Quantifying CO_2 Emissions and Energy Production from Power Plants to Run HVAC Systems in ASHRAE-Based Buildings

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Abstract: Recent evidence available in the literature has highlighted that the high-energy consumption rate associated with air conditioning leads to the undesired "overcooling" condition in arid-climate regions. To this end, this study quantified the effects of increasing the cooling set-point temperature on reducing energy consumption and CO_2 emissions to mitigate overcooling. DesignBuilder software was used to simulate the performance of a generic building operating under the currently adopted ASHRAE HVAC criteria. It was found that increasing the cooling setpoint temperature by 1 °C will increase the operative temperature by approximately 0.25 °C and reduce the annual cooling electricity consumption required for each 1 m^2 of an occupied area by approximately 8 kWh/year. This accounts for a reduction of 8% in cooling energy consumption compared to the ASHRAE cooling setpoint (i.e., t_s = 26 °C) and a reduction in the annual CO_2 emission rate to roughly 4.8 kg/m^2 °C. The largest reduction in cooling energy consumption and CO_2 emissions was found to occur in October, with reduced rates of approximately –1.3 kWh/m^2 °C and −0.8 kg/m^2 °C, respectively.

Keywords: ASHRAE; CO_2 emissions; energy consumption; indoor operative temperature; arid-climate regions

1. Introduction

Heating, Ventilation, and Air Conditioning (HVAC) typically account for a significant share of global building energy use [1,2]. In 2019, building cooling accounted for 20% of worldwide power consumption [3,4]. Population expansion, paired with increased affluence in emerging economies, in countries with hot climates (G.C.C. countries), has caused a 10% rise in the demand for energy for indoor air conditioning between 2018 and 2019 [4]. Energy consumption for indoor air conditioning is expected to increase by 28% between 2015 and 2040 in the Middle East (M.E.), Africa, and non-Organization for Economic Cooperation and Development (non-OECD) members in the Americas (which includes Brazil) [5]. This is due to increases in climatic temperatures driven by global climate change [5]. Because of its hot, dry, and arid nature, as well as harsh temperature conditions, the M.E. is particularly sensitive to the effects of climate change forecasts [6]. For example, in summer, temperatures in Kuwait, Saudi Arabia, and Qatar regularly surpass 50 °C. On the other hand, in winter, the temperature descends to approximately 5 °C in some regions of the M.E. [6].

The construction industry now uses 28% of the overall energy consumption in the M.E., with 70% of that related to indoor air conditioning [3,4,7]. The increased demand for

indoor air conditioning reflects the growing desire for improved thermal comfort in both domestic and nondomestic buildings [1]. Indeed, air conditioning system prevalence in the M.E. is over 65% [3,8]. There are approximately one billion air-conditioning units (three units per capita) worldwide, and by 2050, that number is expected to rise to five units per capita, about three billion units [4,9]. The necessity to drive this expansion sustainably has led to the introduction of many voluntary green building codes (G.B.C.s) on a national and regional level. These regulations are based on international standards (i.e., the American LEED [10] or the British BREEAM [11]). One unintended consequence of adopting these standards is widespread acceptance by the G.B.C.s of these regulations and codes. For thermal comfort, the use of ASHRAE 55 [12] and ISO 7730 [13] is widely accepted. The progression of such codes from optional to mandatory, such as by adoption into G.B.C. rules, is well-known. As a result, it is no surprise that seven of the M.E. nations have implemented ASHRAE 55 and/or ISO 7730 as part of their national G.B.C. rules and compliance procedures. Importantly, the "international" thermal comfort standards are not tailored to hot climates. Instead, they are inadvertently oriented toward colder regions and cultures, and the implementation of these metrics in hot climates may result in discomfort for occupants and inefficient energy use [14,15].

Moreover, it has been suggested that the intricate interplay of various elements might alter thermal comfort standards. Parameters related to behavior (e.g., personal heating/cooling adaptability), physiology (i.e., age, gender, and race), geography, and climates are not taken into account by the international thermal comfort standards [16]. There is no substantial evidence in the literature to support the adoption of the international thermal comfort standards in terms of location or cultural variance [17,18]. In addition, there is solid grounds for believing that the implementation of these standards in hot regions might result in interior temperatures that are colder than expected [19–21]. Nevertheless, if the implementation of international standards does not consistently provide indoor thermal comfort, then further localized codes will be required. This necessitates the development of a new framework for what constitutes adequate cooling for buildings in the M.E., one that may cut energy usage and emissions relative to the ASHRAE setpoint, for instance.

Driven by the evidence available in the literature showing the unnecessarily high energy consumption rate associated with air conditioning that is leading to the undesired "overcooling" condition in hot climates [14,15], the novelty of this study appears in quantifying the effects of increasing the cooling setpoint temperature on reducing energy consumption and CO_2 emissions in Qatar. This was achieved by simulating the performance of a generic building operating under the currently adopted HVAC criteria in Qatar (ASHRAE). This study utilizes the DesignBuilder software and integrates Qatar weather data to assess the generic building response when considering the impact of the change on the cooling setpoint. The results obtained highlight the effects on two levels: (A) overall annual performance, and (B) monthly performance.

Based on the simulation results, a new cooling setpoint temperature is determined, and the data presented in this paper offers an upfront prediction for the temperature limit with respect to the corresponding reduction in energy consumption and CO_2 emissions.

2. Methodology

2.1. The Validity Simulation Software

The professionals, including architects and building service engineers, choose DesignBuilder as the preferred sophisticated user interface for EnergyPlus, the program that is considered to be the industry standard for building energy simulation [22]. Additionally, DesignBuilder [23] provides users with the ability to conduct detailed energy simulations with a user interface that is three-dimensional. The International Energy Agency's BESTest certifies DesignBuilder's energy modeling accuracy [24]. BESTest is utilized by the US Department of Energy and the worldwide community to evaluate building energy modeling programs [25]. DesignBuilder's CFD numerical technique is based on the primitive variable, which requires the solution of a set of equations representing the conservation

of heat, mass, and momentum (the three velocity components), and the k– turbulence model, with the finite-volume upwind discretization scheme [23]. It generates a complete simulation that takes into account a variety of sub-hourly local climatic and environmental conditions [22,26].

2.2. Numerical Model Specifications and Assumptions

The aims and objectives of this paper are to quantify the effect of air conditioning (AC) temperature setpoint on the energy consumption and CO_2 emissions of a generic ASHRAE-based residential building. The model studied herein has been developed in DesignBuilder using a set of essential parameters, including building layout, which is shown in Figure 1 [27,28]. In addition, the parameters include the building design specifications, which include the construction materials (to define insulation and predict heat transfer) [27,28], the HVAC systems [12,23], the lighting system [12,23], and the activity templets [12,23]). These parameters are specified in Tables 1 and 2. Moreover, the weather data has been defined for Qatar [29]; see Figure 2. The DesignBuilder simulation software has been utilized herein to benchmark the effect of increasing the cooling setpoint temperature up to an additional 6 °C, with a step size of 0.5 °C, compared to a control case that follows the ASHRAE HVAC control criteria [12,23], see Table 1. The activity templates and occupancy schedules maintained control for all the cases of the study, as proposed by the ASHRAE criteria [12] and as defined in the DesignBuilder database (i.e., activity template: ASHRAE Residential Dwelling Unit and occupancy schedule: ASHRAE Residential Occ [23]). The HVAC configuration in this study has been defined as 'split-no fresh air' using the DesignBuilder database. The adopted building in this paper (in Figure 1) is a generic building that has been well-defined and reported in the literature [27,28]. The specifications of the building have been implemented in DesignBuilder, as shown in Table 2.
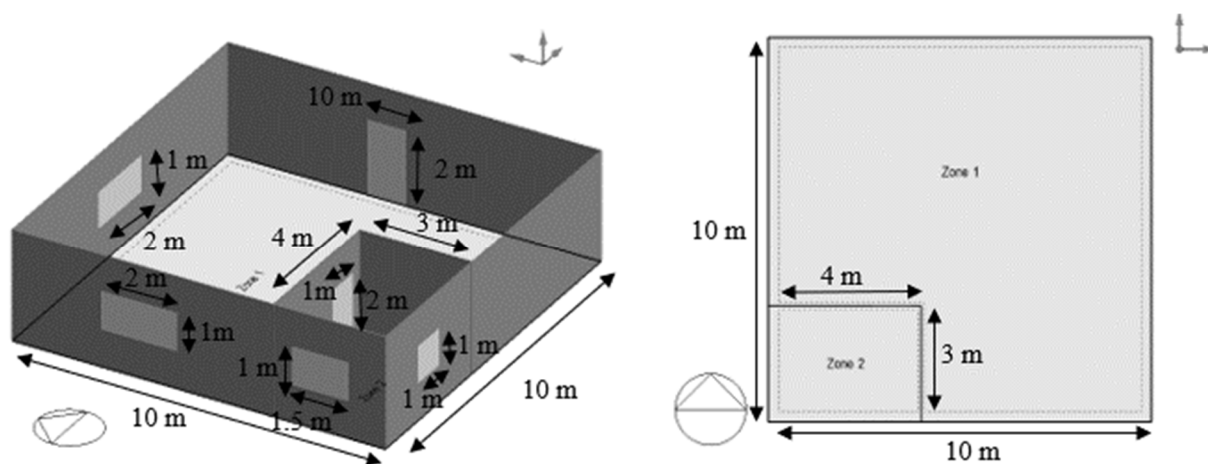

Figure 1. The 3-D model and plan for the generic building.

As discussed in Section 1, the investigation performed in this paper is for an ASHRAE-based building in an arid region, where ASHRAE standards are adopted. Therefore, the Doha-Qatar region was chosen as the scope of this paper in light of its hot climate and the fact that the city's currently adopted HVAC standards are based on the ASHRAE specifications [12]. The weather data, displayed in Figure 2, was loaded into the software following the reference [29]. As suggested by the literature [27,28], the simulation program was configured to execute an annual energy simulation with 30 steps per hour and to provide energy and thermal comfort analysis for the building throughout the year in order to produce accurate findings.

Table 1. HVAC control parameters.

Parameter Category	Parameter	ASHRAE Control Case [12,23]	Variable Interval
Heating setpoints	Heating setpoint when the building is occupied [°C]	20	Constant
	Heating setpoint when the building is unoccupied [°C]	13	Constant
Cooling setpoints	Cooling setpoint when the building is occupied [°C]	26	[26–32 °C] with a step size of 0.5 °C
	Cooling setpoint when the building is unoccupied [°C]	32	Constant
Operation Schedule	Heating	Limited by the occupancy schedule (ASHRAE Residential Occ)	Constant
	Cooling	Limited by the occupancy schedule (ASHRAE Residential Occ)	Constant

Table 2. Design specification and assumptions of the generic building.

| Parameter	Specification		Reference
Building dimensions	As shown in Figure 1		
Airtightness	0.05 ac/h		[27,28]
	Fluorescent	T8 25 mm diam	
	Power density	10.2 W/m^2	
	Control	ON/OFF demining daylighting control	
HVAC system	Configuration	Split-no fresh air	[12,23]
	Heating	Within ASHRAE definition	
	Cooling	Within ASHRAE definition	
	Natural ventilation	Within ASHRAE definition	
Occupancy	Occupancy density [people/m^2]	0.0215	
	Schedule	ASHRAE Residential Occ	
Construction	External wall	Layer 1: Cement Plaster: 0.03 m	[27,28]
		Layer 2: Block: 0.2 m	
		Layer 3: Cement plaster 0.03 m	
	Internal wall	Layer 1: Cement Plaster: 0.03 m	
		Layer 2: Block: 0.1 m	
		Layer 3: Cement plaster 0.03 m	
	Roof	Layer 1: Cast Reinforced concrete: 0.1 m	
		Layer 2: Block + Reinforced concrete: 0.15 m	
		Layer 3: Cement plaster 0.03 m	
	Floor	Layer 1: Gravel-based Soil: 0.2 m	
		Layer 2: Sand: 0.05 m	
		Layer 3: Cast reinforced concrete: 0.1 m	
	Windows	Sliding, single clear glazing: 0.06 m, 50% glazing open	
		Aluminum framing: 0.05 m	
	Doors	Area door opens: 100%	
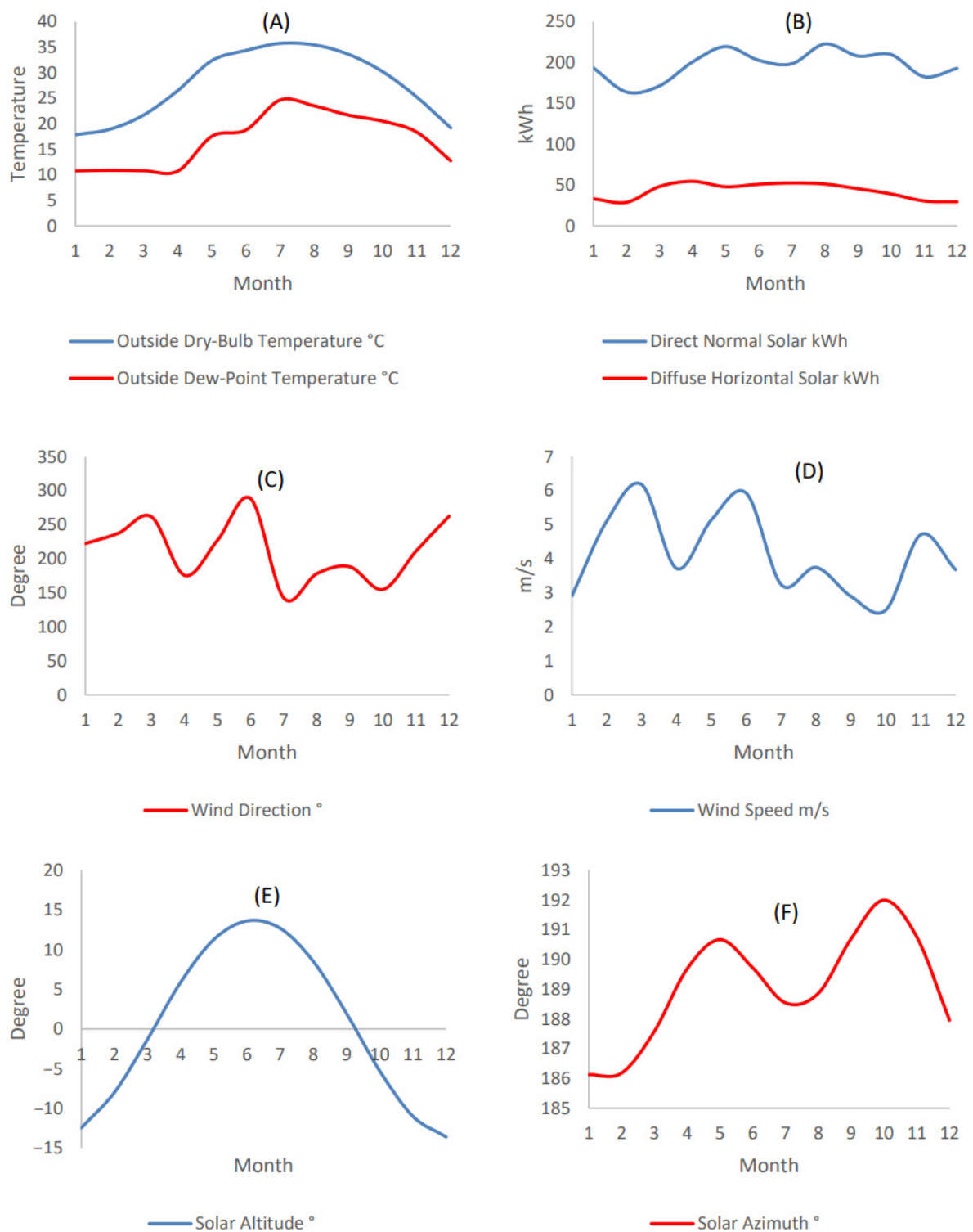
Figure 2. Site weather data (Doha-Qatar). (**A**) Outside dry-bulb and dew-point temperatures; (**B**) Direct normal and diffusive horizontal solar intensity; (**C**) Wind direction; (**D**) Wind speed; (**E**) Solar altitude; (**F**) Solar azimuth.

3. Results and Discussion

3.1. Overall Annual Performance

The cooling setpoint (t_s) defines "the ideal temperature in the space when cooling is required" (i.e., the setting of the cooling thermostat) [12,23]. On the other hand, operative temperature (t_o) can be defined as "the average of the mean radiant and ambient air

temperatures, weighted by their respective heat transfer coefficients" [12,23]. Figure 3 correlates the average annual operative temperature to the cooling setpoint temperature within the interval of [26–32 °C] with a step size of 0.5 °C. As shown in Figure 3, the DesignBuilder-generated data points have been curve-fitted using cftool-MATLAB into a polynomial correlation. To quantify the sensitivity of the operative temperature toward the cooling setpoint temperature, the first derivative of the second-order correlation has been utilized. The sensitivity of the operative temperature towards the cooling setpoint temperature within the tested interval (dt_o/dt_s) has been found to be approximately 0.25. This essentially means that increasing the cooling setpoint temperature by 1 °C would only increase the operative temperature by approximately 0.25 °C.
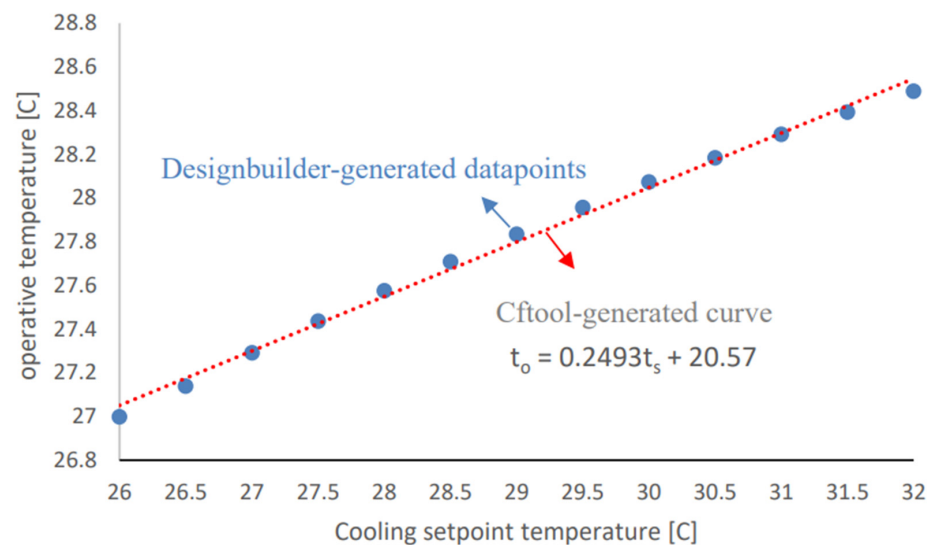

Figure 3. The average annual operative temperature with respect to the cooling setpoint temperature.

However, increasing the cooling setpoint temperature has a more significant impact on reducing energy consumption, as shown in Figure 4. In similarity to the adopted approach to quantify the sensitivity of t_o towards t_s, the DesignBuilder-generated data of the annual cooling energy consumption, with respect to the cooling temperature setpoint, have been curve-fitted using cftool-MATLAB, yielding a generic correlation that describes cooling energy consumption (E_c) as a function of the cooling setpoint temperature.
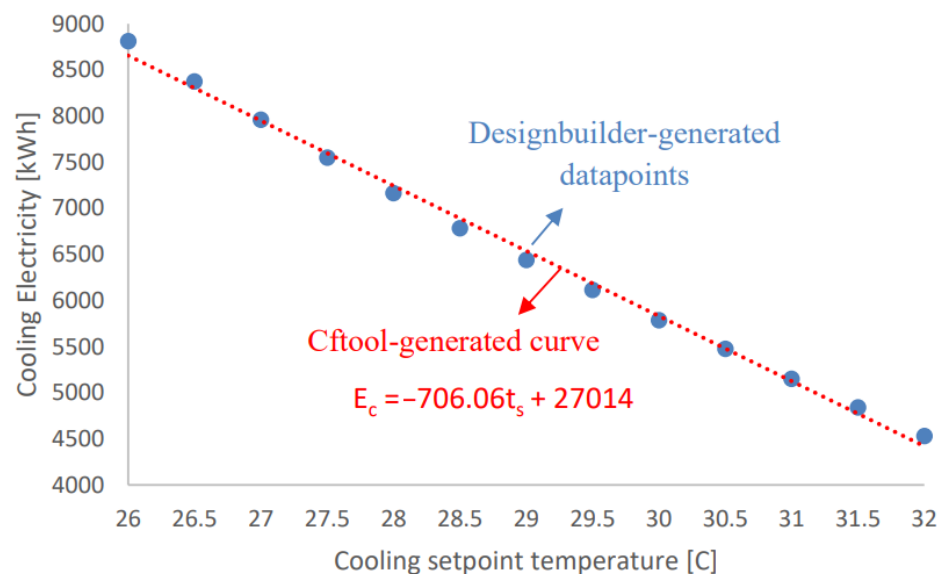

Figure 4. Cooling electricity consumption with respect to the cooling setpoint temperature.

The sensitivity of the cooling energy consumption (E_c) towards the cooling setpoint temperature t_s (dE_c/dt_s) was found to be approximately -706 kWh/$^\circ$C, meaning that increasing the cooling setpoint temperature by 1 $^\circ$C would reduce the annual cooling electricity consumption by approximately 706 kWh. Furthermore, to benchmark the effect of cooling setpoint temperature on energy consumption against the ASHRAE criteria (i.e., $t_s = 26$ $^\circ$C), Figure 5 shows the energy reduction percentage for each cooling temperature setpoint with respect to the ASHRAE criteria. The increase in cooling setpoint temperature by an additional 1 $^\circ$C has the effect of reducing the cooling energy consumption by approximately 8% compared to the ASHRAE cooling setpoint (i.e., $t_s = 26$ $^\circ$C).
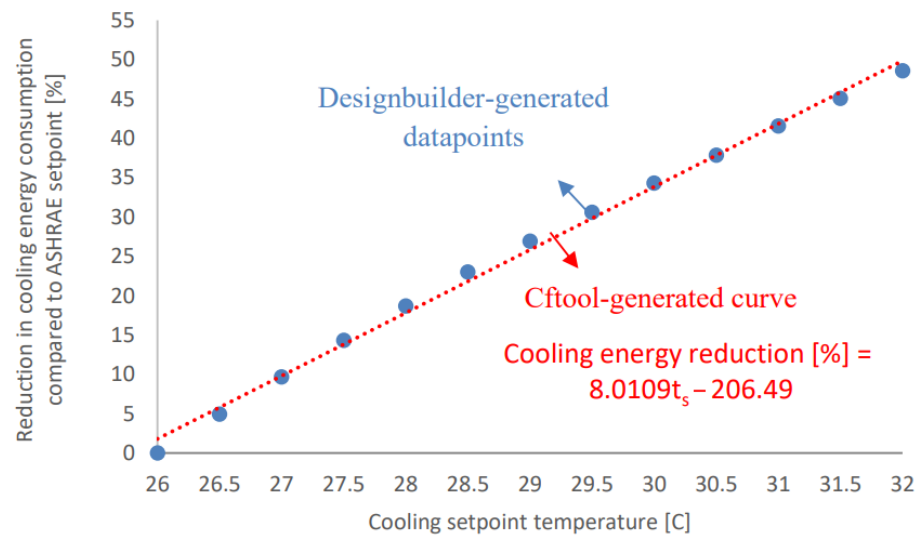

Figure 5. Energy reduction percentage for each cooling temperature setpoint with respect to the ASHRAE criteria.

Figure 6 shows a more descriptive correlation between cooling energy consumption and the cooling setpoint temperature. This correlation could potentially provide a better prediction for other building geometries where the energy consumption rates have been normalized by the occupied area ($\hat{E}_c$). Figure 6 illustrates the sensitivity of the normalized cooling energy consumption ($\hat{E}_c$) towards the cooling setpoint temperature t_s ($d\hat{E}_{cc}/dt_s$) to be approximately -8 kWh/m^2°C. This means that increasing the cooling setpoint temperature by 1 $^\circ$C would reduce the annual cooling electricity consumption required for each 1 m^2 of the occupied area by approximately 8 kWh.
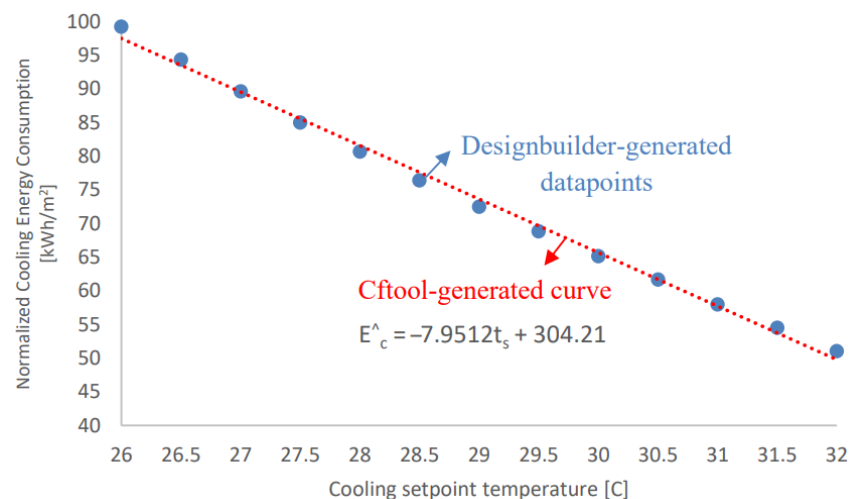

Figure 6. Normalized cooling energy consumption with respect to the cooling setpoint temperature.

Figure 7 shows the potential reduction in annual CO_2 emissions from increasing the cooling temperature setpoint when compared to the ASHRAE-based cooling setpoint (i.e., $t_s = 26\,°C$). The sensitivity of the annual reduced CO_2 emissions (m_{CO_2}) towards the increased cooling setpoint temperature compared to the ASHRAE-based cooling setpoint (dm_{CO_2}/dt_s) was found to be approximately $-4.8\,kg\,CO_2/m^2\,°C$. Therefore, increasing the cooling setpoint temperature by $1\,°C$ would reduce the annual CO_2 emissions by 4.8 kg for each $1\,m^2$ of the occupied area.
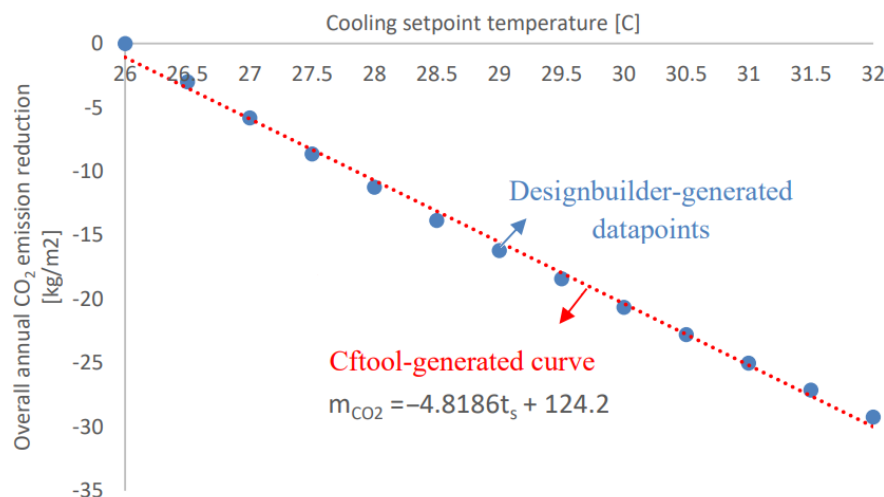

Figure 7. CO_2 emission reduction with respect to increasing the cooling setpoint temperature compared to the ASHRAE-based cooling setpoint ($26\,°C$).

3.2. Monthly Performance

By plotting the monthly cooling energy consumption with respect to the cooling setpoint (Figure 8A), it was found that monthly cooling energy consumption is reduced approximately linearly as the cooling setpoint increases. The corresponding monthly average reductions in cooling energy consumption with respect to the cooling setpoint temperature increase ($d\overline{E_c}/dt_s$) have been estimated for all months, as shown in Figure 8B.

Plotting $d\overline{E_c}/dt_s$ highlights the months in which the effect of increasing the cooling setpoints most significantly reduces the cooling energy consumption. As shown in Figure 8A, the largest reduction in cooling energy consumption (by increasing the cooling setpoint temperature) is achieved in October, with a reduction rate of $d\overline{E_c}/dt_s = -119.1\,kWh/°C$. This is followed by May, with a reduction rate of $d\overline{E_c}/dt_s = -101.5\,kWh/°C$. Therefore, increasing the cooling setpoint temperature by $1\,°C$ in October and May would effectively reduce the building's energy consumption by approximately 119.1 kWh and 101.5 kWh, respectively.

In June, July, and August, the energy reduction rates were approximately equivalent (i.e., $-90\,kWh/°C$, $-88.7\,kWh/°C$, and $-90.3\,kWh/°C$, respectively) as the outside temperature in these months did not vary significantly, as shown in the weather data (Figure 2A). In April, September, and November, the opportunity of reducing energy consumption is less significant compared to the previously mentioned months (i.e., $-70.1\,kWh/°C$, $-77.6\,kWh/°C$, and $-61.2\,kWh/°C$). Finally, the possible energy reduction rates in January, February, March, and December are negligible because the usage of air conditioning is low during these relatively cool months (Figure 2A).

As shown in Figure 9, the monthly energy consumption rates have been normalized by the occupied area ($\hat{E}_c$). It was found that the average sensitivity of the normalized cooling energy consumption ($\hat{E}_c$) towards the cooling setpoint temperature t_s ($d\hat{E}_c/dt_s$) is approximately $-1.3\,kWh/m^2°C$ and $-1.1\,kWh/m^2°C$ in October and May, respectively. In June, July, and August, the values are approximately $-1\,kWh/m^2°C$, while in September, April, and November, the values are approximately $-0.9\,kWh/m^2°C$, $-0.8\,kWh/m^2°C$, and $-0.7\,kWh/m^2°C$, respectively. These figures essentially reflect the average amount

of energy that could be reduced each month, 1 m^2 of occupied space, by increasing the cooling setpoint temperature by 1 °C.
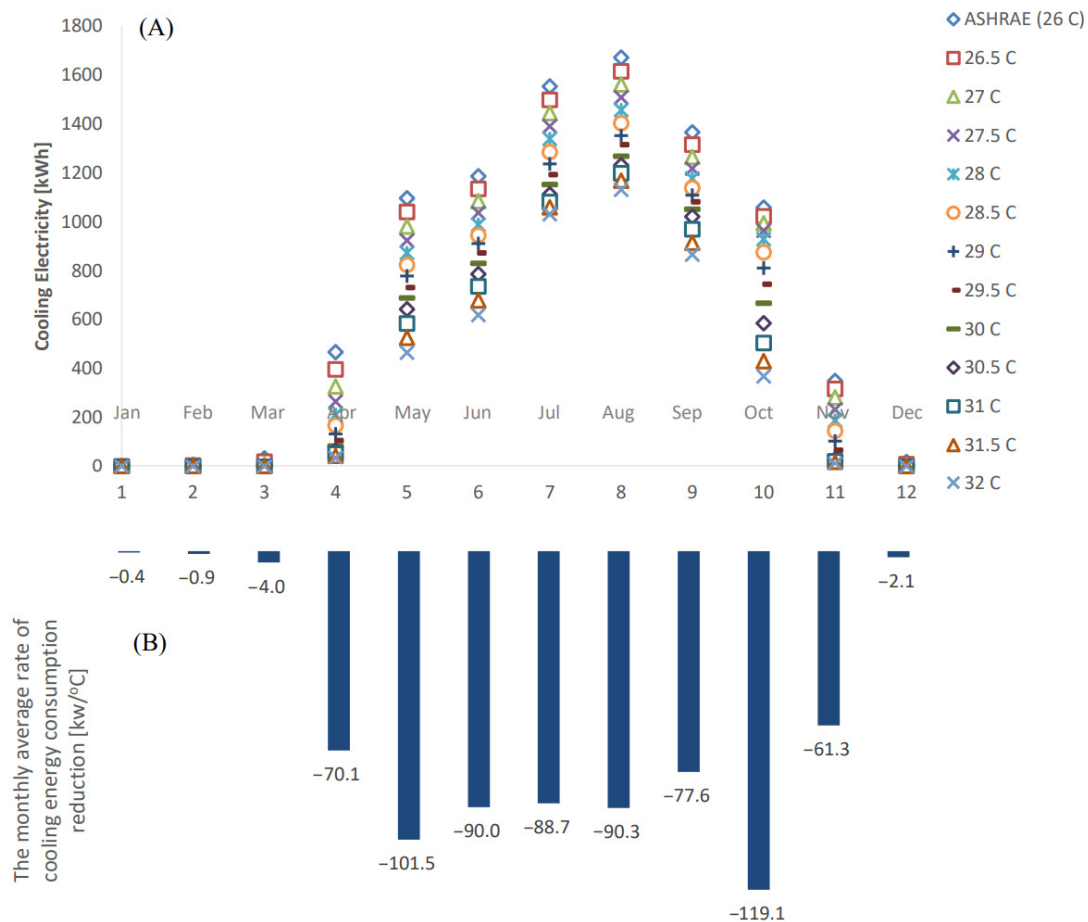

Figure 8. (**A**) The monthly cooling energy consumption with respect to the cooling setpoint; (**B**) The monthly average rate of cooling energy consumption reduction with respect to the cooling setpoint temperature increase ($d\overline{E_c}/dt_s$).

The corresponding monthly CO$_2$ emission reduction is achievable by increasing the cooling temperature setpoint compared to the ASHRAE-based cooling setpoint (i.e., $t_s = 26$ °C) is shown in Figure 10A. The sensitivity of the monthly reduced CO$_2$ emissions (m_{CO_2}) towards the increased cooling setpoint temperature when compared to the ASHRAE-based cooling setpoint (dm_{CO_2}/dt_s) was estimated and is shown in Figure 10B. In October, increasing the cooling setpoint temperature by 1 °C would reduce the CO$_2$ emissions by approximately 0.8 kg for each 1 m^2 of occupied space. In May, the reduction rate of CO$_2$ is less than in October by 0.1 kg/m^2 °C (i.e., $dm_{CO_2}/dt_s = -0.7$ kg/m^2 °C), while in June, July, and August, it is less than October by 0.2 kg/m^2 °C (i.e., $dm_{CO_2}/dt_s = -0.6$ kg/m^2 °C). In April, September, and November, dm_{CO_2}/dt_s is approximately -0.5 kg/m^2 °C, -0.5 kg/m^2 °C and -0.4 kg/m^2 °C, respectively. In January, February, March, and December, CO$_2$ emission reduction rates are negligible because the usage of air conditioning in these relatively cool months (Figure 2A) is negligible.

3.3. Techno-Economic

Operating on the basis of the obtained results, describing the monthly normalized cooling energy consumption with respect to the cooling setpoint (Figure 8), and utilizing the electricity price for residential buildings in Qatar (0.032 USD/kWh, as reported in [30–32]), the annual and monthly breakdown of the normalized cost of each cooling setup can be estimated as shown in Figure 11. Since the electricity price in Qatar is constant throughout

the year [32], the patterns of the monthly breakdown of the normalized cost of each cooling setup follow the patterns of the monthly and normalized cooling energy consumption in Figure 8.

This essentially means that, as shown in Figure 10B, the greatest opportunity to reduce cooling costs is by increasing the cooling setpoint temperature in October, with a reduction rate of 0.043 kW/m^2 °C. In June, July, and August, the cost reduction rates were approximately equivalent at -0.032 kW/m^2 °C, -0.032 kW/m^2 °C, and -0.033 kW/m^2 °C, respectively). In April, September, and November, the opportunity to reduce energy costs is less significant compared to the previously mentioned months (i.e., -0.025 kW/m^2 °C, -0.028 kW/m^2 °C, and -0.022 kW/m^2 °C, respectively). Finally, the possible cost reduction rates in January, February, March, and December are negligible. Figure 11C shows the annual normalized cost of each cooling setup, and it can be concluded that increasing the cooling setpoint temperature by 1 °C has the effect of reducing annual energy costs by approximately 0.3 USD/m^2, which accounts for an approximate 10 to 12% cost reduction.

Finally, to summarize this section, Tables 3 and 4 show the annual and the monthly effects of increasing the cooling setpoint temperature by 1 °C, respectively.
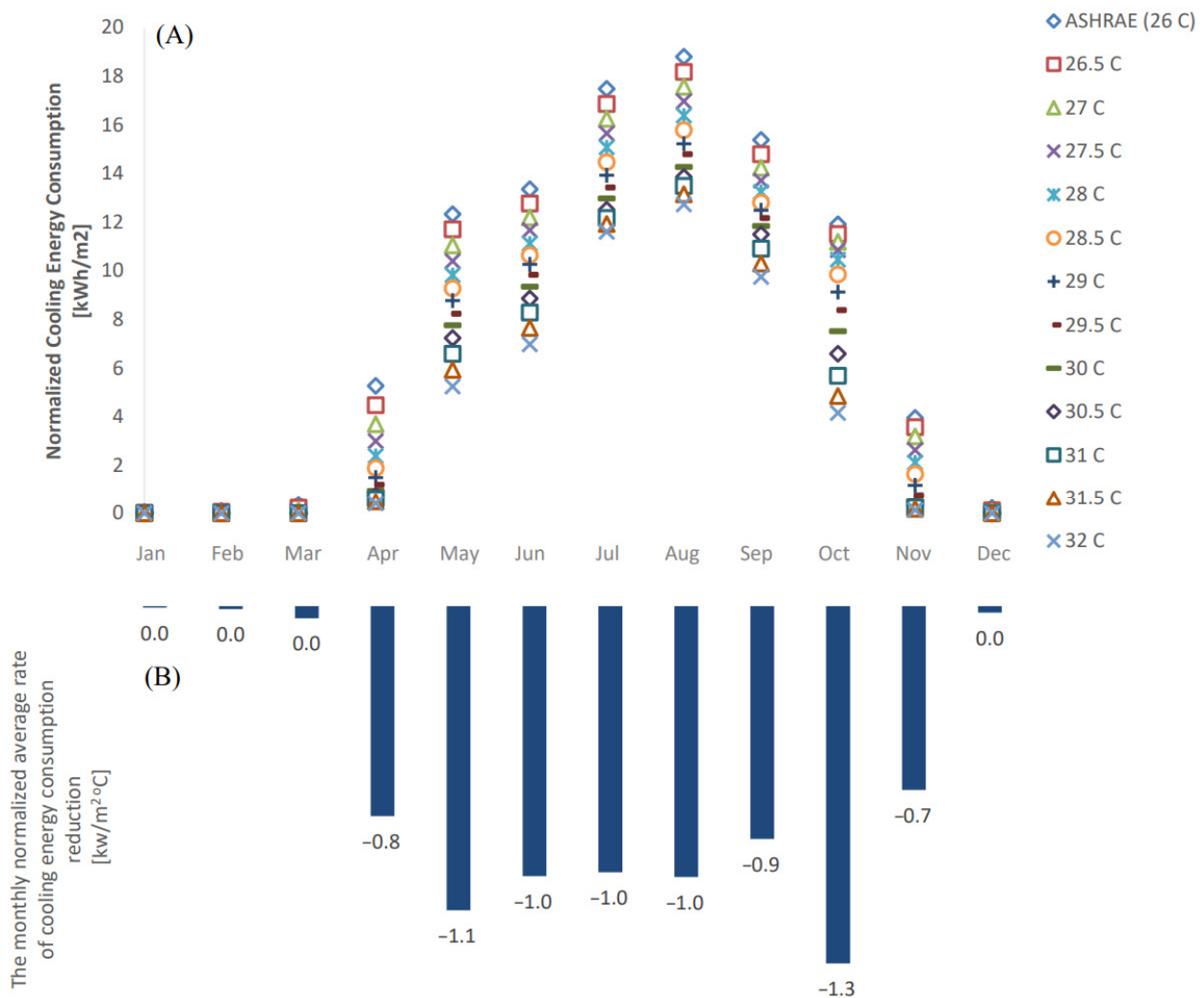

Figure 9. (**A**) The monthly normalized (by occupied area) cooling energy consumption with respect to the cooling setpoint; (**B**) The monthly average rate of normalized cooling energy consumption reduction with respect to the cooling setpoint temperature increase ($d\hat{E}_c/dt_s$).
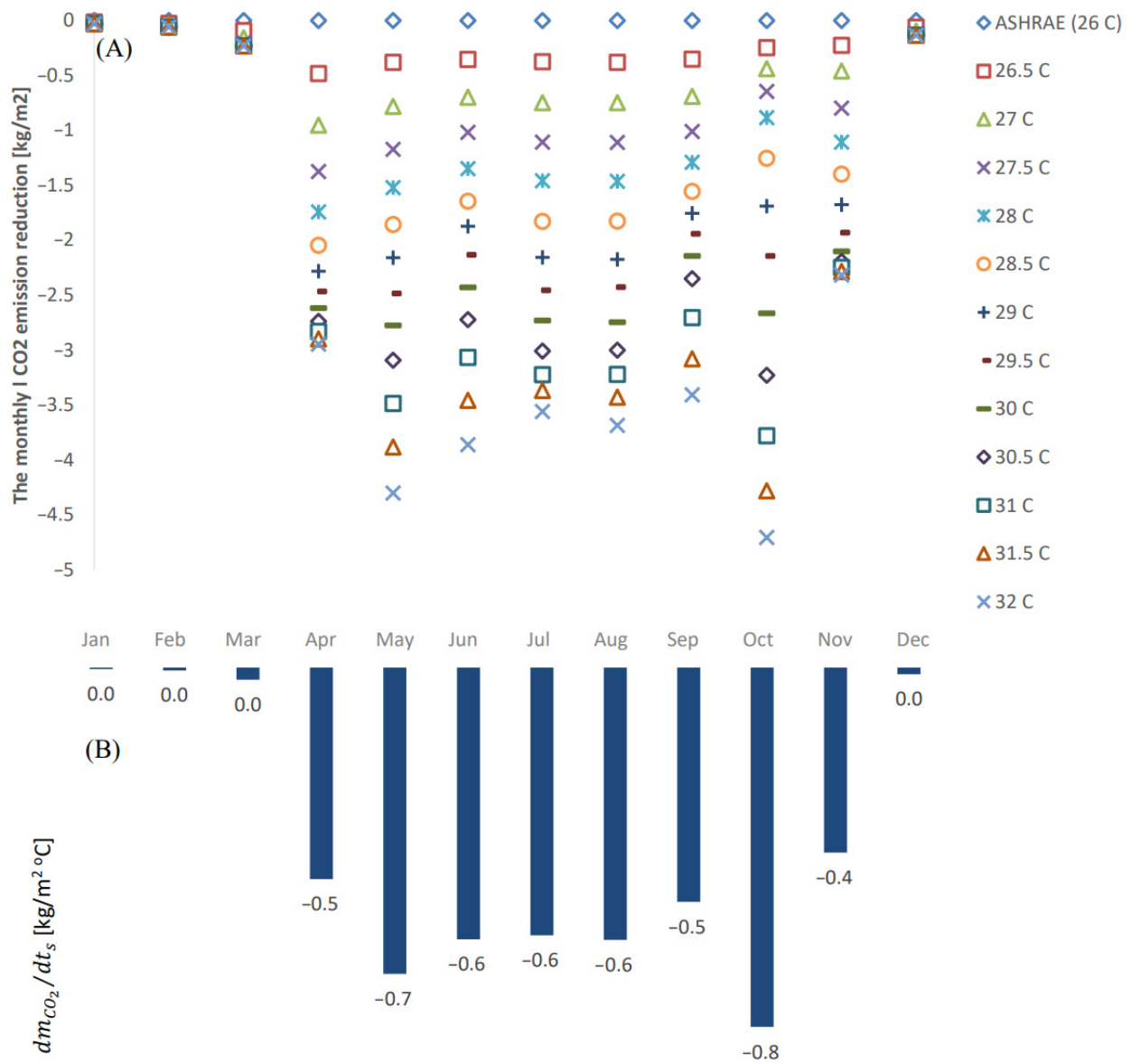
Figure 10. (**A**) The monthly amount of the reduced CO_2 emissions by increasing t_s from the ASHRAE-based cooling setpoint (26 °C); (**B**) The sensitivity of the monthly reduced CO_2 emissions (m_{CO_2}) towards the increased cooling setpoint temperature compared to the ASHRAE-based cooling setpoint (dm_{CO_2}/dt_s).

Table 3. The annual effects of increasing the cooling setpoint temperature by 1 °C.

Parameter	Effect
Operative temperature	Increased by an additional 0.25 °C
The overall cooling energy consumption of the building.	Reduction of 706 kWh
The overall CO_2 emissions of the building.	Reduction of 426.24 kg
The percentage reduction in the overall cooling energy consumption of the building.	Reduction of 8% compared to ASHRAE standard setpoint.
The normalized (by occupied area) cooling energy consumption.	Reduction of 8 kWh for each 1 m^2 of the occupied area.
The normalized (by occupied area) CO_2 emissions.	Reduction of 4.8 kg for each 1 m^2 of the occupied area.

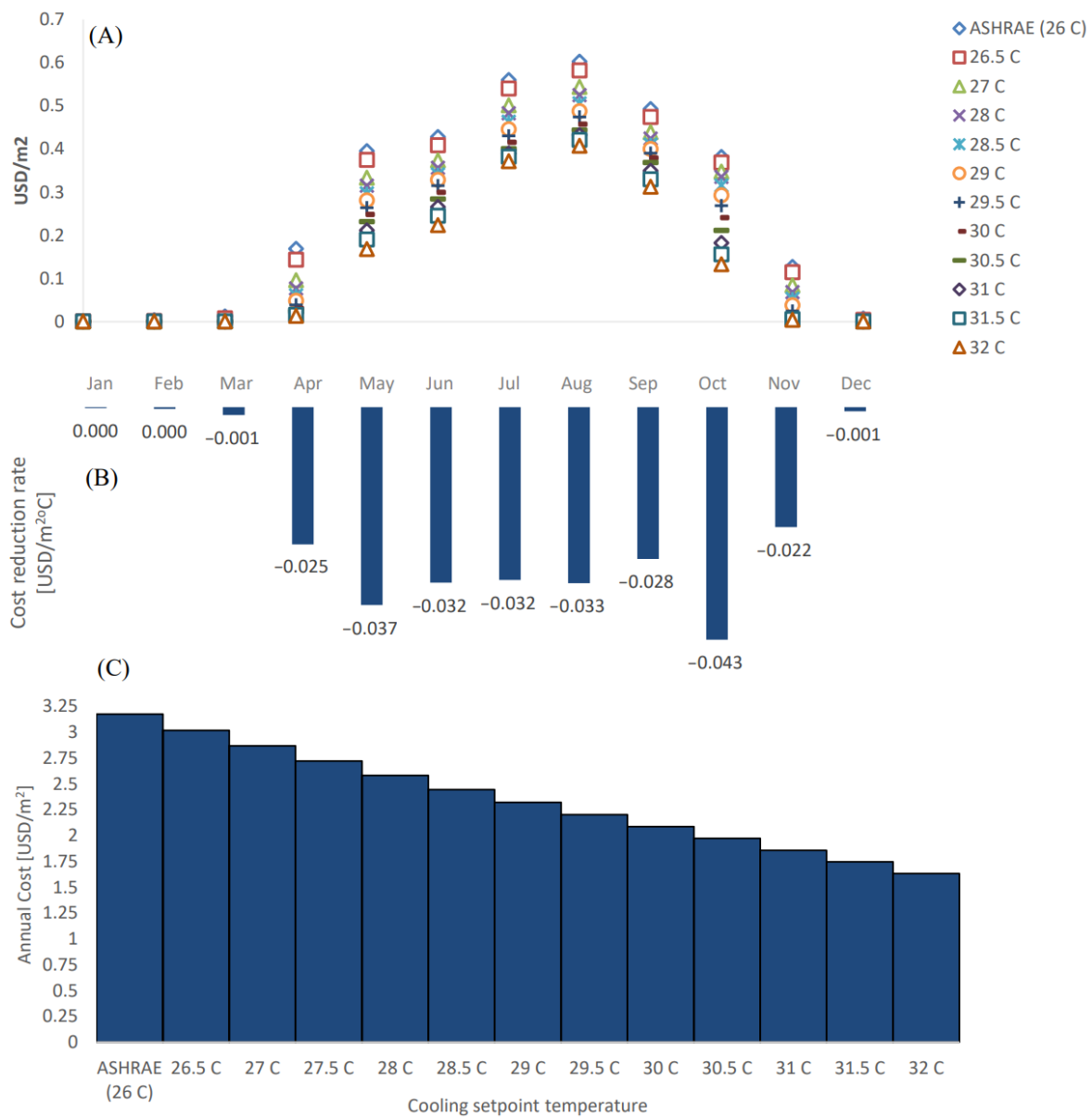**Figure 11.** (**A**) The monthly normalized (by occupied area) cooling energy cost with respect to the cooling setpoint; (**B**) The monthly average rate of normalized cooling energy cost reduction with respect to the cooling setpoint temperature increase; (**C**) The annual normalized cost of each cooling setup.

Table 4. The monthly effects of increasing the cooling setpoint temperature by 1 °C.

Month	Cooling Energy Reduction Rate $(d\hat{E}_c/dt_s)$ [kWh/m² °C]	CO₂ Emission Reduction Rate (dm_{CO_2}/dt_s) [kg/m² °C]
October	−1.3	−0.85
May	−1.1	−0.7
June, July, and August	−1	−0.6
September	−0.9	−0.5
April	−0.8	−0.45
November	−0.7	−0.4
January, February, March, and December	Negligible	Negligible

4. Conclusions

This study quantified the effects of increasing the cooling setpoint temperature on reducing energy consumption and CO_2 emissions by integrating Qatar weather data into the DesignBuilder software to simulate the performance of a generic building under the currently adopted HVAC criteria in Qatar (ASHRAE). This was motivated by the evidence available in the literature showing the unnecessary high energy consumption rate associated with air conditioning that is leading to the undesirable "overcooling" condition in Qatar. The results showed that raising the cooling setpoint temperature by 1 °C causes the operative temperature to rise by approximately 0.25 °C and reduces the annual cooling electricity consumption needed for each 1 m^2 of an occupied area by approximately 8 kWh, which equates to an 8% decrease in energy consumption when compared to the energy consumption at the ASHRAE cooling setpoint (i.e., 26 °C). The corresponding annual CO_2 emission reduction rate was about 4.8 kg/m^2 °C. Additionally, throughout the year, October was the month found to present the greatest opportunity for reducing cooling energy use and CO_2 emissions, with reduction rates of approximately 1.3 kWh/m^2 °C and 0.8 kg/m^2 °C, respectively. In addition, it was found that increasing the cooling setpoint temperature by 1 °C has the effect of reducing annual energy costs by approximately 0.3 USD/m^2, which accounts for an approximately 10 to 12% cost reduction.

In future studies, it is crucial to be able to specify the extent to which cooling setpoint temperature could be increased. This increase is limited by public acceptability and preference. The increase could be estimated by performing conventional thermal comfort surveys. Once this temperature limit is determined, the data presented in this paper could offer an upfront prediction for this temperature limit with respect to the corresponding reduction in energy consumption and CO_2 emissions. Additionally, in future studies, simulations and experimental work will be required to confirm the study results by field testing in existing buildings.

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