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The effectiveness of the Iranian building code in mitigating climate change in Bandar Abbas

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ABSTRACT

Climate change has a varying impact on building energy demand. In Bandar Abbas, a city on the southern coast of Iran, global warming is expected to exacerbate an already harsh climate. Although the Iranian building code has an energy efficiency ranking with specific design requirements, its effectiveness in mitigating climate change is still to be fully understood. Furthermore, Iran's energy mix based on fossil fuels makes filling this gap even more urgent. This study assesses the magnitude of the impact of global warming on a real-case multi-apartment building in this region and evaluates the effectiveness of the different energy efficiency levels designated in the building code in reducing energy consumption under present and future climate conditions. Depending on the projected shared socioeconomic pathways scenarios, the annual electricity consumption may increase by 14 % to 21 % and 21 % to 40 % in 2050 and 2080 timeframes, respectively. When implementing Iranian building code requirements for the envelope's higher levels of energy efficiency, energy consumption reduces substantially, thus contributing to mitigating the impact of global warming. By applying these regulations, energy savings of 5 % to 19 % and HVAC electricity reductions of 9 % to 26 % can be achieved for units on different building floors. In order for Iran to meet the carbon neutrality targets, we recommend making the highest energy efficiency level of the building code mandatory immediately and pushing forward new and more stringent legislation.

Introduction

Climate change poses a significant concern for current and upcoming generations (Borràs et al., 2022; Jim et al., 2023). It is widely recognized that climate change will significantly affect buildings' energy demand, and heating and cooling loads will depend on the building type, location, and regional climate (Tahir & Al-Ghamdi, 2023). Although the accuracy of future energy demand estimates may not be guaranteed, findings show a consistent pattern—heating loads will decrease, while cooling loads will increase in many regions (Tahir & Al-Ghamdi, 2023; Verichev et al., 2021). Regions that show a high cooling demand today will likely experience even greater cooling needs as the climate gets warmer (Azimi Fereidani et al., 2021; Jim et al., 2023).

The Iranian building sector has high energy consumption (Sadafi et al., 2021), with levels approximately five times greater than the global average (Providas, 2021). Buildings in urban areas contribute significantly, up to four times higher than the global average (Providas, 2021). In the southern coastal cities of the country, which have hot-humid climates, buildings experience even higher energy demands, mainly attributed to residential use and largely due to the excessive use of cooling electric devices (IRNA, 2021). Therefore, buildings in this region with already high cooling demand are particularly susceptible to the effect and consequences of global warming.

In order to mitigate the high energy demands that contribute to a higher level of carbon emissions, many countries have set ambitious targets to meet the carbon neutrality targets set under the Paris Agreement, including achieving net zero emissions by 2030. As a signatory to the Paris Agreement, Iran has also taken steps toward the target. In this sense, the Ministry of Housing and Urban Development of Iran has implemented legislation to address the current energy demand issue to reduce energy consumption and associated emissions in the building sector. However, this requirement has been widely neglected by building design practitioners, largely due to the limited knowledge and understanding of the regulations among the public and employees involved in the industry (Sarkheyli et al., 2012). Furthermore, the government has not taken sufficient action to enforce these regulations or emphasize the significance of complying with them (Omrany & Marsono, 2016).

Therefore, to understand the effectiveness of the Iranian building

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code, which serves as the primary measure for reducing energy demands, we need to assess the efficiency of the requirements in the present day as well as its capability to mitigate the impact of climate change. Thus, this study analyzes and compares the energy performance of a reference building in different energy efficiency levels stated in the building code under current and future climate scenarios. As cities with already high cooling demand are more vulnerable to the effects of global warming, this study focuses on a real residential apartment in Bandar Abbas, a southern coastal city in Iran with high cooling energy demand. This type of building was selected because the residential sector consumes more energy than any other sector in this country.

Therefore, this paper will answer the questions "How does climate change affect the energy need of a real residential building located in the southern coastal region of Iran?" and "Does the Iranian building code contribute to the mitigation of climate change impact in this region?"

In a previous study (Azimi Fereidani et al., 2021), researchers revealed a scarcity of studies on how the energy demand of Iranian buildings will be affected by climate change in the future, along with a lack of attention toward mitigation strategies.

Available studies analyzing the impact of climate changes on the future weather condition in Iran show a significant increase in air temperatures for cities in southern Iran. For example, in cities near the Persian Gulf and Oman Sea, temperatures are expected to increase by 2 °C to 3 °C by 2060, with a corresponding rise in relative humidity between 5 % and 7 % (Roshan, Arab, & Klimenko, 2019). Also, an increase in the number and severity of hot discomfort days due to climate change is predicted (Roshan, Arab, & Klimenko, 2019). Another study of a hot-dry city in the southwest of Iran predicts a half-degree increase in average temperature by 2060 (Roshan & Negahban, 2015). Regarding the impact of the estimated temperature rises on the energy demands of buildings in southern regions, the same author found that central and eastern regions of the country with a hot-arid climate currently have the highest cooling needs. However, these demands will shift to southern regions with a hot-humid climate in 2025, 2050, and 2075 (Roshan et al., 2012).

Therefore, from the results of the studies above, it is likely that southern coastal regions will be more exposed and vulnerable to the impacts of climate change. Nevertheless, only three studies thus far have focused on assessing the strategies which may mitigate the impact of climate change.

In the first one, Givoni's bioclimatic chart is adapted for Iranian cities to provide various recommendations for the different climates of Iran (Roshan, Oji, & Attia, 2019). The study indicates that in hot-humid regions, conventional air conditioning and dehumidification are the only effective measures for buildings in the future. In contrast, buildings in hot-dry regions can utilize indirect evaporative cooling, high thermal mass, and night ventilation to prevent overheating under future climatic conditions (Roshan, Oji, and Attia, 2019). In the second research work, the impact of green passive design strategies on the energy consumption of an apartment building in Kerman (hot-dry) and Bandar Abbas (hot-humid) was assessed under the RCP2.6 scenario for the observed (2000–2019) and projected (2050) periods (Roshan et al., 2022). The results revealed that global warming might decrease heating energy consumption in Kerman, where the demand for heating is moderate, from 61 % to 47 %. However, for Bandar Abbas, where nearly all the energy demand is for cooling, the annual energy consumption is not expected to change by 2050. The study suggests that green passive design strategies are more effective in reducing heating energy demand than cooling needs. Moreover, it concludes that green walls have better energy performance and higher CO_2 reduction than green roofs (Roshan et al., 2022). A recent study seeking to determine the trend for ideal thermal transmittance for single-family houses in different climate regions of Iran revealed that, for Bandar Abbas, current and future optimal values should be the lowest possible due to outdoor air temperatures around the year (Rodrigues, Fereidani, et al., 2023).

Due to limited literature on this climate region, we expanded our search to cover all climate regions in Iran. Only two additional studies which analyzed mitigation strategies under future weather conditions were identified. However, both studies focused on Tehran, which has a medium heating demand in the current period.

The first research work conducted a multistage optimization study on an educational building in Tehran, considering passive measures (glazing and insulation) and active strategies (HVAC). Results indicate that the optimized solutions for the present day are not effective in 2080. However, the chosen future-optimized strategies can reduce total energy consumption by 49 % for the present day and 52 % for the future, compared to the base case (Aram et al., 2022).

Another study found that implementing energy retrofit strategies, including passive measures (adding insulation and improving window glazing) and active measures (using PV panels and altering HVAC setpoints and coefficient of performance), can significantly improve environmental performance and reduce thermal discomfort. However, the impact of climate change on a building's external thermal loads can have a distinct effect on the selection of optimal systems. As a result, the recommended optimal packages shift toward more expensive and energy-efficient cooling systems due to the higher demand for cooling than heating in the future. However, despite the shift in optimal systems, overall primary energy consumption and CO_2 emissions decreased due to the reduction in heating demand in the case study building (Mostafazadeh et al., 2023).

From the above literature, we realize that research on the impact of climate change on energy demands in buildings across all climate regions in Iran is still limited, especially in the more vulnerable southern coastal regions where buildings require a high cooling demand even under the current climate condition.

Moreover, while few mitigation strategies have been studied for buildings in Iran, those that have, have been primarily used for the Tehran region, with the need for more region-specific research being highlighted as climate change affects different regions and climates in unique ways. In addition, the few existing studies focus on single-family houses or educational buildings, but there are still other building types that require the researchers' attention, such as apartment buildings. Although building standards in Iran can potentially reduce energy demand, their effectiveness on present or future building performance has not been assessed.

Therefore, the novelty of this study lies in its focus on investigating the impact of climate change on the energy demands of a real apartment building situated in a coastal city in the south of Iran, characterized by high cooling demands. This study uniquely evaluates the value of building code requirements as a potential mitigation strategy for tackling climate change.

Furthermore, the use of future weather data generated from the latest climate models and the analysis of alternative IPCC's Shared Socioeconomic Pathways have been lacking, underlining the importance of further research in this field. Thus, the study uses 21st-century weather as a baseline and generates future weather based on the latest CMIP6 experiments, providing more up-to-date and accurate results than prior research.

The study's objective is to provide valuable insights into the impact of climate change on buildings in Iran. The findings of this study contribute to the body of knowledge on sustainable building practices and provide practical implications for future strategies aimed at enhancing energy efficiency and promoting climate-resilient construction, particularly in coastal regions with similar climatic conditions. Furthermore, by highlighting the potential role of building code requirements as a mitigation strategy, the study informs decision-making processes related to energy-efficient and climate-resilient building practices.

Materials and methods

A real building in the southern coastal region of Iran was first selected to represent the residential multi-apartment buildings (criteria for its selection are presented in Section 'Selection of the reference building'). Then, the reference building was modeled and validated against the energy bills of a real apartment in the second step (model characterization and validation procedure are presented in Sections 'Modeling of the reference building' and 'Building model validation'). In the third step, 21st-century weather was mathematically transformed into a future climate (the procedure to generate future weather is depicted in Section 'Climate scenarios'). Then, the opaque and transparent elements of the building envelope were adjusted to match the requirements for different energy efficiency levels set by the Iranian National Building Code (characterization presented in Section 'Iranian building code requirements'). In this step, we simulated the energy performance of each building case in each climate scenario. Finally, the results were curated as a dataset.

The last step entailed analyzing and discussing all results obtained from the simulations. In this step, future weather data was first analyzed for the selected scenarios (Section 'Future climate in Bandar Abbas'). Then, the energy performance of the reference building was simulated in the second step (Section 'Impact of climate change on the reference building'). Next, the energy demands of buildings aligned with national building code requirements and ASHRAE were simulated under current (Section 'Impact of Iranian building code requirements on the reference building') and future climate conditions (Section 'Future climate energy consumption comparison'). Comparisons show the effectiveness of the Iranian national building code in mitigating the impact of climate change on the reference building. Fig. 1 illustrates the study concept framework.

Selection of the reference building

The reference building was selected based on data from the latest Iranian national census, which states that apartment buildings with five or more stories are the most common type in Iran (Statistical Center, 2016). Additionally, the census data indicates that apartment units with two bedrooms (ranging in area from 80 m^2 to 100 m^2) and units with three bedrooms (ranging in area from 101 m^2 to 150 m^2) are frequent (Statistical Center, 2016).

Regarding energy demands, the census data shows that around 71 % of apartment blocks in Iran use evaporative air-cooling systems. However, the most used cooling systems in the specific region of Bandar Abbas are HVAC split units and window air conditioners, as high relative humidity negatively affects the efficiency of evaporative air-cooling systems (Statistical Center, 2016). Heating is not usually required in Bandar Abbas, only the occasional use of electric heaters when the winter is colder. The energy needs for cooking and hot water are mainly addressed through the consumption of liquid gas (Statistical Center, 2016).

Based on the information above, a 7-story residential apartment with a concrete structure was selected as the reference building (Fig. 2). The ground floor is an open parking lot; the remaining six floors include two apartment units. The left-side apartments have three bedrooms and an area of 127 m^2, while the right-side apartments have two bedrooms and 98 m^2. Both units have two balconies, one living room, one kitchen, and two bathrooms. Living rooms and bedrooms are equipped with split units. There are two adjacent building blocks of a similar type on each side of the building. A summary of the characteristics of the selected building is provided in Table 1, which follows the common types of apartment buildings in the region.

The available information regarding the apartment units is limited to a two-bedroom apartment on the middle floor, currently occupied by a family of three. Details about the apartment's lighting and electric equipment may be found in ref. (Azimi Fereidani et al., 2023). Because there are no heating needs in this region, living rooms/kitchens and bedrooms in this building are equipped with a single split unit with a cooling capacity of 3.52 kW for bedrooms and 7.03 kW for living rooms.

The thermophysical properties of the construction elements collected from detailed architectural drawings are presented in Table 2. Based on this apartment unit, windows are also covered with cream-colored semitransparent interior curtains.

Modeling of the reference building

The reference building's geometry was modeled in OpenStudio software based on blueprints and technical drawings, and the adjacent buildings were incorporated as shading surfaces (Fig. 3). Then, the model was completed in IDF Editor from the EnergyPlus package.

To simulate the electricity consumption of the reference apartment unit, schedules for the HVAC systems and internal gains (people, lighting, and electrical equipment) were established, corresponding to the two-bedroom apartment unit with three occupants. Since liquid gas is used for heating water and cooking, they were not included in the simulation. When data from the reference building was unavailable, information from relevant regulations and the Iranian building code was used for input parameters.

The activity levels of people range from 72 W·person^{-1} to 110 W·person^{-1} for bedrooms, 99 W·person^{-1} to 171 W·person^{-1} for living rooms, and a fixed value of 130 W·person^{-1} for bathrooms. For the electric lights, the maximum lighting design level per room is calculated based on the type and number of lights in each zone in the real unit, which is 320 W, 125 W, and 90 W for the living room/kitchen, master bedroom, and one single bedroom, respectively. The maximum

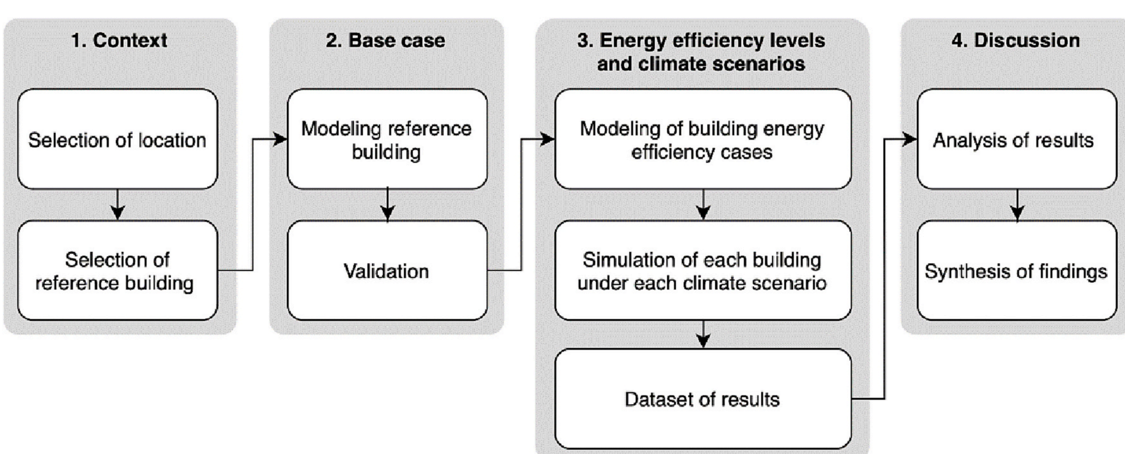


Fig. 1. Study concept framework.

(a) Building facade.

(b) Building surroundings.

Fig. 2. Reference building façade and surroundings.

Table 1
Specifications of the common residential apartment building (Statistical Center, 2016) and the selected building.

Residential apartments	The common type of residential apartments according to the Iranian National Census (2016–2017)	Selected building
Number of stories	5 or more stories	7-Story residential building
Area (m^2) and number of rooms	2-Bedroom units with area between 80 and 100 m^2 3-Bedroom units with area between 101 and 150 m^2	2-Bedroom units (total area of 98 m^2) 3-Bedroom units (total area of 127 m^2)
Main source of energy	Electricity for cooling and heating; liquid gas and electricity for cooking and hot water	Electricity for cooling and heating and liquid gas for heating DHW and cooking

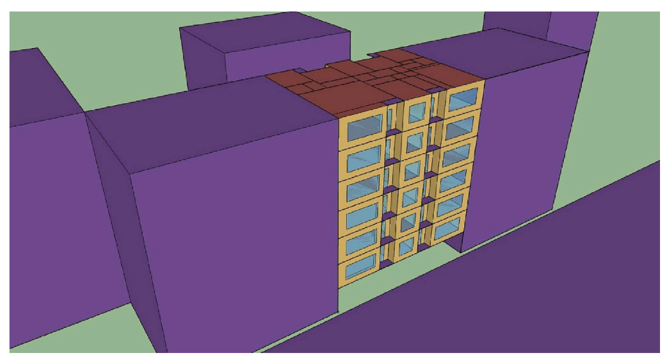


Fig. 3. Reference building model in Open Studio environment.

Table 2
Thermophysical properties of the building elements.

Element	Layer	Thick. (m)	k (W·m^{-1}·K^{-1})	ρ (kg·m^{-3})	c_p (J·kg^{-1}·K^{-1})	U (W·m^{-2}·K^{-1})	SHGC (–)
Exterior wall (South and North)	Travertine stone	0.030	2.170	1860	2500	1.890	–
	Plastering (cement)	0.030	0.700	840.0	800.0		
	Clay block	0.200	0.500	1300	800		
	Plastering (cement)	0.030	0.700	840.0	800.0		
	Gypsum plaster	0.030	1.100	1400	837.0		
Exterior wall (East and West)	Plastering (cement)	0.030	1.100	840.0	800.0	1.949	–
	Clay block	0.200	0.500	1300	800		
	Plastering (cement)	0.030	0.700	840.0	800.0		
	Gypsum plaster	0.030	1.100	1400	837.0		
Floor	Gypsum plaster	0.030	1.100	1400	837.0	1.027	–
	Roof structure	0.300	0.379	25.00	1300		
	Lightweight concrete	0.050	0.530	1280	840.0		
	Plastering (cement)	0.030	0.700	840.0	800.0		
	Mosaic	0.025	1.400				
Roof	Asphalt	0.030	0.200	1050	900.0	0.907	–
	Asphalt cement plaster	0.045	1.150	2000	800		
	Lightweight concrete	0.050	0.530	1280	840.0		
	Roof structure	0.300	0.379	25.00	1300		
	Gypsum plaster	0.030	1.100	1400	837.0		
Window	Clear (glazing)	0.006	0.900			2.685	0.703
	Air (gas)	0.012					
	Clear (glazing)	0.006	0.900				

equipment design level per room is also calculated based on the equipment in each zone of the real unit, which is 8037 W, 112 W, 35 W, and 1520 W for the living room/kitchen, master bedroom, single bedroom, and bathrooms, respectively. More information regarding the internal gain schedules for each space can be found in ref. (Azimi Fereidani et al., 2023).

Regarding HVAC and airflow specifications, living rooms and bedrooms are the only spaces with heating and cooling, with the system's availability depending on the occupancy of each room. As each room in the building is equipped with a single split unit, we used an HVAC package terminal heat pump as a split cooler separately for each room for energy simulations. The coefficient of performance is 3 W/W for cooling, and the setpoint is 26 °C. The time schedules for the associated rooms are presented in (Azimi Fereidani et al., 2023). As for natural ventilation, when the outside air temperature is below 25 °C, a fixed value of 2 h^{-1} air changes is considered for rooms having windows. Additionally, mechanical ventilation is considered in WCs and bathrooms with an exhaust rate of 0.02 m^3/s during occupancy, as defined for these zones. Furthermore, an additional 0.7 h^{-1} air changes are considered for outdoor air infiltration in zones with exterior openings based on the average Iranian new-built building (Department of Housing and Urban Development, 2019).

Building model validation

The model was calibrated by changing assumed input parameters, such as schedules for lighting, electrical devices, and HVAC systems, to match the energy consumed reported in the electricity bills. Table 3 and Fig. 4 show the energy simulation results for a single unit on the middle floor. These also include the electricity bills of the real apartment unit for comparison. The annual difference between the base case electricity consumption and the simulation result is only −4 %, indicating that the results correlate with the energy consumption represented in the bills. The monthly comparison also shows a 9 % increase in difference during the two colder months of January and February. However, for the warmer months, the differences range between −1 % to −9 %.

It is important to note that the results from this specific unit may not apply to all other units within the building. However, in the subsequent analysis, we considered extrapolating the resulting parameters to similar units within the building, which have similar characteristics regarding floor plan design, window size, orientation, and energy use profile. These units are those (two-bedroom units) located on the right side of the building.

Climate scenarios

Recently, the Integrated Assessment Modeling (IAM) community, in collaboration with the Intergovernmental Panel on Climate Change (IPCC), have developed five scenarios called Shared Socioeconomic Pathways (SSPs), which provide a more comprehensive picture of future socioeconomic development and the interactions with the environment (Riahi et al., 2017). SSPs portray a range of possible pathways for social and economic development, including population, economic growth, and resource use (from sustainability to fossil fuel development) and estimated global temperature increases by 2100. In the best-case scenario of SSP1, the global temperature is predicted to increase by 1.7 °C, while the worst-case scenario of SSP5–8.5 is estimated to result in a 4.4 °C rise by 2100. Also, SSPs are more detailed scenarios of the Representative Concentration Pathways (RCPs), with SSP1–2.6 corresponding to RCP2.6, SSP2–4.5 to RCP4.5, SSP3–7.0 to RCP6.0, and SSP5–8.5 to RCP8.5 (IPCC, 2021).

Future weather was generated by morphing present-day weather data to match the selected scenarios. The morphing procedure transforms meteorological weather records to be statistically consistent with projected climate scenarios obtained from numerical climate models. For that, each weather variable is stretched, shifted ($x = x_0 + \Delta x_m$), or stretched ($x = \alpha_m \cdot x_0$) and shifted simultaneously ($x = x_0 + \Delta x_m + \alpha_m \cdot x - \alpha_m \cdot x_0$) using monthly changes (delta difference, Δx_m, or fraction, α_m) between a present-day baseline (x_0) and a future climate timeframe. The remaining variables are computed from solar model equations or psychometric functions. The procedure is essentially a delta method, thus not requiring bias correction.

However, the morphing procedure has associated uncertainties. These are related to the validity of the climate model data, the representativeness of the climate model grid, the representativeness of the present-day weather to be morphed, and the morphing procedure (Jentsch et al., 2013). In order to limit these uncertainties, the latest and state-of-the-art morphing tool Future Weather Generator was employed (Rodrigues, Fernandes, & Carvalho, 2023). This tool has climate data from the EC-Earth3 model, utilized in the CMIP6 experiments that served as the basis for the IPCC's 6th Assessment Report. The climate model grid has 131,072 points representing an atmospheric resolution of T255 (~80 km) and 1.0° for the ocean (ORCA1L75), and the variable monthly changes are spatially downscaled using a bilinear interpolation method of the four nearest points of the grid to the weather data's location. In addition, the tool morphs more variables and overcomes several issues found in other morphing tools (Rodrigues, Fernandes, and Carvalho, 2023). Monthly changes are computed from each median month of the present-day period (1985–2014) and the two future timeframes – 2050 (2036–2065) and 2080 (2066–2095). The tool and the formulation are available on the tool's website (Rodrigues et al., 2022).

Iranian building code requirements

Many countries have established regulations on building design and construction to decrease the current level of energy consumption in buildings and play a part in mitigating global warming. A key aspect of these regulations is the requirement for energy-efficient building envelopes. For example, it defines maximum *U*-values for opaque and transparent elements. In recent decades, Iran has also introduced some provisions regarding the energy efficiency of envelopes in its building code. However, despite such provisions, their implementation has been widely neglected (Omrany & Marsono, 2016). As mentioned earlier, the main reason for this disregard is the low level of awareness among citizens and those employed in this sector (Sarkheyli et al., 2012) as well as the absence of government enforcement efforts to implement these provisions and to emphasize the importance of compliance (Omrany & Marsono, 2016).

The Iranian building code classifies buildings into four groups based on their type (residential, commercial, among others) and location (cities with low, medium, or high energy demand), indicating the urgency of energy efficiency measures. Buildings with the highest priority for energy savings are placed in Group 1, while those with the lowest priority are in Group 4. According to the latest version of the code, buildings in all four groups must meet the minimum thermal resistance (*R*-value) requirements for non-translucent elements of the envelope. The minimum values are 0.5 m^2·K/W for walls, 0.7 m^2·K/W for roofs, and 0.65 m^2·K/W for floors (in contact with air).

Table 3
Monthly report of the real electricity bills for the apartment unit and the simulation results.

Month	Real electricity bills (kW·h)	Simulated electricity consumption (kW·h)	Difference (%)
Jan–Feb	728.18	790.8826	9 %
March–Apr	1312.45	1297.692	−1 %
May–June	2267.6	2137.278	−6 %
July–Aug	2521	2453.837	−3 %
Sep–Oct	2308.64	2096.236	−9 %
Nov–Dec	1154.81	1145.518	−1 %
Annual	10,292.67	9921.443	−4 %

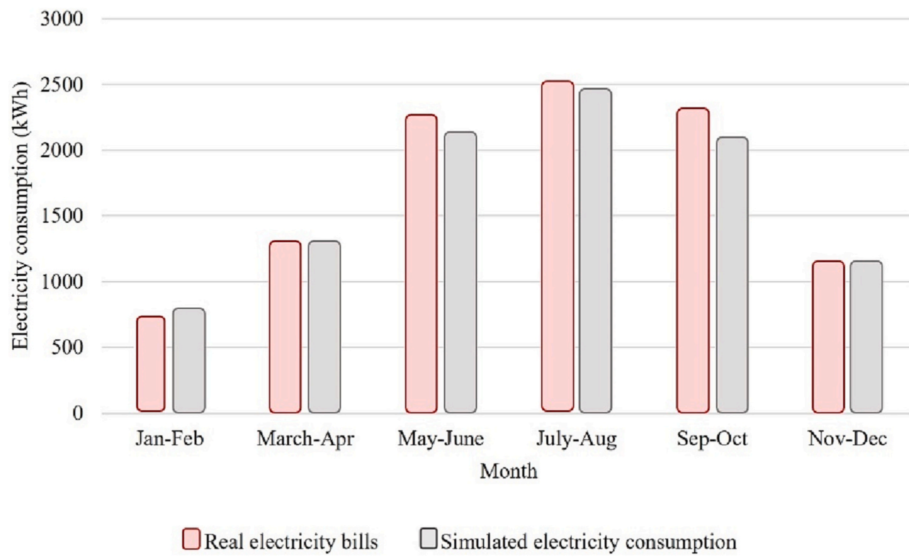


Fig. 4. Monthly comparison of the real electricity bills for the apartment unit with the simulation results.

The building code recently introduced three energy levels, EC, EC+, and EC++, increasing the buildings' energy efficiency. The EC level is considered the minimum standard, and it is mandatory for all buildings except those in Group 4. The EC+ and EC++ levels are optional, and the legislator intended them to define low- and very low-energy buildings, respectively. These levels come with their associated requirements. Additionally, the requirements set by ASHRAE for this region were also assessed to provide a broader perspective.

In this study, the reference building only meets the minimum thermal resistance (*R*-value) requirements and does not comply with any of the recently defined energy levels. However, given that the reference building is a residential building located in Bandar Abbas, characterized by high-cooling energy demand, it should comply with the requirements outlined for Group 1, summarized in Table 4. Also, Table 5 presents ASHRAE requirements for residential buildings with more than three stories in Bandar Abbas. According to the latest version of the ASHRAE's "Energy Standards for Buildings," Bandar Abbas is classified as Climate Zone 0.

Therefore, the opaque and transparent elements of the reference building were modified to meet the requirements of each of the three energy levels (EC, EC+, and EC++) and ASHRAE. This change involved adding expanded polystyrene (EPS) insulation of varying thicknesses to the external building envelope to meet the minimum *R*-value requirements for opaque elements. In addition, the building was equipped with a simple glazing system for transparent elements, which addresses the requirements of all energy levels. By modeling the reference building based on three different energy levels and applying ASHRAE standards, for both present and future timeframes, it was possible to evaluate the impact of the Iranian building code and ASHRAE requirements on the energy performance of the reference building in Bandar Abbas. The results are analyzed and compared in the following section.

Table 5
ASHRAE requirements for climate zone 0.

Requirements	Opaque elements			Transparent elements		
	Wall	Roof	Floor	Glazing		
	Min *R*-value (m^2·K/W)			Max *U*-value (W/m^2K)	Max SHGC	Max TV/SHGC
Climate zone 0	1	5.3	–	3.52	0.20	1.2

Results and discussions

Future climate in Bandar Abbas

For the present-day climate, 21st-century hourly weather for Bandar Abbas was retrieved from the climate.onebuilding.org website (Climate.OneBuilding.Org, 2021). The weather data follows the TMY/ISO 15927-4:2005 and is derived from meteorological records between 2004 and 2018. The present-day data was then morphed to match different SSP scenarios in the 2050 and 2080 timeframes.

Table 6 compares the most relevant weather variables impacting the building energy performance in Bandar Abbas for present-day and SSP climates (2050 and 2080 timeframes). The average dry bulb temperature is expected to increase by approximately 1.6 °C for scenario SSP1 and around 1.8 °C for scenario SSP2 in the 2050 timeframe. Meanwhile, higher temperature increases of 2 °C and 2.4 °C are predicted for scenarios SSP3 and SSP5, respectively. In 2080, the differences range from 1.5 °C for SSP1 to 4.5 °C for SSP5. These changes demonstrate that Bandar Abbas will be particularly impacted by global warming, as the increase in the local average temperature will be greater than the increase in the global average temperature for the SSP5–8.5 scenario in 2100. Also, daily minimum and maximum average temperatures are

Table 4
Iranian building code requirements for different energy levels.

Requirements	Opaque elements				Transparent elements		
	Exterior wall	Interior wall	Roof	Floor	Glazing		
	Min *R*-value (m^2·K/W)				Max *U*-value (W/m^2·K)	Max SHGC	Max TV/SHGC
EC level	1.2	1	2.3	2.2	3.1	0.4	1.2
EC+ level	1.7	1.4	3.3	3.1	2.4	0.37	1.7
EC++ level	2.4	2	4.6	4.4	2.2	0.35	2.2

Table 6
Dry-bulb temperature, relative humidity, global horizontal radiation, and wind speed variables comparison between present-day and 2050 and 2080 timeframes for Bandar Abbas (hourly average and present-day to timeframe difference).

Climate scenario	Timeframe	Dry-bulb temperature				Relative humidity		Global horizontal radiation		Wind speed	
		°C	Δ °C	Max °C	Min °C	%	Δ %	$W \cdot h \cdot m^{-2}$	Δ $W \cdot h \cdot m^{-2}$	$m \cdot s^{-1}$	Δ $m \cdot s^{-1}$
Base case	Present day	27.5		32.4	22.6	64		246		3.7	
SSP1–2.6	2050	29.1	1.6	34.0	24.2	64	0	245	−1	4	0
	2080	29.1	1.6	34.1	24.1	64	0	247	1	4	0
SSP2–4.5	2050	29.4	1.8	34.3	24.4	64	0	241	−5	4	0
	2080	30.3	2.8	35.3	25.3	63	−2	243	−3	4	0
SSP3–7.0	2050	29.6	2.1	34.4	24.8	65	0	237	−9	4	0
	2080	31.2	3.6	36.0	26.3	63	−1	238	−8	4	0
SSP5–8.5	2050	30.0	2.4	34.8	25.0	64	0	240	−6	4	0
	2080	32.1	4.5	37.0	27.1	62	−2	242	−4	4	0

predicted to increase for all scenarios, ranging from 1.6 °C in SSP1 to 2.4 °C in SSP5 in 2050 and from 1.5 °C in SSP1 to 4.5 °C in SSP5 in 2080, which will negatively impact the potential for night cooling.

There is no variation in relative humidity between the present day and 2050, and only a slight decrease is presented between present-day and 2080 climates. The trend ranges from 0 % for SSP1–2.6 to −2 % for SSP5–8.5 in 2080. As for global horizontal radiation, the differences range from a negligible −1 $W \cdot h \cdot m^{-2}$ to −9 $W \cdot h \cdot m^{-2}$ in 2050 and 1 $W \cdot h \cdot m^{-2}$ to −9 $W \cdot h \cdot m^{-2}$ in 2080, showing a slight decrease. Wind speed will be similar when comparing future timeframes to present-day climate.

Additionally, for the 2050 timeframe, Fig. 5 compares monthly average temperatures for different scenarios with the baseline. The chart lines show that the monthly differences range from 1.1 °C to 2 °C for scenario SSP1–2.6 and from 1.3 °C to 2.2 °C for scenario SSP2–4.5. The temperature differences are even more significant between scenario SSP3–7.0 and the baseline, ranging from 1.4 °C to 2.6 °C, with the greatest variation observed for SSP5–8.5, which varies between 1.7 °C to 2.8 °C. Regarding the 2080 timeframe, as expected, the comparisons indicate larger differences for most scenarios (Fig. 6). For instance, the difference in the average temperature increases by 3.4 °C in March of SSP2–4.5, while the highest difference is 4.6 °C in November of SSP3–7.0. Also, scenario SSP5–8.5 has the largest differences, with most months having more than 4 °C. For this scenario, the maximum difference is 5.5 °C for February. However, among the scenarios, the predicted average temperatures are similar or even lower for most months in scenario SSP1–2.6 compared to its results for 2050. Only February, March, and September show slightly higher temperatures. These results can be attributed to the assumption of the scenario SSP1–2.6 that CO_2 emissions will reach net zero around 2075 as green technologies replace fossil fuels, resulting in lower warming from the mid-century onward.

The monthly average temperature differences between scenarios in the 2050 timeframe are smaller compared to 2080. For 2050, the largest difference is around 1.3 °C, while the difference reaches up to 3.8 °C for January in the 2080 timeframe. This variation can be related to the fact that most scenarios have similar predictions for CO_2 emissions and warming until 2050, with a slightly lower increase in SSP1 and SSP2. However, the scenarios diverged in their paths from mid-century to 2100, resulting in tangible effects on their estimated warming.

After conducting the analyses, two scenarios were selected: SSP2–4.5 and SSP5–8.5. The former was chosen since it takes the middle ground and is more plausible (Hausfather & Peters, 2020). In this scenario, the dry bulb temperature in Bandar Abbas is expected to increase by 2 °C in 2050 and by 3 °C in 2080. Although the latter scenario is unlikely, it was selected since it has the most impactful consequences on the city (around a 5 °C increase in air temperature by the end of 2100), as some researchers highlight the importance of analyzing this scenario for these reasons (O'Neill et al., 2016).

Impact of climate change on the reference building

The reference building was simulated for scenarios SSP2–4.5 and SSP5–8.5. Fig. 7(a) displays the results of the annual total electricity consumption for the two-bedroom units located on the first (FF), middle (MF), and last floors (LF) of the reference building. This scenario predicts a 14 % increase in the total annual electricity consumption for both FF and MF and a 16 % increase in the LF in the 2050 timeframe. For 2080, electricity consumption will increase by 21 % for the MF, 22 % for

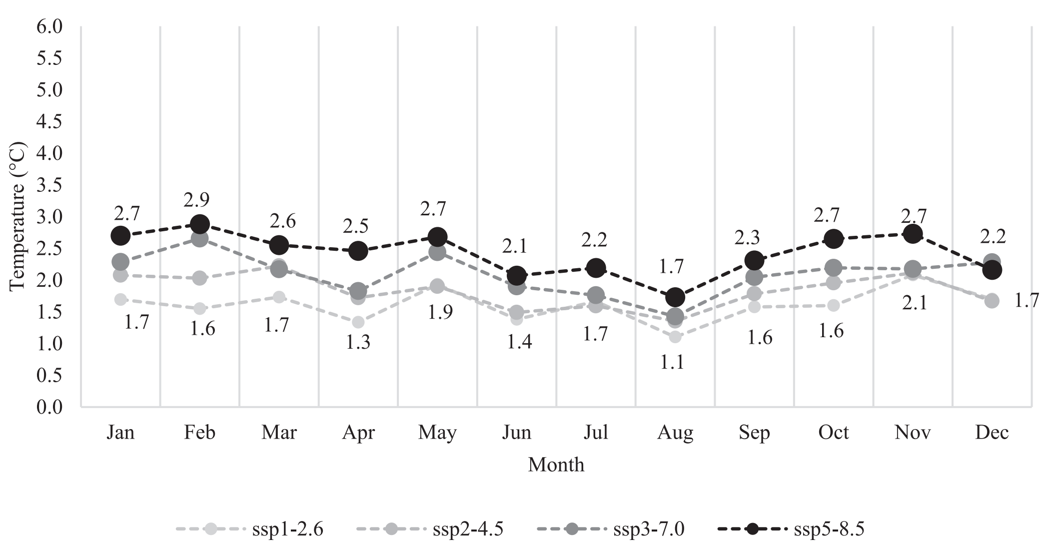


Fig. 5. Monthly values of average temperatures (°C) differences between 2050 and baseline climate.

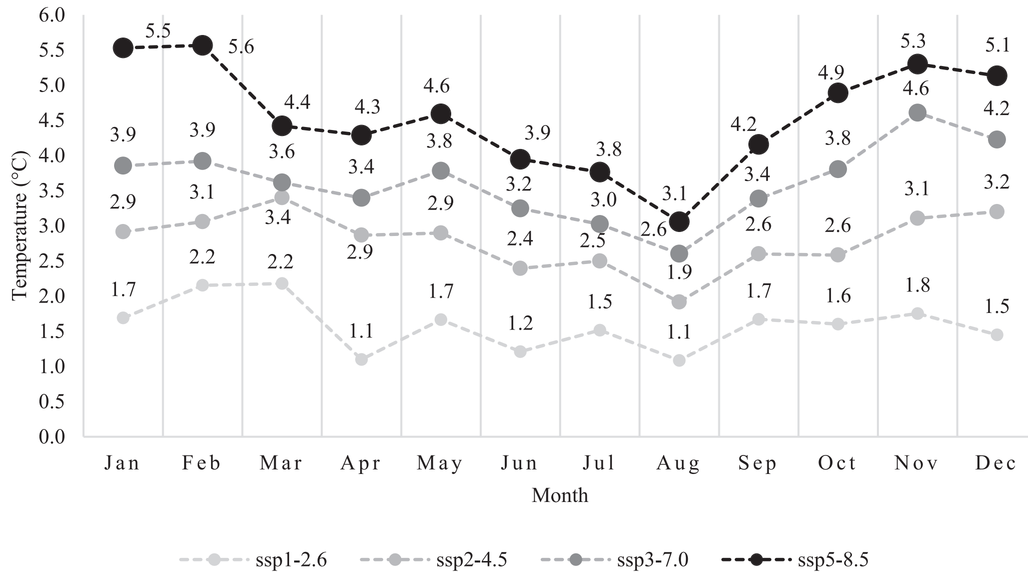
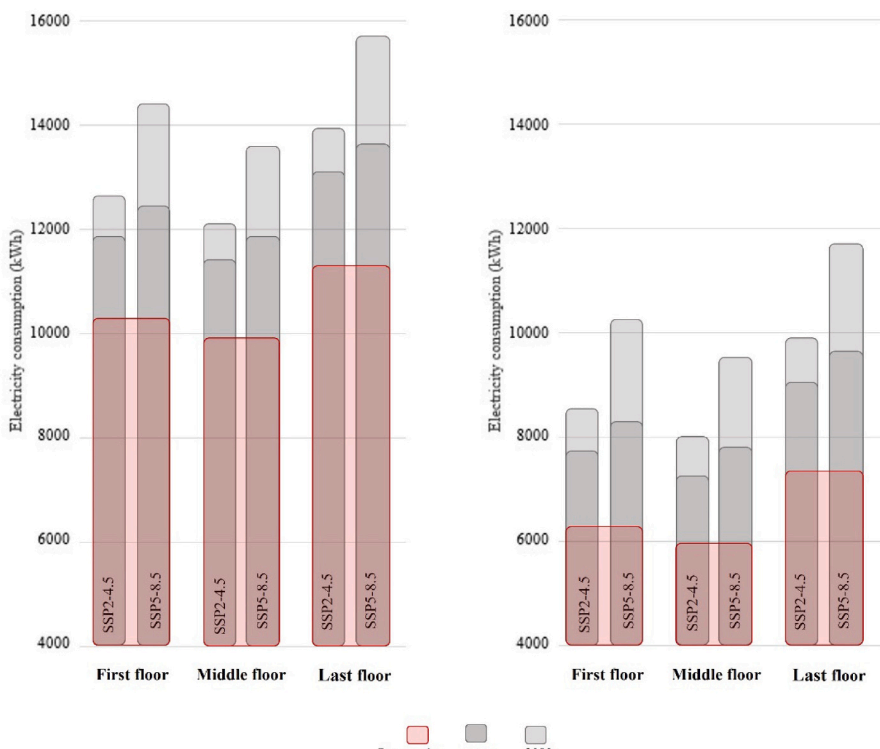


Fig. 6. Monthly average temperatures (°C) differences between 2080 and baseline climate.



(a) Total electricity consumption. (b) HVAC electricity consumption.

Fig. 7. Annual electricity consumption for the base case, 2050 and 2080 timeframes under SSP2–4.5 and SSP5–8.5 scenarios.

the FF, and 23 % for the LF. In the SSP5.8–5 scenario, the annual electricity consumption will rise by 19 % for the MF, 20 % for the FF, and 21 % for the LF in the 2050 timeframe. The increments for the 2080 timeframe, however, are predicted to almost double those in 2050, presenting a 37 % increase for the MF and 40 % for the FF and LF.

Comparing the scenarios in the 2050 timeframe, total annual electricity consumption for SSP5–8.5 is around 6 % higher than in SSP2–4.5 for all floors. However, the difference is even more significant, at 17 % in the 2080 timeframe. This higher difference in consumption is consistent with the assumptions of each of the scenarios regarding the increase in air temperatures and, thus, in cooling demand, which is projected to plateau from mid-century to 2100 in the case of SSP2–4.5 but continues to rise in the SSP5–8.5 scenario.

Regarding energy consumed on different floors, as the apartment units on the first and last floors have a higher exterior surface area, they exhibit slightly higher differences.

Electricity consumption will increase in future timeframes, particularly due to the HVAC system, as there is a greater need for cooling in the warmer future. As shown in Fig. 7(b), cooling energy is predicted to increase up to 25 % and 37 % by 2050 and 2080, respectively, in SSP2–4.5 for all apartments. The increase is even higher for the SSP5–8., with cooling energy expected to rise by up to 33 % in 2050 and 65 % in 2080. Therefore, the results for electricity consumption under the SSP scenarios confirm that climate change has a negative impact on the energy consumption of buildings in the coastal city of Bandar Abbas.

Impact of Iranian building code requirements on the reference building

After modifying the opaque and transparent components of the reference building envelope to meet the requirements for different energy levels set by the Iranian National Building Code, the energy performance of each level case was simulated for present-day weather.

The results are shown in Fig. 8(a), indicating that applying the EC level requirements for the building envelope can reduce the annual electricity consumption. For instance, the FF would see a decrease from 10,313 kWh to 9542 kWh (7 %), the MF from 9921 kWh to 9282 kWh (6 %), and the LF from 11,248 kWh to 10,064 kWh (11 %). The reduction would even be more significant if EC+ (up to 14 %) or EC++ (up to 16 %) requirements were applied. The ASHRAE requirements would also result in a reduction in annual electricity consumption. For example, the FF would experience a drop from 10,313 kWh to 9792 kWh (5 %), the MF from 9921 kWh to 9155 kWh (8 %), and the LF from 11,248 kWh to 9517 kWh (15 %).

With regard to HVAC demands, as presented in Fig. 8(b), the reductions for the EC level vary between 13 % to 17 % for different floors. For EC+, the decrease ranges between 15 % and 22 %, and for EC++ from 16 % to 25 %. For ASHRAE, the highest reduction is seen on the last floor (26 %), while for the middle and first floors, the reductions are 15 % and 10 %, respectively.

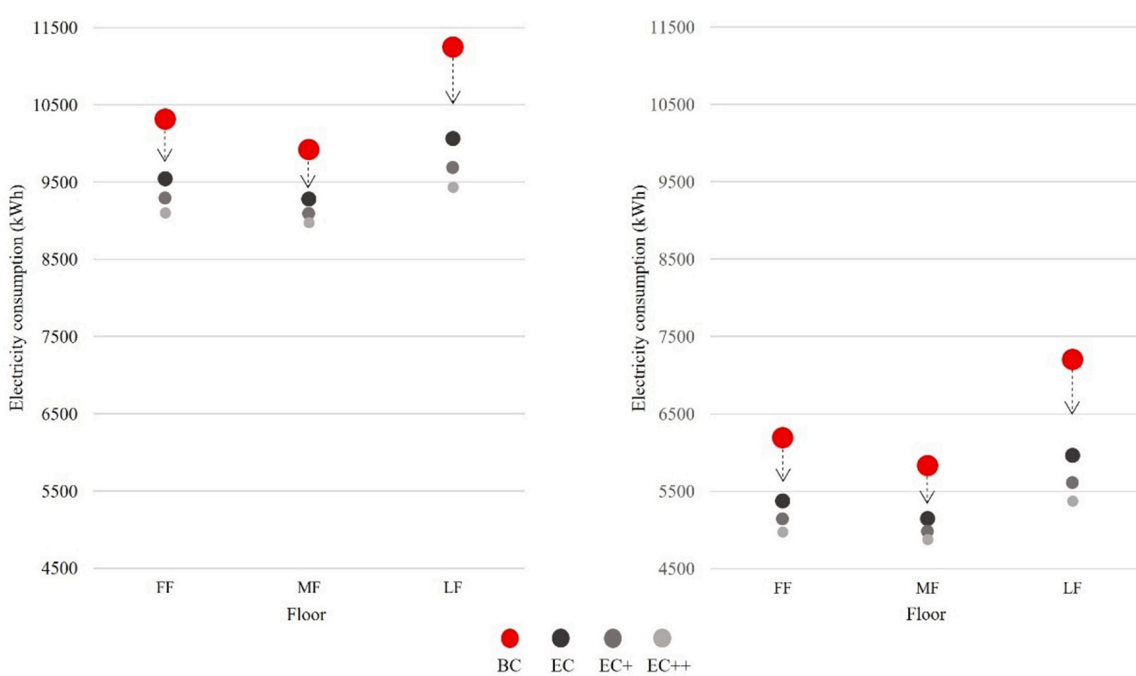
When comparing the various energy levels, it was possible to observe that as the thermal transmittance of the envelope elements decreased, the HVAC energy consumption reduced significantly for all floors. Although the building merely has cooling energy consumption, a more insulated envelope reduces the heat flux from the hot and humid outdoor environment. When coupled with the lower solar radiation entering the building through windows, it significantly reduces the cooling load. Relatively to the ratio of visible transmittance (VT) to solar heat gain coefficient (SHGC), a higher ratio means that windows allow more visible light to pass through while reducing the amount of solar heat gain, which also helps to reduce cooling loads in the hot and humid climate of Bandar Abbas.

The presented facts can also explain the different annual electricity savings for each floor. For the FF, the national building code of Iran shows higher reductions compared to ASHRAE, as the latter does not specify minimum *R*-values for floors adjacent to air in this climate region, while the former sets minimum *R*-values (ranging from 2.2 $m^2 \cdot K/W$ for EC to 4.4 $m^2 \cdot K/W$ for EC++). The MF also displays a similar trend, with ASHRAE proposing a lower minimum *R*-value (1 $m^2 \cdot K/W$) compared to the national code (ranging from 1.2 $m^2 \cdot K/W$ for EC to 2.4 $m^2 \cdot K/W$ for EC++). However, the results differ for the LF. In this case, the minimum *R*-value proposed by ASHRAE (5.3 $m^2 \cdot K/W$) is higher than the national building code levels, resulting in 15 % less energy consumed for buildings following ASHRAE standards, which is less than the EC and EC+ levels and equal to EC++.

In general, when compared to the EC, the EC+ only results in a 3 % reduction in electricity demand for all floors, and the EC++ only contributes an additional 2 % reduction compared to the EC+.

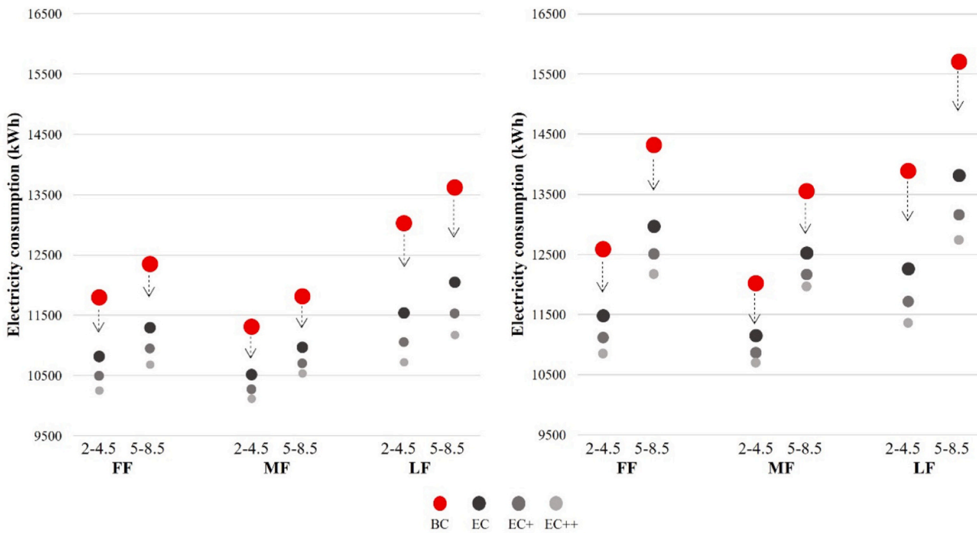
Future climate energy consumption comparison

In this step, the energy performance of buildings that adhered to the energy levels was simulated using future scenarios (SSP2–4.5 and SSP5–8.5) to determine their impacts and the potential of the building code to mitigate the impacts of climate change. Fig. 9(a) and Table 7 indicate that, for the EC building in the SSP2–4.5 and SSP5–8.5 scenarios, total annual electricity consumption is reduced by 7 % for the MF and 12 % for the LF in 2050 compared to the base case demand under the same scenario and timeframe. In 2080, energy savings are almost similar for both scenarios - see Fig. 9(b). EC+ demonstrates greater reductions in electricity consumption, ranging from 9 % to 15 % for 2050 and a



(a) Annual electricity consumption.   (b) HVAC electricity consumption.

Fig. 8. Electricity consumptions for the base case (BC) and different energy levels based on the Iranian building code.



(a) 2050. (b) 2080

Fig. 9. Comparison between total annual electricity consumption for the base case (BC) and Iranian building code energy levels under scenario SSP2–4.5 and SSP5–8.5 for the 2050 and 2080 timeframes.

Table 7
Reduction in total and HVAC electricity consumption of base case by applying Iranian building code energy levels under SSP2–4.5 and SSP5–8.5 scenarios for 2050 and 2080.

Energy level	Time frame	FF				MF				LF			
		SSP2–4.5		SSP5–8.5		SSP2–4.5		SSP5–8.5		SSP2–4.5		SSP5–8.5	
		Total	HVAC	Total	HVAC	Total	HVAC	Total	HVAC	Total	HVAC	Total	HVAC
EC	2050	−8 %	−13 %	−9 %	−13 %	−7 %	−12 %	−7 %	−12 %	−11 %	−17 %	−12 %	−17 %
	2080	−9 %	−14 %	−9 %	−14 %	−7 %	−12 %	−8 %	−11 %	−12 %	−17 %	−12 %	−17 %
EC+	2050	−11 %	−17 %	−11 %	−17 %	−9 %	−15 %	−9 %	−15 %	−15 %	−22 %	−15 %	−22 %
	2080	−12 %	−18 %	−13 %	−18 %	−10 %	−15 %	−10 %	−15 %	−16 %	−22 %	−16 %	−22 %
EC++	2050	−13 %	−20 %	−13 %	−20 %	−11 %	−17 %	−11 %	−17 %	−18 %	−26 %	−18 %	−26 %
	2080	−14 %	−21 %	−15 %	−21 %	−11 %	−17 %	−12 %	−17 %	−18 %	−26 %	−19 %	−26 %
ASHRAE	2050	−5 %	−9 %	−5 %	−9 %	−8 %	−14 %	−8 %	−14 %	−16 %	−25 %	−17 %	−25 %
	2080	−5 %	−9 %	−5 %	−8 %	−8 %	−14 %	−8 %	−13 %	−17 %	−25 %	−17 %	−24 %

further 1 % increase for 2080 in both scenarios across all floors. Meanwhile, EC++ displays the highest reductions, ranging from 11 % to 18 %, with similar trends observed in SSP2–4.5 and an additional 1 % energy saving in SSP5–8.5 in 2080. As for ASHRAE requirements, electricity consumption is predicted to decrease by 5 % for the FF, 8 % for the MF, and 17 % for the LF in 2050 compared to the base case under both SSP2–4.5 and SSP5–8.5 scenarios. Energy savings are similar for both scenarios in 2080.

Table 7 also illustrates the reduction in annual HVAC electricity consumption for the EC building under the SSP2–4.5 and SSP5–8.5 scenarios. Results show a 12 % to 17 % decrease for all floors in 2050 compared to the base case demand under the same scenario and timeframe. Similarly, the EC+ building displayed even greater reductions ranging from 15 % to 22 %, while the greatest decrease in demand was in the EC++ building, with results ranging from 17 % to 26 % for both scenarios across all floors. For the 2080 timeframe, the trend remained consistent for the MF and LF, with an additional 1 % reduction for the FF considering all energy levels.

With the ASHRAE standard, HVAC electricity consumption decreased by 9 % to 25 % from the first to the last floor in 2050 compared to the base case in SSP2–4.5 and SSP5–8.5. In 2080, energy savings were almost similar to those observed in 2050 for both scenarios and floors.

Upon comparing all energy levels with the base case under the same scenarios and timeframes, it was possible to observe that the national building code and ASHRAE standards were able to contribute to energy savings ranging from 5 % to 19 % in the reference building as well as reductions between 9 and 26 % in HVAC energy consumption. These energy savings are comparable to the reductions observed in present-day total and HVAC electricity consumption through the implementation of energy level requirements (as discussed in Section 'Impact of Iranian building code requirements on the reference building'). This means that not only are building code requirements currently effective in promoting energy efficiency, but they will continue to be so in a warmer future.

One of the most intriguing findings is shown in Fig. 10, where the monthly electricity consumption of buildings in future timeframes is compared to the current-day base case for units on different floors. For the MF, scenario SSP2–4.5 for 2050 indicates that the present-day base case energy demand is in line with EC+ and EC++ levels in warm months or even lower than EC++ in some colder months. Meanwhile, the energy demand in the present-day base case aligns with EC, EC+, and EC++ levels for units on the FF and the LF in warmer months and is equal to or lower than EC++ in colder months. This trend remains consistent in 2080 for the FF and LF, with the base case aligning with EC+ in warm months and being equal to or lower than EC++ in colder months—the SSP5–8.5 scenario for 2050 exhibits a similar trend to SSP2–4.5 for 2080. However, the electricity demand in the base case for present day was significantly lower than that of buildings with energy levels in 2080 under SSP5–8.5. Graphs for other scenarios and timeframes are presented in ref. (Azimi Fereidani et al., 2023).

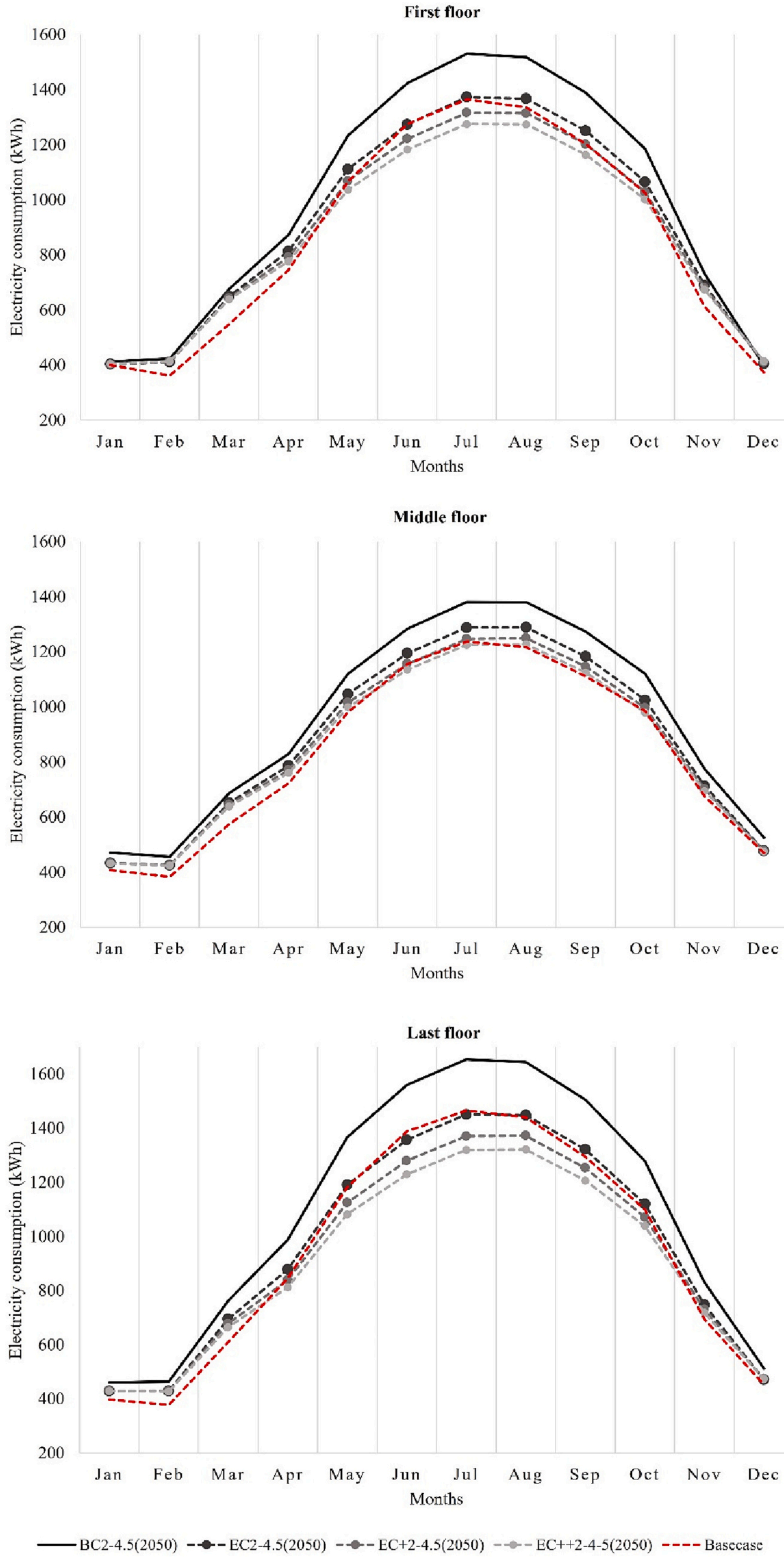


Fig. 10. Monthly electricity consumption of buildings with different energy levels under the scenario SSP2–4.5 for the 2050 timeframe.

In a warmer future (assuming SSP2–4.5 is the most likely scenario), electricity consumption in buildings that have implemented the building code requirements will be similar to the consumption level of the current-day base case. However, this is only true in the warm months, as demand increases in the cold months. In other words, the impact of global warming in this region will be so severe that applying the national building code requirements for the envelope will only allow us to have similar energy demands in the future as the base case in today's climate. Therefore, under the SSP5–8.5 in 2080, buildings adhering to the national code will have a significantly higher electricity demand in the future than in the current-day base case.

This result emphasizes the pressing need for the strict application of building codes in this region and even for further improvements to the requirements beyond the current national building codes. Therefore, upgrading existing buildings to higher energy levels such as EC, EC+, or EC++ is not only necessary but also an effective measure to mitigate the impact of global warming on buildings.

However, it is important to note that this study only analyzes building code requirements related to the envelope. The latest version of the Iranian building code proposes a broader range of strategies for mechanical and electrical areas. One such strategy relates to electricity production through renewables, which is becoming increasingly important in the electrical sector. For instance, the EC, EC+, and EC++ codes require electricity production at 22.4 kWh/m^2, 32.0 kWh/m^2, and 45.7 kWh/m^2 on the building's roof, respectively. Implementing these requirements can lead to further improvements in meeting the codes' objectives and international aims for reducing carbon emissions. However, the economic feasibility of such strategies is still a matter of concern, particularly in a country with significant subsidies on energy prices.

Overall, the findings of this study align with existing literature on cooling-dominant climates in Iran, supporting the prediction of significantly higher energy demand for buildings in the future (Roshan, Arab, and Klimenko, 2019; Roshan & Negahban, 2015; Roshan et al., 2012), as discussed in the introduction. However, there is a limited body of research specifically addressing energy-efficient measures to mitigate the impact of climate change in these cooling-dominant climates in Iran. The only envelope-related study has found that the building envelope thermal transmittance must be the lowest possible for Bandar Abbas (Rodrigues, Fereidani, et al., 2023). In a broader context, a study conducted in the UAE, a Middle Eastern country with a similar climate to southern cities in Iran, demonstrated the effectiveness of thermal improvements in building envelopes in coping with climate change (Radhi, 2009). The findings from both studies are consistent with the ones provided in the present study.

While the existing literature provides some insights, there was a need for further research to explore and develop more comprehensive strategies for energy efficiency in these regions. Therefore, the current study assessed the energy-efficient measures in building codes designed to address the specific challenges posed by cooling-dominant climates. By incorporating envelope requirements and implementing energy-efficient measures, such as those outlined in the Iranian national code, it is possible to make significant progress in reducing energy demand and associated emissions under current and future climate conditions.

Furthermore, the implications of this research extend beyond Iran and are relevant across the Middle East region. Various other countries share the climate conditions in the region, and the findings and recommendations of this study may be applied to them. Implementing stricter building requirements, codes, and regulations will contribute to more sustainable urban development and help achieve carbon neutrality targets. Policymakers, architects, and urban planners should take note of these findings and recognize the urgency of implementing robust policies and building codes to promote energy efficiency and foster sustainable development.

Moreover, it is important to note that this study focuses specifically on multi-apartment buildings in the hot and humid climate of southern Iran. However, it is important to recognize that Iran's diverse geographical features, including the central plateau, bodies of water in the north and south, and mountains in the northwest, create distinct microclimates and varying climate conditions across regions. This variation may lead to different impacts of climate change in different regions. For instance, in regions with a dominant heating demand like Tehran, it is projected that overall primary energy consumption and CO2 emissions will decrease due to reduced heating demand in the future. On the other hand, the present study conducted in Bandar Abbas predicts a significant increase in total energy demand since this region already has high cooling demands. Additionally, different building types, such as commercial buildings, may be affected differently by climate change. Therefore, further research is needed to explore the impact of climate change on all types of buildings in Iran, encompassing both residential and commercial structures. This future work will contribute to a more comprehensive understanding of the energy efficiency challenges and opportunities associated with different building types and diverse regional climates.

Conclusions

From the most recent scenarios of SSP, we observe that the southern coast climate in Iran will be drastically impacted—*e.g.*, dry bulb temperature is predicted to increase between 1.5 °C to 4.5 °C—which directly affects the building's energy demand.

The obtained results from the energy simulations of the reference building in Bandar Abbas indicated that the building's annual electricity consumption may increase between 14 % to 21 % and 21 % to 40 % for the timeframes 2050 and 2080, respectively, using the latest SSP2–4.5 and SSP5–8.5 scenarios. Additionally, HVAC demand is expected to increase between 25 % and 33 % by 2050 and 37 % and 65 % by 2080.

This study found that implementing the envelope requirements from the Iranian national code may substantially reduce energy consumption and contribute to mitigating climate change. When satisfying the mandatory regulation, energy savings of up to 19 % and HVAC electricity of up to 26 % may be achieved today. We also observed that as the minimum *U*-values for envelope elements decrease for other energy levels (EC, EC+, EC++, or ASHRAE), the electricity and HVAC energy demand for buildings in this specific climate region also decreases significantly.

However, the study also revealed that buildings in this region, even if they follow the requirements for the envelope set in the Iranian building code, will consume the same or more electricity in a warmer future, considering the more plausible scenario. Accordingly, the worst-case scenario predicts a significantly higher electricity demand than today.

Therefore, the Iranian government must take immediate action to enforce the highest level of energy efficiency in the building code and even introduce new legislation to reduce greenhouse gas emissions further. By doing so, policymakers will help the built environment to be better equipped to meet sustainability goals and future climate challenges. Otherwise, it will be difficult for Iran to effectively meet the carbon neutrality targets established by the Paris Agreement.

CRediT authorship contribution statement

Nazanin Azimi Fereidani: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Eugénio Rodrigues:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Adélio R. Gaspar:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Resources.

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.

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