller ensures 21.15% of the annual cooling demand, and the electric chiller production supplies the remaining amount. Table (13) summarizes the performance of configuration 1 and the base configuration.

Table 13. Annual performances of configuration (1) and base configuration

	Economic	Energy indicators	Environmental indicators	
	Total cost ($)	$f_{PVT,elec}$ (%)	PE^{sys} kWh oil-equivalent	PE^{sys} kWh oil-equivalent
Configuration 1	343,758	45.07	6,797,412	6,797,412
Base configuration	362,822	0	16,882,130	16,882,130

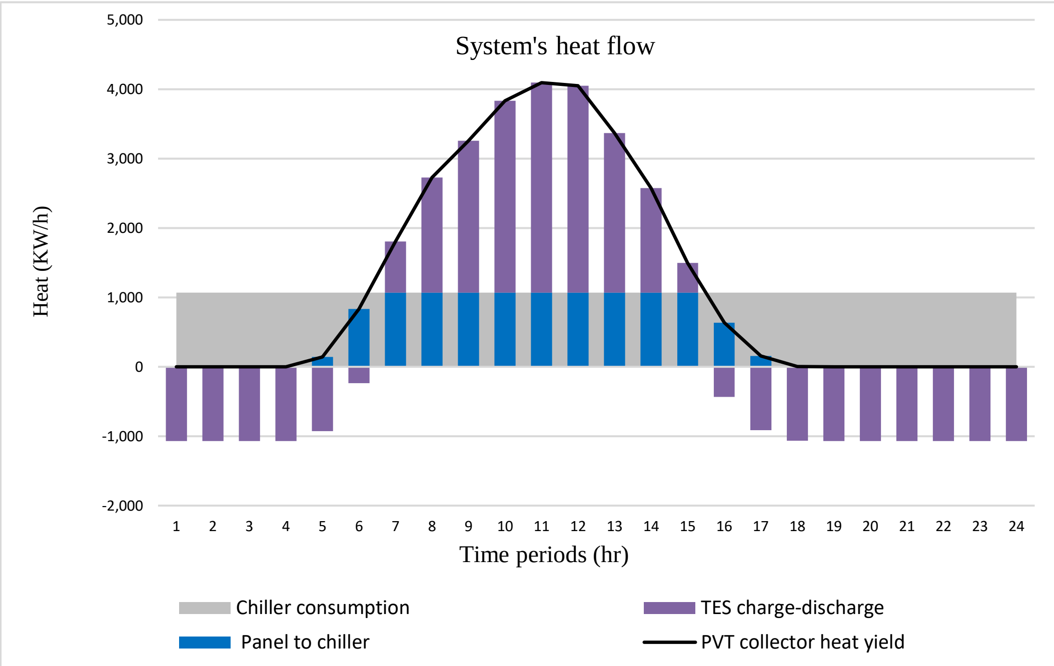


Figure 39. System's heat flow

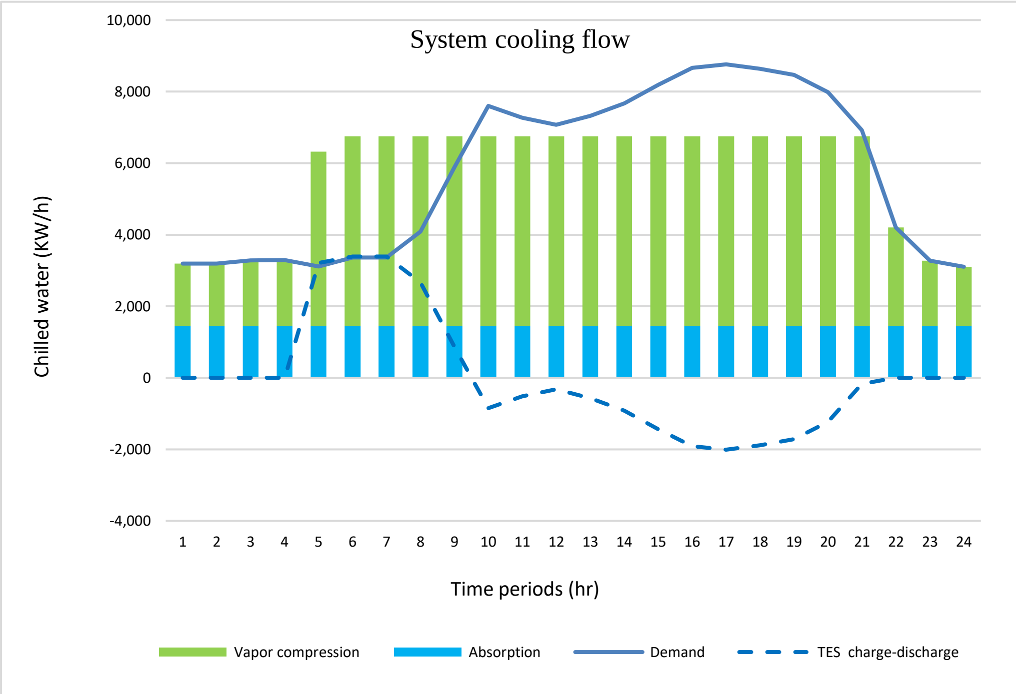


Figure 40. Cooling demand satisfaction

6.3.2 Scenarios and configurations assessment

In Qatar, the electricity price (P^{Elec}) depends on the customer category (productive farms, residential, industrial, hotel, commercial, and government). The government encourages investment in sectors like agriculture, industry, and tourism by subsidizing electricity with different degrees. Also, the applied tariff for residential and government institutions is different. The electricity tariff is in the range [$0.02KWh, $0.09 KWh]. In the urban region, the available installation area for the solar collector is not identical for all buildings. It may depend on the area of the building, the presence of parking, and the unused area. To reflect this local context, 9 scenarios are designed (Figure 41). For the electricity, low, medium, and high tariffs represent $0.02 KWh, 0.055 KWh, and $0.09 KWh. Low, medium, and high availability for the installation area is considered consecutively representing 3,000 m^2, 6,000 m^2, and 9,000 m^2. For example, scenario 5 represents medium area availability and energy tariff.

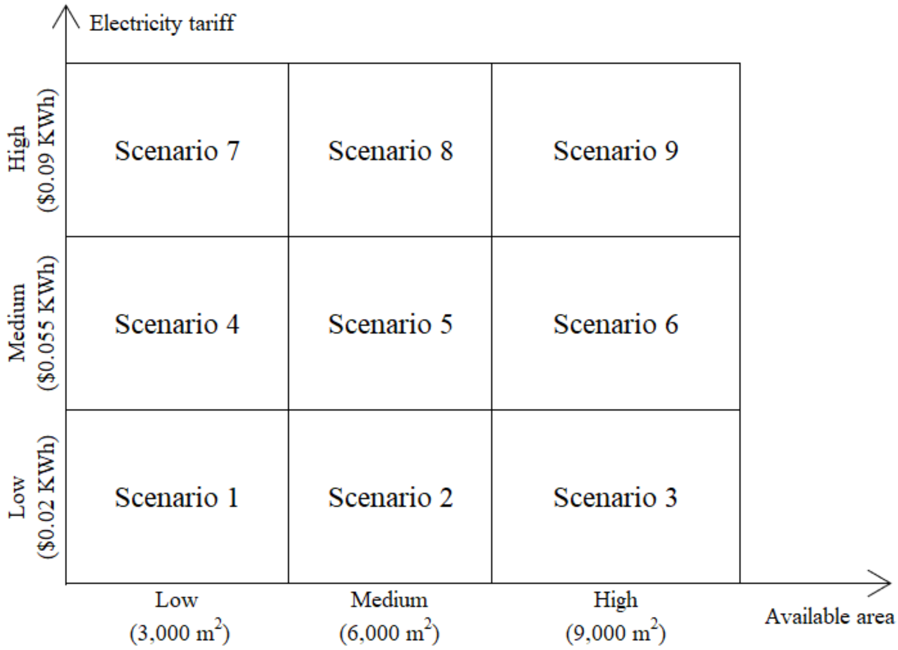


Figure 41. Scenarios setting

6.3.2.1 Optimal configuration (economic assessment)

All scenarios are simulated for the three configurations and the base Grid-DCS by varying the electricity tariff (P^{Elec}) and the available installation area (A). Figure (42) shows the optimal configuration based on the economic assessment (objective function). At low electricity tariffs (scenarios 1, 2, 3), the base configuration (Grid-DCS) is more competitive than configurations one, two, and three.

When the electricity tariff increases (medium or high), the solar cooling configurations become more competitive than the base. However, configuration three (T-DCS) is competitive only at high tariffs. Configuration one is competitive at medium electricity tariff when the available area is medium and above.

This is true for configuration three at a high electricity tariff. Therefore, the available installation area may impact the competitiveness of the solar cooling configuration.

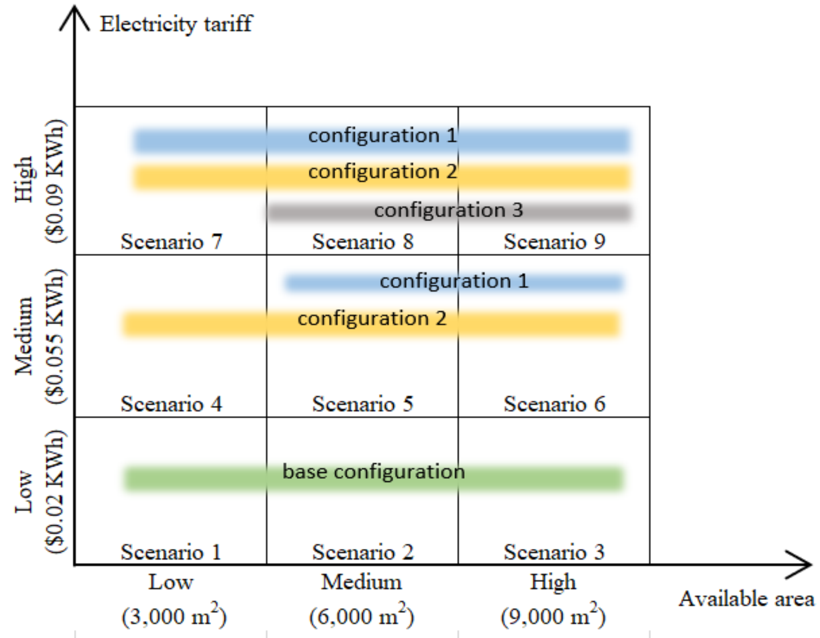


Figure 42. Optimal economic configuration

6.3.2.2 Base configuration performance

The Grid-DCS is considered base configuration; the economic, energy, and environmental performance are as follows. Concerning the economic performance, the investment and maintenance cost remains unchanged for all scenarios since the design is composed only of an electric chiller and chilled water tank. However, the operation cost varies and depends on the electricity tariff, impacting the total cost. The base configuration is powered exclusively by grid electricity. Hence, the final energy saving (renewable energy) is considered null. The electricity generation in the power plant is mainly based on fossil fuels, and their combustion generates CO_2 emissions. The yearly electricity consumption of the Grid-DCS contributes to the consumption of 16,882,130 KWh oil-equivalents of primary energy and the emissions of 3,060,981 Kg CO_2-equivalents (Figure 43). The grid electricity in Qatar is produced exclusively based on the fossil fuel (natural gas). Therefore, the renewable energy performance is equal to zero.

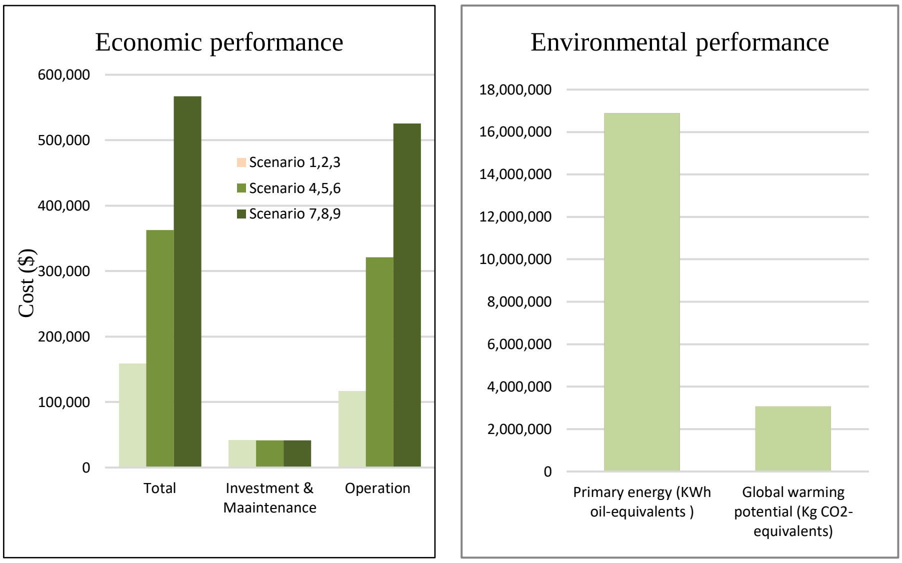


Figure 43. Base configuration economic, renewable energy use, and environemental performances

6.3.2.3 Economic performance comparison (scenarios 4 to 9)

At low electricity tariff (scenarios 1, 2, and 3), The Grid-DCS is the optimal configuration, and the economic performance is detailed in Figure (43). For the remaining scenarios (4 to 9), the Figure (44) shows that the investment and maintenance cost of the Grid-DCS system is the lowest due to the absence of an absorption chiller, hot water tank, and solar collector in the system design. However, the operation cost is the highest among the other configurations due to the grid electricity consumption. The total cost of the PV system is the lowest. The investment and maintenance cost of the PV system is less by 40% to 60% than PVT and T systems due to the absence of absorption chiller and hot water tank in the design, and superior by 60% to 180% than the Grid-DCS configuration mainly due to the PV panel installation cost. The operation cost of the PVT system is the lowest due to the heat and electricity cogeneration. The total cost of the PVT system is slightly superior to the PV system and is in the range of

2% to 4% in the case of high electricity tariff and 19% to 31% for the medium tariff. However, the operation cost of the PVT-DCS configuration is lower by 59% to 89% compared to the Grid-DCS configuration, when electricity tariff is medium, and by 30% to 90% when electricity tariff is high. The T system is more competitive than the base configuration at high electricity tariffs and medium or high available areas. The total cost is almost similar to the base configuration (-2%). This is explained by compensating for the operation cost-saving and the investment cost.

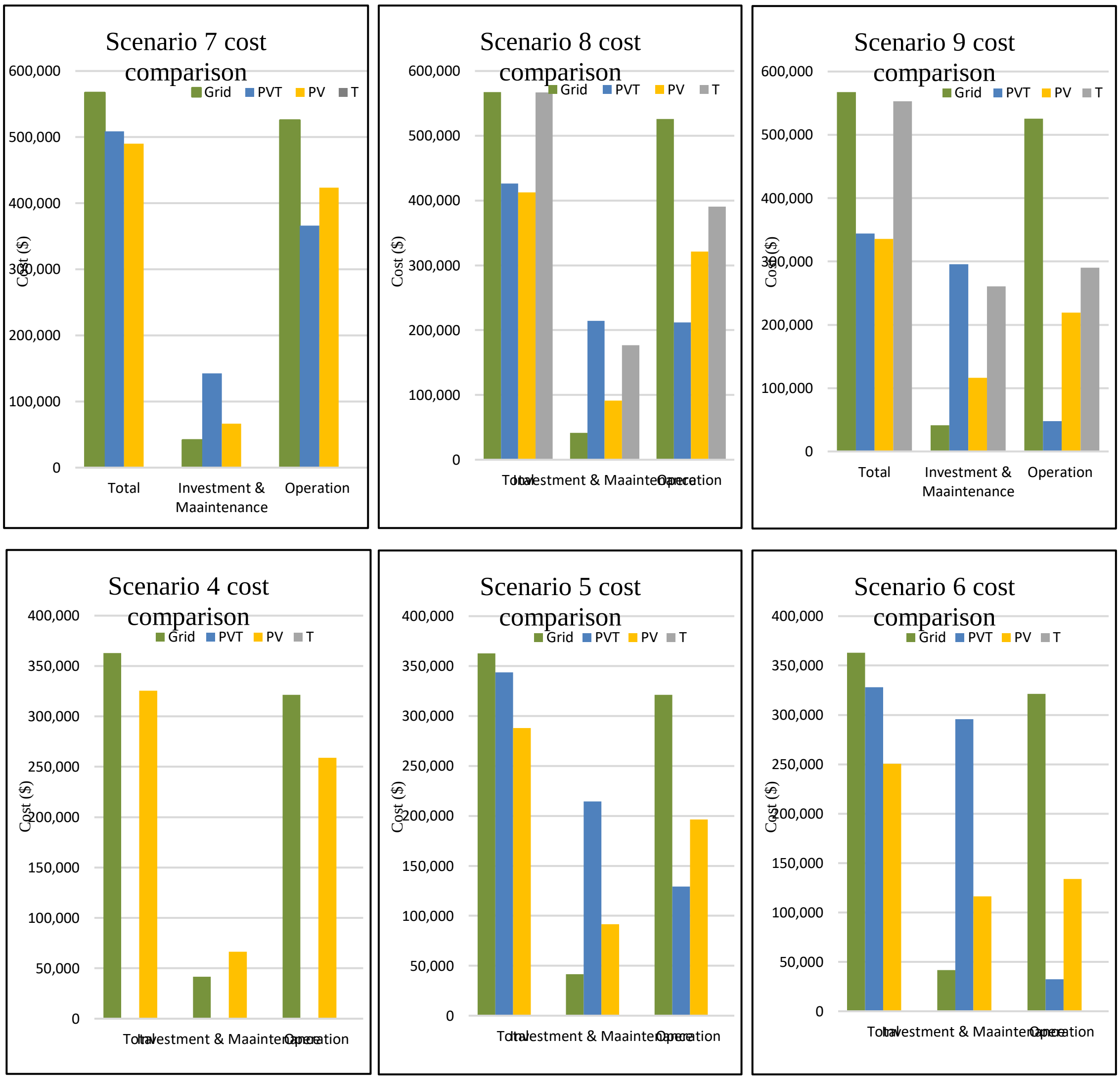


Figure 44. Scenarios' cost comparison

6.3.2.4 Energy saved and renewable energy fraction comparison (scenarios 4 to 9)

At low electricity tariff (scenarios 1, 2, and 3), The Grid-DCS is the optimal configuration based on the economic performance, and the energy performance is detailed in Figure (43). Figure 45 shows renewable energy use saving performance for the remaining scenarios (4 to 9). The equivalent energy saved (gas or electricity) depends on the renewable energy generated by the installed area. The gas equivalent saved is proportional to the produced heat and depends on the solar radiation, thermal efficiency, and the installed area. The electricity saved is equal to the electricity generated and depends on the solar radiation, electric efficiency, and the installed area. The hybrid solar technology generates both heat and electricity, which is not the case for the photovoltaic and thermal. Consequently, the renewable fraction is superior to PV and T systems.

Figure (46) shows the maximum renewable energy fraction achieved by the PVT, PV, and T systems are respectively 94.70%, 58.30%, and 79.26% for the high installation area scenarios. The minimum fraction for PVT and PV systems are respectively 54.82% and 19.43% for the low installation area scenarios. The minimum for the T system is 63.23% for the medium installation area scenario.

Figure 45. Scenarios' energy saved comparison

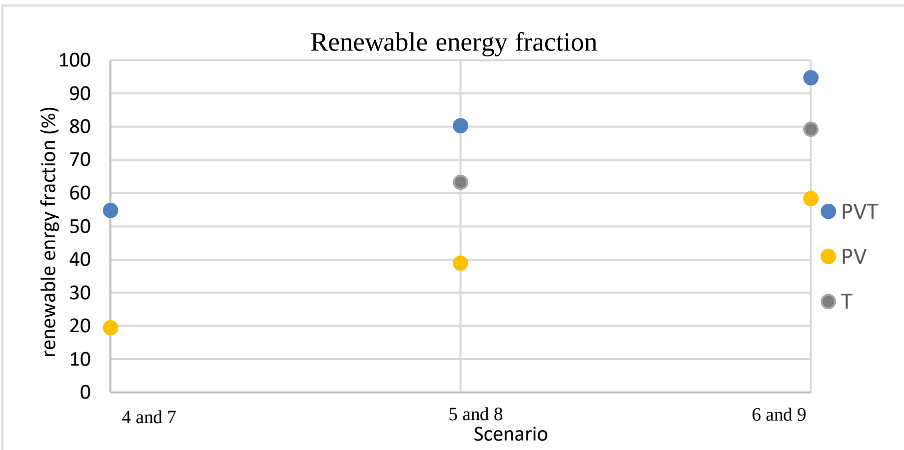


Figure 46. Scenarios' renewable energy fraction

6.3.2.5 Environmental performance comparison (scenarios 4 to 9)

At low electricity tariff (scenarios 1, 2, and 3), The Grid-DCS is the optimal configuration, and the environmental performance is detailed in Figure (43). Figure (47) shows the environmental performance for the remaining scenarios (4 to 9). The Grid-DCS system has the highest primary energy use and global warming potential. In contrast, the hybrid technology has the lowest primary energy use and global warming potential. For high available installation areas, the PVT system reduces the environmental impact by 89.5% compared to the Grid-DCS system, by 59.74% in medium installation area scenarios, and by 30.33% in the case of low installation area scenarios. The PV system reduces the environmental impact by 58.3%, 38.87%, and 19.43% when the installation area is high, medium, and low. The T system reduces the environmental impact by 43.76% and 25.71% when the installation area is high and medium.

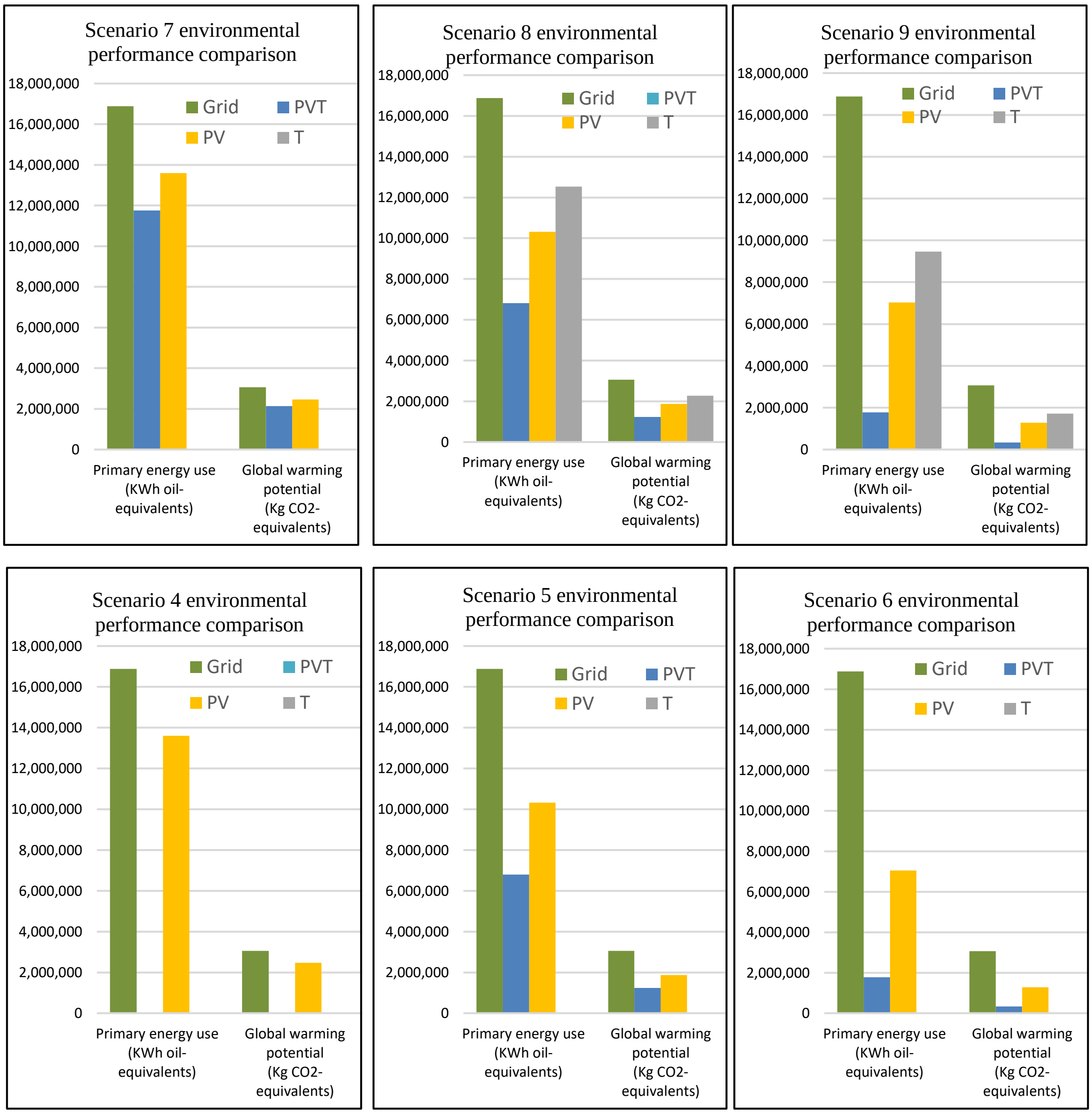


Figure 47. Scenarios' environnemental performance comparison

6.4 Summary

In the hot climatic regions, the abundance in solar irradiation and high cooling load patterns form a synergy that can be exploited for an ideal sustainable integrated system. Various solar and cooling technologies exist, implying different possible configurations that satisfy the cooling demand. Therefore, this research focused on the optimization and the assessment of the solar cooling systems in comparison to the conventional grid-based district cooling system. The optimal solution leads to the best sizing of the system components, including the technology selection and the optimal production policy in terms of energy generation, hot and chilled water production, and storage.

The assessment and the comparison of the four configurations is performed based on the economic, renewable energy use, and environmental performances. The electricity tariff and available installation area shape the local building context. Therefore, nine scenarios are simulated by varying these parameters. The analysis shows that:

- The electricity tariff and the available installation area impact the integration of solar energy. When electricity tariff is medium or high, the more installed area, the better is for the total cost, renewable energy use, and the environmental impact
- At a low electricity tariff rate (subsidized), the conventional Grid-based DCS remains the most competitive among the other configurations. However, the environmental performance is the worst.
- The annual assessment of 10,000KW district cooling system powered with the grid-electricity shows that 16,882,130 kWh oil-equivalent of primary energy is consumed, which impacts the environment by 3,060,981 Kg CO2-equivalent
- The PV-DCS configuration is the most competitive among solar assisted cooling systems. The annual total cost is less by 2% to 4% than PVT-DCS configuration when electricity tariff is high, and less by 19% to 31% when electricity tariff is medium. It reduces the environmental impact compared to the Grid-DCS configuration by 58.3%, 38.87%, 19.43% when the installation area is high, medium, and low.
- The PVT-DCS configuration has the lowest operation cost among solar assisted

cooling systems and is lower by 59% to 89% than the Grid-DCS configuration, when electricity tariff is medium, and by 30% to 90% when electricity tariff is high. The PVT system also has the best environmental performance by decreasing the primary energy use and the global warming potential by 89.5% compared to the Grid-DCS system, by 59.74% in medium installation area scenarios, and by 30.33% in the case of low installation area scenarios.

- The T-DCS configuration is more economically competitive than the conventional Grid-DCS configuration only at high electricity tariffs and medium to high available installation areas. The total system cost is slightly less than the Grid-DCS configuration (-2%). Despite the high renewable energy fraction in the range 63.23% and 79.26% respectively for medium and high installation areas, the environmental performance is relatively less than PVT and PV systems. The T system reduces the environmental impact by 43.76% and 25.71% when the installation area is high and medium compared to the Grid-DCS configuration.

The model was compared with other published models using simulation (TRNSYS) and similar results were concluded by Ayadi et al. [91]. Authors concluded that the enviro-economic performance of photovoltaic systems is superior in comparison with thermal and grid-based configurations. However, the use of hybrid technology has not yet been investigated at the district-cooling level

The proposed model has some limitations. The model assumes that the chiller efficiency is constant during the operation. In general, the efficiency outcomes can be varied. Therefore, the energy consumption pattern can change, exhibiting nonlinear effects in terms of energy requirements and the cooling load supply. However, this would increase the complexity of the model. Therefore, further research can focus on changing the solution approach by decomposing the problem and developing a heuristic to solve the sub-problems.

It should be further noted that the exploitation of solar energy is based on solar irradiation and weather conditions, and these factors are stochastic by nature. Therefore, the model can be extended by considering the probabilistic distribution of irradiance and its impact on electricity and thermal energy generation.

Chapter 7: Conclusion and Future Research

This chapter will conclude the study by summarizing the key research findings related to research aims and questions and the contributions. It will also review the study's limitations and propose opportunities for future research.

This study aimed to investigate the modeling and the optimization of district cooling system towards sustainable development by decreasing cost, energy consumption, and emissions. The key findings of the design and operation optimization of multi-chiller DCS by considering the stakeholders and system requirements are as follows:

i. The variation of the sequencing control requirement, representing the technology specification (time threshold between startups), has an immediate effect on the amount of chilled water produced, stored, and energy consumed. There is a direct relation between the system reactivity and the interaction with a change in cooling demand, and it requires an efficient system control.

ii. The design of a cost-effective and energy efficient DCS requires the understanding of the DCS structure, fluctuation in chiller capacity, their utilization, and the expected demand. In addition, the control strategy to be implemented should consider the chillers sequencing and staging based on the cooling demand variation. Operating different capacity chillers has an impact on the energy efficiency. Therefore, the change of the developer design requirement may provide opportunity to consider other alternatives.

The key findings of the modeling , optimization, assessment, and comparison of solar cooling configurations based on the economic, energy use, and environmental performance are as follows:

i. The electricity tariff and the installation area made available for solar technology impact the economic competitiveness of technology integration. When electricity tariff is subsided (low), the conventional grid based DCS is the most competitive.

ii. The PV-DCS configuration is economically competitive among the solar assisted cooling systems, and it can contribute to reducing the environmental impact by 58.3%.

iii. The PVT-DCS configuration has the lowest operation cost and the highest environmental performance by decreasing the global warming potential by 89.5%. The T-DCS configuration becomes economically competitive only at high electricity tariffs.

There are three research questions explored in this thesis. These questions focus on the modeling and optimization of the design and operation of DCS towards cost-effective, energy-efficient, and environmentally friendly. The addressing of these research questions in this thesis are given as followed.

RQ1: What is the impact of stakeholders and system requirements on the DCS performance?

The first path investigated the impact of stakeholders and system requirement on the DCS performance. Based on the analysis done in this research, the requirements have an impact on the optimal design, operation, and performance of the DCS. The change in the technology requirement, reflecting the chillers operation (threshold between startups), and formulated as sequencing control impact the DCS behaviors in terms of cooling production, chilled water storage, and energy consumption. The increase of one period of the threshold constrains the system reactivity to satisfy the cooling demand efficiently. Resulting in decreasing the storage amount by more than 26% and limiting the anticipation of the cooling demand. Therefore, the energy efficiency is decreased by 0.08%. The consideration of multi-capacity instead of chillers equal capacity as stated by the developer requirements have a positive impact on the efficiency.

RQ2: What are the most effective solar cooling configurations for sustainable DCS based on energy price and availability of installation area?

The second path investigate the design and operation optimization of solar cooling systems in Qatar climate by considering the energy prices and available installation area. The solar and cooling technologies diversity results in diverse configuration that can be considered to satisfy the cooling demand. A generalized model imitating these configurations is developed to optimize the design and the operation of each configuration. To compare these configurations, a set of performance indicators are implemented allowing the assessment of the economic, renewable energy use, and environmental performance. The annual assessment of the grid, photovoltaic, thermal, and hybrid based DCS configuration analysis show that the electricity tariff and the availability of the installation area affect the competitiveness of technology integration. In the case of subsidized electricity tariff (low), the grid-based DCS is the most competitive among the solar-cooling configurations. However, the grid-based DCS has the worst environmental performance, with 16,882,130 kWh oil-equivalent of primary energy consumption and 3,060,981 Kg CO_2-equivalent emissions. The photovoltaic-DCS configuration achieves the best economic performance among solar assisted cooling systems. The annual cost is less by 2% to 4% than hybrid-DCS configuration when electricity tariff is high, and less by 19% to 31% when electricity tariff is medium. Also, the PV-DCS reduces the environmental impact by 58.3%, 38.87%, 19.43% when the installation area is high, medium, and low compared the grid based DCS. The hybrid-DCS configuration has the lowest operation cost and the best environmental performance. The PVT-DCS configuration operation cost is lower by 59% to 89% than the Grid-DCS configuration, when electricity tariff is medium, and by 30% to 90% when electricity tariff is high. The PVT system primary energy use and global warming potential are lower than the grid-based configuration respectively by 89.5, 59.74%, 30.33%, when the installation area is high, medium, and low. The thermal-DCS configuration is economically competitive than the conventional grid-DCS configuration only at high electricity tariffs and medium to high available installation areas. The total system cost is slightly less than the grid-DCS configuration (-2%). The thermal-DCS configuration reduces the environmental impact by 43.76% and 25.71% when the installation area is high and medium compared to the Grid-DCS configuration.

RQ3: What modeling methodology can be formulated for efficient design and operation of DCS?

The modeling of the design and operation of DCS requires the integration of the DCS structure, behavior, and requirements simultaneously. The structure contains mainly the cooling technology, the energy source, and the system configuration. This latter expresses the energy balance. The diversity in the choice leads to a combinatorial problem formulation by using binary design decision variables. The DCS behavior reflects the behavior of each installed component in term of energy production, storage, losses, and consumption. The formulation of the requirement statements further delimits the research space by adding more constraints. The resulting model is a mixed-integer non-linear programming. It can be solved by using a non-linear solver, also by using a linear solver such as branch-and bound algorithm after the linearization. The modeling using algebraic modeling language lies mainly in the formulation of constraints that reflect all these aspects: requirements, structure, behavior including the control, and technical constraint for linearization purpose. The developed framework gives a practical way to understand, develop, and implement such model that reflects the system based engineering concepts.

7.1 Limitations and future research.

Based on this research, the limitation consideration can be dressed for future research in modeling and optimization of DCS as follow.

- The energy efficiency assessment using a deterministic linear search algorithm limits the consideration of a long schedule horizon and the nonlinear power consumption curve. Consequently, the problem size is to be balanced by a short horizon, piecewise approximation function and set sizes. Exploring a nonlinear algorithm or nature-based algorithm (genetic or particle swarm) may contribute to overcoming this limitation.
- District cooling systems' modeling and optimization efforts at the conceptual design level require assumptions that the energy community may misunderstand. The combination of optimization and simulation (optimization-based simulation) gives more value to the work by considering other system operational aspects, such as the accurate operational parameter (temperature, heat flow, fluid pressure, heat transfer, and cooling losses).

- The proposed model focuses on the system's conceptual design, which is one of the earlier stages of the system life cycle development. Further research can focus on the system measurement and the predictive control aspects when the system development reaches advanced stages, such as preliminary and final design.
- Diverse parameters are used in the modeling process. Some are stochastic by nature, such as solar irradiance, weather condition, chiller efficiency, and cooling load. In contrast to the deterministic approach, stochastic programming considers the uncertainty aspects of these parameters. The decision to be made during technology selection, which is the case of solar technology in this study, is often based on multi-objective optimization (cost and emissions). This requires the consideration of the diverse objectives in the problem formulation; approaching the numerical solution by metaheuristic is valuable in this case.
- The use of the algebraic modeling language necessities constraints formulation to reflect the requirements, system structure, and behaviors. Consequently, this task requires a higher efforts and time consuming. The problem size impacts the computational time. The use of algebraic modeling language in addition to other language such as the SysML in system analysis can be envisaged by exploring the parametric block in the SysML framework. The parametric block considers the formulation of constraints, however, the software should be integrated with an external solver.
- The gap between academic research and the district cooling practitioners should be further tined at the system control level by more applied research on DCS automation and programming towards energy efficiency.

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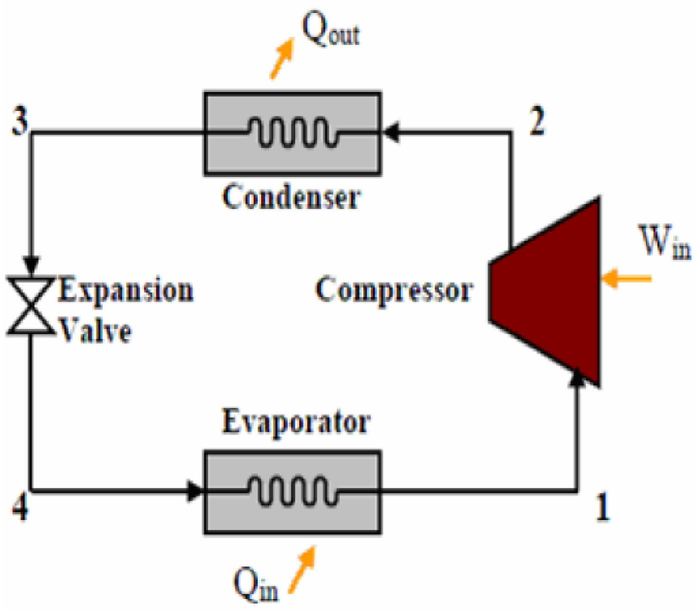
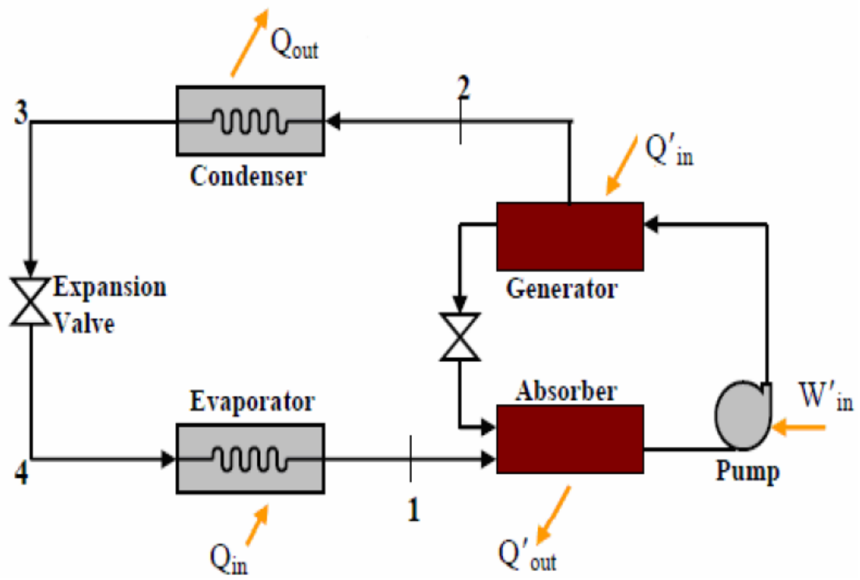
Appendix A: vapor compression and absorption cycles



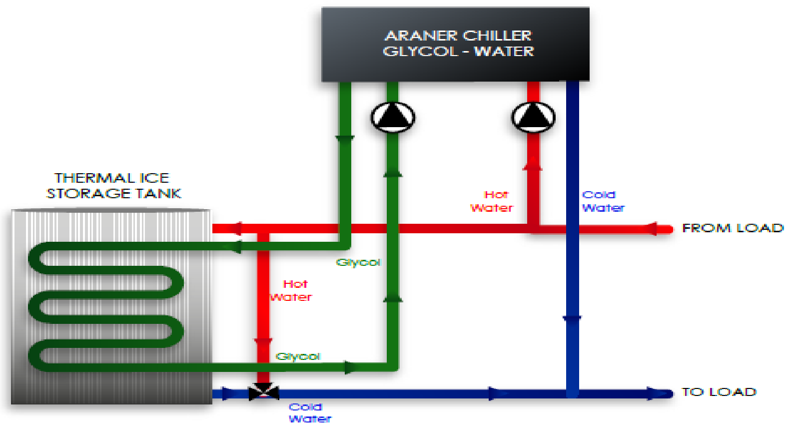
Vapor Compression Cycle



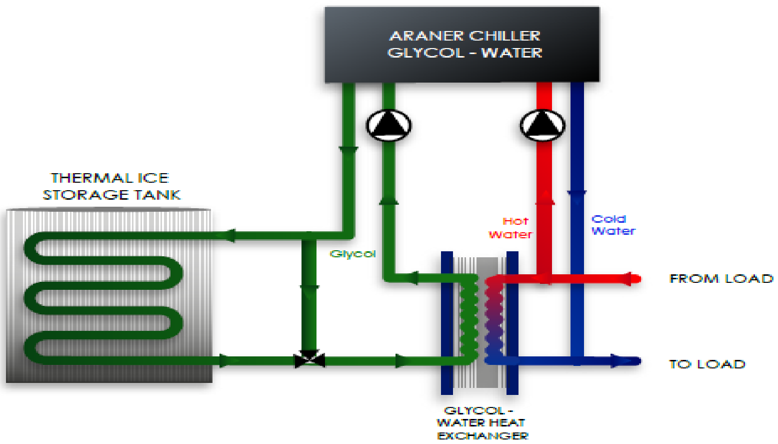
Vapor Absorption Cycle

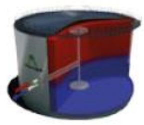
Appendix B: Thermal Energy Storage Technologies (Technical Reference ebook technical Araner)

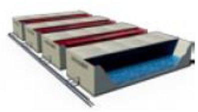
EXTERNAL MELT-ON-COIL



INTERNAL MELT-ON-COIL

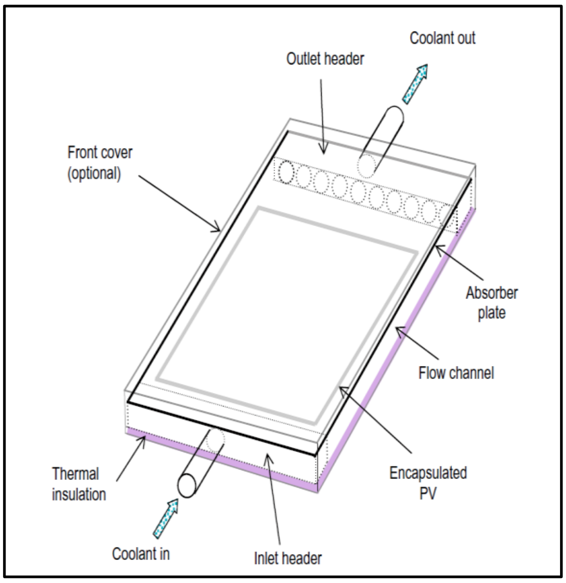




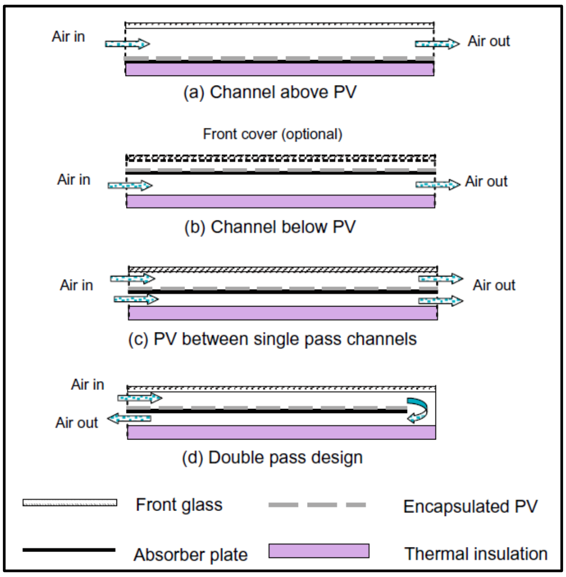


	ICE HARVESTING	EXTERNAL MELT ICE-ON-COIL	INTERNAL MELT ICE-ON-COIL	ENCAPSULATED ICE	STRATIFIED WATER	MULTI - TANK
CHILLER EFFICIENCY	Low	Medium	Medium	Medium	High	High
TANK VOLUME	Small	Small	Small	Small shape-adaptable	Medium	High
DISCHARGE FLUID	Water	Water	Second Coolant	Glycol	Water	Water
TANK INTERFACE	Open Tank	Open Tank	Closed Circuit	Close or Open Tank	Open Tank	Open Tank
CHILLERCOST	High	Medium	Medium	Medium	Low	Low
TANK COST	Medium - High	High	High	High	Low	Medium
TEMPERATURE QUALITY	High	Low	Low	Low	High	High

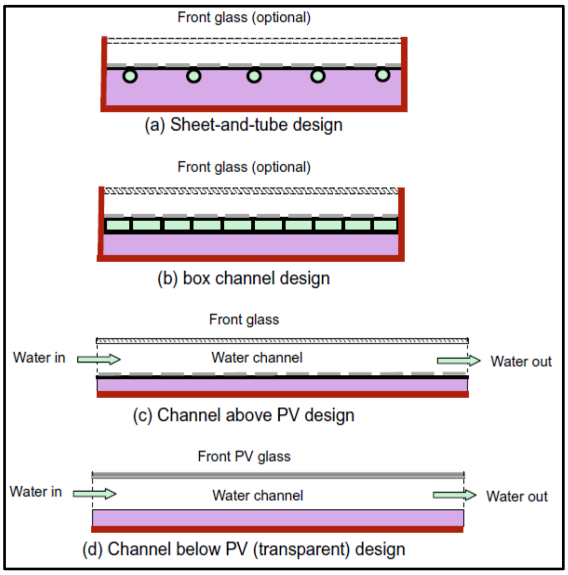
Annex C: Photovoltaic-Thermal Hybrid Solar Collector Design Features [55]



Example of Flat-plate PVT collector



Example of longitudinal cross-section



Example of cross-section of PVT