Energy Conversion and Management: X 6 (2020) 100028

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.journals.elsevier.com/energy-conversion-and-management-x

Optimization of design and operation of solar assisted district cooling systems

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ARTICLE INFO

Keywords:
Solar assisted district cooling
Mixed integer linear model
Absorption chiller
Thermal energy storage

ABSTRACT

The demand for air conditioning and cooling services is rapidly increasing worldwide. As cooling demand has high coincidence to occur in countries with high solar irradiation, the combination of solar thermal energy and cooling appears to be an exciting alternative to replace traditional electricity-driven cooling systems where electricity is generated from fossil fuels. Nevertheless, solar assisted cooling is not yet widely deployed because of many barriers amongst them the presumed high investment cost of solar cooling technology. This research aims at making this technology more affordable by providing a holistic optimization design of solar assisted district cooling systems. Toward this end, a mixed-integer linear programming model (MILP) is proposed that captures the key design and operation variables of a solar-assisted district cooling system. Hence, the proposed model aims at finding the optimal system design (i.e., the system's main components along with their optimal capacities) together with the optimal hourly policies for production and storage of hot and cold water while satisfying the expected cooling demand. The model was validated using collected real data of different case studies. The optimal system design of some cases showed that solar collectors covered about 46% of the chiller's heat demand. Moreover, the existence of the cold-water TES in the system depends on the chosen chiller capacity and the cooling demand of the case study. Furthermore, a sensitivity analysis was carried out to study the model robustness. The sensitivity analysis shows that the chiller COP had the highest impact on the annual total system cost, where increasing COP by 20% of its initial value, will decrease the annual total system cost by 4.4%.

1. Introduction

During the last decades, experts around the world have been consistently warning about severe global warming caused by the huge emissions of greenhouse gases. However, over the past few years those warnings have dramatically escalated after the publication of numerous studies detailing the catastrophic environmental, economic, and social consequences of global warming [41]. Paradoxically, the global warming phenomenon has been consistently driving a worldwide surge in the demand for cooling services, which in turn is contributing to an increasing demand for fossil fuel-generated electricity and consequently further exacerbating CO_2 emissions, and thereby global warming. For instance, in China, the energy demand for cooling services has increased at an accelerated pace of 13% per year since 2000, and reached nearly 400 terawatt-hours in 2017. Interestingly, cooling services accounted about 16% of peak electricity load in 2017, and as much as 50% of peak electricity demand on some days. Consequently, cooling-related CO_2 emissions increased fivefold between 2000 and 2017 [17]. An extreme case is represented by Qatar where it is estimated that cooling energy accounts for up to 70% of peak electricity demands in summer months [2]. As a result, Qatar has been reported to have the highest CO_2 emissions per capita [15].

This vicious circle, where the additional demand for cooling services is itself contributing to intensifying the global warming phenomenon, needs to be broken or (at least) mitigated. In this regard, two main compatible strategies may lead to more sustainable air cooling that reduce energy consumption and related CO_2 emissions. The first one requires raising energy performance standards for cooling equipment, and significantly enhancing building design standards. The second alternative, requires relying on renewable or clean energy for providing cooling services. In this context, solar energy appears to be an excellent candidate, because it happens; fortunately, that cooling energy is mostly required in countries where plenty of solar radiation is available. Thus, out of the offered clean energy, the focus of this paper will be on using solar energy in District Cooling Systems (DCS). Coupled with solar energy, there is an alternative technology for producing

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https://doi.org/10.1016/j.ecmx.2019.100028
Received 20 August 2019; Received in revised form 27 November 2019; Accepted 22 December 2019
Available online 14 January 2020

cooling services, which is based on thermal-driven chillers instead of electricity-driven chillers. Hence, one of the opportunities the DCS research area has to offer is the integration of renewable energy with CS. That includes the substitution of fossil electricity-powered compression cooling with renewable-heat-powered absorption cooling, where such technology has been the most investigated alternative recently. The heat-powered absorption cooling has been reported to reduce DCS energy consumption by 10–70% based on system design and operation features and modeling approaches of DCS [9,24].

Sarbu and Sebarchievici [31], He et al. [16] Montagnino [23] and Shirazi et al. [35] highlighted the main components of a typical solar absorption cooling system. These components include a solar thermal collector, an absorption chiller, storage tanks, and an auxiliary boiler. The main benefits of such system include the following: (i) it can be integrated with thermal energy storages (TES) where they can be designed as dual systems to satisfy the heating or cooling demands; (ii) it eliminates the need for any compressor, so it is characterized by low noise and vibration operations; (iii) it decreases GHG emissions by avoiding using refrigerant gases and reducing fossil fuel burning; and (iv) it uses solar energy which is clean and naturally available.

In the literature, solar absorption cooling systems are being investigated widely and extensively, but not from an optimization point of view. Such investigation is done by Tsoutsos et al. [40], Qu et al. [29], Ortiz et al. [25], Praene et al. [26], Martinez et al. [21], Vasta et al. [42], Sokhansefat et al. [38], Soussi et al. [39], and Khan et al. [19]. Where these authors focused only on constructing an *ad-hoc system* using simulation methods without considering the system cost as a major player. Hence, that has limited the use of such technology in lots of applications. The main obstacle behind why this technology is not spread or widely used is its cost. So far, it is generally believed that it is costlier than electricity-driven cooling systems, and there are previous studies that showed that such a system is not competitive [28,21,42]. However, there are many decisions made during the design stage of the system that significantly impact the system cost and makes solving such problem very complex [32,33]. Such decisions are related to the selection of a system's component with existing numerous options and technologies in the market. Moreover, the design specifications and requirements related to the different components used in the system increases the problem complexity from optimization point of view. It is very crucial to select the right system's component with the right capacity to meet the hourly cooling demand; otherwise, the system will fail to operate optimally. Therefore, finding the optimal system configuration, which includes types, efficiency, and capacity of each component of DCS to minimize the annual total design and operation cost, is necessary.

Thus, there is a need for a systematic optimization approach, and this is precisely the objective of this paper. More specifically, the objective of this paper is to investigate the optimal design of a solar-assisted cooling system (SAC), which includes the optimal selection and operation of the system components to function within the appropriate level of efficiencies while obtaining the minimum system cost. Toward this end, we propose a mathematical model that captures all relevant design variables and seeks to find an optimal system design along with the associated operational policy.

The remainder of this paper is organized as follows. Section 2 includes a literature review with a focus on the design and operation optimization of SAC systems. Moreover, it includes a summary of the paper's contributions. Section 3 provides a formal description of the problem that is addressed in this paper, along with the mathematical model formulation. Section 4 discusses the collected data of the model parameters, and exhibits the main results obtained from the computational experiments conducted on different design cases and scenarios. Section 5 highlights the results of a sensitivity analysis of model parameters. Finally, Section 6 is dedicated to the conclusion and describes some future research avenues.

2. Literature review

The optimization of renewable energies integrated with DCS; specifically, SAC system area has been the interest of many researchers. Many papers published in SAC area which discussed how the performance of SAC system impacted by design parameters (i.e., features of the solar field, and chiller) and variable parameters like climatic conditions and building cooling demand using simulation approach. Simulation is a very convenient tool which can be used to understand and evaluate the performance of a system under different design scenarios. The papers reviewed in this section are all were carried out using TRaNsient System Simulation program (TRNSYS) by Tsoutsos et al. [40], Qu et al. [29], Ortiz et al. [25], Praene et al. [26], Martinez et al. [21], Vasta et al. [42], Sokhansefat et al. [38], Soussi et al. [39], and Khan et al. [19] focused on studying the performance of SAC system and optimizing different parameters that effected on the performance of the system including collectors area and slope, back-up heater, TES and absorption chiller capacities to minimize the system cost and maximize other aspects such as environmental benefits. Tsoutsos et al. [40] found that one of the scenarios that they studied had a SAC system which was able to cover 74.23% and 70.78% of solar fraction cooling and heating, respectively. While Qu et al. [29] concluded that the developed SAC system was able to cover 39% and 20% of cooling and heating demand, respectively, of the application when the system had a proper TES size. Praene et al. [26] concluded that the absorption chiller was operating at half of its cooling capacity, and that was sufficient to provide comfort cooling for a classroom. Martinez et al. [21] designed SAC system parameters based on energy savings during cooling periods. They found that 29% of the solar energy absorbed by the solar collectors was stored at the hot water TES. Martinez et al. [21] designed SAC system parameters based on energy savings during cooling periods. They found that 29% of the solar energy absorbed by the solar collectors stored at the hot water tank. Vasta et al. [42] indicated that simulation results showed that solar collectors area influenced mainly COP of absorption chiller and solar fractions. Sokhansefat et al. [38] conducted a parametric analysis besides using the simulation software to find the optimum parameters' values that affect the behavior of the system. Soussi et al. [39] highlighted that the solar collectors' efficiency improved from 35% to 57% and the absorption chiller to 1.29 after the addition of an auxiliary boiler and increasing solar collectors' area. The solar collectors were able to meet 32.3% of cooling demand, and the absorption chiller was functioning 75.8% of its total operational time. The proposed system achieved 82.3% of energy saving more than conventional cooling systems.

On the other hand, Molero et al. [22], and Hang et al. [13] focused in their study on studying the effect of integrated TES on the behavior of the SAC system using TRNSYS. Molero et al. [22] carried out a comparison between two systems configurations. The first had only hot water storage tank, while the other had both cold and hot water tank. The simulation results showed that the benefits of cold-water tank disappeared when the collector area increased. The simulation results indicated that the benefits of cold-water TES disappeared when the collector area increased. Hang and Qu [12] integrated two TES in the SAC system, a hot water TES included in the solar collection loop, while a cold-water TES included in the load loop. The system was able to cover 50% of cooling demand.

Balghouthi et al. [5], Marc et al. [20], Sim [37], and Asaee et al. [4] studied and developed a SAC system while considering the climatic conditions of their country as a part in their study using TRNSYS. They pointed out that the climatic conditions had a crucial effect on the behavior of the system. Sim [37] indicated that the water tank was able to deliver hot water 4 h continuously and the absorption chiller decreased the electricity consumption by 47% compared to the traditional system when considering Qatar climatic conditions as an input to the developed model. Pongtornkulpanich et al. [27], Agyenim et al. [3], Hang et al. [13], and Shirazi et al. [36], designed and developed the capacity of the SAC system based on the peak cooling demand of the application (i.e., University building) and observed the performance of the system using TRNSYS.

To this end, most of the cited papers did not focus on finding the optimal design and operational parameters of the SAC system while optimizing a specific objective function. This approach led to designing a SAC system with a higher initial cost than a conventional system in most cases. The main drawback of using simulation is that the design parameters values are more likely to be trapped in optimal local areas. Hence, there is a necessity to implement a proper optimization approach to have the optimal SAC system. There are few studies which use optimization approaches to find the optimal SAC system while satisfying objective function(s). Calise [6], Calies et al. [7], Calise [8], Hang et al. [13], and Hang et al. [14], conducted an optimization process with a single objective function on a SAC system. Calise et al. [6], and Calies et al. [7,8] developed an optimization model to find the minimum total system cost or simple payback period of the system. The optimization model was developed using TRNOPT optimization program that links TRNSYS with optimization algorithm called GenOpt. The authors did not consider cost related to equipment, piping and integration, escalation rates, and prices of fuel in the objective function. Hang et al. [13], and Hang et al. [14], used a linear regression analysis to a data set found from a parametric study of the SAC system which generated three equations related to present worth cost, carbon dioxide emission life cycle, and plant life cycle energy to optimize the SAC system design. The equations were combined into one objective to find the optimal SAC design. However, this approach had a drawback since the objective function formulated from a parametric study; hence, the optimization model solutions might be trapped in optimal local regions. Nevertheless, Gebreslassie et al. [11], Iranmanesh and Mehrabian [18], and Shirazi et al. [35] developed a multi-objective functions model to optimize the SAC system design. Gebreslassie et al. [11] designed a SAC system by developing a mixed integer non-linear programming model to maximize economic and environmental performances. The system had an absorption chiller powered by a primary energy source which was a natural gas boiler and by an alternative energy source represented in solar collectors. The objective was to minimize investment cost and operating cost of components along with associated emission levels to optimize the SAC system. During the study, trade-off solutions obtained where a Pareto optimal front set found by using a customized branch and bound technique. The authors found out that emission levels had decreased significantly, and the model solved in short computational times for different case studies. Iranmanesh and Mehrabian [18] optimized the design of a SAC system by developing a multi-objective functions optimization model to minimize energy consumption and maximize the profit of the system. The optimization was carried out on MATLAB software, and the non-dominated sorting genetic algorithm was used to optimize the system. The results pointed out that it was impossible to operate the absorption chiller without an auxiliary energy source to provide the required thermal energy for it during the day. Sharafi and Elmekkawy [34] developed a PSO-simulation based approach to find the multi-objective Pareto front of a hybrid renewable energy system. Shirazi et al. [35] used TRNSYS software along with MATLAB to develop a multi-objective optimization model, and the genetic algorithm was used to minimize fixed investment cost, fuel cost, CO_2 emission penalty cost, maintenance cost and operating cost and energy consumptions.

This paper features the following contributions:

It describes an integrated optimization model for the design and operation of a SAC system. Specifically, the proposed model adopts a holistic approach to compute the optimal design variables (capacity of the absorption chiller, capacity of the cold water thermal energy storage tank, capacity of the hot thermal energy water storage tank, size of the solar collectors area, and size of the back-up boiler) as well as the optimal operational variables (hourly amounts of chilled and hot water to be produced and stored) with the objective of meeting a time-varying demand at the minimum total annual cost. By contrast, most of the papers published so far focus on using simulation approaches (i.e., TRNSYS) in studying and analyzing *ad-hoc* designs. It is known that simulation is not used for optimization as a stand-alone tool. On the other hand, very few articles used optimization approaches in their study, but they either concentrate on optimizing the system design based on a developed simulation model (i.e., TRNOPT) or do not mention the employed optimization approach explicitly. However, a limited number of them use mathematical modeling approaches to optimize only the design aspects of a SAC system while ignoring operating policies.

The proposed integrated model was validated using real annual hourly cooling data that was collected in Qatar. In doing so, it fills a gap since there is a lack of academic research papers that use the actual annual hourly cooling demand profile related to a specific application (i.e., buildings, schools, etc.). Indeed, we found that most of the published studies validate their developed models based on peak loads only. This data will provide direct guidelines for district cooling operational improvements and design retrofits along with providing supportive information as a reference for the development and evaluation of an expected district cooling demand and performance models [9].

3. Problem description and formulation

3.1. Problem description and scope

This paper addresses the problem of finding the optimal design along with the operational policy of a solar assisted cooling (SAC) system using mixed-integer linear programming. The objective is the minimization of the overall investment and operating costs. The main components of the SAC system are the following:

I. An absorption chiller having a specific COP, capacity, and cost.
II. Solar collectors having a specific type, efficiency, and cost.
III. Thermal storage tanks. This equipment is optional. They will be included in the design if they contribute to lowering the total cost. The system shall consider storing cold water, hot water, or both of them. In each case, the thermal storage tank will have a specific capacity and cost.
IV. An auxiliary back-up heating unit having a specific capacity, efficiency, and cost.

Fig. 1 illustrates the scope of the proposed SAC system considered in the problem and highlights the energy flow in the form of hot and chilled water among the system components (i.e., direction of the arrows). To give an overview of how the proposed system would operate, it starts with the solar collectors that absorb the thermal energy collected from the solar radiation (L_t), so the water flowing through solar collectors will heat up. If the hot water is at the required temperature, then it will be fed directly to the absorption chiller (L_{ct}). However, if the hot water is not at the necessary temperature, then it will be supplied to the auxiliary boiler where it will heat the water to the required temperature and then be fed to the absorption chiller (B_t). In case of peak solar radiation and the chiller is running with only a portion of the thermal energy generated by solar collectors, the additional thermal energy will be stored at the hot water TES (M_t) to be consumed later in limited radiation periods (D_t^{HWT}). Once the hot water with the required temperature is pumped into the absorption chiller (F_t^{In}), the chiller will either produce (F_t^{o}) the required chilled water to meet the cooling demand (S_t^{CW}) or will generate more chilled water than what is needed (E_t). The additional chilled water will be stored in the cold-water TES to be used at later periods to meet the cooling demand (D_t^{CWT}).

We can see that the system's components are intimately intertwined, and hence we propose an integrated model that appropriately captures

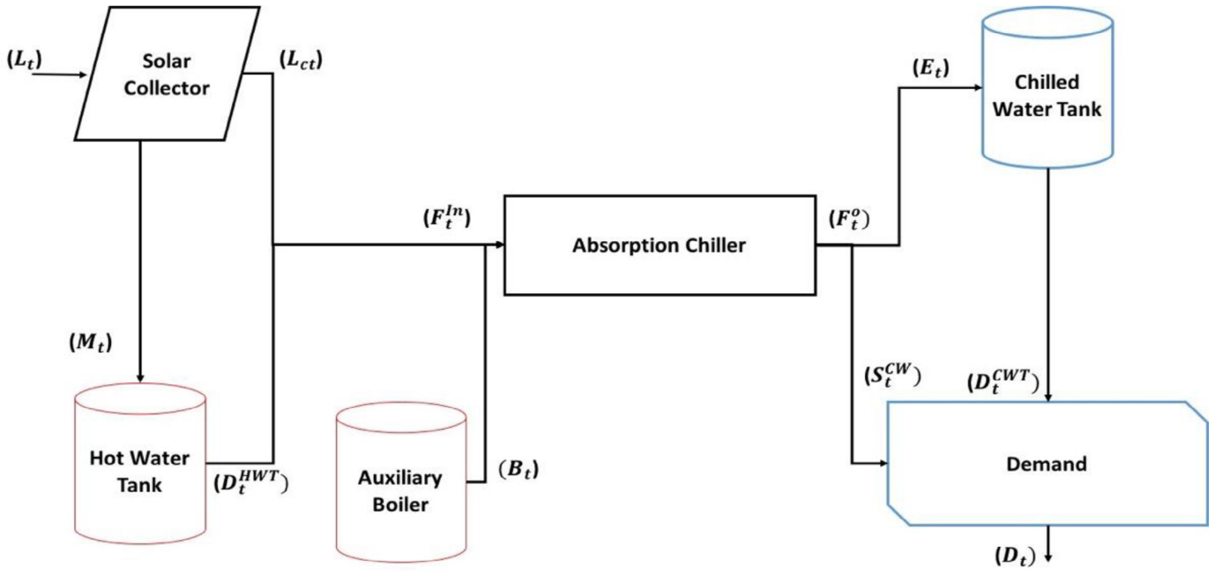

Fig. 1. System configuration of solar thermal cooling system.

Table 1
Sets and indices of the mathematical model.

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

all these interdependencies. More precisely, given an expected hourly demand over a one-year horizon, the solution of the proposed mathematical model, will specify:

a) The type and optimal area of the solar collectors,
b) The capacity of the absorption chiller along with the corresponding COP,
c) The capacity of the cold-water storage tank (if any),
d) The capacity of the hot water storage tank (if any),
e) The capacity of the auxiliary back-up unit,
f) The amount of chilled water to be produced during each hour of the year,
g) The amount of cold water to be stored during each hour of the year (if any).
h) The amount of hot water to be stored during each hour of the year (if any).

3.2. Problem formulation

The problem is formulated and modeled as mixed integer linear programming (MILP). The MILP contains sets, indices, and parameters related to the system components such as fixed cost, variable cost, capacities, efficiencies, hourly demand, etc… While the decision variables of the model related to the selection of a component in the system, amount of power, cooling or heating consumed or stored at a specific component and inventory levels at TES. The objective function minimizes the sum of the annual fixed costs and annual operation costs of the components. Finally, the constraints cover areas related to system configuration, energy balance, supply demand, and non-negativity and integrality constraints.

The following assumptions are considered during the mathematical model formulation:

- The hourly cooling demand is estimated in advance and deterministic
- TES functions with full efficiency with negligible losses
- The solar collector efficiency is known in advance and constant
- The system operates in a steady state

The sets, parameters, decision variables, objective functions, and constraints of the developed mathematical model are listed below.

3.2.1. Sets and indices

Table 1 shows the sets and indices of the mathematical model along with their definitions.

3.2.2. Parameters

The below Table 2 shows the parameters of the mathematical model along with their definitions.

3.2.3. Decision variables

Table 3 shows the decision variables of the mathematical model along with their definitions.

3.2.4. Objective function

The objective function minimizes the sum of the annual fixed cost of installing an absorption chiller, solar collectors, a chilled and hot water TES and, an auxiliary boiler. Along with minimizing the annual variable cost of producing hot and chilled water from the absorption chiller and auxiliary boiler, respectively, and the annual variable cost of storing hot and chilled water at TES. The fixed costs of all components are multiplied by a ratio to convert them into an annualized value. The ratio includes the interest rate and life cycle of a component. In this model, all components are assumed to have the same interest rate and life cycle (that is, i:interest rate = 8% and n: life cycle = 20 years. The model reads as follows.

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

Table 4 shows the objective function terms of the mathematical model along with their definitions.

Table 2
Parameters of the mathematical model.

Definition	Symbol
Fixed investment cost per unit area of an installed solar collector	F^{SC}
Fixed investment cost of installing a chiller of capacity, $\forall k \in K$	FC_k^{Ch}
Fixed investment cost of installing a chilled water TES tank of capacity, $\forall \boldsymbol{h} \in H$	FC_h^{CW}
Fixed investment cost of installing a hot water TES tank of capacity, $\forall j \in J$	FC_j^{HW}
Fixed investment cost of installing an auxiliary boiler of capacity, $\forall q \in Q$	FC_q^{HW}
Variable cost of producing a unit of chilled water at chiller during a period, $\forall t \in T$	VC_t^{Ch}
Variable cost of storing a unit of hot water at TES tank during a period, $\forall t \in T$	VC_t^{Hsto}
Variable cost of storing a unit of chilled water at TES tank during a period, $\forall t \in T$	VC_t^{Chsto}
Variable cost of producing a unit of hot water at auxiliary boiler during a period, $\forall t \in T$	VC_t^{HW}
Global solar radiation during the period expressed in W/m^2, $\forall t \in T$	G_t
Efficiency of the solar collector	n_{sc}
k^{th} capacity for a chiller expressed in KW, $\forall k \in K$. (Assume that $Q_1 < . . < Q_k$)	Q_k
h^{th} capacity for a chilled water TES tank expressed in KWh, $\forall h \in H$	D_h
j^{th} capacity for a hot water tank TES tank expressed in KWh, $\forall j \in J$	R_j
q^{th} capacity of an auxiliary boiler expressed in KW, $\forall q \in Q$	L_q
Amount of customer demand for cooling during a period expressed in KW, $\forall t \in T$	D_t
Efficiency of an auxiliary boiler of bth capacity, $\forall q \in Q$	EFF_q
Maximum area of installed solar collector, expressed in m^2	A
The duration of every periods, expressed in hour (h).	τ

3.2.5. System configuration constraints

Table 5 shows the system configuration constraints of the mathematical model along with their definitions.

3.2.6. Energy balance constraints

Table 6 shows the energy balance constraints of the mathematical model along with their definitions.

3.2.7. Supply demand constraints

Table 7 shows the supply demand constraints of the mathematical model along with their definitions.

3.2.8. Non-negativity and integrality constraints

Table 8 shows the non-negativity and integrality constraints of the mathematical model along with their definitions.

4. Experimental results and analysis

4.1. Data collection

The data are collected on model parameters to include SAC components and other parameters as well to test the proposed optimization model. The below Fig. 2 gives a comprehensive overview of data collected on different SAC system components.

Moreover, the annual hourly cooling demand for Qatar are collected (i.e., 8784 h/year), but the hourly cooling demand for a day in each month was the only data available and was obtained from the below Fig. 3 in Saffouri et al. [30]. Nonetheless, the hourly cooling demand for all days of 12 months in a year (i.e., 8784 h/year) is the required data. So, to find the cooling demands of other days in a month, the average temperature for each day in the month is calculated and the day with the highest average temperature assigned to the cooling demand given in Fig. 3. This day is set as a reference day where the cooling demand of other days is calculated based on it. The cooling demands of the other days are calculated by multiplying a ratio of the hourly temperature of the day (i.e., the day to find the cooling demand for) to the hourly temperature of the reference day with the cooling demand of that hour of the reference day. The detailed steps of how to find cooling demands of 8784 hr/year are explained in details in data paper with the complete graphs.

Also, data related to the hourly variable cost of producing a unit of chilled and hot water from absorption chiller and auxiliary boiler, respectively, and storing a unit of hot and chilled water at hot and cold-water TES are collected from KAHRAMAA [28]. These variables cost based on the electricity rate of Qatar, which is constant throughout the year. Lastly, data on annual hourly global solar radiation (W/m^2) for Qatar collected from KAHRAMAA. The complete data are shown in details in the data paper [1].

4.2. Experimental results

The proposed model is validated and verified by considering four different cases which represent very high, high, medium, and low cooling demand cases. Hence, the following applications selected, a health center in KSA, Texas A&M University at Qatar (i.e., TAMUQ),

Table 3
Decision variables of the mathematical model.

Definition	Symbol
Binary variable that takes a value of 1 if a chiller having a capacity of Q_k is installed, $k \in K$	y_k
Area of installed solar collectors, expressed in m^2	x
Binary variable that takes a value of 1 if a chilled water TES having a capacity of D_h installed, $h \in H$.	g_h
Binary variable that takes a value of 1 if a hot water TES having a capacity of R_j installed, $j \in J$.	z_j
Binary variable that takes a value of 1 if an auxiliary boiler having a capacity of L_q installed, $q \in Q$.	w_q
Amount of power consumed by a chiller $k \in K$ during period $t \in T$, expressed in KW	F_{kt}^{In}
Amount of power consumed by a chiller during period $t \in T$, expressed in KW	F_t^{In}
Amount of cooling produced by a chiller during period $t \in T$, expressed in KW	F_t^{o}
Amount of customer cooling consumption met from chiller during period $t \in T$, expressed in KW	S_t^{CW}
Amount of power reaching the solar collectors during period $t \in T$, expressed in KW	L_t
Amount of power produced by solar collectors during $t \in T$, expressed in KW.	L_t^{C}
Inventory level of cooling energy stored at TES tank at the end of period $t \in T$, expressed in KWh	I_t^{CW}
Inventory level of heating energy stored at TES tank at the end of period $t \in T$, expressed in KWh	I_t^{HW}
Amount of cooling produced from a chiller and delivered to chilled water TES tank during period $t \in T$ expressed in KW.	E_t
Amount of power produced from solar collectors and delivered to hot water TES tank during period $t \in T$ expressed in KW	M_t
Amount of customer cooling consumption, met from chilled water TES tank during period $t \in T$ expressed in KW	D_t^{CWT}
Amount of power supplied from hot water TES tank to the chiller during period $t \in T$ expressed in KW.	D_t^{HWT}
Amount of power supplied by the auxiliary boiler to the chiller during period $t \in T$, expressed in KW.	B_t

Table 4
Objective function of the mathematical model.

Definition	Term
This term is a ratio to convert the present worth (i.e. fixed costs) to an annualized worth where i is the interest rate and n is the life cycle	$\frac{i*(i+1)^n}{(1+i)^n-1}$
This term represents the fixed cost of a selected chiller where only a chiller will be installed in the system	$\sum_{k\in K} FC_k^{Ch} y_k$
This term represents the fixed cost of an installed solar collector area	$FC^{SC}x$
This term represents the fixed cost of a specific selected chilled water TES if it exists in the system	$\sum_{h\in H} FC_h^{CW} g_h$
This term represents the fixed cost of a specific selected hot water TES if it exists in the system	$\sum_{j\in J} FC_j^{HW} z_j$
This term represents the fixed cost of a specific selected auxiliary boiler if it exists in the system	$\sum_{q\in Q} FC_q^{HW} w_q$
This term represents the summation of the variable costs of producing cold water from the chiller during the observed periods (i.e., 8784 h)	$\sum_{t\in T} VC_t^{Ch} F_t^o$
This term represents the summation of the variable costs of storing cold water at chilled water TES during the observed periods (i.e., 8784 h)	$\sum_{t\in T} VC_t^{Chsto} I_t^{CW}$
This term represents the summation of the variable costs of storing hot water at hot water TES during the observed periods (i.e., 8784 h)	$\sum_{t\in T} VC_t^{Hsto} I_t^{HW}$
This term represents the summation of the variable costs of producing hot water from the auxiliary boiler during the observed periods (i.e., 8784 h)	$\sum_{t\in T} VC_t^{HW} B_t$

Lusail District in Qatar and Qatar University (QU) campus where they represent low, medium, high and very high cooling demand cases, respectively. For each of the following cases, two design scenarios are considered, the main design scenario which has all components presented in the system and the proposed mathematical model is used to find the optimal solution. The other scenario is a special design where heat produced only from the solar collectors (i.e., the auxiliary boiler is absent) in the system. Hence, the auxiliary boiler value w_q is set to zero in the mathematical model to ensure no heat will produce from it. Nonetheless, that will lead to an infeasible solution since the system under study starts operating during night periods and solar collectors do not produce heat as the sun is absent (i.e., global solar radiation values are zero during night periods). So, the absorption chiller demand for heat cannot fulfill. Therefore, two assumptions are made to solve such infeasibility. The first is related to the existence of hot water quantities at hot water TES in the first period to feed the absorption chiller with the required hot water in the first six periods during the sun absence. The other is assumption related to hot water quantities supplied to the absorption chiller to ensure the absorption chiller satisfies its demand for the hot water in the first period. These two assumptions incorporated into the mathematical model, and they are reflected in constraint number 13. An initial value assigned to I_t^{HW} and D_t^{HW}, and the updated constraints are:

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

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

$$If \quad t=1 \quad then \quad D_t^{HW} = Hot \quad water \quad supplied \quad to \quad absorption \quad chiller \quad in \quad the \quad first \quad period$$

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

This paper present the results of two case studies, namely; the medium cooling demand (i.e., TAMUQ), and the very high cooling demand case (i.e., QU campus). Each case is solved assuming two different design scenarios. These cases and scenarios are selected to show the obtained optimized SAC system for different applications with different cooling demands patterns. The proposed mathematical model was solved for these cases and scenarios and the results are reported in the below tables. TAMUQ has an academic section with an area of 30,800 m^2 and consists of 4 floors. The building's operation hours are from 8:00 am to 5:00 pm, from Sunday to Thursday where the building is occupied mainly by students. The number of students enrolled at TAMUQ is around 450 students and there are around 150 faculties and staffs. There are several breaks offered during the semester where both the student and non-student population decreases such as Eid Al-Fitr and Eid-Al-Adha holidays. The maximum cooling demand occurs in August with around 12,445 kW.

Table 9 shows the obtained results of the main design scenario of TAMUQ.

The observations of the obtained results are:

- The solar collectors supply 46% of the heat demand required by the absorption chiller while 54% are satisfied by the back-up boiler.
- There is a cold-water TES tank with a capacity of 63,000 kWh and a

Table 5
System configuration constraints of the mathematical model.

Definition	Constraint
This constraint enforces that only one chiller of a capacity k is installed in the system	$\sum_{k\in K} y_k = 1$
This constraint enforces that if a chilled water TES is installed in the system, it shall have only one capacity of h	$\sum_{h\in H} g_h \le 1$
This constraint enforces that if a hot water TES is installed in the system, it shall have only one capacity of j	$\sum_{j\in J} z_j \le 1$
This constraint enforces that if an auxiliary boiler is installed in the system, it shall have only one capacity of q	$\sum_{q\in Q} w_q \le 1$
This constraint introduces the total area selected of the solar collector where it should be less than or equal to the available area A and greater than or equal to the needed area to produce the required thermal energy. This constraint is summed over the observed periods (i.e., 8784 h)	$\frac{L_t}{\eta_{sc} G_t} \le x \le A$
This constraint ensures that the cooling produced from the selected chiller does not exceed the capacity of the installed chiller. This constraint is summed over the observed periods (i.e., 8784 h)	$F_t^o \le \sum_{k\in K} Q_k y_k$
This constraint ensures that the inventory level of the selected chilled water TES does not exceed the capacity of the installed chilled water TES. This constraint is summed over the observed periods (i.e., 8784 h)	$I_t^{CW} \le \sum_{h\in H} D_h g_h$
This constraint ensures that the inventory level of the selected hot water TES does not exceed the capacity of the installed hot water TES. This constraint is summed over the observed periods (i.e., 8784 h)	$I_t^{HW} \le \sum_{j\in J} R_j z_j$
This constraint ensures that the power produced from the selected auxiliary boiler does not exceed the capacity of the installed auxiliary boiler. This constraint is summed over the observed periods (i.e., 8784 h)	$B_t \le \sum_{q\in Q} L_q w_q EFF_q$
This constraint introduces the coefficient of performance of the selected chiller. However, it needs to be linearized since there are two decision variables multiplied with each other (i.e., $F_t^{In} y_k$). The linearization of this constraint is explained in the appendix	$F_t^o = \sum_{k\in K} COP_k F_t^{In} y_k$

Table 6
Energy balance constraints of the mathematical model.

Definition	Constraint
This constraint imposes the energy balance constraint for the selected chilled water TES where the inventory level of cooling at the previous period summed with the cooling quantities delivered to chilled water TES at the current period is equal to the inventory level of chilled water TES at the current period summed with the cooling quantities delivered to the customer. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$I_{t-1}^{CW} + \tau E_t = I_t^{CW} + \tau D_t^{CWT}$
This constraint imposes the energy balance constraint for the selected hot water TES where the inventory level of heat at the previous period summed with the heating quantities delivered to hot water TES at the current period is equal to the inventory level of hot water TES at the current period summed with the heating quantities delivered to the chiller. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$I_{t-1}^{HW} + \tau M_t = I_t^{HW} + \tau D_t^{HWT}$

Table 7
Supply demand constraints of the mathematical model.

Definition	Constraint
This constraint enforces that the customer demand for cooling could be met by the chiller, chilled water TES or both. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$S_t^{CW} + D_t^{CWT} = D_t$
This constraint enforces that the chiller demand for power could be met by solar collectors, hot water TES, or auxiliary boiler. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$L_t^C + B_t + D_t^{HWT} = F_t^{In}$
This constraint enforces that heat produced by solar collectors could be pumped directly into the chiller or hot water TES. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$L_t^C + M_t = L_t$
This constraint enforces that cooling produced by the chiller could be pumped directly to meet the customer demand or stored into the chilled water TES. This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$S_t^{CW} + E_t = F_t^o$

Table 8
Non-negativity and integrality constraints of the mathematical model.

Definition	Constraint
This constraint is to ensure that the decision variables y_k, g_h, z_j, w_q are binary variables where they take the value of 1 or 0	$y_k, g_h, z_j, w_q \in \{0, 1\}$
This constraint is to ensure that these decision variables are non-negative (i.e., are always positive). This constraint is expressed for each period t over the planning horizon (i.e., 8784 h)	$x, F_t^o, F_t^{In}, S_t^{CW}, L_t, L_t^c, I_t^{CW}, I_t^{HW}, E_t, M_t, D_t^{CWT}, D_t^{HWT}, B_t, F_{kt}^{In} \geq 0$

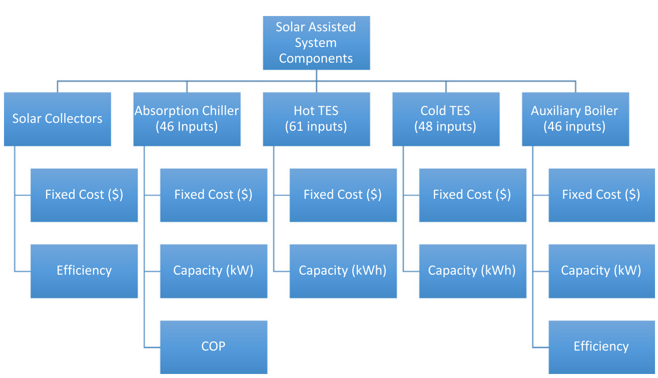

Fig. 2. Overview of the parameters' data collected.

fixed cost of $24,948 installed in the system.

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

Table 10 shows the obtained results of the special design scenario of TAMUQ assuming the required heat energy is only produced from the solar collectors (i.e., no auxiliary boiler). However, the existence of the other components remains the same as in the first design scenario.

The observations on the generated results are:

- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%).
- There is a hot water TES tank with a capacity of 126,000 kWh and a fixed cost of $49,896 installed in the system.
- There is a cold-water TES tank with a capacity of 63,000 kWh and a fixed cost of $24,948
- The absorption chiller's annual investment cost represents 51% of annual total investment cost which is equivalent to $177,932.
- The solar collector's annual investment cost represents 47% of total investment cost which is equivalent to $163,234.
- The cold-water TES tank's annual investment cost represents 1% of annual total investment cost which is equivalent to $2541.
- The hot water TES tank's annual investment cost represents 1% of total investment cost which is equivalent to $5,082.
- The annual operational cost to produce cold water from the absorption chiller represents 27% from the annual total operational cost which is equivalent to $2,240,489.
- The annual operational cost to store hot water at the hot water TES tank represents 73% from the annual total operational cost which is equivalent to $6,079,344.

The following observations and discussions were made to compare the obtained results from the two design scenarios (i.e., the main and

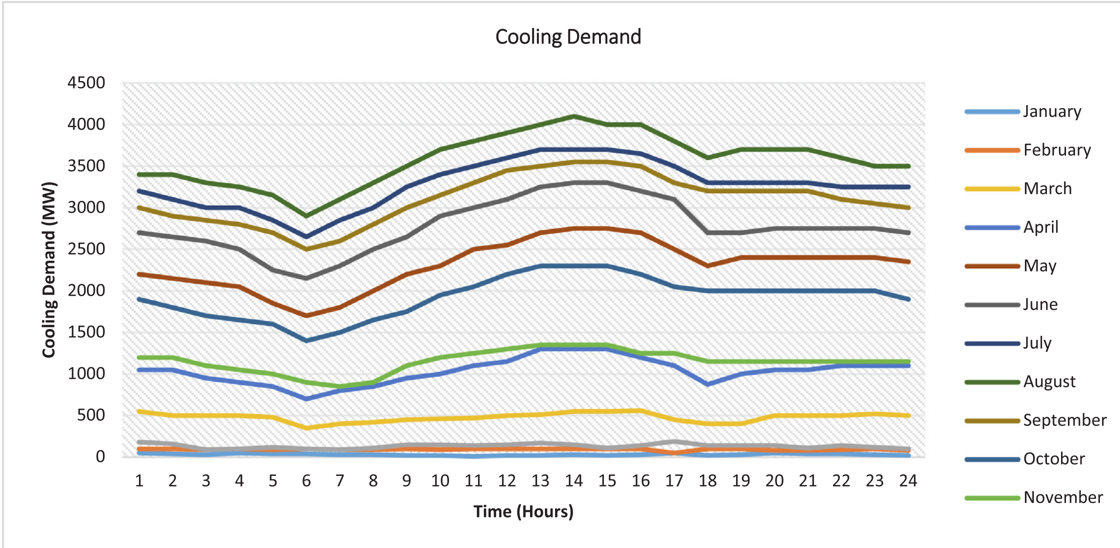

Fig. 3. Hourly cooling demand of Qatar over the year.

Table 9
Obtained results of solving the TAMUQ main design scenario using the mathematical model.

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

Table 10
Obtained results of the TAMUQ special design scenario.

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

Table 11
Obtained results of the QU main design scenario.

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

Table 12
Obtained results of the QU special design scenario.

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

Table 13
Summary of obtained results from all different design cases.

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Auxiliary Boiler	Annual Total Cost
Low Cooling Demand Scenario (5,820 kW)	5,830 kW; 1,053,280$; COP: 1.36	223.9 m^2; 67,170$; 0.75	N/A	N/A	6,156 kW; 123,096$; 0.85	1,589,951$
Medium Cooling Demand Scenario (12,445 kW)	12,000 kW; 1,746,960$; COP: 1.36	478.4 m^2; 143,520$; 0.75	N/A	63,000 kWh; 24,948$	10,260 kW; 205,160$; 0.85	3,342,561$
High Cooling Demand Scenario (17,590 kW)	17,640 kW; 2,568,031$; COP: 1.36	677.6 m^2; 203,280$; 0.75	N/A	N/A	17,850 kW; 318,750$; 0.85	4,742,285$
Very High Cooling Demand Scenario (21,101 kW)	24,000 kW; 3,493,920$; COP: 1.36	809.7 m^2; 242,910$; 0.75	63,000 kWh; 24,948$	N/A	17,850 kW; 318,750$; 0.85	5,705,970$

the special design):

- The solar collector's area and fixed costs have increased by 1017% compared to the main design scenario. This is reasonable as the solar collectors are the only source to produce the required heat to meet the absorption chiller's demand. The difference between the two annual fixed costs is around $148,616.
- A hot water TES tank exists in the special design scenario where it was absent in the main design scenario with a capacity of 126,000 kWh and a fixed cost of $49,896. This is expected as in the special design scenario, only solar collectors are used to generate heat (i.e., the auxiliary boiler is absent) during the day-time period. Hence, the solar collectors have to generate and store as much as possible of hot-water during the day-time period to be used during the night-time periods. Therefore, a hot water TES with a big capacity exists in the special design scenario.
- A cold-water TES tank of the same capacity and fixed cost exist in both of design scenarios, because the same chiller's capacity is being used in both of scenarios. Hence, the same quantities of water are being stored at the cold-water TES.
- The annual total cost of the system has increased by 159% compared to the main design scenario.
- The annual investment cost has increased by 61% due to several reasons which are the solar collectors area has increased significantly where the annual fixed cost of the solar collectors increased by 148,616$, and a hot water TES existed in the system with an annual fixed cost of $5,082.
- The annual operational cost has increased by 166% compared to the main design. One of the main reasons for such increase is the addition of the hot water TES, where more quantities of water need to be stored at the tank during the day-time period to be consumed at the night-time periods. Hence, that leads to consume more electricity due to storing more quantities of hot water in the hot TES tank. The annual operational cost of storing the hot water at the hot water TES tank represents 73% of the annual total operational cost in the special design scenario.

The other studied case is QU campus. QU has nine colleges with around 20,000 students and 2000 faculties. The operations time of QU start from 8 am to 8 pm from Sunday to Thursday. Along with the summer break, there is a semester break that occurs from mid of December to mid of January, and there is a week-long spring break in March. The cooling demand is around 6000 TR according to Takyeef Electromechanical website [10].

Table 11 shows the obtained results from the mathematical model optimization on the main design scenario of QU campus.

The observations on the generated results are:

- The boiler satisfies 54% of the heat demand required by the absorption chiller, while 46% are satisfied by solar collectors.
- There is a hot water TES with a capacity of 63,000 kWh and a fixed cost of $24,948 installed in the system.
- There is no cold-water TES installed in the system.
- The absorption chiller annual investment cost represents 86% of annual total investment cost, which is equivalent to $355,863.
- The solar collectors' annual investment cost represents 6% of annual total investment cost, which is equivalent to $24,741.
- The hot water TES annual investment cost represents 1% of annual total investment cost, which is equivalent to $2,541.
- The auxiliary boiler annual investment cost represents 8% of annual total investment cost, which is equivalent to $32,465.
- The annual operating cost to produce chilled water from the absorption chiller represents 72% of the total operating cost, which is equivalent $3,791,596.
- The annual operating cost to produce hot water from the auxiliary boiler represents 28% of the total operating cost, which is equivalent

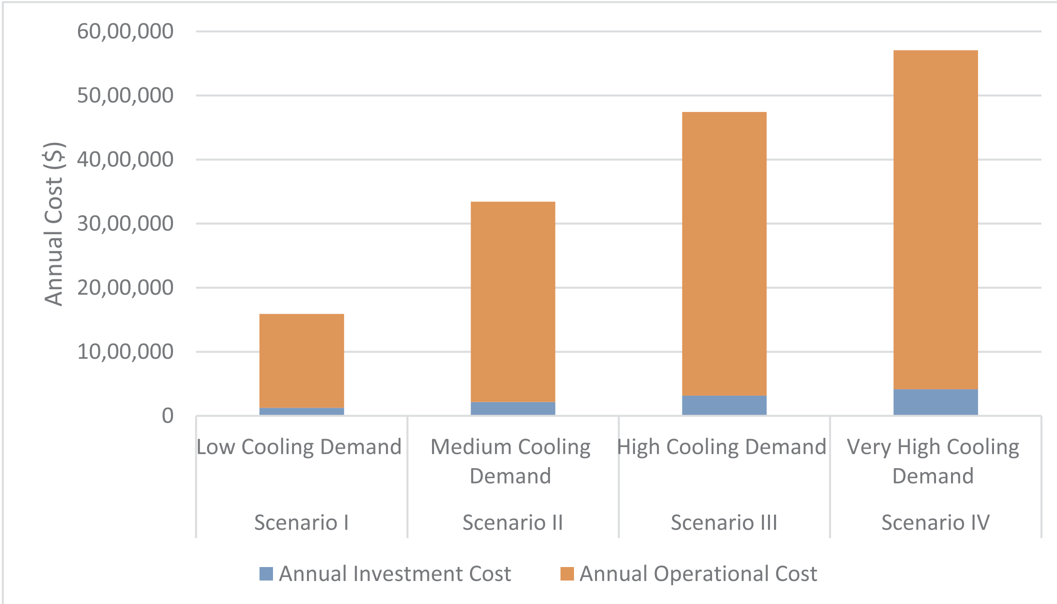

Fig. 4. Breakdown of annual total cost of each case for main design scenario.

to $1,498,749.

Table 12 shows the results obtained from the mathematical model optimization of the special design scenario of QU campus where heat produced only from the solar collectors (i.e., no auxiliary boiler). However, the existence of the other components remains the same as in the first design scenario.

The observations of the results obtained are:

- The solar collectors satisfy the complete heat demand required by the absorption chiller (100%).
- There is a hot water TES with a capacity of 270,000 kWh and a fixed cost of $106,920 installed in the system.
- There is no cold-water TES installed in the system.
- The absorption chiller annual investment cost represents 55% of annual total investment cost, which is equivalent to $355,863.
- The solar collectors' annual investment cost represents 43% of annual total investment cost, which is equivalent to $276,242.
- The hot water TES annual investment cost represents 2% of annual total investment cost, which is equivalent to $10,890.
- The annual operating cost to produce chilled water from the absorption chiller represents 27% of the total operating cost, which is equivalent to $3,791,596.
- The annual operating cost to store hot water at the hot water TES represents 73% of the total operating cost, which is equivalent to $10,288,158.

The following observations and discussions were made to compare the obtained results from the two different design scenarios:

- The solar collectors' area and fixed cost increased by 1017% compared to main design scenario. The difference between the two annual fixed costs is $251,501. This is a reasonable increase as the solar collectors are the only source to generate the required heat (i.e., the auxiliary boiler is absent) to meet the absorption chiller's demand.
- The hot water TES capacity and fixed cost increased by 329% compared to main design scenario. Hence, the annual fixed cost increased by $8349 compared to the main design scenario. The reason behind this increase in the hot water TES capacity, because the solar collectors are the only source to generate heat (i.e., the auxiliary boiler is absent) during the day-time periods. Hence, the solar collectors have to generate and store the required hot-water quantities during the day-time periods to be used during the night-time periods as well. Therefore, a hot water TES with a big capacity exists in the special design scenario.
- There is no cold-water TES in both of design scenarios and the reason behind this, is that an absorption chiller with a capacity greater than the peak cooling demand is selected in both of design scenarios. Hence, that eliminated the need to have a cold-water TES tank, since the absorption chiller will be able to generate the peak cooling demand at any time.
- The annual total system cost increased by 158% compared to the main design scenario.
- The annual investment cost increased by 55% due to increasing the hot water TES capacity by an annual fixed cost of $8349. However, most importantly, due to increasing the solar collectors', the annual fixed cost increased by $251,501 compared to main design scenario.
- The annual operational cost increased by 166% compared to main design. One of the main reasons for such increase is increasing hot water TES tank capacity, where more quantities of water needs to be stored at the TES tank during the day-time periods to be consumed at night-time periods. Hence, that leads to consuming more electricity due to storing more quantities of hot water in TES. The annual operating cost of storing hot water at TES represents 73% of the total operating cost in the special design scenario.

Table 13 summarizes the results of all cases.

Fig. 4 shows the annual investment and operating cost of each cases obtained from the main design scenario where all the components are considered in the mathematical model including the auxiliary boiler. The figure highlights that the fourth case (i.e., the very high cooling demand) has the highest annual total system cost which includes both the highest annual investment and highest annual operational cost. This is expected since the cooling demand of that case is the highest compared to other cases which mean that components with high capacities and high costs need to be installed to accommodate the required high cooling demand. Hence, as the cooling demand increases, the size and the cost of the system increase as well. There are couple points to highlight from Table 13:

Table 14 summarizes the special design scenarios results of all cases obtained from the mathematical model optimization.

Table 14
Summary of obtained results from special design scenario of all cases.

	Absorption Chiller	Solar Collectors	Hot Water TES	Cold Water TES	Annual Total Cost
Low Cooling Demand Scenario (5,820 kW)	5,830 kW; 1,053,280$; COP: 1.36	2,500.6 m^2; 750,180$; 0.75	63,000kWh; 24,948$	N/A	4,080,628$
Medium Cooling Demand Scenario (12,445 kW)	12,000 kW; 1,746,960$; COP: 1.36	5,342.2 m^2; 1,602,660$; 0.75	126,000kWh; 49,896$	63,000 kWh; 24,948$	8,669,053$
High Cooling Demand Scenario (17,590 kW)	17,640 kW; 2,568,031$; COP: 1.36	7,566.2 m^2; 2,269,860$; 0.75	270,000kWh; 106,920$	N/A	12,287,125$
Very High Cooling Demand Scenario (21,101 kW)	24,000 kW; 3,493,920$; COP: 1.36	9,040.6 m^2; 2,712,180$; 0.75	270,000 kWh; 106,920$	N/A	14,722,750$

Fig. 5 shows the annual investment and operating cost of each case obtained for the special design scenario where all the components are considered in the mathematical model except the auxiliary boiler. The very high cooling demand case has the highest annual total system cost due to the highest cooling demand amongst the others. However, with the main design scenario, there are two important points to highlight:

- The solar collector area increases, and hence the associated fixed cost due to the absence of the auxiliary boiler. The solar collectors are the only available source of heat in the system to cover the demand of the chiller. This is also related to the existence of the hot water TES tank in the optimized system. If a hot water TES tank already exist in the main design scenario, then its capacity increases in the special design scenario as more quantities of hot water will be stored at the tank. However, if there is no hot water TES tank in the main design scenario, then there will be a tank with large capacity for the same reason. This behavior can be noticed in all of the cases,
- If the capacity of the absorption chiller is greater than the peak cooling demand of the system, then this eliminates the need to have a cold-water TES since the chiller is able to cover the peak cooling demand of the customer. Such behavior can be noticed in low, high and very high versus medium cooling demand cases.

5. Sensitivity analysis

The purpose of sensitivity analysis is to measure the sensitivity of the optimal solution to changes made to one parameter at a time while the other parameters are kept fixed at their base values. The analysis conducted on the very high cooling demand case (i.e., QU campus). Table 15 shows the parameters studied during the analysis along with indicating the maximum (20%) and minimum (-20%) values that the base value is varied at using the incremental value. The maximum and minimum values are plotted on the x-axis, while the y-axis shows the Percentage of Total Cost Difference (PTCD) which is calculated using the following equation:

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

Table 16 summarizes the obtained results where it highlights the parameters that have a significant effect on the annual total system cost. Most of the obtained trends are straight-line which means a directly proportional relationship between the parameters and the annual total system cost observed for solar collectors' efficiency and cost, chiller COP and cost, boiler cost, and hot water TES cost as indicated from R^2 values in the Table 16. However, the boiler efficiency parameter has the only non-linear trend, and such behavior will be explained below.

The chiller COP parameter has the most effect on the annual total system cost, where increasing it by 20% will decrease the annual total system cost by -4.431% and decreasing it by 20% will increase the annual total system cost by 8.372%. Hence, the focus should be on increasing the COP to reduce the annual total system cost. Nevertheless, if that is infeasible due to technology availability or price, then decreasing the chiller cost parameter should be considered as a second alternative as it will decrease the annual total system cost by -1.247%. Also, if that is infeasible due to chiller type availability, then reducing the boiler cost parameter should be considered later. Lastly, the solar collector cost and efficiency, and hot water TES cost to be considered later, respectively. Fig. 6 highlights the behavior of the boiler efficiency parameter on the annual total system cost.

Fig. 6 shows the relationship of how varying the boiler efficiency effects on the annual total cost where increasing it above 0.85 (i.e., base value) doesn't effect on the annual total system cost. However, if the efficiency dropped below 0.85, then the annual total system cost starts to increase slowly. The reason behind that is the efficiency is changing from one period to another according to constraint number 10 and the

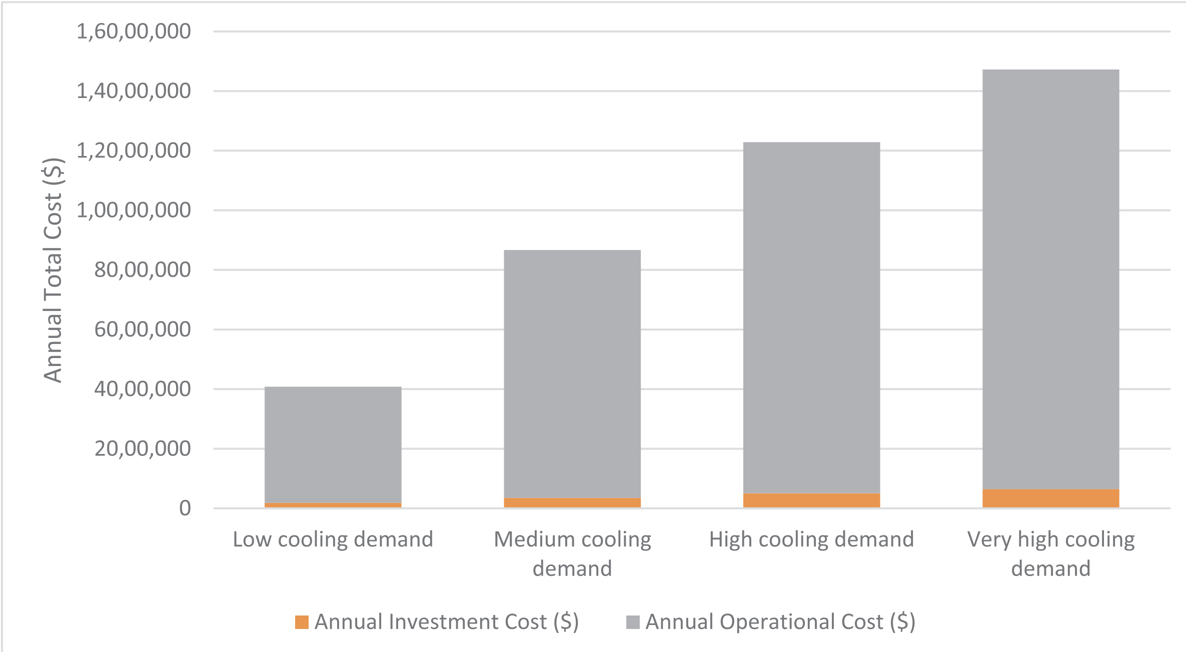

Fig. 5. Breakdown of annual total cost of each case for special design scenario.

Table 15
Parameters' values of the sensitivity analysis.

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

maximum efficiency the boiler operates at during the examined periods is 0.85. This behavior indicates that the full capacity of the boiler utilized at certain periods. Hence, selecting a boiler with an efficiency of more than 0.85 would not lead to minimizing the annual total system cost. This information is a useful indicator to the system owner, as employing a boiler with high capacity and efficiency with high fixed cost could be avoided since it will not contribute to decreasing the annual total system cost.

Figs. 7 and 8 summarize the sensitivity analysis results conducted on model parameters.

Fig. 7 shows the impact of efficiencies of solar collectors, chiller, and boiler on annual total system cost. According to generated straight-line equations, the chiller COP impacts the annual total system cost the most by 0.5986%. While the boiler efficiency impacts the annual total system cost of the system by 0.0393%. However, solar collector efficiency doesn't impact the annual total system cost significantly compared to others with an impact of 0.0088%. To this end, the focus should be on increasing the chiller COP as it effects the most on the objective function, which is finding an optimal system with a minimum annual total cost. The chiller is observed as a critical component in the system as it connects all components. Hence, increasing or decreasing the chiller COP will impact other components. For instance, increasing the COP will decrease the chiller capacity as more chilled water will produce for the same or less hot water quantities. As a result, solar collectors efficiency and area, hot water TES capacity and boiler capacity and efficiency will decrease as less hot water quantities will be required to produce the necessary chilled water. On the other hand, the annual total cost could reduce by increasing the solar collectors efficiency, but its effect on the objective function is way less than the impact of chiller COP on the objective function.

Fig. 8 shows the impact of fixed costs of solar collectors, chiller, boiler, and hot water TES on the annual total system cost. According to generated straight-line equations, the chiller fixed costs impacts the annual total cost the most by 0.1247%. While the boiler fixed cost impacts the annual total cost by 0.0114%. However, solar collectors and hot water TES fixed cost impacts the annual total cost the least by 0.0087% and 0.0009%, respectively. To this end, the focus should on

Table 16
Results of sensitivity analysis.

Parameters	Maximum Annual System Cost Difference Percentage (20%)	Minimum Annual System Cost Difference Percentage (−20%)	Generated Straight Line Equation	Coefficient of Determination R^2
Solar Collector Efficiency	−0.063	0.116	$y = -0.0088x + 0.1066$	$R^2 = 0.9745$
Chiller COP	−4.431	8.372	$y = -0.5707x + 6.2243$	$R^2 = 0.974$
Boiler Efficiency	0	1.268	Non-Linear Trend	$R^2 = 0.4766$
Solar Collector Cost $/m^2$	0.087	−0.087	$y = 0.0087x - 0.0954$	$R^2 = 1$
Chiller Cost $	1.247	−1.247	$y = 0.1247x - 1.3721$	$R^2 = 1$
Boiler Cost $	0.11	−0.11	$y = 0.0114x - 0.1252$	$R^2 = 1$
Hot Water Storage Tank Cost $	0.0089	−0.0089	$y = 0.0009x - 0.0098$	$R^2 = 1$

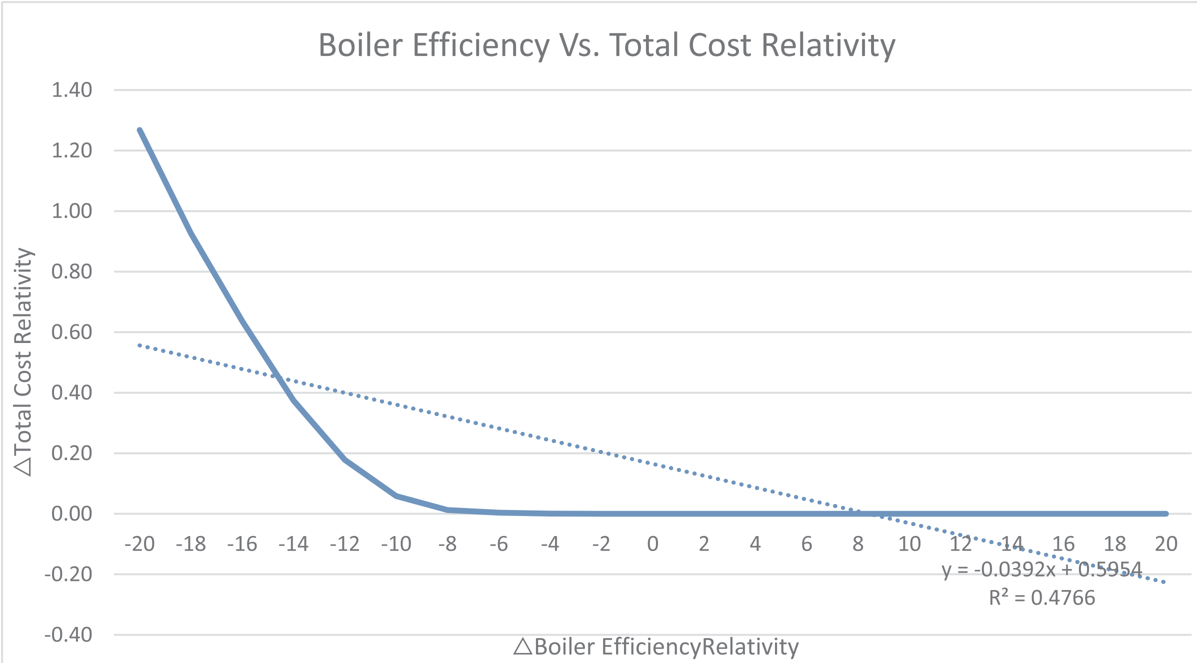

Fig. 6. Auxiliary boiler sensitivity analysis.

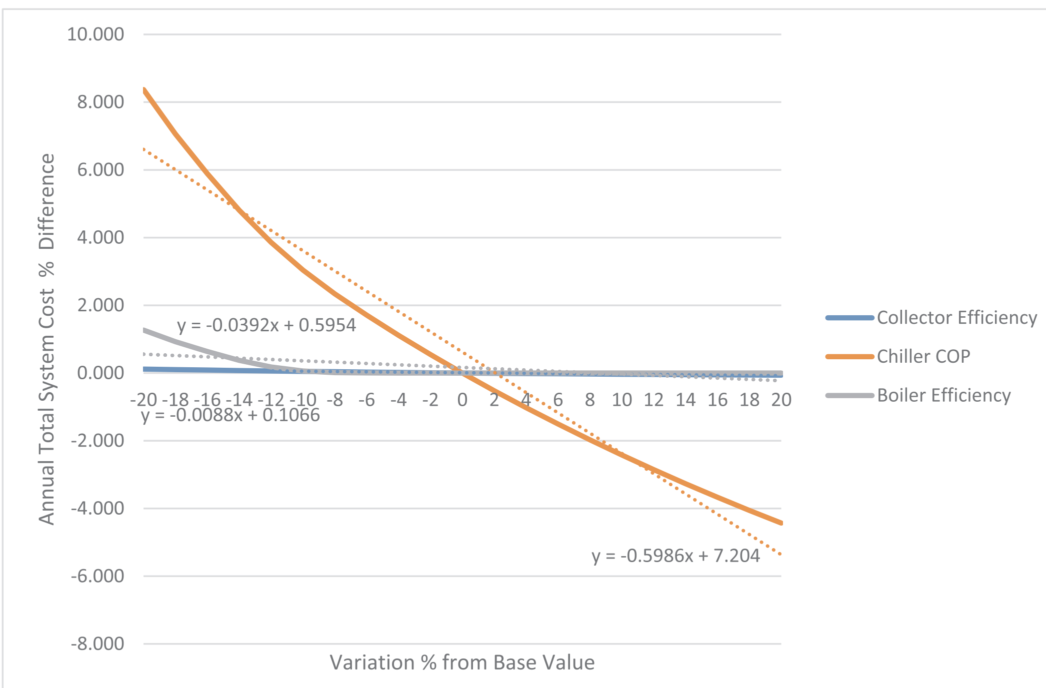

Fig. 7. Sensitivity analysis of efficiencies of specific parameters.

decreasing the chiller fixed cost as it affects the most on the objective function. Nevertheless, if the chiller fixed cost can't reduce due to a specific chiller type availability at the market, then boiler fixed cost should be considered as a second alternative. It will decrease the objective function, but not significantly as the chiller fixed cost would. As mentioned before, solar collectors and hot water TES fixed costs have the least impact on objective function compared to others. Nonetheless, decreasing their fixed cost is still considered as a viable option, especially if the system owner is trying to find different alternatives to reduce the total cost as much as possible.

6. Conclusion

In this paper, the problem of finding the optimal design and operation of the SAC system that minimizes the system's annual investment and operational costs are investigated. The problem is modeled as MILP problem and solved using CPLEX solver to obtain the optimal sizing of the system components and the optimal production and storage of cold and hot water on an hourly basis while satisfying the annual hourly cooling demand. The model was fed with real data collected from various reliable sources. The model was tested and analyzed over 8784 h/year using different annual demand patterns. Moreover,

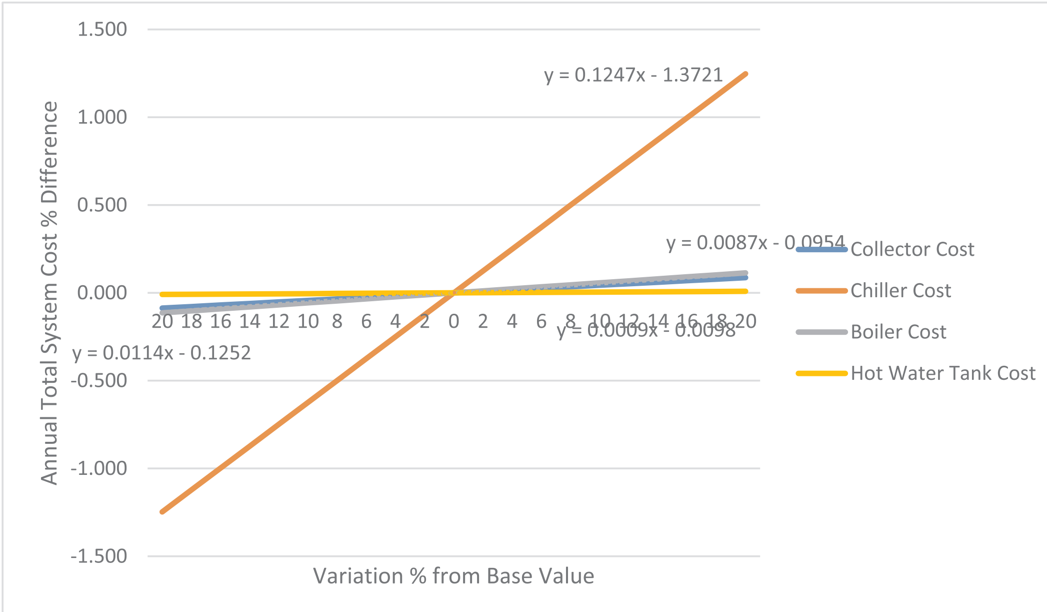

Fig. 8. Sensitivity Analysis of Fixed Cost of Parameters.

TAMUQ and QU campus were taken as case studies for model validation. The findings of the paper showed that solar collectors covered 46% of the chiller's heat demand. Moreover, in QU campus case study, the cold-water TES was absent in both design scenarios, because the selected chiller capacity is higher than the maximum cooling demand over the year. However, it is not the case for TAMUQ design case study, where a cold-water TES tank existed in both of design scenarios becasue of selecting a chiller with smaller capacity than the peak cooling demand. For QU campus, the solar collectors' area of the second design scenario (usage of 100% solar energy) had significantly increased by 1017% which created the need to have a hot-water TES tank with large capacity to store the needed quantities of hot water. The same observation can be highlighted for TAMUQ design case. Additionally, the results indicated that the annual total cost had increased by 158%, where the annual investment and operational cost had increased by 55% and 166%, respectively, for the second case compared to the first for both design scenarios. Finally, a sensitivity analysis was carried out on system parameters of QU campus design case, and the results indicated that the chiller COP had the most effect on the annual total system cost compared to other parameters. Where increasing COP by 20% of its initial value, decreases the annual total system cost by −4.431%. This paper provides a new method that helps the decision makers to design an optimal SAC system instead of designing an ad-hoc system built to meet only the peak demand without considering the cost as a major player. The SAC systems reported commonly in the previous works are designed based on the peak cooling demand over the year. This is known by an ad-hoc system which is a system that is only designed and built to satisfy the cooling demand with no regard to the system cost. Hence, these ad-hoc SAC systems as reported in previous works are overpriced compared to conventional solutions. Therefore, this paper develops a mathematical model that considers the initial and operational costs of the components as crucial inputs while satisfying the annual hourly cooling demand. The output of this mathematical model is an optimized system that has both the optimal design and operation of the system. Having this information available to the decision makers would help in making the right decisions related to installing the right components with the right capacities and features such as efficiencies at the right costs. For future research, a thorough comparison needs to be carried out between the performance of this proposed system, and the conventional cooling system and this is an ongoing research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This publication was made possible by the NPRP award [NPRP 10-0129-170280] from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

Authors' contributions

Dana M. Alghool: Ms. Alghool has written this paper based on her Master thesis. She has done all the necessary research work under her thesis supervisors (Dr. Tarek El Mekkawy and Dr. Adel Elomri). She has contributed to the problem definition, developing the mathematical model, collecting the necessary data, performing the experiments, and analyzing the results, writing and editing the manuscript.

Tarek Y. Elmekkawy: Dr. ElMekkawy is lead-PI of the funded research project that includes the work done in this paper. He was the main supervisor of Ms. Dana Alghool. He has contributed to all the work done in the paper.

Mohamed Haouari: Dr. Haouari has significant contribution to problem definition, mathematical modeling, and results analysis. He has contributed to the editing of the manuscript too.

Adel Elomri: Dr. Elomri has contributed to the mathematical modeling, results analysis, and the editing of the manuscript.

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