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MODELLING AND ANALYSIS

Optimal design and operation of conventional, solar electric, and solar thermal district cooling systems

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Abstract

This research investigates the integration of solar energy with traditional cooling technologies using solar electric cooling systems. A holistic optimization process is introduced to enable the cost-effective design of such technology. Two mixed-integer linear programming (MILP) models are developed, one for a baseline conventional cooling system and the other for a solar electric cooling system. The MILP models determine the optimal system design and the hourly optimal quantities of electricity and cold water that should be produced and stored while satisfying the cooling demand. The models are tested and analyzed using real-world data, and multiple sensitivity analyses are conducted. Finally, an economic comparison of solar thermal and solar electric cooling systems against a baseline conventional cooling system is performed to determine the most cost-effective system. The findings indicate that the photovoltaic panels used in solar electric cooling cover 42% of the chiller demand for electricity. Moreover, the solar electric cooling system is found to be the most cost-effective, achieving ~5.5% and 55% cost savings compared with conventional and solar thermal cooling systems, respectively. A sensitivity analysis shows that the efficiency of photovoltaic panels has the greatest impact on the annual cost of solar electric cooling systems—their annual cost only increases by 10% when the price of electricity increases by 20%, making solar electric the most economical system.

KEYWORDS

conventional cooling system, mixed-integer linear programming model, sensitivity analysis, solar electric cooling system, solar energy, solar thermal cooling system

1 | INTRODUCTION

In recent decades, researchers have started to investigate the integration of renewable energy into cooling technology to replace traditional methodologies. These investigations were triggered by enormous increases in both the environmental footprint and energy costs of cooling devices. The use of air conditioners is increasingly common, especially in the world's hottest regions, a result of both increased incomes and population growth. Around two-thirds of the households across the globe will have an air conditioner by 2050, with China, Indonesia, and India together accounting for almost half of the total. Hence, the energy demand for space cooling is expected to triple by 2050, consuming as much electricity as China and India combined, if no actions are taken to improve energy efficiency.[1] This growing cooling demand is affecting the power generation and distribution capacity, particularly during extreme heat events and peak demand periods. In summer 2017, a heatwave across Beijing caused the space cooling in buildings to account for more than 50% of residential peak electricity demand. This significant increase in the cooling demand caused global CO_2 emissions to triple to 1130 million tons between 1990 and 2018.[2] In China, the demand for cooling services has increased at a rate of 13% per year since 2000, reaching 400 TWh in 2017. Interestingly, cooling services represent nearly 16% of the highest load of electricity and, on certain days, may reach 50% of the peak demand. Subsequently, CO_2 emissions in China increased by a factor of five between 2000 and 2017.[3] Qatar represents a critical case, with cooling energy accounting for 70% of the highest demand for electricity during the summertime period.[4] Thus, Qatar has been classified as one of the countries with the highest CO_2 emissions per capita.[5]

Two approaches may result in sustainable air cooling that will decrease energy consumption and its corresponding CO_2 emissions. The first approach involves enhancing the energy performance standards of cooling equipment and considerably increasing the building design standards. The second approach is to employ clean or renewable energy to provide cooling services. The latter is more convenient, as the highest demand for cooling energy occurs in countries with plenty of available solar radiation, making solar energy an attractive choice. This research focuses on integrating solar energy with district cooling systems. The integration of solar thermal or solar electric with cooling technologies, known as solar-assisted cooling (SAC), appears to be an interesting choice for replacing traditional cooling technologies that are driven by fossil fuels or grid electricity. Solar cooling systems could significantly contribute to meeting the growing demand for cooling and could potentially be paired with demand-side management tools to reduce the effect of peak demand on electricity systems.[3] Solar-powered cooling technologies are classified as either solar thermal cooling, which has been thoroughly discussed,[6] or solar electric cooling. The latter uses photovoltaic (PV) panels to generate electricity and power an electricity-driven chiller.[7] Hence, this research investigates solar electric cooling systems (SECSs).

The main components of SECSs are PV panels, a storage battery, an inverter circuit, and a vapor-compression chiller.[7] SECSs have two main application types: grid-connected systems and stand-alone systems. This research will focus on the first type, in which PV panels generate the electricity needed by the compression chiller and any additionally generated electricity is sent to the grid to be used in case of scarce sun radiation. The application of SECSs has been delayed for many years due to the high investment costs of PV panels and the cooling equipment, even though they are easy to implement. Recently, this technology has captured more attention due to (i) the cost of PV panels dropping significantly; (ii) the use of solar energy, which is a clean and naturally available source and reduces the reliance on fossil fuels; (iii) the high coefficient of performance (COP) of compression chillers; and (iv) the low system maintenance and operational costs.[8] Nevertheless, there are disadvantages associated with these systems: (i) They require more space for installation and (ii) there are high costs involved in the production and installation of ad hoc systems.[9] Despite the advantages offered by SECSs, there are significant fixed and operational costs associated with employing such systems. Consequently, to exploit these advantages, the optimization of SECSs at the planning and design phase is crucial.

Nevertheless, the mathematical optimization of SECSs has not been widely investigated.[10] Several studies have focused on constructing ad hoc and oversized SECSs using non-mathematical optimization methods (eg, simulation approaches), where the system cost is rarely considered. Such studies were carried out by Fong et al.,[11] Eicker et al.,[12] Hartmann et al.,[13] and Noro et al.[14] and are reviewed in detail in the literature review section. All of these developed SECSs are ad hoc systems, which means that decisions related to design, installation, and operation are not comprehensively examined from an optimization perspective. These systems are built to satisfy the peak demand without considering the costs.

The system cost is the main barrier preventing SECSs from being widely employed. There is a widespread belief that SECSs are much costlier than traditional cooling systems. Indeed, simulating their proposed systems, certain studies like Al-Ugla et al.[15] and Eicker[16] have found that such systems are not competitive. Nevertheless, there are multiple decisions throughout the system design stage that crucially affect the cost of the system and the complexity of solving such a problem. These decisions are concerned with the system's component selection, where many choices and technologies exist in the market. Moreover, the different system components have many associated design specifications and requirements, and this increases the complexity of the problem from an optimization perspective. It is vital to choose suitable components with appropriate features (ie, capacity and efficiency) to satisfy the hourly demand for cooling; otherwise, the system will not work optimally. To date, however, none of these decisions has been considered in any of the literature. Hence, it is necessary to consider these decisions during the system development stage so as to find the optimal configuration in terms of the type, capacity, and efficiency of each component in the system, thus ensuring the minimum system design and operation costs.

Consequently, the novelty of this research lies in the consideration of these decisions during the system development stage from a mathematical optimization perspective. More precisely, this research aims to find the optimal design variables (ie, compression chiller capacity and COP, cold water thermal energy storage [TES] capacity, and PV panel area) along with the optimal operational variables (ie, hourly amounts of cold water to be produced and stored, hourly amount of electricity delivered to the chiller from the grid, hourly amount of electricity delivered to PV panels from the grid, and hourly amount of electricity delivered from the grid to PV panels) while satisfying a time-varying cooling demand at the lowest annual total system cost (ATSC). To achieve this, the present research proposes mathematical models that capture all of the main design and operation variables of the two systems. The mathematical models guarantee that the optimal design and operation of the system is obtained, unlike the simulation approaches used in previous studies. To enable a reasonable comparison, the ATSC should be determined for both the baseline conventional cooling system (BCCS) and SECS. Finally, this research presents an economic comparison between a solar thermal cooling system (STCS),[17] the SECS, and the BCCS to determine the most cost-effective system.

The remainder of this paper is organized as follows. Section 2 reviews the literature on SECS. Section 3 describes the problem addressed in this research along with the problem formulation for the proposed systems. The data collected for the various parameters are presented in section 4, along with numerical results from solving the developed models. Section 5 describes the sensitivity analyses conducted on the system parameters. Finally, section 6 concludes this paper by summarizing the main findings of this study and highlighting areas for future research.

2 | LITERATURE REVIEW

The optimization of SECSs has been investigated by several researchers. Most of the published papers in this area describe a technical/economic comparison between SECSs and other systems (ie, STCSs and/or conventional cooling systems) using simulation approaches. For example, several papers described the use of the TRaNsient SYstem Simulation (TRNSYS) software in their research. Fong et al.[11] compared five different types of STCS, SECS connected to the grid, and conventional cooling systems. The study was conducted to examine comfort cooling for offices in Hong Kong. The assessment criteria included the solar fraction, COP, primary energy consumption, and solar thermal gain. Their findings highlighted that the SECSs and STCSs reduce energy consumption by 15.6% and 48.3%, respectively, over conventional cooling systems. Similarly, Hartmann et al.[13] compared an STCS and an SECS for cooling offices in Europe. The comparison identified the potential cost and energy savings under the given cooling and heating demand. These two systems were also compared against a traditional cooling system composed of a compression chiller driven by electricity from the grid. The simulation results showed that the SECS achieved the greatest energy and cost savings. Eicker et al.[12] described an economic comparison between reference conventional, solar thermal, and solar electric systems. The SECS was simulated using the INSEL and FORTRAN software, with TRNSYS and TRANSOL used for the solar thermal system. The results showed that solar electric systems meet more than half of the electricity demand, and produce energy savings of close to 50%, compared with 30% for STCSs. Finally, Noro and Lazzarin[14] compared STCSs with SECSs. The systems were developed to function under a certain climate to satisfy a building's demand for cooling. The simulation results showed that STCSs achieve higher overall system efficiency. Moreover, a sensitivity analysis was conducted with respect to the collector's fixed costs, interest rate, and solar ratio. The results pointed out that PV panels had a lower specific cost than solar collectors. Lastly, the solar electric system attained a higher net present worth and discounted payback period than solar thermal and conventional cooling systems.

In addition to the abovementioned studies, several papers have compared different SAC technologies without highlighting the performance evaluation approach (ie, simulation or mathematical). Mokhtar et al.[18] evaluated the performance of different SAC systems in terms of cost, cooling demand, and climate. The approach measured the techno-economic performance of the systems and highlighted the importance of considering the relationship between solar availability and cooling demand, as neglecting such a relationship would cause the capacity of a solar cooling system to be overestimated. Additionally, Mokhtar et al.[18] showed that SECSs were the most economical system and had the highest overall efficiency. Similarly, Otanicar et al.[19] compared different types of SAC systems based on the initial costs of each technology and their environmental effects. The results indicated that the cost of SECSs was dependent on the system COP when the PV price remained constant. Moreover, solar electric systems were found to have lower carbon dioxide emissions than solar thermal systems because of the high COP of SECSs and the small footprint of PV panels. Eicker[16] performed a parametric study comparing conventional, solar electric, and solar thermal systems for cooling. The study evaluated the system performance by measuring the effect of changing one parameter at a time. The paper concluded that SECSs produced the greatest energy savings; however, they had a higher annual cost than traditional cooling systems due to the highly subsidized prices of electricity in Egypt. Porumb et al.[20] studied the effect of ambient temperature and solar radiation on solar collectors and PV panels. Their paper highlighted that STCSs achieved 24.5% annual solar cooling fraction with lower initial fixed costs, while SECSs gave a 36.6% annual solar cooling fraction at higher initial fixed costs. Al-Ugla et al.[15] described a thermo-economic comparison between solar electric, solar thermal, and conventional cooling systems. The economic performance of the systems was evaluated based on their net present value and payback period. The findings indicated that STCSs were more economical than SECSs. Nevertheless, there was a greater possibility of employing solar cooling technologies in larger buildings and at higher electricity rates. Finally, Papoutsis et al.[21] compared solar thermal, solar electric, and hybrid solar cooling systems. The results showed that SECSs had the best performance in terms of system COP (ie, chiller COP and PV efficiency) and the highest cooling efficiency.

In summary, compared with previous studies, the novel aspects of this research are as follows:

1. This research presents a mixed-integer linear programming (MILP) model that adopts a holistic approach to find the optimal design and operation of a BCCS. Precisely, the model computes the optimal design variables (ie, compression chiller capacity and COP, cold water TES capacity) along with the optimal operational variables (ie, hourly amounts of cold water to be produced and stored and hourly amount of electricity delivered to the chiller from the grid) while satisfying a time-varying demand at the minimum ATSC. By contrast, the published work in this area is related to the optimization of the distribution pipeline network design and end-user consumer facilities. These papers do not focus on the optimization of the entire BCCS, including both demand and supply sides. Therefore, it is important to focus on optimizing the design and operation of these systems using mathematical modeling approaches.[10]
2. This research introduces an MILP model that determines the optimal design and operation of an SECS connected to the grid. Precisely, the model computes the optimal design variables (ie, compression chiller capacity and COP, cold water TES capacity, and PV panel area) along with the optimal operational variables (ie, hourly amounts of cold water to be produced and stored, hourly amount of electricity delivered to the chiller from the grid, hourly amount of electricity delivered to PV panels from the grid, and hourly amount of electricity delivered from the grid to PV panels) while satisfying a time-varying demand at the minimum ATSC. By contrast, the majority of the previous studies in this area have not investigated the optimal design and operational parameters of SECSs so as to maximize the environmental benefits and energy savings or minimize the total system cost. The reviewed papers report comparisons between ad hoc SECS designs and other systems (ie, STCS and BCCS). These comparisons are based on evaluating the environmental and/or economic performance of different systems. The common approach used to conduct these comparisons is simulation modeling as a stand-alone approach, such as with TRNSYS. Simulations are a useful tool for understanding and assessing the performance and behavior of such systems under various design conditions, but cannot be used as a stand-alone optimization approach. However, the main downside of using simulation approaches is that the system parameters are likely to become trapped around local optima. Thus, this approach does not guarantee the optimal design and operation of the system. Hence, it is crucial to use optimization approaches to determine the optimal design and operation parameters of the system. Nevertheless, few studies have used mathematical optimization approaches to find the optimal SECS design as part of a bigger system (ie, combined cooling, heating, and power) while satisfying some objective function(s).[22-24] These papers are not purely dedicated to optimizing the SECS, as they do not focus on the optimal design and operation of such a system. All of these developed SECSs are ad hoc systems, which means that decisions related to design, installation, and operation are not comprehensively examined from an optimization perspective. These systems are built to satisfy the peak demand without considering the costs. However, this research *optimizes* the design and operation of an SECS, which will result in an optimal economic system.
3. This research describes an economic comparison of the STCS and SECS configurations against the BCCS model to determine the most cost-effective approach in terms of the ATSC.

3 | SCOPE AND FORMULATION OF THE PROBLEM

3.1 | Scope and description of the problem

The problem addressed in this research is to find the optimal designs and operational policies of a BCCS and an

SECS using MILP models. The objective of these models is to minimize the system's investment and operating costs. The main BCCS components are as follows:

I A compression chiller with a specific COP, cost, and capacity.
II TES tanks with a specific cost and capacity.

In addition to the above components, the SECS includes the following:

III PV panels with a specific type, cost, and efficiency.

Hence, the proposed SECS is composed of three main components: compression chiller, TES, and PV panels. Figure 1 shows the scope of the proposed BCCS and the movement of energy in electricity and cold water forms within the components of the system (indicated by the directions of the arrows) for each period *t*. The proposed system starts by delivering electricity to the chiller from the grid (K_t) to drive the chiller under the required electricity amount (F_t^{In}). The chiller then produces cold water (F_t^o) to satisfy the customer cooling demand (S_t^{CW}), and the surplus cold water is delivered to the cold water TES (E_t) to satisfy the cooling demand at later periods (D_t^{CWT}).

Figure 2 shows the scope of the SECS and the movement of energy in electricity and cold water forms within the components of the system for each period *t*. The system starts with PV panels collecting radiation from the sun (L_t), with the chiller then operated using the electricity generated by the PV panels (L_t^c). If the generated electricity is not sufficient to power the chiller, then the grid will supply the extra electricity needed (K_t). If the generated electricity exceeds that required by the chiller, then the extra electricity generated is delivered to the grid ($\overline{L_t^c}$). Thus, the overall amount of electricity needed by the chiller (F_t^{In}) is covered by the grid, PV panels, or both. The chiller then produces cold water (F_t^o) to satisfy the customer cooling demand (S_t^{CW}), and the surplus cold water is delivered to the cold water TES (E_t) to satisfy the customer cooling demand at later periods (D_t^{CWT}).

The components of both systems are intertwined and interconnected, and so this research proposes integrated models that properly capture all of these interdependencies. More specifically, for a given anticipated hourly demand for one year, the mathematical model's solution will give:

a. The compression chiller's capacity with its COP and cost,
b. The cold water TES capacity with its cost (if any),
c. The amount of cold water produced at each hour of the year,
d. The amount of cold water stored at each hour of the year (if any),
e. The amount of electricity delivered to the chiller from the grid at each hour of the year.

In addition to the above, the solution for the SECS will specify:

f. The optimal area and type of the PV panels,
g. The amount of electricity delivered to the grid from the PV panels at each hour of the year,
h. The amount of electricity delivered from the PV panels to the chiller at each hour of the year.

3.2 | Formulation of the problem

This research addresses the problem of the optimal design and operation of a BCCS and an SECS. Thus, these two systems are formulated as MILP models. Each MILP structure

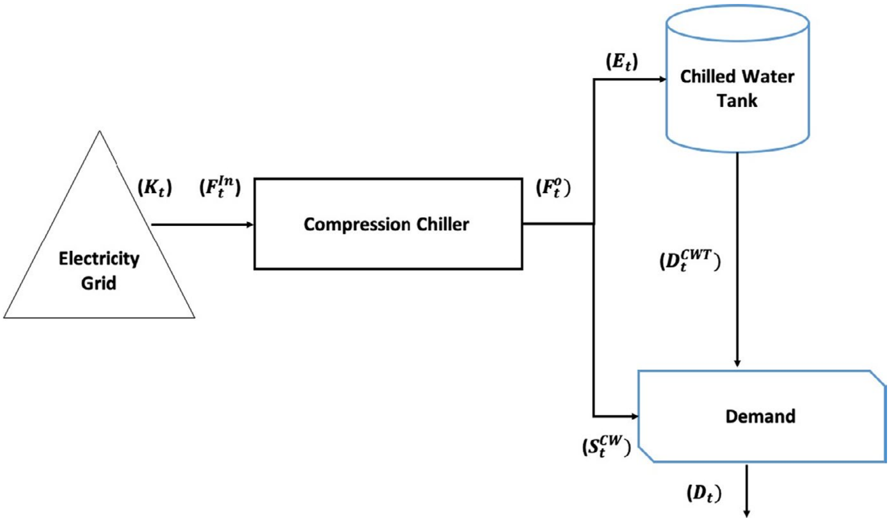

FIGURE 1 System configuration of the BCCS

FIGURE 2 System configuration of the SECS

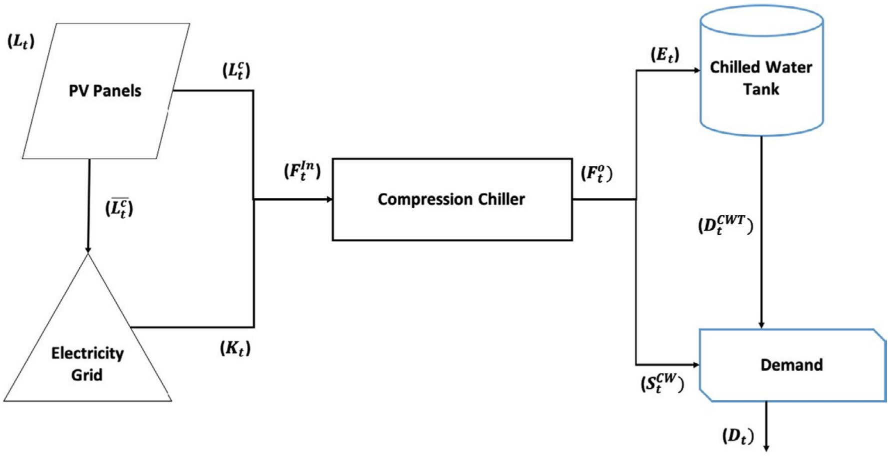

TABLE 1 BCCS sets and indices

Symbol	Definition
T	Time periods, denoted by t
K	Chiller capacities, denoted by k
H	Cold water TES capacities, denoted by h

consists of sets and indices, as well as the parameters that are concerned with the system components (ie, capacities, investment costs, efficiencies). The decision variables cover the systems' component selection, inventory levels at the TES tanks, and electricity and cold water stored in the TES tanks or consumed by a component. The models' objective functions minimize the sum of the component's annual investment costs (AICs) and annual operational costs (AOCs) over the systems' lifetime. Finally, constraints related to the system configuration, supply and demand, energy balance, and system non-negativity integrality are considered.

The model formulation considers the following assumptions:

- The annual hourly demand for cooling is deterministic and known in advance.
- The TES operates completely efficiently with insignificant losses.
- The PV panels' efficiency is constant and identified in advance.
- The systems function in a steady-state condition.

Alghool et al.[6] introduced and discussed the MILP of an STCS; the mathematical model will not be discussed here. To ensure a thorough comparison with the models developed in this research, the BCCS and SECS are compared with the STCS. The structure of the two systems' mathematical models (ie, sets and indices, parameters, decision variables) is described below.

TABLE 2 BCCS parameters

No.	Symbol	Definition
1	FC_k^{Ch}	Selected chiller investment cost of capacity, $\forall k \in K$
2	FC_h^{CW}	Selected cold water TES investment cost of capacity, $\forall h \in H$
3	VC_t^{Ch}	Variable cost of cold water production from a chiller through a period, $\forall t \in T$
4	VC_t^{Chsto}	Variable cost of cold water storage at a TES through a period, $\forall t \in \mathrm{T}$
5	Q_k	k^{th} capacity chiller in kW, $\forall k \in K$
6	COP_k	k^{th} capacity chiller COP, $\forall k \in K$
7	D_h	h^{th} capacity cold water TES in kWh, $\forall h \in H$
8	D_t	Customer cooling demand in kW through a period, $\forall t \in T$
9	τ	Time period duration, in hours
10	VC_t^{Gr}	Variable cost of delivering electricity to the chiller through a period, $\forall t \in T$

3.2.1 | Baseline conventional cooling systems

The model formulation includes the following notation.

Sets and Indices

Table 1 highlights the sets and indices included in the BCCS model and their definitions.

Parameters

Table 2 highlights the parameters included in the BCCS model and their definitions.

Decision variables

Table 3 highlights the decision variables included in the BCCS model and their definitions.

TABLE 3 BCCS decision variables

No.	Symbol	Definition
1	y_k	Binary decision variable that takes a value of 1 if a chiller with capacity Q_k is selected, $k \in K$, and 0 otherwise
2	g_h	Binary decision variable that takes a value of 1 if a cold water TES with capacity D_h is selected, $h \in H$, and 0 otherwise
3	F_{kt}^{In}	Power consumed by a chiller $k \in K$ in kW through a period $t \in T$
4	F_t^{In}	Power consumed by chillers in kW through a period $t \in T$
5	F_t^o	Cold water produced by chillers in kW through a period $t \in T$
6	S_t^{CW}	Customer cooling demand satisfied from chillers in kW through a period $t \in T$
7	I_t^{CW}	Cold water inventory level stored at a cold water TES in kWh at the end of a period $t \in T$
8	E_t	Cold water delivered to a cold water TES from chillers in kW through a period $t \in T$
9	D_t^{CWT}	Customer cooling demand satisfied from a cold water TES tank in kW through a period $t \in T$
10	K_t	Power supplied to chillers from the grid in kW through a period $t \in T$

Objective function

The objective function aims to minimize two parts: the system components' AIC and the AOC of these components. The AIC is the sum of the AICs of the compression chiller and the cold water TES. The AOC is the sum of the annual variable costs of producing cold water from the compression chiller, storing cold water in the TES, and delivering electricity to the chiller from the grid. The investment costs of the components are multiplied by a ratio (ie, find A given P [A/P] factor) to find their annual values. The ratio considers the component lifecycle and interest rate. In this research, the same interest rate and lifecycle are assumed for all components.

$$\text{Minimize} \left(\frac{i*(i+1)^n}{(1+i)^n-1} \left[\sum_{k \in K} FC_k^{Ch} y_k + \sum_{h \in H} FC_h^{CW} g_h \right] \right) + \sum_{t \in T} VC_t^{Ch} F_t^o + \sum_{t \in T} VC_t^{Chsto} I_t^{CW} + \sum_{t \in T} VC_t^{Gr} K_t$$

where the system lifetime $n = 20$ years and the interest rate $i = 8\%$.

Table 4 highlights the objective function terms included in the BCCS model and their definitions.

Constraints

Table 5 highlights the constraints included in the BCCS model and their definitions.

3.2.2 | Solar electric cooling systems

The model formulation consists of the following notation.

Sets and indices

The sets and indices are the same as for the BCCS (see Table 1).

Parameters

In addition to parameters 1–10 in Table 2, Table 6 presents the additional parameters included in the SECS model and their definitions.

Decision variables

In addition to decision variables 1–10 in Table 3, Table 7 shows the additional decision variables included in the SECS model and their definitions.

Objective function

With reference to the objective function of the BCCS, the SECS objective function has an investment cost term for the PV panels and an annual selling price of electricity to the grid from the PV panels.

$$\text{Minimize} \left(\left(\frac{i*(i+1)^n}{(1+i)^n-1} \left[\sum_{k \in K} FC_k^{Ch} y_k + FC^{PV} x + \sum_{h \in H} FC_h^{CW} g_h \right] \right) + \sum_{t \in T} VC_t^{Ch} F_t^o + \sum_{t \in T} VC_t^{Chsto} I_t^{CW} + \sum_{t \in T} VC_t^{Gr} K_t \right) - \sum_{t \in T} P\overline{L_t^C}$$

where the system lifetime $n = 20$ years and the interest rate $i = 8\%$.

In addition to terms 1–6 in Table 4, Table 8 lists the objective function terms included in the SECS model and their definitions.

Constraints

In addition to constraints 1–8, 10, and 11 in Table 5, Table 9 lists the constraints included in the SECS model and their definitions.

TABLE 4 BCCS objective function terms

No.	Term	Definition
1	$\frac{i*(i+1)^n}{(1+i)^n-1}$	Ratio for converting present values to annual values, where n is the system lifetime and i is the interest rate
2	$\sum_{k\in K}\text{FC}_k^{\text{Ch}}y_k$	Selected chiller investment cost when one chiller is installed in the system
3	$\sum_{h\in H}\text{FC}_h^{\text{CW}}g_h$	Selected cold water TES investment cost if it exists in the system
4	$\sum_{t\in T}\text{VC}_t^{\text{Ch}}F_t^o$	Sum of the variable costs of cold water produced from the chiller over a period of 8784 h
5	$\sum_{t\in T}\text{VC}_t^{\text{Chsto}}I_t^{\text{CW}}$	Sum of the variable costs of cold water stored at the cold water TES over a period of 8784 h
6	$\sum_{t\in T}\text{VC}_t^{\text{Gr}}K_t$	Sum of the variable costs of supplying electricity to the chiller from the grid over a period of 8784 h

TABLE 5 BCCS constraints

No.	Constraint	Definition
1	$\sum_{k\in K}y_k = 1$	Ensures that one chiller with capacity k is selected and installed in the system
2	$\sum_{h\in H}g_h \leq 1$	Ensures that the cold water TES has capacity h, if it exists in the system
3	$F_t^o \leq \sum_{k\in K}Q_k y_k$	Ensures that the cold water produced from the installed chiller does not exceed its capacity, summed over 8784 h
4	$I_t^{\text{CW}} \leq \sum_{h\in H}D_h g_h$	Ensures that the stored cold water in the installed cold water TES does not exceed its capacity, summed over 8784 h
5	$F_t^o = \sum_{k\in K}\text{COP}_k F_t^{\text{In}} y_k$	Selected chiller COP. This constraint needs to be linearized, as two decision variables (ie, $F_t^{\text{In}}y_k$) are multiplied by one another. The constraint is summed over 8784 h
6	$I_{t-1}^{\text{CW}} + \tau E_t = I_t^{\text{CW}} + \tau D_t^{\text{CWT}}$ $I_0^{\text{CW}} = I_T^{\text{CW}}$	Energy balance, where the previous period's cold water inventory level added to the current period's cold water delivered to the cold water TES is equal to the current period's cold water inventory level added to the current period's cold water delivered to the customer. The constraint represents each period t over 8784 h
7	$S_t^{\text{CW}} + D_t^{\text{CWT}} = D_t$	Ensures that the customer cooling demands can be satisfied by the cold water, chiller, or both. The constraint represents each period t over 8784 h
8	$S_t^{\text{CW}} + E_t = F_t^o$	Ensures that the cold water produced by the chiller can be stored in the cold water TES or can satisfy the customer cooling demands. The constraint represents each period t over 8784 h
9	$K_t = F_t^{\text{In}}$	Ensures that the electricity demand of the chiller is met by the grid. The constraint represents each period t over 8784 h
10	$y_k, g_h \in \{0,1\}$	Guarantees that the decision variables y_k, g_h are binary variables with values of 0 or 1
11	$F_t^o, F_t^{\text{In}}, S_t^{\text{CW}}, I_t^{\text{CW}}, E_t, K_t, D_t^{\text{CWT}}, F_{kt}^{\text{In}} \geq 0$	Guarantees that the decision variables are non-negative. The constraint represents each period t over 8784 h

4 | DATA COLLECTION AND EXPERIMENTAL RESULTS

4.1 | Data Collection

For this research, data related to the model parameters and system components were collected. Figure 3 shows an overall summary of the data collected for the various system components.

Data related to the annual hourly cooling demand in Qatar were collected over 8784 h. The process of obtaining these data is explained in an associated data paper.[17] In addition, data related to the variable cost of storing a unit of cold water in TES, producing a unit of cold water from a compression chiller, and supplying electricity from the grid to the chiller were collected. These variable costs represent the energy prices in the mathematical model. The variable costs are estimated to be 0.058 \$/kW according to the Qatar General Electricity & Water Corporation website.[25] This value represents the electricity cost that is charged by the grid. Furthermore, the price of selling extra power generated by the PV panels to the grid is assumed to be 0.999 times the variable cost of supplying electricity from the grid to the chiller, that is, 0.0579 \$/kW. The

TABLE 6 Additional SECS parameters

Symbol	Definition
G_t	Global solar radiation in W/m^2 through a period, $\forall\, t \in T$
F^{PV}	Investment cost of an installed unit area of PV panels
η_{PV}	PV panels' efficiency
A	Maximum area of PV panels installed, in m^2
P	Price of selling extra power generated by the PV panels to the grid
τ	Time period durations, in hours

TABLE 7 Additional SECS decision variables

Symbol	Definition
x	Area of PV panels installed, in m^2
L_t	Power reaching the PV panels in kW through a period $t \in T$
L_t^C	Power produced by PV panels in kW through a period $t \in T$
$\overline{L_t^c}$	Extra power generated by PV panels and sold to the grid in kW through a period $t \in T$

TABLE 8 Additional SECS objective function terms

Term	Definition
$\mathrm{FC}^{\mathrm{PV}}x$	Investment cost for the installed area of PV panels
$\sum_{t \in T} P\overline{L_t^C}$	Sum of the revenue generated from selling power produced by PV panels to the grid over a period of 8784 h

TABLE 9 Additional SECS constraints

Constraint	Definition
$L_t^C + K_t = F_t^{\mathrm{In}}$	Ensures that the power demand of the chillers can be satisfied by the grid or PV panels. The constraint represents each period t over 8784 h
$L_t^C + \overline{L_t^c} = L_t$	Ensures that the power produced by the PV panels is either used to power the chiller directly or sold to the grid. The constraint represents each period t over 8784 h
$\frac{L_t}{\eta_{\mathrm{PV}} G_t} \leq x \leq A$	Ensures that the selected total area of PV panels is greater than or equal to the area necessary for generating the required power and less than or equal to the maximum available area. The constraint represents each period t over 8784 h
$x, L_t, L_t^c, \overline{L_t^c}, \geq 0$	Guarantees that the decision variables are non-negative. The constraint represents each period t over 8784 h

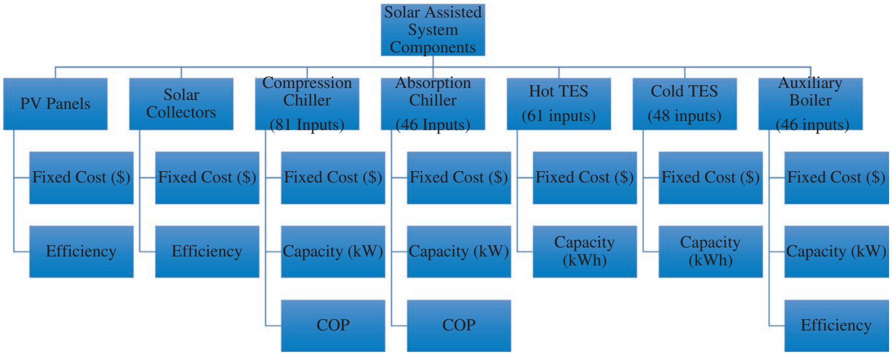

FIGURE 3 Overview of the data collected regarding the model parameters

TABLE 10 Performance characteristics and specifications of the compression chiller

Performance characteristics and specifications	Compression chiller
Type	Water cooled centrifugal
Number of stages	2 stages compression cycle
Number of compressors	Dual compressors
Refrigerant type	HFC134a refrigerant
Minimum cooling water temperature (°C)	12
Maximum working pressure (MPa)	2.5
Insulation	Thermal insulation
Isolator	Spring isolator
Flow control	Variable flow control for chilled and cooling water
Minimum cooling capacity	10% of capacity
Dimension [Length × Width × Height] (mm)	5250 × 3500 × 3700
Shipping weight (kg)	24,500
Operating weigh (kg)	28,500
Capacity (kW)	19,350
Efficiency	6.7
Capital cost ($)	3,298,295

selling price is assumed to be slightly less than the buying price in the mathematical model. Finally, data related to Qatar's annual hourly global solar radiation were obtained from the same source. Details of all collected data and the associated graphs can be found in an associated data paper.[17]

4.2 | Experimental results

The case study discussed in this research is based on very high cooling demand at a facility at Qatar University (QU). QU has ten colleges with more than 20,000 students and 2000 faculties, and mainly operates from 08:00–20:00, Sunday to Thursday. Along with the summer break, a semester break occurs from mid-December to mid-January, and there is a week-long spring break in March. The cooling demand is around 6000 TR, which is estimated to be 21,101 kW.[26] Tables 10–12 present the performance characteristics and specifications of the selected compression chiller, cold water TES, and PV panels in the system. The characteristics and specifications of the components can also be found in an associated data paper.[17]

Table 13 highlights the results obtained from optimizing the BCCS model.

TABLE 11 Performance characteristics and specifications of the cold water TES

Performance characteristics and specifications	Cold water TES
Type	Pit water tank (PTES)
Storage medium	Water
Density (kg/m^3)	1000
Specific heat (J/kg·K)	4190
Temperature range (°C)	0–100
Size (m^3)	2100
Depth (m)	5–15
Storage period	Day – Month - Year
Thermal energy capacity (kWh/m^3)	30
Capacity (kWh)	63,000
Efficiency	N/A
Capital cost ($)	24,948

TABLE 12 Performance characteristics and specifications of the PV panels

Performance characteristics and specifications	PV panels
Solar cell type	Monocrystalline silicon
Solar cell dimension [length × width × height] (mm)	70 × 65 × 3.2
Open circuit voltage (Voc)	38
Maximum power voltage (Vmp)	31.4
Maximum power current (Imp)	8.29
Tolerance of maximum power rating	−0/+5%
Normal operating cell temperature (°C)	45.7
Weight (kg)	18 each
Area (m^2)	100,000
Power per unit area (kW/m^2)	185
Efficiency	0.20
Capital cost ($)	18,500,000

The key observations from these results are as follows:

- The CPLEX solver in the AIMMS software package was used to generate the results over 37,687 iterations; the solving time was 426.74 s
- The AIC and AOC of the optimized BCCS constitute 7% and 93% of the ATSC, respectively
- The AIC of the compression chiller is 99% of the annual total investment cost (ATIC) and is equal to $335,939
- The AIC of the cold water TES is 1% of the ATIC and is equal to $2541

TABLE 13 Results obtained from mathematically optimizing the BCCS model

Component	Capacity	AIC ($)	Efficiency
Compression chiller	19,350 kW	335,939	6.7
Cold water TES	63,000 kWh	2541	N/A
ATSC ($) = AIC + AOC	$4,704,371 (338,479 + 4,365,892)		

TABLE 14 Results obtained from mathematically optimizing the SECS model

Component	Capacity	AIC ($)	Efficiency
Compression chiller	19,350 kW	335,939	6.7
PV panels	Area = 100,000 m^2	1,884,265	0.20
Cold water TES	63,000 kWh	2541	N/A
ATSC ($) = AIC + AOC − Revenue	$4,458,961 (2,222,746 + 4,127,860) − 1,891,645		

- The AOC of cold water produced from the compression chiller is 87% of the annual total operational cost (ATOC) and is equal to $3,791,596
- The additional AOC of electricity delivered to the chiller from the grid is 13% of the ATOC and is equal to $565,910

Table 14 presents the results obtained from optimizing the SECS model.

The key observations from these results are as follows:

- The CPLEX solver in the AIMMS software package was used to generate the results over 53,205 iterations; the solving time was 539.72 s
- PV panels cover 42% of the chiller demand for electricity, while the grid covers the remaining 58%
- The AIC and AOC of the optimized SECS each constitute 50% of the ATSC
- The annual revenue from selling electricity generated by PV panels to the grid is $1,891,645
- The AIC of the compression chiller is 15% of the ATIC and is equal to $335,939
- The AIC of the cold water TES is 0.11% of the ATIC and is equal to $2541
- The AIC of the PV panels is 85% of the ATIC and is equal to $1,884,265
- The AOC of cold water production from the compression chiller is 92% of the ATOC and is equal to $3,791,596
- The additional AOC of delivering electricity to the chiller from the grid is 8% of the ATOC and is equal to $327,878

It is noteworthy to highlight the impact of PV panels on producing cold water. Its impact can be understood by looking at how much the PV panels are contributing to supplying the required electricity to the compression chiller. In the proposed SECS model, it can be noted that the PV panels cover 42% of the electricity demand of the compression chiller. Therefore, this results in significant savings in the cost associated with supplying electricity from the grid to the compression chiller. In the BCCS model, the cost of supplying all the required electricity by the compression chiller is $565,910; however, the cost in the SECS model is $327,878. This reduction in cost, which is $238,032, is a result of installing PV panels in the system. Hence, PV panels contribute to reducing the cost and the quantity of electricity supplied from the grid to meet the electricity demand of the compression chiller. The below constraint represents that the electricity demand of the compression chiller can be met by PV panels, the grid, or both in the SECS model:

$$L_t^C + K_t = F_t^{\mathrm{In}}$$

where

L_t^C is the power produced by PV panels in kW through a period $t \in T$.

K_t is the power supplied to the compression chiller from the grid in kW through a period $t \in T$.

F_t^{In} is the power consumed by chillers in kW through a period $t \in T$.

In this system, when the photovoltaic panels are not generating the required electricity for the operation of the compression chiller, the grid will supply the required electricity K_t to the compression chiller. There is an electricity price $\mathrm{VC}_t^{\mathrm{Gr}}$ associated with the quantities of electricity supplied from the grid to the compression chiller. Hence, as the quantities of electricity supplied from the grid increase, the total cost associated with it increases as well. This is represented by the following term in the objective function of the mathematical model:

$$\sum_{t \in T} VC_t^{Gr} K_t$$

where

$\mathrm{VC}_t^{\mathrm{Gr}}$ is the variable cost of delivering electricity to the compression chiller from the grid through a period, $\forall\, t \in T$.

K_t is the power supplied to the compression chiller from the grid in kW through a period $t \in T$.

TABLE 15 Comparison of the results obtained from the three models

System component	STCS	BCCS	SECS
Chiller	\$355,863	\$335,939	\$335,939
Hot water TES	\$2541	N/A	N/A
Cold water TES	N/A	\$2541	\$2541
Solar collectors	\$24,741	N/A	N/A
PV panels	N/A	N/A	\$1,884,265
Auxiliary boiler	\$32,465	N/A	N/A
ATSC (\$) = AIC + AOC	\$6,932,282 (415,610 + 6,516,672)	\$4,704,371 (338,479 + 4,365,892)	\$4,458,961 (2,222,746 + 4,127,860) − 1,891,645

Nevertheless, the system is designed to sell the surplus electricity generated by the photovoltaic panels to the grid. Hence, this reduces the total grid cost associated with quantities of electricity generated by the grid. In some cases, the system makes profits from selling this surplus electricity to the grid.

The electric grid prices impact is controlled and optimized through the developed mathematical model which aims at finding a global optimum solution that features the best trade-off between different investment alternatives and operating policies.

In addition, this research conducted a sensitivity analysis to analyze the sensitivity of varying the electricity prices associated with the system components on the mathematical model's objective function in Section 5.2.

The STCS results were presented and discussed in a previous study.[6] Table 15 compares the results obtained from the three models.

Table 15 shows that the SECS has the lowest ATSC, some \$245,410 (ie, 5.5%) less than that of the BCCS and \$2,473,321 (ie, 55%) less than that of the STCS. Furthermore, the SECS has an AOC that is 58% lower than that of the STCS and 6% lower than that of the BCCS. This is because the PV panels cover 42% of the chiller demand for electricity under the optimized SECS, whereas for the BCCS, the grid covers the chiller's electricity demand. Unlike the STCS, the SECS does not have a back-up boiler, as it depends on PV panels (42%) and the grid (58%) to fulfill the chiller demand for electricity. In the case of the STCS, the boiler works day and night to cover 54% of the absorption chiller demand. In terms of the AIC, the SECS is 85% more expensive than the BCCS because of additional components such as PV panels and its AIC. Moreover, it is 81% costlier than the STCS because of the extra area covered by PV panels compared with solar collectors, which increases the system's AIC substantially.

To conclude, the following observations can be made from the results obtained from four case studies covering low, medium, high, and very high cooling demand using the STCS, SECS, and BCCS models:

- In terms of the ATSC, the SECS is the cheapest by an average of 5.5% and 55% in comparison with the BCCS and STCS, respectively
- In terms of AOC, the SECS is the cheapest by 6% and 58% in comparison with the BCCS and STCS, respectively
- In terms of AIC, the SECS is the costliest system. The SECS is 81% and 85% costlier than STCS and BCCS, respectively. This is reasonable because the AIC of the PV panels' installation constitutes a huge percentage of the investment cost (ie, 85%). Hence, the investment cost associated with the PV panels increases the system's AIC significantly. The reason for the large area of PV panels is that the model sells surplus electricity back to the grid at a price slightly less than the cost at which electricity is purchased from the grid. Hence, the model tends to increase the area of PV panels to generate as much revenue as possible. Consequently, the model uses all of the available area, causing the AIC of the system to increase. However, the revenue associated with the PV area increases due to the surplus electricity being sold to the grid, which lowers the ATSC sufficiently for SECS to be the most profitable system. The price at which electricity is sold to the grid is assumed to be slightly less than that of buying electricity from the grid to allow the electricity company to make some profit from the process of buying and selling electricity.

5 | SENSITIVITY ANALYSIS

The sensitivity of the optimal solution to variations in the model parameters is analyzed in this section. Multiple sensitivity analyses were conducted using the BCCS and SECS models. The sensitivity of the STCS model has been discussed in a previous research.[6] This section presents the sensitivity analysis conducted to measure the sensitivity of the system parameters (ie, PV panels' unit costs and efficiency) and the electricity prices of the system components on the mathematical model's objective function (ie, annual total system cost).

TABLE 16 SECS parameters used in the sensitivity analysis

Parameter	Minimum value (−20%)	Base value	Maximum value (+20%)	Incremental value
PV panels' unit cost ($\$/m^2$)	148	185	222	3.7
PV panels' efficiency	0.16	0.20	0.24	0.004

TABLE 17 Results of sensitivity analysis for SECS model

Parameter	Maximum ATSC difference percentage (+20%)	Minimum ATSC difference percentage (−20%)	Straight-line equation	Coefficient of determination R^2
PV panels unit cost ($\$/m^2$)	8.49	−8.49	$y = 0.8488x - 9.3368$	1
PV panels efficiency	−9.59	9.59	$y = -0.959x + 10.55$	1

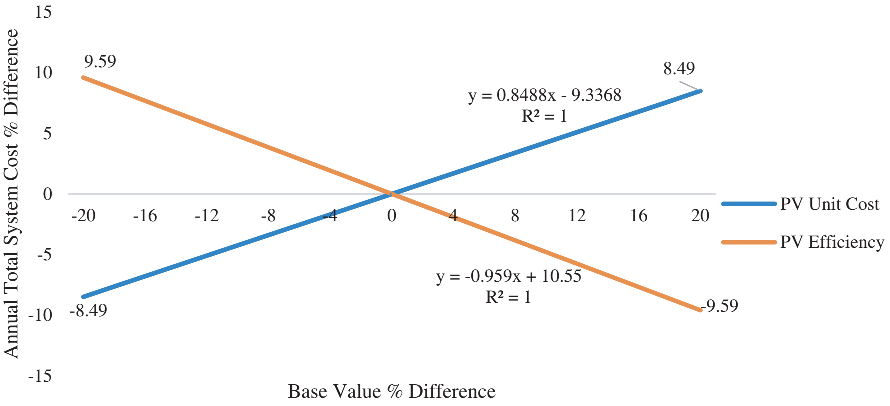

FIGURE 4 Sensitivity analysis results for the SECS model

5.1 | System parameters' sensitivity analysis

This section presents the sensitivity analysis conducted on the system parameters of the two SECS parameters, namely, the PV panels' unit costs, and efficiency. The effects of these two parameters on the annual total system cost were measured. The parameters in the mathematical model are expressed and defined as follows:

F^{PV}: Investment cost of an installed unit area of PV panels.

η_{PV}: PV panels' efficiency.

The base values were varied by ±20%, as indicated in Table 16. The percentage of total cost difference (PTCD) was estimated using the following equation:

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

Table 17 presents the results obtained from the sensitivity analysis, demonstrating that both parameters have a different effect on the ATSC. The PV panels' efficiency has a stronger effect (ie, −9.59%) on the ATSC than the PV panels' unit cost (ie, −8.49%). However, the PV panels' unit cost and efficiency parameters both exhibit a linear relationship with the ATSC based on the obtained R^2 value (ie, $R^2 = 1$). This means that a linear relationship exists among the two parameters and the ATSC. In detail, the ATSC decreases by −8.49% if the PV panels' unit cost decreases by 20% (ie, 148 $\$/m^2$), so the ATSC would be $4,063,000. In contrast, the ATSC decreases by −9.59% if the PV panels' efficiency increases by 20% (ie, 0.24), so the ATSC would be $4,014,090. This indicates that the ATSC is more sensitive to changes in the efficiency of the PV panels than their unit cost. In other words, the PV panels' efficiency has the greatest impact on the ATSC.

Figure 4 highlights the coefficient of determination, behavior, and straight-line equations of the analyzed parameters.

5.2 | Electricity prices' sensitivity analysis

This section presents the sensitivity analysis conducted on the electricity prices of the system component to measure their effects on the objective function (ie, annual total cost). The three models were analyzed to investigate the impact of electricity prices on their objective functions. The sensitivity analysis was conducted on the parameters listed in Table 18, which also gives the maximum values (ie, base value +20%) and the increments. The electricity prices are related to the following components, compression chiller, electric grid, and cold water thermal energy storage tank. The parameters which represent the electricity prices are expressed and defined in the mathematical model as follows:

$\mathrm{VC}_t^{\mathrm{Ch}}$: Variable cost of cold water production from a chiller through a period, $\forall\, t \in T$.
$\mathrm{VC}_t^{\mathrm{Chsto}}$: Variable cost of cold water storage at a TES through a period, $\forall\, t \in T$.
$\mathrm{VC}_t^{\mathrm{Gr}}$: Variable cost of delivering electricity to the chiller through a period, $\forall\, t \in T$.

The components' electricity prices are explicitly accommodated in the objective function. The corresponding terms are:

$\sum_{t\in T}\mathrm{VC}_t^{\mathrm{Ch}}F_t^{o}$: Sum of the variable costs of cold water produced from the chiller over a period of 8784 h.
$\sum_{t\in T}\mathrm{VC}_t^{\mathrm{Chsto}}I_t^{\mathrm{CW}}$: Sum of the variable costs of cold water stored at the cold water TES over a period of 8784 h.
$\sum_{t\in T}\mathrm{VC}_t^{\mathrm{Gr}}K_t$: Sum of the variable costs of supplying electricity to the chiller from the grid over a period of 8784.

All the electricity prices are controlled and optimized through the developed mathematical model, which aims at finding a global optimum solution that features the best trade-off between different investment alternatives (ie, chiller capacity, cost and COP; cold water TES capacity, and cost; PV panels area, and cost) and operating policies (ie, quantities of the cold water produced by the compression chiller and stored in the cold water thermal energy storage; quantities of the electricity produced by PV panels and supplied from the grid).

Table 19 summarizes the results obtained from the sensitivity analysis. Table 19 and Figure 5 show that a

TABLE 18 Parameters used in the sensitivity analysis of all three models

Parameter	Base value	Maximum value	Incremental value
Producing cold water variable cost	0.055	0.066	0.00055
Storing cold water variable cost	0.055	0.066	0.00055
Storing hot water variable cost	0.055	0.066	0.00055
Supplying electricity to the chiller variable cost	0.055	0.066	0.00055

TABLE 19 Sensitivity analysis results for the three models

Model	Maximum annual system cost difference percentage (+20%)	Straight-line equation	Coefficient of determination R^2
STCS	18.80%	$y = 0.94x - 0.94$	1
BCCS	18.56%	$y = 0.9281x - 0.928$	1
SECS	10.03%	$y = 0.5015x - 0.5015$	1

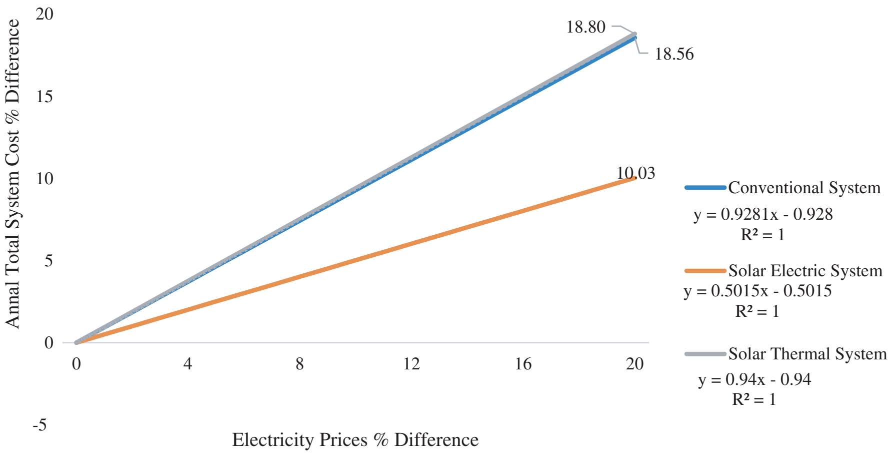

FIGURE 5 Sensitivity analysis results on electricity prices for the three systems

linear relationship exists between the three models' ATSC and electricity prices, as confirmed by the R^2 value. The slopes indicate that the SECS has the smallest increase in the ATSC if electricity prices increase. The slope for the SECS is 0.50, compared with 0.93 and 0.94 for BCCS and STCS, respectively. If the electricity price increases by 20% (ie, $0.066), the ATSC will increase by 18.80% for STCS, giving a new ATSC of $8,235,617. The ATSC will increase by 18.56% to $5,577,549 for BCCS, and by 10.05% to $4,906,204 for SECS. The differences between these new costs and their respective base costs are $447,243, $873,178, and $1,303,334 for the SECS, BCCS, and STCS models, respectively. In other words, the STCS is more sensitive to changes in electricity prices, as indicated by the slope (ie, 0.94) and by the percentage increase (ie, 18.80%), than SECS and BCCS. Notably, the SECS is the most economical as it has the smallest increase in the ATSC (ie, 10.05%).

6 | CONCLUSION

This research has addressed the issue of determining the optimal system design and hourly operational policies of the BCCS and SECS by minimizing the AIC and AOC. Each system was modeled using MILP, and the models were solved using the CPLEX solver. The model output gave the optimal capacities of the system components and the optimal hourly policies for producing and storing cold water and electricity while satisfying a time-varying cooling demand. The models were tested and validated using real data and analyzed over 8784 h using various patterns of annual cooling demand. A case study of the Qatar University campus enabled the two systems to be compared with the STCS.[6]

The findings presented in this research indicate that the PV panels in the SECS cover 42% of the chiller demand for electricity. In addition, the comparison highlighted that the SECS is the most economical, with an ATSC that is 55% lower than that of STCS and 5.5% lower than that of BCCS. The SECS also has the lowest AOC, some 58% below that of STCS and 6% less than that of BCCS. However, the SECS has an AIC that is 81% costlier than STCS and 85% more expensive than BCCS.

Finally, multiple sensitivity analyses were conducted on the SECS's PV unit cost and PV efficiency. The analysis results indicated that the PV panel's efficiency has the greatest impact on the ATSC. A further sensitivity analysis was conducted on the electricity prices, and the results highlighted that SECS was the least sensitive to electricity costs, and therefore the most economical. A 20% increase in the price of electricity would increase the ATSC of SECS by 10.05%, compared with increases of 18.80% for STCS and 18.56% for BCCS. Future studies will investigate the effects of stochastic, rather than deterministic, cooling demand.

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