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Article

Effect of thermal and cool paints on energy consumption of residential buildings

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ABSTRACT

The paper aims to evaluate the technical and economic impact of cool and thermal paints on cooling and heating loads in different climates. To study the effect of thermal and cool paints, DesignBuilder software has been chosen. The sample under examination is a standard five-story residential building in Iran, where the ratio of painted wall area to total surface area is 49. In this building, the heating system is natural gas-based, and the cooling system is electricity-based, each with different prices and tariffs. The cooling and heating loads for three paint colors—black, gray, and white—on this building were examined in four cities: Bushehr, Shiraz, Tehran, and Tabriz, which have hot desert (BWh), hot semi-arid (BSh), and cold semi-arid (BSk) climates, respectively. According to the simulation results, cool paints have resulted in a 3% to 10% reduction in cooling load. The white paint has the highest percentage reduction in cooling load, and its impact on cooling load is greater in colder regions. Thermal paints have led to a 7% to 50% reduction in heating load, and according to the simulation results, the percentage reduction in heating load energy is greater in warmer regions.

1. Introduction

According to published statistics, 90% of people's time is spent indoors and in buildings, which highlights the importance of ensuring their environmental comfort [1]. Individuals' needs for environmental comfort can be summarized into seven categories: (1) cooling, (2) heating, (3) lighting, (4) cooking, (5) refrigeration, (6) electrical appliance, and (7) hot water for domestic use and sanitation [2]. Energy consumption is influenced by people's culture, climate, and income level. Up to half of the world's total energy is consumed in buildings [3]. One of the major issues related to energy consumption worldwide is the emission of greenhouse gases and the increase in CO_2 levels, which have a negative impact on the climate and atmosphere of the Earth. Notably, 25% of greenhouse gas emissions are due to energy consumption in buildings [4]. Numerous solutions have been proposed to reduce energy consumption and greenhouse gas emissions while maintaining individuals' comfort. These solutions are generally divided into two categories: active and passive that they are stated in Table 1. One of the passive methods explained in Table 1 for reducing energy consumption is the use of paints. The main advantage of this method is that it can be applied to old buildings and used for aesthetic enhancement while simultaneously reducing energy consumption. This method has low operating costs. It is a one-time implementation method. Using a single type of paint (cool or thermal) may reduce one load (e.g., cooling) while increasing another (e.g., heating). In a city that experiences four climates, using one paint could potentially increase annual energy consumption. Additionally, in some regions, cooling energy is supplied by electricity and heating energy by gas, making their economic values different. Therefore, reducing the heating load might not be economically viable if it leads to an increase in the cooling load. Consequently, this article examines the impact of paints on different climates.

2. Modeling

According to the Köppen climate classification, the cities of Shiraz, Tabriz, Tehran and Bushehr have the climates Bsh, Bsk, Bsk, and Bwh respectively. Figure 1 shows the different climates of the world based on the Köppen criteria [18]. Building models could be divided into three categories: (1) Time series, (2) Econometric, and (3) Technical engineering model. The time series model considers energy consumption as a function of time, econometric models consider it a function of economic factors, and the technical engineering model considers it a function of building conditions and thermal properties of the building. Due to the examination of the impact of paint on buildings, the technical engineering model is the most suitable among the three energy estimation models for buildings (time series, econometric, and technical engineering).

Table 1. Active and passive methods for reducing heating and cooling loads in buildings

	Method	Description	Advantages	Disadvantages
Active	Evaporating-cooling	Water-Based Air Cooling: Direct and Indirect	Efficiency of up to 80% [5]	High water consumption Potential for mold and corrosion Health concerns in the direct method [6]
	Phase Change Materials	Store or release heat by changing phase.	Stores a large amount of energy with small temperature changes [7]	Requiring auxiliary devices.
Passive	Shading	Installing shade prevents direct exposure to sunlight	Low operating cost Using natural shade (trees) can reduce energy consumption by up to 15% compared to unshaded conditions [8] Shade combined with PCM delays the PCM's melting point [9]	Not applicable for all buildings
	Orientation of building	The amount of energy received from sunlight increases or decreases based on the orientation of the building and the shape factor [10]	The optimal building orientation is when the longest wall faces south [10] Square building with window-to-floor areas ratio of half and 50° south orientation achieves lowest energy consumption [11]	Low impact on energy consumption [12]
	Insulation	The rate of heat transfer decreases with the use of thermal insulation.	Reduces peak heating and cooling loads by 20% [13] Building with external insulation (exposed to ambient air) achieves lowest peak heating and cooling loads [14]	Insulation
	Cool paint	A cool paint has a higher reflectance coefficient compared to a wall, so the energy present on the surface is less than it would be if the wall were unpainted. $E_{abs1} = \alpha_{\text{Paint}} E_{sun}$ $E_{abs2} = \alpha_{\text{Wall}} E_{sun}$ If $\alpha_{color} < \alpha_{wall} \rightarrow E_{abs1} < E_{abs2}$	In Mediterranean climates, white acrylic paint can reduce annual energy consumption by up to 3%, with summer savings reaching 16% [15] Combining polymethylpentene with acrylic resin and SiO_2 on glass with aluminum foil backing reduces temperature by 5.2°C during the day and 1.5°C at night [16] Cool paints lower summer temperatures by 5°C and annual heating load by ~33% [17]	Increasing the heating load
	Thermal paint	A thermal paint has a higher absorption coefficient than a wall and a cool paint. Thus, it absorbs solar energy and reduces the heating load. $E_{abs1} = \alpha 1_{color} E_{sun}$ $E_{abs2} = \alpha_{wall} E_{sun}$ If $\alpha 1_{color} > \alpha_{wall} \rightarrow E_{abs1} > E_{abs2}$		Increasing the cooling load

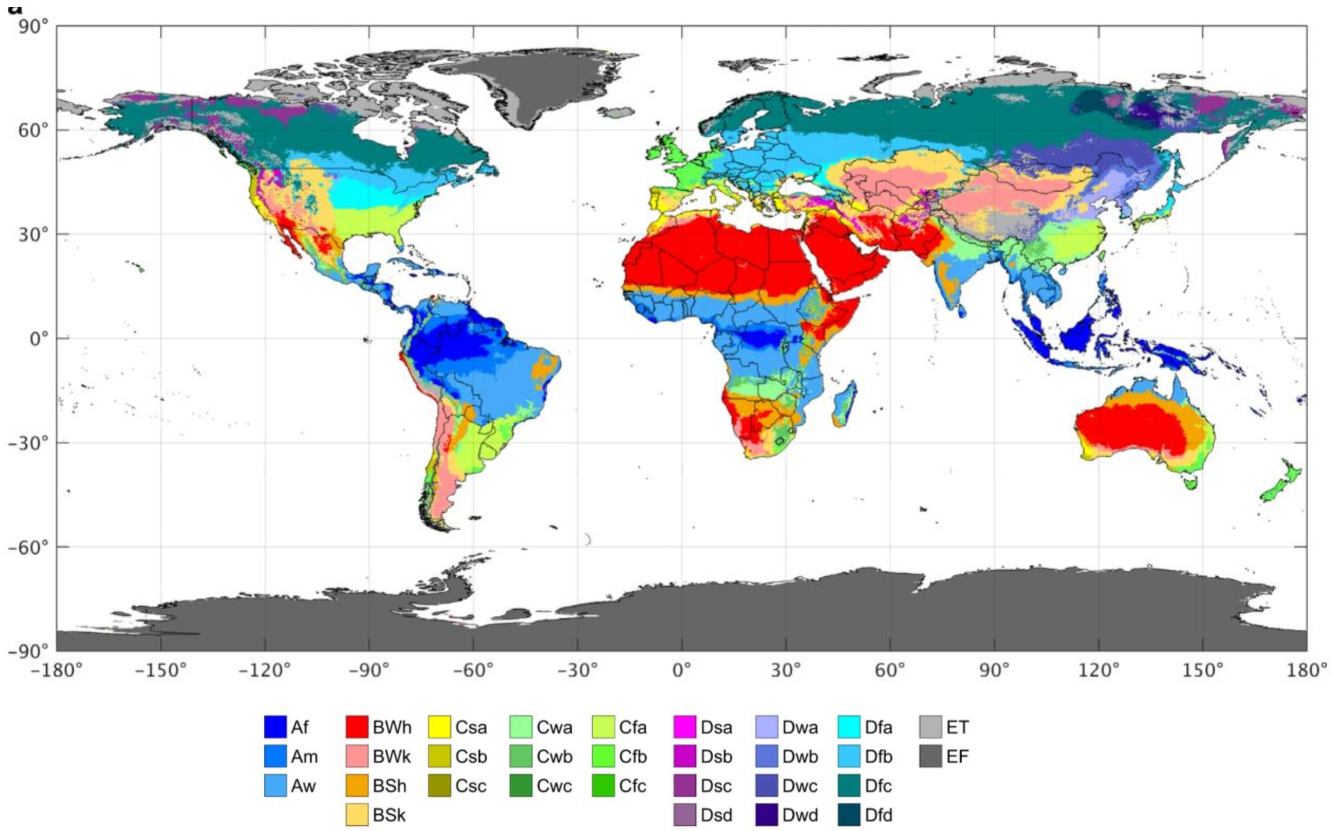


Figure 1. Different climates of the world [18]

Technical engineering models are developed based on physical phenomena and empirical data. Technical engineering models can be divided into two types: forward modeling and inverse modeling [19]. In forward modeling, software such as EnergyPlus and TRNSYS can be used. To simulate heating and cooling loads, the effects of weather, received light and solar reflection, and heat transfer from the external walls of the zone to the interior and vice versa must be considered. DesignBuilder software is used, which solves the simulation based on time and continues until the zone temperature and thermal load converge. Figure 2 shows the heat transfer method considered by the software. There are three heat transfer mechanisms in buildings: conduction, convection, and radiation. The solution algorithm is based on the Conduction Transfer Function (CTF). In the simulation, sky diffuse modeling is set to simple sky diffuse modeling. Initially, the heat flux transferred from the outer layer of the wall is calculated using Equation (1). Figure 3 demonstrate a schematic of the building.

In Equation (1), $q''_{a.sol}, q''_{lwr}, q''_{c.ext}$, and q''_{ko} represent the absorption of short-wave direct and diffuse solar radiation the net long-wave radiation the convective heat transfer between the surface and the external environment and the conduction heat transfer on the outside face of wall respectively. The convection heat transfer coefficient calculates according to the DOE-2 algorithm. When the characteristics of the external surface change (such as solar absorbance and reflectivity), the heat fluxes $q''_{a.sol}$ and q''_{lwr} change, and according to Equation (1), the amount of conductive heat flux changes accordingly. Equation (2) pertains to heat transfer within the zone.

$$q''_{a.sol} + q''_{lwr} + q''_{c.ext} = q''_{ko} \quad (1)$$

$$q''_{nrz} + q''_{sw} + q''_{lwz} + q''_{ki} + q''_{r.t} + q''_{conv} = 0 \quad (2)$$

In equation(2), $q''_{nrz}, q''_{sw}, q''_{lwz}, q''_{ki}, q''_{r.t}, q''_{conv}$ represent the net radiative heat transfer between surfaces within a zone or a set of zones , shows the heat flux incident on the surface from internal lighting, the long-wave radiative heat flux from equipment within a zone or a set of zones, conduction heat flux through the wall , the solar radiative flux that has passed through transparent surfaces and the convective heat transfer between the surface and the indoor environment, with the convective heat transfer coefficient obtained from the TRAPP algorithm respectively.

The simulated model in DesignBuilder software uses the Conduction Transfer Function model with the simulation equations Equation (3) to (8).

$$q''_{ki}(t) = -Z_o T_{i.t} - \sum_{j=1}^{j=n} Z_j T_{i,t-j\Delta t} + P_o T_{o,t} + \sum_{j=1}^{nz} P_j T_{o,t-j\Delta} + \sum_{j=1}^{nq} \phi_j q''_{ki,t-j\Delta} \quad (3)$$

$$q''_{ko}(t) = -P_o T_{i,t} - \sum_{j=1}^{j=n} P_j T_{i,t-j\Delta} + F_o T_{o,t} + \sum_{j=1}^{nz} F_j T_{oi-j\Delta} + \sum_{j=1}^{nq} \phi_j q''_{ko,t-j\Delta} \quad (4)$$

Considering that the relationships of (3) and (4) are differential. The DesignBuilder software solves the above equations using the state-space method and Equations (5) and (6).

$$\frac{d[x]}{dt} = A[x] + B[u] \quad (5)$$

$$[y] = [C][x] + [D][u] \quad (6)$$

In Equations (5) and (6), the symbols A, B, C and D represent the matrix coefficients. The symbols u, y and x represent the input vector, output vector and vector of state variables respectively, and t represents time.
If solving for transient heat conduction is desired, the Equations (3) and (4) are solved using the finite difference grid method, with the relevant relationships provided in Equations (7) and (8).

$$\frac{d\begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix}}{d(t)} = [A]\begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} + [B]\begin{pmatrix} T_i \\ T_o \end{pmatrix} \quad (7)$$

$$\begin{pmatrix} q''_i \\ q''_o \end{pmatrix} = [C]\begin{pmatrix} T_i \\ \vdots \\ T''_n \end{pmatrix} + [D]\begin{pmatrix} T_i \\ T_o \end{pmatrix} \quad (8)$$

In equation (7), T_1 to T_n represent the finite difference nodal temperatures. The symbol n represents the number of nodes, and T_i and T_o represent the interior and exterior temperatures, respectively. In equation of (8), the symbol of q''_i *and* q''_o are inlent and outlet heat fluxes.

3. Results

The building under review is a 5-story structure, with its general specifications shown in Figure 3 and summarized in Table 2. It is situated on the east and west sides, with the north and south facades and the roof of the building painted. The corresponding model has been examined in four cities with different climates. The climatic data for the four cities were obtained from the Climate One Building website, and the data used are the average climatic data from 2007 to 2021 [20]. Specification of paints obtained from DesignBuilder material library.

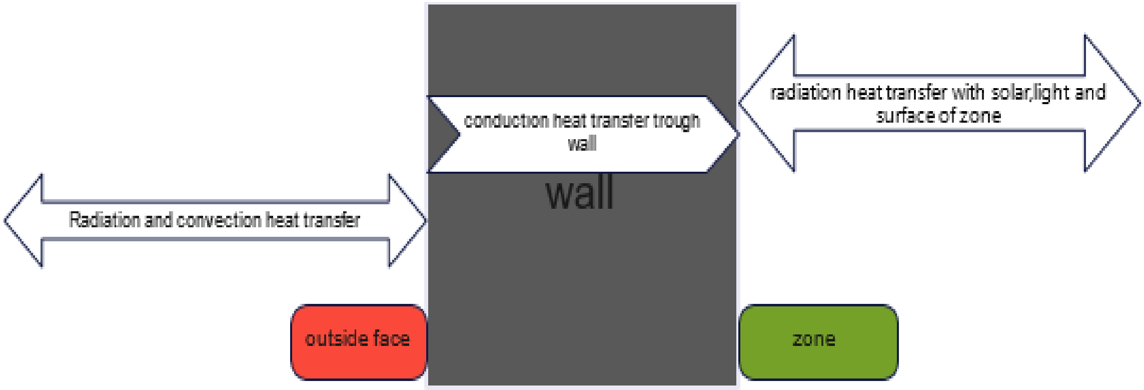
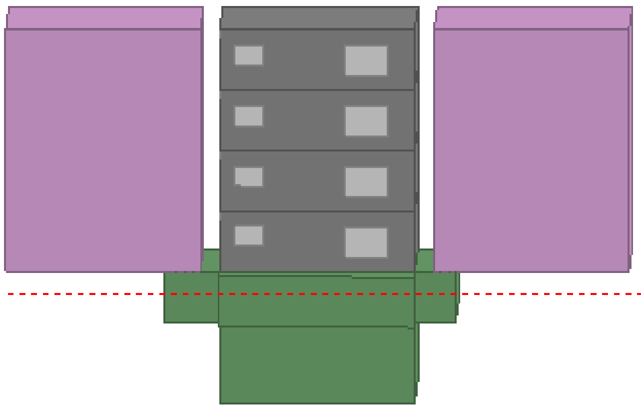
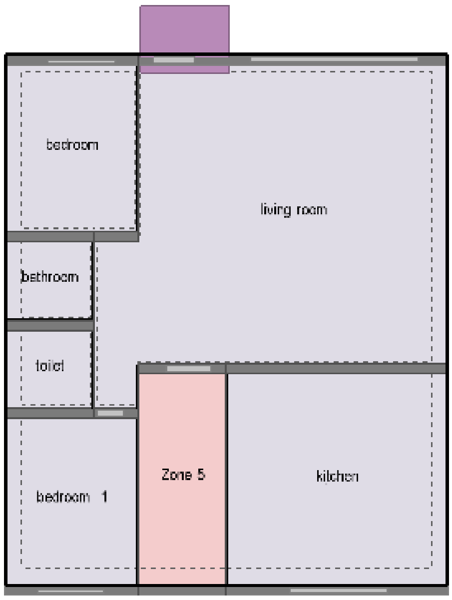


Figure 2. Heat balance in the DesignBuilder



(a) Overall view of building



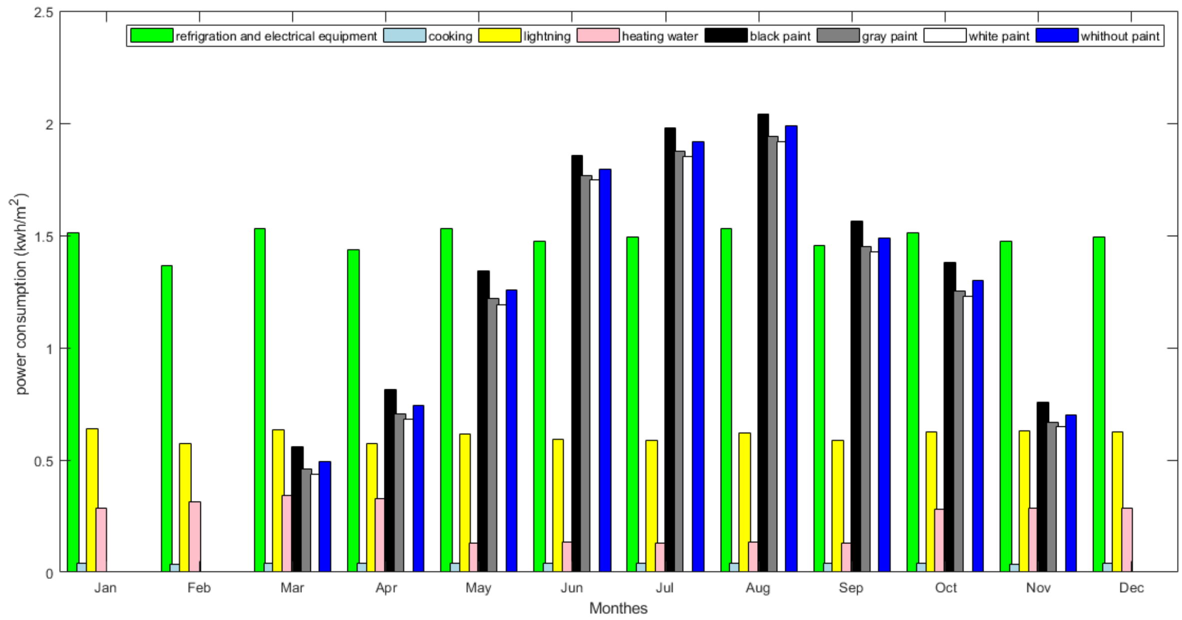
(b) View of each floor

Figure 3. Schematic of the building

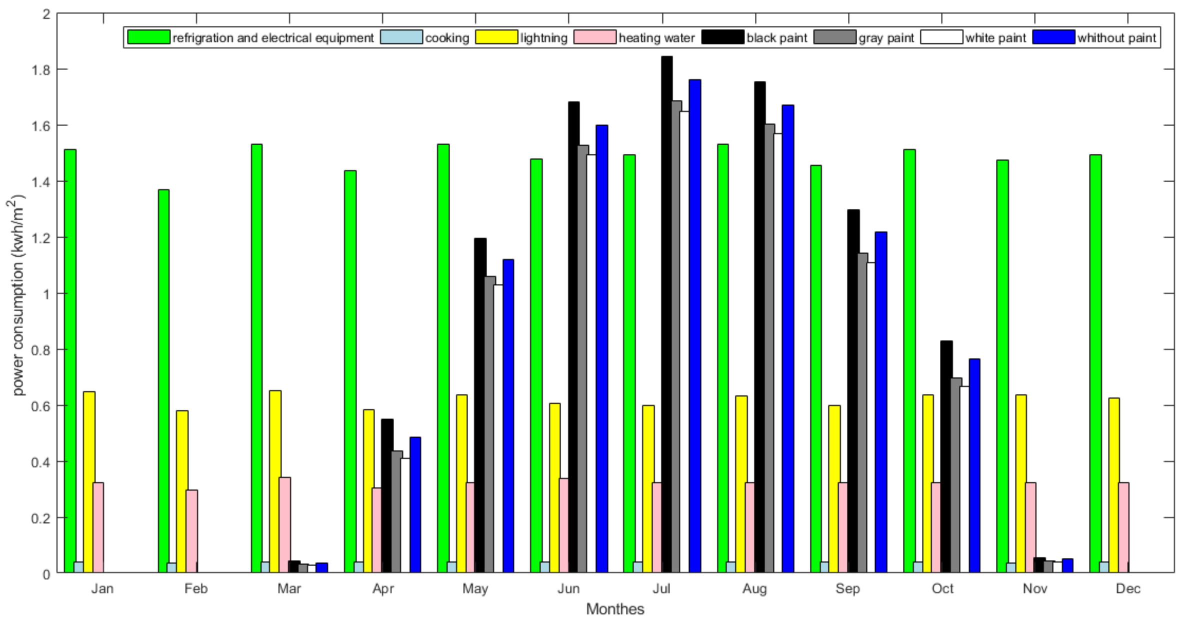
Table 2. Building specifications

Building Area	110 m²
Number of Floors	5
Number of Rooms	One kitchen One living room Two bedrooms One bathroom
Building Orientation	North-south direction,
Number of People per floor	3
Painted area per total facade area of building	0.49

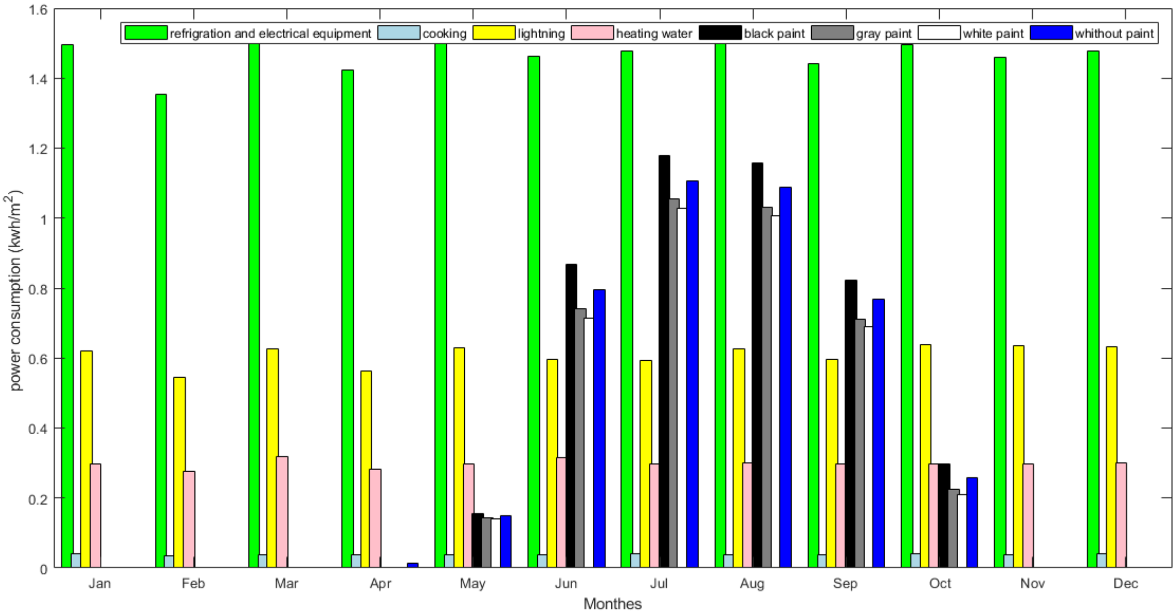
The simulation results obtained in the DesignBuilder software are shown in Figure 4 and Figure 5 respectively show the cooling and heating loads alongside other consumption loads. For the city of Bushehr, according to the simulation data, white and gray paints reduce the cooling load by 5% and 3%, respectively, while black paint increases the cooling load by 5%. In the city of Shiraz, white and gray paints result in a reduction of 8% and 5.5% in cooling load, respectively, while black paint leads to a 6% increase in cooling load compared to the base case (without paint).



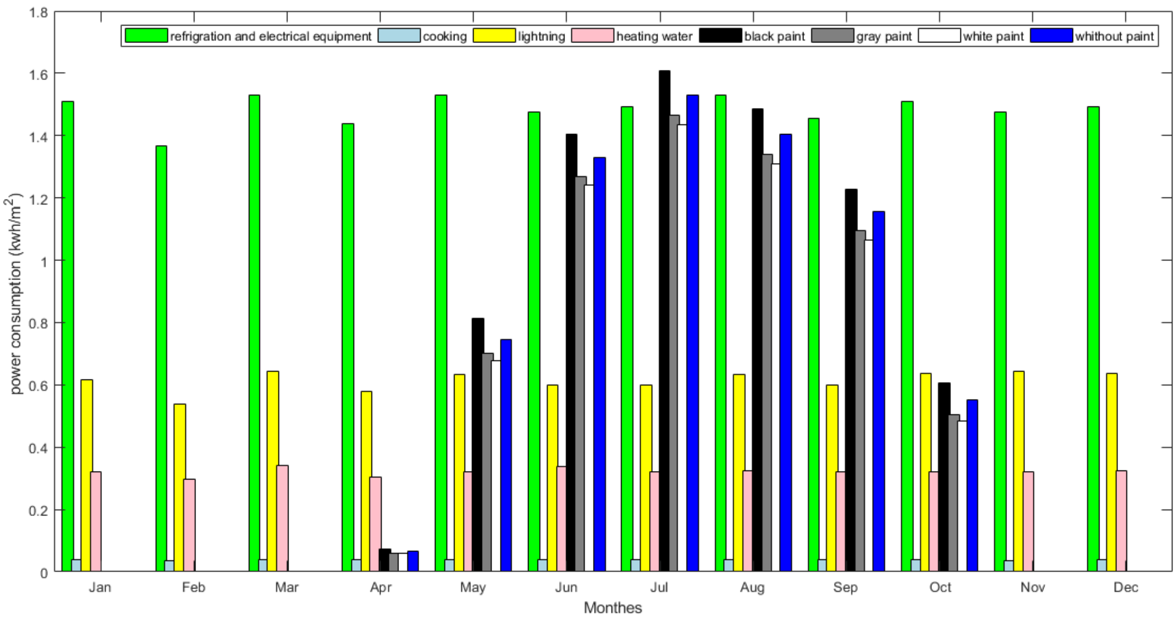
(a) Bousher



(b) Shiraz



(c) Tabriz



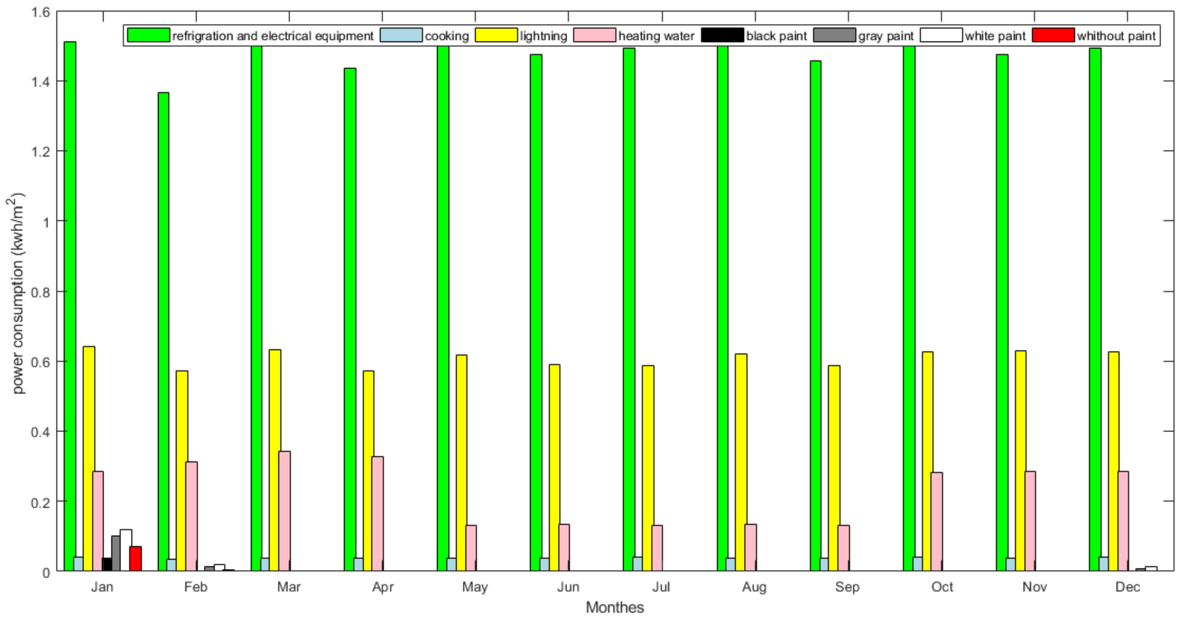
(d) Tehran

Figure 4. Cooling demand in the state of painted and unpainted residential building during warm season

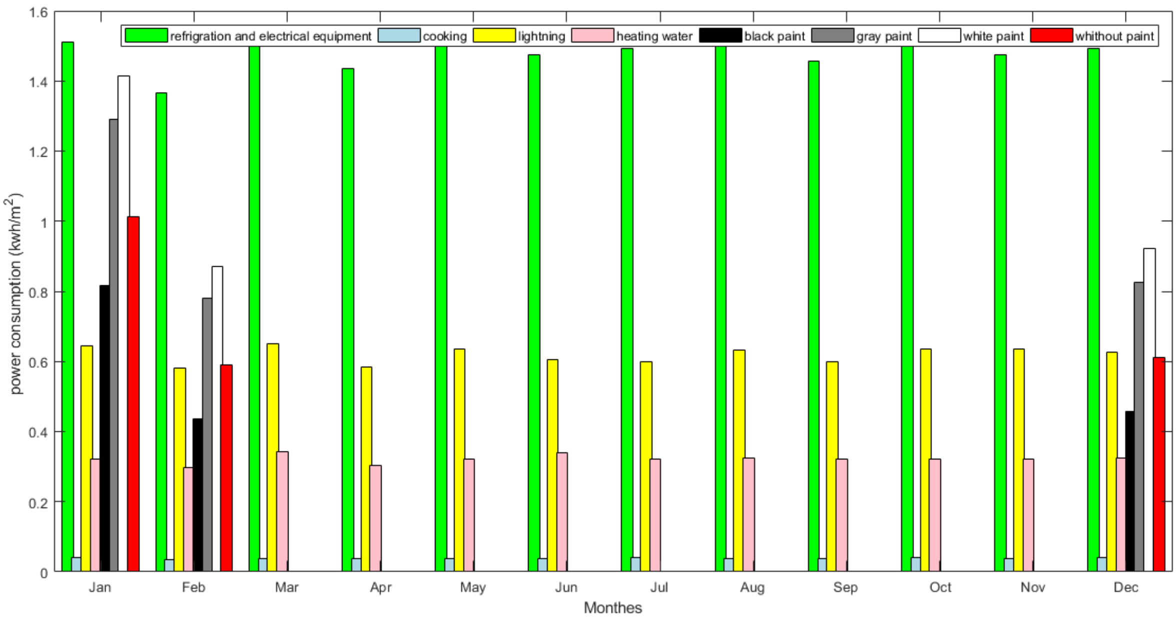
In the city of Tehran, white and gray paints result in a reduction of 7.7% and 5.3% in cooling load, respectively, while black paint leads to a 6.33% increase. In the city of Tabriz, white and gray paints reduce the cooling load by 10% and 7%, respectively, compared to the base case. However, black paint increases the cooling load by 6.7%.

Based on the obtained data, In Bushehr, using white paint results in a 97% increase in heating load, while gray paint leads to a 58% increase. Black paint, on the other hand, reduces the heating load by 49%.

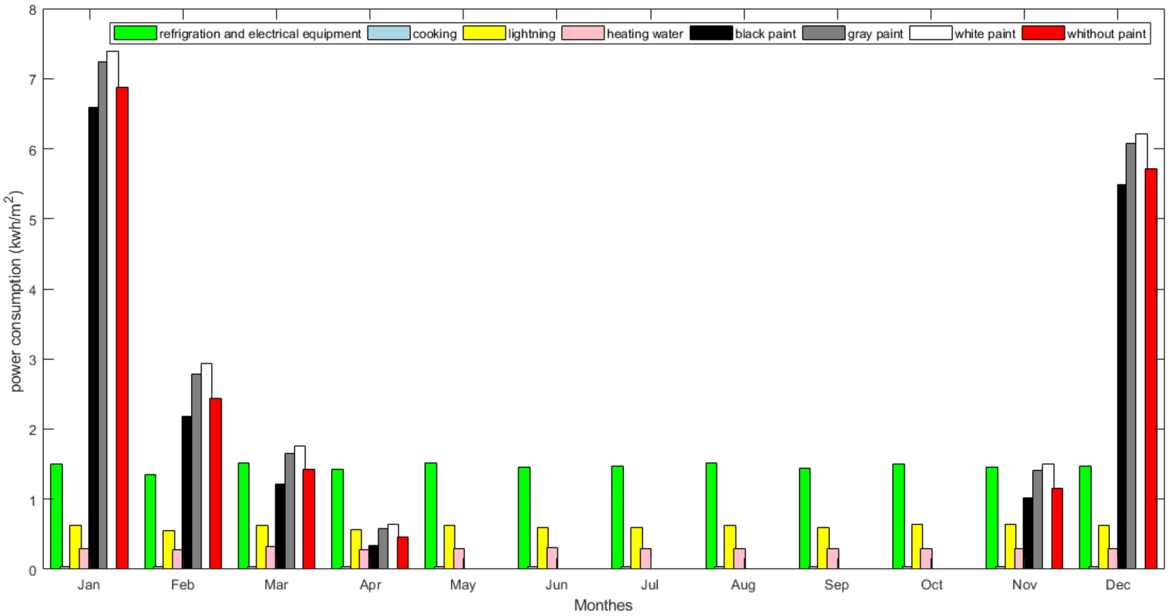
In Shiraz, the use of white and gray paint increases the heating load by 45% and 31%, respectively, whereas black paint reduces the heating load by 22%. In Tehran, white paint increases the heating load by 27%, and gray paint increases it by 6.5%. However, black paint reduces the heating load by 12%. In Tabriz, white and gray paints increase the heating load by 13% and 9%, respectively, while black paint decreases the heating load by 7%.



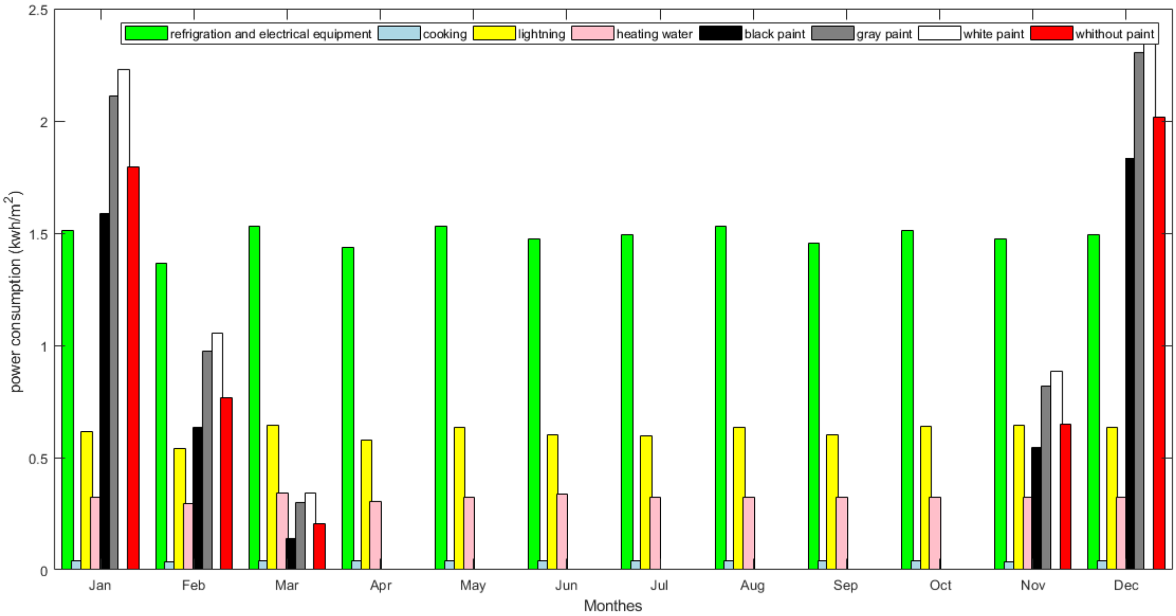
(a) Bousher



(b) Shiraz



(c) Tabriz



(d) Tehran

Figure 5. Heating demand in the state of painted and unpainted residential building during cold season

4. Conclusion

In this study, the effects of cool and thermal paints on the heating and cooling loads of a typical residential building were examined. It was observed that cool paints (such as white and gray) consistently reduce cooling loads and increase heating loads, whereas the opposite is true for thermal paints. Thermal paints act like thermal insulators, while cool paints, due to their higher reflectivity of sunlight, prevent the increase in the temperature of building walls, thereby reducing cooling loads in the warm season and increasing heating loads in the cold season. The extent of load reduction or increase for each paint in cooling and heating demands depends on the behavior of the occupants and the climatic conditions. Climatic conditions are influenced by temperature variations in each climate, the amount of solar radiation, and atmospheric conditions. Based on the results obtained from the simulation, the white paint achieved the highest reduction in cooling load among the three paints examined. The greatest reduction in cooling load was observed in Tabriz, with a 10% decrease compared to the unpainted state, while the smallest reduction was in Bushehr, with a 5% decrease compared to the unpainted state. The percentage reduction ratio of gray to white ranges between 6% and 7% for the three cities of Shiraz, Tehran, and Tabriz, which have Bsh and Bsk climates, respectively. For Bushehr, which has a Bwh climate, this ratio is 6%. Among the paints studied, only black led to a reduction in heating load, with the highest reduction of 97% observed in Bushehr (Bwh climate) compared to the unpainted state, and the smallest reduction of 7% in Tabriz (Bsk climate) compared to the unpainted state. Therefore, based on the results obtained, white and black paints have achieved the highest percentage reduction in cooling and heating loads, respectively. Additionally, considering that the rates of gas and electricity are different, the economic impact of these two points is not the same. According to the payback period analysis, the use of these paints does not offer economic benefits in Iran under the current gas and electricity rates. However, in countries with higher gas and electricity tariffs, the use of these paints could be economically beneficial.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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Nomenclature

q''_{sw}	Heat flux incident on the surface from internal lighting.
$q''_{a.sol}$	Absorption heat flux of direct and diffuse solar radiation
q''_{lwr}	Heat flux of net long wave radiation
$q''_{c.ext}$	Convective heat transfer between the surface and the external environment
q''_{ko}	Conduction heat flux on the outside surface of wall
q''_{o}	Outside Heat flux (radiative, conduction, convection)
q''_{i}	Inside heat flux (radiative, conduction, convection)
q''_{ki}	Conduction heat flux on the inside surface
q''_{nrz}	Net radiative between surface in zone
$q''_{r.t}$	Solar radiative flux that has passed through transparent surfaces.
q''_{conv}	Convective heat transfer between the surface and the indoor environment
q''_{lwz}	Long-wave radiative heat flux from equipment within a zone or a set of zones
P	Cross conduction transfer function coefficient
F	Outside conduction transfer function coefficient
subscript(t)	Transient with time
Z_j	Inside conduction transfer function coefficient.
T_i	Inside temperature
T_o	Outside temperature
A, B, C, D	Matrix coefficient
u	Input vector
y	Output vector
PP	Payback period
subscript 1,2,...,n	Node of 1,2,n.
CPEX	Investment Cost
ECC	Electrical Consumption Cost
GCC	Gas consumption cost
∅	Flux conduction transfer function coefficient
$\%L$	Percentage increase in heating load
$\%P$	Percentage decrease in cooling load