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Passive Strategies for Building Retrofitting: Performances Analysis and Incentive Policies for the Iranian Scenario †

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Abstract: A large amount of the Iranian energy demand is related to the building sector, mainly due to its obsolescence. In this paper, a second-skin system has been implemented as a retrofit action for an office building, evaluating the effect of a tensile material as second-skin in terms of primary energy saving, carbon dioxide equivalent emissions, and simple payback period. The analysis was carried out through numerical simulations across a whole year and for four Iranian cities (Tabriz, Teheran, Yazd, and Bandar Abbas) in four different climates (cold, temperate, hot-dry, and hot-wet), and with the building aligned at either north-south or east-west. Moreover, an economic analysis was carried out suggesting different incentive policies to promote building energy refurbishment. The simulation results highlighted a favorable orientation for buildings in Iran, suggesting a guideline for new constructions. Indeed, the best results were achieved for an east-west orientation of the building (up to a primary energy saving of 13.6% and reduction of carbon dioxide equivalent emissions of 45.5 $Mg_{CO_2,eq}$, in Yazd), with a decrease of the annual specific total (cooling and thermal) energy demand of 37.9 kWh/m^2/year. The simple payback period values were also lower in the east-west orientation than the north-south one.

Keywords: building energy efficiency; simple payback period; tensile facade; second-skin facade; carbon dioxide equivalent emissions; office building refurbishment; TRNSYS

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1. Introduction

Iran hosts the third largest oil reserves and the second-largest natural gas reserves in the world [1] and from 1900 to 2019 it consumed an extraordinary amount of non-renewable energy resources compared to international standards [2]. In addition to the low share of renewable energy and the dependence of the country's economic growth on fossil fuels, one of the main reasons for this high consumption could be the abundance of oil and gas resources in the country [3] and the low prices enforced by the government [4].

In more detail, Iranian primary energy consumption has increased by about 33% in the last decade [5] and, following worldwide statistical trends, one of the largest sources of energy demand (almost 40%) is in buildings [6], which also account for 28% of total CO_2 emissions [7]. In particular, the high emissions in the big industrial cities lead to several health problems in citizens, due to low air quality. In Tehran, the capital of Iran and among the most air-polluted cities in the world, for about 350 days in one year, the daily PM2.5 level was greater than the WHO standard, AQG 2021 (15 µg/m^3) [8].

In general, most of this energy demand related to the building sector is associated with heating and cooling [9]. In the Iranian building panorama, most of the existing building stock is obsolete and, therefore, the associated energy consumption is high [10,11], while the adoption of the Building Energy Codes (BECs) stays low [12]. In particular, in comparison with successful BECs worldwide, the Iranian BECs encountered several obstacles, including: (i) less attention to designing energy-efficient buildings, (ii) a lack of supervision by the authorities, (iii) constant use of conventional construction techniques, (iv) a common opinion that following the BEC would raise building costs, (v) a low rate of building refurbishment and (vi) no BEC attention to renewable energy sources [13].

Therefore, in order to acknowledge the problems of energy efficiency, indoor comfort, and sustainability, several systems and methodologies have been proposed [14], highlighting an ever-growing interest of the scientific community in the facade domain [15], with a particular focus on the use and optimization of passive systems [14,16,17].

This research evaluated the impacts of a retrofit action involving the facade of an office building and integrating a second-skin system, from the energy, environmental and economic points of view.

1.1. Literature Review

In the last two decades, many energy-efficient solutions have been analyzed to improve the energy performance of the building envelope by adding additional external insulation layers, responsive facade elements, or a second-skin layer [17–24]. There are two main approaches to improving the energy efficiency of buildings: (i) active or (ii) passive refurbishments [25]. The active approach consists of applying more efficient Heating, Ventilation and Air Conditioning (HVAC) systems and/or replacing obsolete and highly energy-intensive appliances (old models of natural gas-fired boiler, electric heat pump, lighting system, etc.) installed in the building, thus reducing its overall energy consumption [25]. The other way to improve a building's energy efficiency is passive refurbishment, which consists of a retrofit action that reduces the energy lost through the building envelope, improving its thermal resistance and reducing the energy demand [25]. In addition, passive retrofit actions are usually less invasive, allowing for renovations without changing the structure of historical buildings [26]. One of the most useful passive strategies to decrease energy usage in buildings is installing a second-skin (SS) facade system [17,20,23,27–34]. The *SS* facade systems consist of a standard facade, an air cavity, and an additional external skin. According to [17,20,23,27–34], the proper design of the *SS* facade systems can lead to several environmental and economic advantages; these benefits can be summarized as:

- reduction of space heating and cooling loads;
- reduction of energy consumption;
- enhancement of the thermal comfort;
- improvement of daylighting and glare control;
- upgrade of the acoustic insulation;
- enhancement of the aesthetic of the building;
- reduction of operating costs.

Several types of research have been performed in the last year to evaluate the effectiveness of *SS* facade systems in the Iranian climate [27–30,35,36]. In particular, in Hashemi et al. [27], a building with a *SS* facade system was monitored for two weeks during summer and two weeks during winter in the hot arid climate of Iran to observe the behaviors of the facade both in hot and cold conditions. In addition, a case study building has been simulated, with and without a double skin facade, to determine the effectiveness of the *SS* facade system. This study showed that, in summer, the cavity is essential to cool down the inner facade in countries, such as Iran, with high solar incidence [27]. In [28], the effectiveness of a *SS* facade system was investigated by comparing the proposed system to conventional ones. In more detail, five building models, located in Tehran (Iran), were modeled in Design Builder software [37] and examined in terms of both heating and cooling demands to achieve comfort conditions. The simulation results highlighted a reduction of the cooling and heating energy demand of about 45% compared to a building with a conventional facade system [28]. Radmard et al. [29] analyzed the cooling effect of natural convection influenced by a box-window retrofit *SS* facade on an office room in Karaj (Iran). The research showed the great potential in terms of both energy and environmental benefits during the hot season. In [30], the authors designed the optimal *SS* facade for an office building in Tehran upon varying: (i) the facade spatial configuration, (ii) shadings typologies, and (iii) cavity ventilation strategies, by dynamic simulations. The best case was selected based on minimum energy demand and maximum thermal comfort hours. The numerical analysis results highlighted a reduction of the energy consumption of between 7.9% and 14.8%, while the operational CO_2 emission was cut down by a maximum of 17% [30]. In [35], the authors provided information for developing and selecting an appropriate *SS* facade system simulation using CFD, verifying the effect of using two types of boundary conditions: (i) the surfaces' temperatures and (ii) the outdoor conditions correlated to the solar radiation. The authors highlight how the modeling of the outdoor conditions allows studying complex geometries, particularly when focusing on passive approaches. Finally, Sadafi et al. [36] investigated the impact of different facade designs on the heating and cooling energy demand through numerical models for an Iranian temperate and humid climate. The results showed the importance of calibrating the Windows-to-Wall Ratio (WWR) to combine the benefit of daylight with management of cooling energy demand, highlighting the importance of a well-designed shading system.

The literature review [17,20,23,27–36] highlighted a number of benefits achievable using the *SS* facade system. In addition, the part of the literature review related to the Iranian climate [27–30,35,36] highlighted that: (i) all the analyzed researches are focused on temperate climates, (ii) glass is usually used as *SS* material, and (iii) only one research evaluated the reduction of carbon dioxide emissions. Therefore, the literature review related to the usage of the *SS* facade systems in Iran [27–30,35,36] shows gaps regarding: (i) the performance investigation under cold climate and hot climate, (ii) the use of lightweight materials (such as the PVC-coated polyester fabric [38] investigated in this research), (iii) the environmental effects of these systems and (iv) their economic impacts.

1.2. Research Aims

In this research, the assessment of the benefits derived from the refurbishment of an existing office building, in terms of reduction of primary energy consumption, carbon dioxide equivalent emissions, operating costs, and simple payback period has been evaluated across a whole year, by means of the dynamic simulation software TRNSYS [39]. The proposed refurbishment involves the implementation of a PVC-coated polyester fabric [38] as an external layer of the *SS* facade system on the main facades of the building. The analysis has been performed varying the orientation of the building and using an optimized control strategy, in four different cities of Iran: (i) Tabriz, (ii) Tehran, (iii) Yazd, and (iv) Bandar Abbass, with cold, temperate, and hot climates.

Therefore, this research aims to bridge the gaps highlighted in the previous section concerning the *SS* facade system applications in Iran.

The present research is based on [40] and has been extended thanks to the following points: (a) new research findings have been integrated, described, and discussed; (b) the list of the case studies has been extended to consider an additional Iranian location and climate condition; (c) the energy analysis considers the space heating and cooling loads; (d) simulation has also been performed including the operating costs according to the Iranian market scenario; (e) simulation has been carried out also including the calculation of simple payback period; (f) three different incentive policies have been hypothesized and suggested to promote the endorsement of energy efficiency measures on existing buildings.

The objectives of this research can be summarized as:

- to assess the impact of passive retrofit actions in the Iranian climate, in particular when using a light and flexible material;
- to define a best-practice example for existing building renovation in the Iranian scenario, upon varying the climate conditions and the building orientation;
- to highlight the need for incentive policies for building energy efficiency.

1.3. Research Structure

The research is structured as follows: Section 2 reports in detail on the modeled office building, the retrofit action, the set of considered case studies, as well as the energy, environmental and economic methodologies used to carry out the research. Section 3 shows the results of the research from the energy, environmental and economic points of view. Section 4 offers a broader discussion, considering the limitations of this and current works and comments for future activities. Finally, Section 5 summarizes the main results and considerations.

2. Materials and Methods

This section describes the protocols and methods used to carry out the research. First, the numerical model of the investigated office building is described, from the geometrical model up to the definition of the main simulation parameters used through the study. Then, the methodology used to assess the energy, environmental and economic impact of the retrofit action is also described, highlighting the values assigned to the energy, environmental and economic variables considered in the equations.

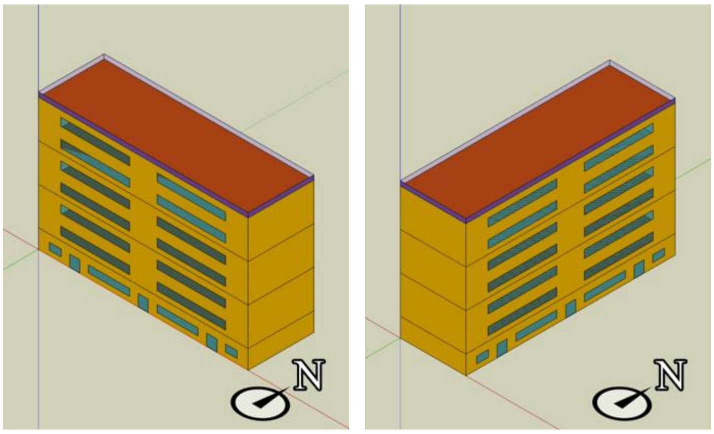
2.1. Building Modeling

Usually, simulation software is used to predict the energy consumption associated with the building during a building design phase. This numerical modeling is a complex task because many variables (weather conditions, building orientation, building occupancy, etc.) affect building envelope performance. In addition, when new building envelope components have been developed and tested only in the laboratory [17,32,41], before realizing a real case study, the simulation can help to verify the energy and economic feasibility. Nowadays, the software often used in the literature [31,42–47] to simulate building performance includes EnergyPlus [48], TRNSYS [49], IDA ICE [50], and IES VE [51]. Depending on the final purpose and the user perspective, each of these types of software could be the most appropriate; however, according to [42,43], the dynamic simulation software TRNSYS is the most complete and appears to be the better performing software when studying the heat flux through a building component. One limitation can be highlighted, related to the fact that TRNSYS is not able to link with AutoCAD Software [52] for importing and exporting 2D and 3D drawings of buildings; however, this limitation can be overcome by installing the TRNSYS3D [53], a plugin for SketchUp [54].

His study focuses on retrofitting a "typical" office building [55–57]. It proposes a best practice for retrofit actions in the Iranian territorial context. The assessment of the potential benefits of the passive refurbishment action involving a *SS* facade system implemented with a PVC-coated polyester fabric [38] has been carried out by means of the software TRNSYS 18 [39], calculating the primary energy saving and the reduction of carbon dioxide equivalent emissions, while also looking for payback periods.

The geometrical model of the reference building investigated in this research is based on a "typical" seven-story office building from the International Energy Agency (IEA) Annex 27 activity [55]: each floor has a 661 m^2 floor area and 4.13 m height. As suggested in [58–60], two main building characteristics have been considered, which mainly affect the building's passive behavior and performance: the building orientation and the Windows-to-Wall Ratios (WWR). Two different building orientations have been considered for the modeling and the simulations: north-south (Figure 1a) and east-west (Figure 1b) [32,58].

The building model is provided with fenestrations on the two main facades, with different WWR upon varying their orientation [58,61–63]. In particular, in order to minimize WWR influences on the building energy performance, the WWR has been set as suggested by [58] for warmer climates and considering, for each facade orientation, the setting which would provide the best results in terms of overall energy consumption and the best balance between the two building orientations [58]. Indeed, the choice of the WWR is a critical criterion, especially in warm climates where a value far from the optimal range could lead to a significant increase in cooling energy consumption [58]. Table 1 reports the values of optimal WWR upon varying the orientation of the office building's two main facades.



(a) (b)

Figure 1. Axonometric view of the building model in: (**a**) north-south and (**b**) east-west orientations [32].

Table 1. Optimal WWR, varying the orientation of the building's two main facades [58,61–63].

North-South Orientation		East-West Orientation	
North Facade	**South Facade**	**East Facade**	**West Facade**
0.37	0.27	0.33	0.34

Iran's territory is divided into four diverse climates [64]: (i) mild and wet, in the north of Iran (near the Caspian Sea), (ii) hot and dry, mainly in the central regions, (iii) cold and dry, in the high mountains, (especially in the north-west), and (iv) hot and wet, in the southern regions (near the Persian Gulf and the Gulf of Oman), as reported in Figure 2.

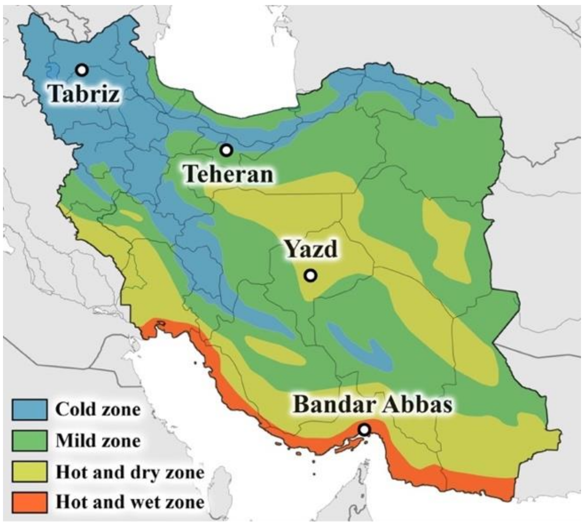


Figure 2. Climatic zones in Iran and the location of the four cities.

Four cities in four different Iranian climatic zones [64,65] were considered in this study, as indicated below.

- Tabriz (38°04′ N–46°18′ E), located at 1385 m above sea level, shows a cold climate (2223 heating degree days and 435 cold degree days [66]), with an annual rainfall of about 318 mm and average high and low temperatures of about 18.2 °C and 7.0 °C, respectively;

- Teheran (35°41′ N–51°25′ E), located at 1120~1670 m above the sea level, has a mild climate (1474 heating degree days and 1012 cold degree days [66]), with an annual rainfall of about 429 mm and average high and low temperatures of about 20.4 °C and 10.5 °C, respectively;
- Yazd, (31°54′ N–54°22′ E), located at 1216 m above the sea level, has a hot and dry climate (1063 heating degree days and 1207 cold degree days [66]), with an annual rainfall of about 49 mm and average high and low temperatures of about 26.5 °C and 11.4 °C, respectively;
- Bandar Abbas, (27°11′ N–56°16′ E), located at 9 m above the sea level, has a hot and wet climate (51 heating degree days and 2299 cold degree days [66]), with an annual rainfall of about 170 mm and average high and low temperatures of about 32.1 °C and 21.7 °C, respectively.

Figure 3 reports a comparison of the monthly trends of outdoor air temperatures and the average global horizontal solar radiation for all locations. In Figure 3, the minimum temperatures (T_{min}, marked by a hyphen sign), average temperatures (T_{avg}, marked by a rhombus), and maximum temperatures (T_{max}, marked by a plus sign) are shown, along with the average global horizontal solar radiation (G_{avg}, represented by the curves): the values for Tabriz are in black, those for Teheran are in red, those for Yazd are in blue, and those for Bandar Abbass are in orange. This figure highlights that: (i) the lowest T_{min} is reached in Tabriz (−13.9 °C), while the highest T_{max} is reached in Yazd and Bandar Abbass (42.2 °C), (ii) Yazd returns the highest value of G_{avg} (467.5 W/m^2) while Tabriz returns the lowest one (385.3 W/m^2).

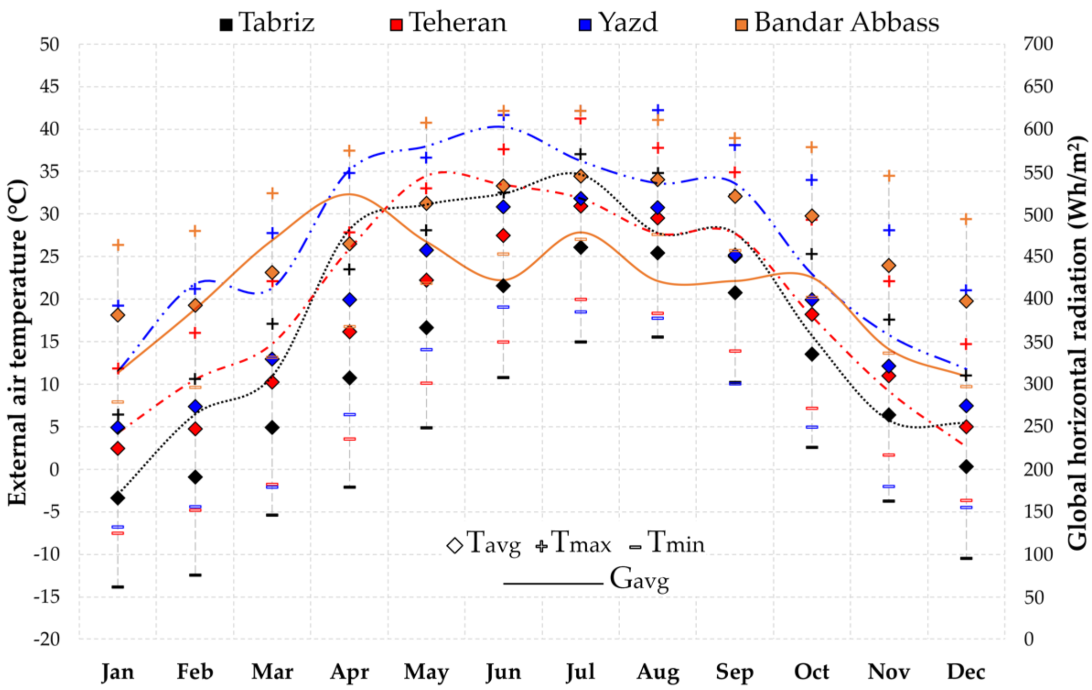


Figure 3. Monthly trends of $T_{min}/T_{avg}/T_{max}$ and G_{avg} for each city.

Chapter 19 [65] from the National Building Regulations of Iran includes the main reference codes for buildings' energy efficiency in Iran. These regulations were first approved by the government in 1991 and have been revised annually since then. In Chapter 19 sets out the buildings' typologies and energy requirements (to be defined to design a retrofit intervention), the threshold characteristics for the retrofit of the building envelope and HVAC systems, and a classification of the internal gains. According to these classifications, the reference office building for the present study falls in the "Type B" occupancy type [65], and different retrofit approaches are highlighted upon varying the location:

- in Tabriz, which is a city with a "high heating energy requirement", the retrofit falls in the "medium-priority actions" category [65];
- in Teheran and Yazd, which are cities with a "medium heating energy requirement", the retrofit falls in the "low-priority actions" category [65];
- in Bandar Abbas, which is a city with a "high cooling energy requirement", the retrofit falls in the "medium-priority actions" category [65].

As a starting point, the reference cases, in both north-south and east-west orientations and each city, have been characterized according to Kari et al. [56], who provides an insight into the more common envelope characteristics of the buildings built before the publication of Chapter 19 of the National Building Regulations of Iran [65], and therefore the kind of buildings more in need of retrofit actions. The thermal characteristics of the envelope components used to typify the reference case studies are reported in Table 2, and are the same for all the locations [56].

Table 2. Reference office building: U-values for the four locations [56].

Surface	Thermal Transmittance (W/m^2K)
Vertical Walls	1.80
Roof	1.20
Floor	1.80
Windows	6.0

The geometrical model of the office building has been realized in 3D-modeling software SketchUp [54] and then imported into TRNSYS [49] in order to characterize the envelope, the internal gains, the infiltration rate, and the temperature setpoint for the cooling and heating systems. In TRNSYS, the building model is managed by Type 56, a component whose characteristics are defined in TRNBuild, an interface for creating and editing all of the non-geometric information required by the TRNSYS building model.

Table 3 reports the nominal values [65,67,68] of the main simulation parameters used in this research.

Table 3. Nominal values of the main simulation parameters [65,67,68].

Parameter	Detail	Value
Lighting system	Lighting power density	11.5 W/m^2
Equipment	Thermal gain associated with the equipment	14.0 W/m^2
People	Thermal gain associated with occupants	11.5 W/m^2

Table 4 reports the occupancy profile, the schedules of the heating-cooling system setpoints and infiltration rates, as well as the profile of utilization of the lighting system and office equipment [65]. In particular, the schedules and the profiles reported in Table 4 have been set according to the Chapter 19 of the National Building Regulations of Iran [65] and have been set as "schedules" in TRNBuild, modifying the nominal values expressed in Table 3 upon varying the hour of the day and the day of the week. As an example, the value of the specific space thermal gain associated with the presence of people in the building (nominal value 11.5 W/m^2, Table 3) ranges between 0 W/m^2 (nighttime, no people in the office building) and 10.93 W/m^2 (central hours of the workday, almost full attendance of office personnel).

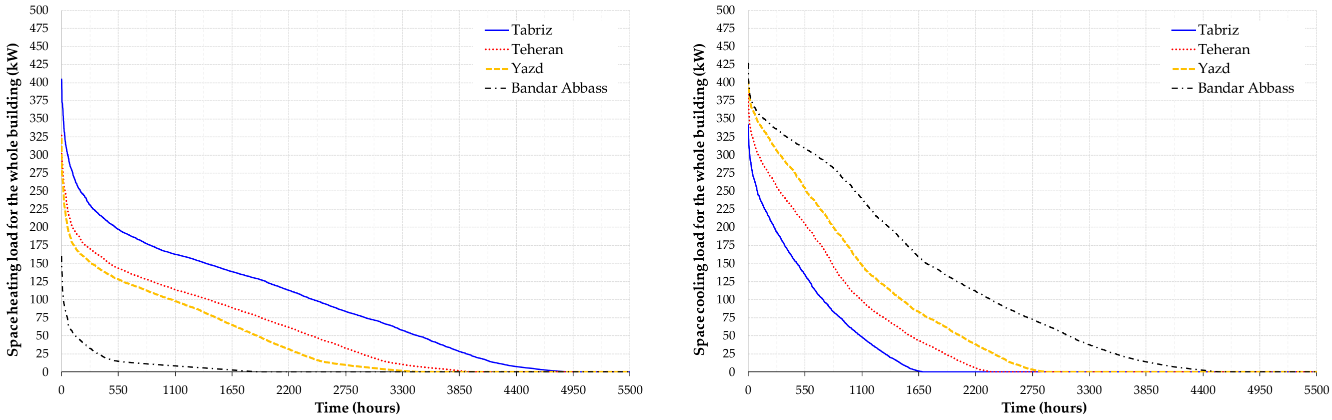
Table 4. Occupancy profile, heating-cooling system setpoints and infiltration rate schedules, the lighting system and office equipment profiles of utilization, during workdays (WD) and weekends (WE) [65].

Hour of the Day	Occupancy (%)	Heating Setpoint (°C)		Cooling Setpoint (°C)		Lighting (%)		Infiltration Rate (Air Changes/Hour)		Equipment (%)	
	WD	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE
1	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
2	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
3	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
4	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
5	0	15	15	30	32	0.05	0.05	0	0	0.05	0.05
6	0	17	15	30	32	0.05	0.05	0	0	0.05	0.05
7	0.1	17	15	30	32	0.1	0.05	0.5	0	0.1	0.05
8	0.5	20	15	28	32	0.1	0.05	0.5	0	0.3	0.05
9	0.95	20	15	28	32	0.9	0.05	1	0	1	0.05
10	0.95	20	15	28	32	0.9	0.05	1	0	1	0.05
11	0.95	20	15	28	32	0.9	0.05	1	0	1	0.05
12	0.95	20	15	28	32	0.9	0.05	1	0	1	0.05
13	0.5	17	15	30	32	0.9	0.05	1	0	1	0.05
14	0.5	17	15	30	32	0.9	0.05	1	0	1	0.05
15	0.95	20	15	28	32	0.9	0.05	1	0	1	0.05
16	0.95	17	15	28	32	0.9	0.05	1	0	1	0.05
17	0.5	17	15	30	32	0.9	0.05	1	0	0.3	0.05
18	0.3	17	15	30	32	0.1	0.05	0.5	0	0.1	0.05
19	0.1	15	15	32	32	0.1	0.05	0.5	0	0.1	0.05
20	0.1	15	15	32	32	0.1	0.05	0.5	0	0.05	0.05
21	0.1	15	15	32	32	0.1	0.05	0.5	0	0.05	0.05
22	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
23	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05
24	0	15	15	32	32	0.05	0.05	0	0	0.05	0.05

In addition, the weather conditions of each city are reproduced by their specific EnergyPlus weather data file [69].

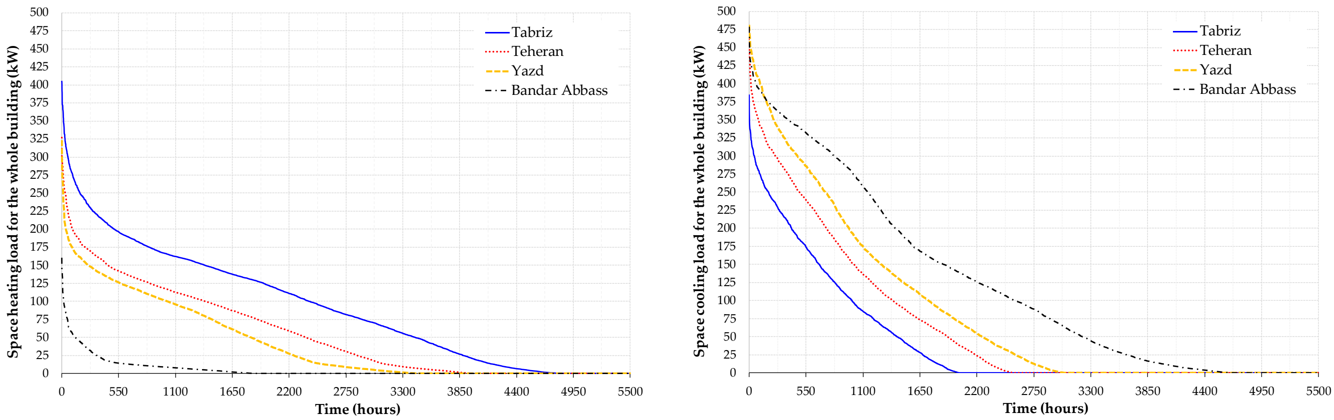
A preliminary analysis has been carried out by running a simulation in order to assess the space heating and cooling loads of the reference building for each location and in both orientations. In this preliminary analysis, the building envelope (modeled as "massless wall" in TRNBuild by using the thermal transmittance values reported in Table 2), the internal gains (lighting, equipment, and people, Tables 3 and 4), and the infiltration rate (Table 4) have been fully characterized, while only the temperature setpoints have been set for the heating and cooling systems (Table 4), leaving "unlimited" available heating and cooling powers, in order to assess the maximum systems load. In this way, the calculated peak values of heating and cooling load are used to calibrate the size of a commercial electric heat pump model for the simulations of the case studies.

Figures 4a,b and 5a,b show the space heating and cooling load-duration diagram associated with the two different orientations for each location. These figures highlight that for the space heating load, both building orientations show similar trends; in contrast, the space cooling load peaks are higher and collected in a narrower range when considering the building in an east-west orientation. In particular, Figure 4a highlights that the space heating load differs for each location, and it is equal to about 4908 h for Tabriz, 3958 h for Teheran, 3437 h for Yazd, and 1908 h for Bandar Abbass. Figure 4b shows that the space cooling load is about 1690 h for Tabriz, 2357 h for Teheran, 2887 h for Yazd, and 4561 h for Bandar Abbass. In addition, it can be noticed that, for the north-south orientation cases, the maximum thermal load is achieved in Tabriz (404.8 kW), while the maximum cooling load is calculated in Bandar Abbass (426.4 kW). Moreover, Figure 5a highlights that the space heating load differs for each location: in particular, it is equal to about 4815 h for Tabriz, 3961 h for Teheran, 3427 h for Yazd, and 1854 h for Bandar Abbass. Figure 5b shows that the space cooling load is equal to about 2024 h for Tabriz, 2545 h for Teheran, 3046 h for Yazd, and 4647 h for Bandar Abbass. In addition, it can be noticed that, for the east-west orientation cases, the maximum thermal load is achieved in Tabriz (404.8 kW), while the maximum cooling load is calculated in Yazd (481.6 kW).



(**a**) (**b**)

Figure 4. Space (**a**) heating and (**b**) cooling load-duration diagram associated with the whole building for the north-south orientation cases.

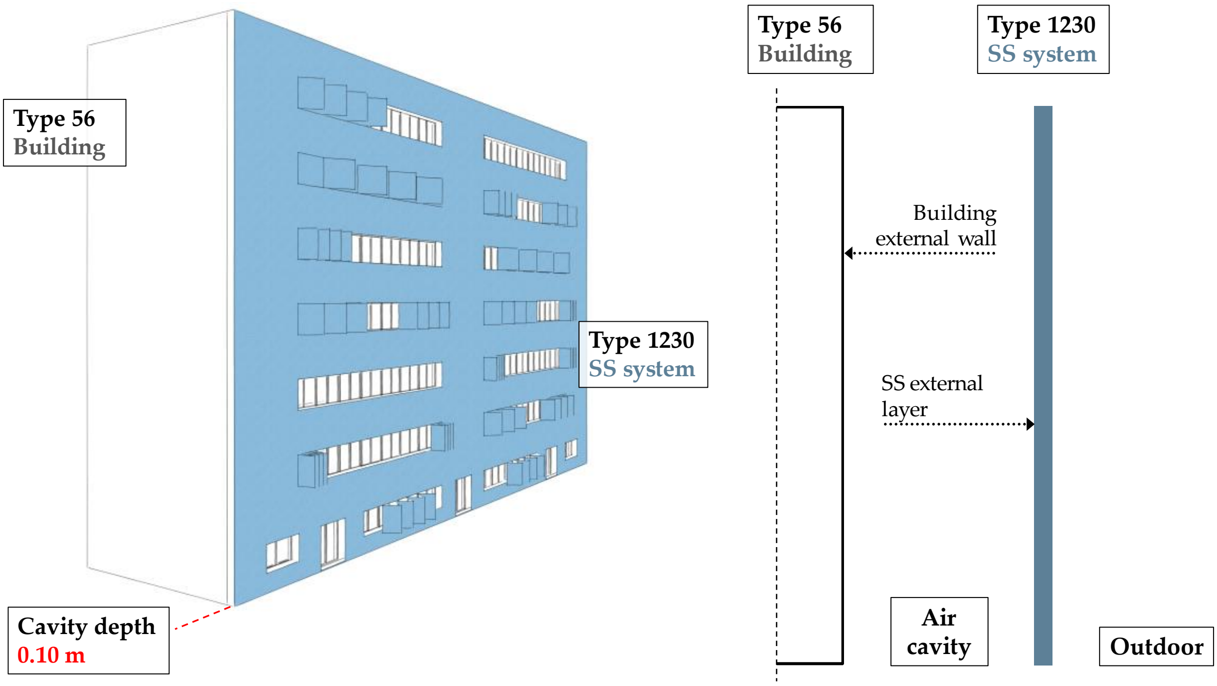


(**a**) (**b**)

Figure 5. Space (**a**) heating and (**b**) cooling load-duration diagram associated with the whole building for the east-west orientation cases.

These results allowed selection of an appropriately sized commercial model of electric heat pump capable of covering the energy needs and guaranteeing the achievement of the temperature setpoints for all the locations. Thus, in each of the seven building floors, three commercial electric heat pump (EHP) units (Clint CRA/K 101 [70]) are installed, connected in parallel, and coupled with a multi-split type air conditioning system. Each EHP unit is characterized by a cooling capacity of 28.6 kW with an energy efficiency ratio (EER) equal to 2.33, and a heating capacity of 36.7 kW with a coefficient of performance (COP) equal to 2.82.

The refurbishment cases have been modeled considering the installation of a *SS* facade system consisting of the PVC fabric [38] as *SS* outer layer, a 10 cm deep air cavity, and insulation panels on the external wall of the building. The *SS* facade system has been implemented only on the two main reference building's facades, leaving the other surfaces as in the reference case. In TRNSYS, Type 1230 [71] has been used to model the *SS* facade system (SS external layer and the air cavity behind it, Figure 6) following the methodology presented and experimentally validated by the authors in [17]. In [17], the numerical model showed good reliability, with a root mean square error of 0.5 °C and 0.4 °C for the indoor air temperature and the temperature of the air cavity, respectively [17], when comparing the experimental results with the numerical ones.



(**a**) (**b**)

Figure 6. Schematic view of Type 56 (building) and Type 1230 (SS facade system): (**a**) axonometry and (**b**) section.

By means of Type 1230 is possible to account for the effects of the solar and longwave radiation and air convection on the *SS* external layer, the thermal energy transmission and storage in the *SS* external layer, the radiative exchanges in the air cavity and the thermal energy transmission through the building external wall. Indeed, Type 1230 (SS facade system) and Type 56 (building) are connected in TRNSYS by coupling the building wall surface temperature and its thermal resistance to the related inputs in Type 1230 settings (Figure 6). Type 1230 parameters related to the *SS* facade system instead have been set by using the data provided by the PVC fabric manufacturer [38], in particular the thickness (0.0009 m), the density (579 kg/m^3), and the thermal conductivity (1.64 W/mK).

Different thicknesses of the insulation layer (Expanded PolyStyrene—EPS, λ = 0.041 W/mK) have been set in order to reach the basic U-value thresholds reported in Chapter 19 of the National Building Regulations of Iran [65] for the four locations. Table 5 reports the insulation layer thicknesses (sEPS) and the U-values of the refurbished walls, for all the locations: (i) Tabriz (Ta), (ii) Teheran (Te), (iii) Yazd (Ya) and (iv) Bandar Abbas (Ba). In particular, for each location, four different case studies have been investigated: cases NS and EW correspond to the reference cases, in north-south and east-west orientation, respectively; then, cases rNS and rEW correspond to the retrofit cases with the *SS* facade system, in north-south and east-west orientation, respectively.

Finally, considering the openness factor of the PVC fabric (equal to 30% [38]), the *SS* facade system has been deployed on the whole facade: in particular, by operating the portions installed in correspondence of the windows (Figure 6a), it is possible to conveniently manage the solar gains during different seasons, reducing their contribution during the summer while maximizing it during the winter. Also, the ventilation through the air cavity of the *SS* facade system is managed by a set of shutters at the inlet and the outlet, allowing for free natural ventilation during the cooling season while keeping the air cavity closed during the heating one.

Table 5. Parameters of the case studies for the four Iranian cities.

Location	Classification	Case Study	sEPS (m)	Walls U-Value [65] (W/m^2K)
Tabriz	Cold zone,	Case NS-Ta & Case EW-Ta	-	1.80
	medium priority action	Case rNS-Ta & Case rEW-Ta	0.018	0.88
Teheran	Mild zone,	Case NS-Te & Case EW-Te	-	1.80
	low priority action	Case rNS-Te & Case rEW-Te	0.011	1.02
Yazd	Hot and Dry zone,	Case NS-Ya & Case EW-Ya	-	1.80
	low priority action	Case rNS-Ya & Case rEW-Ya	0.011	1.02
Bandar Abbas	Hot and Wet zone,	Case NS-Ba & Case EW-Ba	-	1.80
	medium priority action	Case rNS-Ba & Case rEW-Ba	0.011	1.02

2.2. Energy, Environmental and Economic Methodologies

This section presents the energy, environmental and economic methodologies used to compare the proposed cases with the *SS* facade system (*PC*) to their corresponding reference cases (RC).

The energy comparison considers the primary energy consumption through the evaluation of the index *PES* (primary energy saving) [17] calculated as reported below:

$$PES = \left[\left(E_p^{RC} - E_p^{PC}\right)/E_p^{RC}\right] \cdot 100 \quad (1)$$

where E_p^{RC} is the primary energy consumption associated with the reference cases (cases NS and EW, see Table 5), while E_p^{PC} is the primary energy consumption associated with each of the eight proposed cases (cases rNS and rEW, see Table 5). When the index *PES* is positive, the proposed passive retrofit actions allow for a primary energy reduction compared to the reference case.

The values of E_p^{RC} and E_p^{PC} are calculated as reported in the following equations:

$$E_p^{RC} = \left(\frac{E_{th}^{RC}}{COP} + \frac{E_{cool}^{RC}}{EER} + E_{el,equipment} + E_{el,lighting}\right) \Big/ \eta_{PP} \quad (2)$$

$$E_p^{PC} = \left(\frac{E_{th}^{PC}}{COP} + \frac{E_{cool}^{PC}}{EER} + E_{el,equipment} + E_{el,lighting}\right) \Big/ \eta_{PP} \quad (3)$$

where η_{PP} is the average efficiency of the power plants and it has been considered equal to 0.38 [72].

The environmental comparison has been evaluated considering the reduction of carbon dioxide equivalent emissions (ΔCO_2) [17]:

$$\Delta CO_2 = m_{CO_{2,eq}}^{RC} - m_{CO_{2,eq}}^{PC} \quad (4)$$

where $m_{CO_{2,eq}}^{RC}$ is the carbon dioxide equivalent emission mass for the reference cases (cases NS and EW, see Table 5), while $m_{CO_{2,eq}}^{PC}$ is the carbon dioxide equivalent emission mass for each of the eight proposed cases (cases rNS and rEW, see Table 5). Thus, the ΔCO_2 represents the ability of the implemented passive retrofit actions to reduce the carbon dioxide equivalent emission of the refurbished case with respect to the reference one.

The values of the $m_{CO_{2,eq}}^{RC}$ and $m_{CO_{2,eq}}^{PC}$ are calculated as reported in the following equations:

$$m_{CO_{2,eq}}^{RC} = \alpha \cdot \left(\frac{E_{th}^{RC}}{COP} + \frac{E_{cool}^{RC}}{EER} + E_{el,equipment} + E_{el,lighting}\right) \quad (5)$$

$$m^{PC}_{CO_{2,eq}} = \alpha \cdot \left(\frac{E^{PC}_{th}}{COP} + \frac{E^{PC}_{cool}}{EER} + E_{el,equipment} + E_{el,lighting} \right) \quad (6)$$

where α is the CO_2 equivalent emission factor associated with electricity production in Iran, and it is assumed equal to 0.62 [73]. At the same time, the COP and EER values are considered according to the data reported by the manufacturer [70], and equal to 2.82 (COP) and 2.33 (EER), respectively.

With respect to the economic point of view, the analysis concerned the simple payback (SPB) periods. In particular, the SPB period has been calculated considering four different hypotheses of incentives:

- hypothesis a: no incentive for retrofit projects ($I_{0\%}$) of capital costs (CC) spent to perform the refurbishment;
- hypothesis b: an incentive for retrofit projects equal to 5% ($I_{5\%}$) of CC spent to perform the refurbishment;
- hypothesis c: an incentive for retrofit projects equal to 10% ($I_{10\%}$) of CC spent to perform the refurbishment;
- hypothesis d: an incentive for retrofit projects equal to 20% ($I_{20\%}$) of CC spent to perform the refurbishment.

The SPB period without the incentives has been calculated by using the following equation [74]:

$$SPB_{I_{X\%}} = CC^{PC} / \left[OC^{RC} - OC^{PC} + \left(I_{X\%} \cdot CC^{PC} \right) \right] \quad (7)$$

where CC^{PC} is the capital cost associated with the eight proposed cases (cases rNS and rEW, see Table 5), OC^{RC} are the operating costs associated with the reference cases (cases NS and EW, see Table 5), and OC^{PC} are the operating costs associated with each of the eight proposed cases (cases rNS and rEW, see Table 5). The value $I_{X\%}$ is the incentive for retrofit action calculated as a percentage of the CC^{PC} according to the four different hypotheses described above.

The CC^{PC} has been calculated on the basis of the Iranian market reference for the proposed interventions [7,75,76]. In addition, because of the lack of a standardized and detailed price list for construction materials, the authors evaluated and actualized the prices by comparing the references [7,75,76] with the current Iranian market in IRR, then converted to USD considering an IRR/USD exchange rate of ~1/0.000024 [77]. Therefore, in this work, the cost of the whole SS facade system, including the renovation materials (for the insulation panels, metal structure for the ventilated facade, and tensile material), and the cost for the scaffolding and the cost of labor, has been assumed equal to 21.78 $\$/m^2$.

The values of the OC^{RC} and OC^{PC} are calculated as reported in the following equations:

$$OC^{RC} = UC_{el} \cdot \left(\frac{E^{RC}_{th}}{COP} + \frac{E^{RC}_{cool}}{EER} + E_{el,equipment} + E_{el,lighting} \right) \quad (8)$$

$$OC^{PC} = UC_{el} \cdot \left(\frac{E^{PC}_{th}}{COP} + \frac{E^{PC}_{cool}}{EER} + E_{el,equipment} + E_{el,lighting} \right) \quad (9)$$

where UC_{el} is the unit cost of the electric energy assumed equal to 0.013 \$/kWh, according to the Iranian scenario [78] and considering the same IRR/USD exchange rate.

3. Results

In this section, the results of the numerical analysis are reported. In particular, the results related to the primary energy saving, the reduction of carbon dioxide equivalent emissions, the whole building heating and cooling energy demands as well as the simple pay back periods are discussed in detail.

Figure 7a,b reports the PES (Equation (1)) and ΔCO_2 (Equation (4)) for the proposed cases in the four Iranian cities.

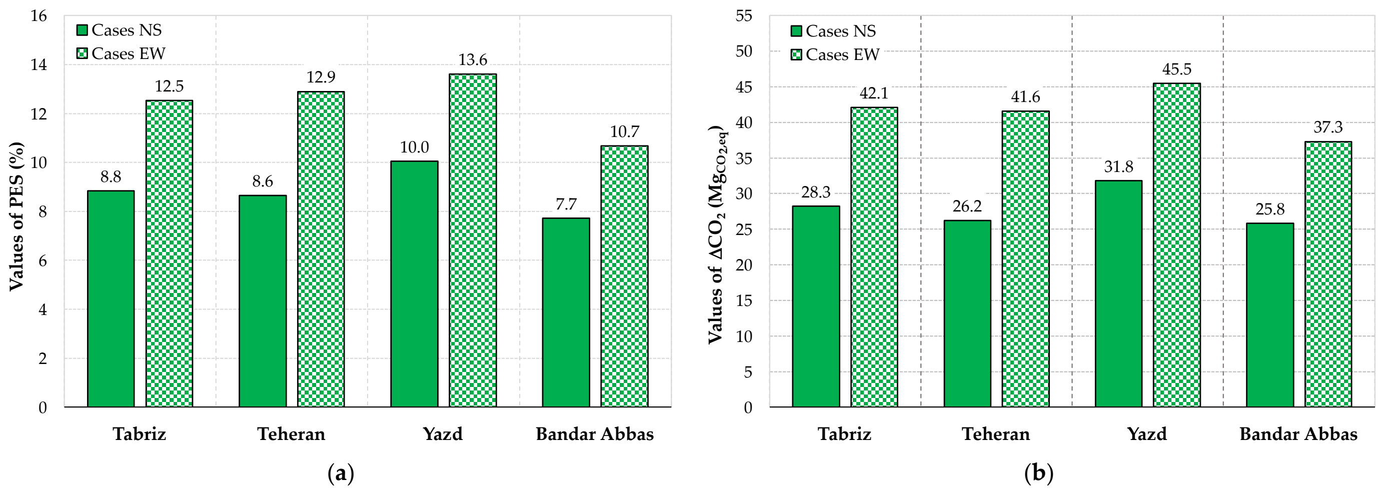


Figure 7. Values of (**a**) *PES* and (**b**) ΔCO_2 according to location.

Figure 8a–d reports the values associated with the whole office building for thermal and cooling energy flows upon varying the simulation case (Table 5) and the month of the year. In particular, in Figure 8a–d, the values associated with the north-south oriented case studies (case NS-Ta, case rNS-Ta, case NS-Te, case rNS-Te, case NS-Ya, case rNS-Ya, case NS-Ba, and case rNS-Ba) are reported by using solid-filled bars. In contrast, the values associated with the east-west oriented case studies are reported by using striped-filled bars (case EW-Ta, case rEW-Ta, case EW-Te, case rEW-Te, case EW-Ya, case rEW-Ya, case EW-Ba, and case rEW-Ba).

Table 6 reports the space cooling and thermal energy demand for every case study and location. In particular, the first two rows of Table 6 refer to the reference cases, cases NS and EW, in north-south and east-west orientation, respectively; then, the second two rows of Table 6 refer to the retrofit cases with the *SS* facade system, cases rNS and rEW, in north-south and east-west orientation, respectively. Moreover, Table 6 is divided into two main vertical sections, reporting the thermal energy for space cooling (left) and heating (right) demands associated with the whole office building upon varying the location.

Table 6. Yearly cooling and thermal energy demand per square meter associated with the whole building for each case study.

	Space Cooling Energy Demand Associated to the Whole Office Building (kWh/m^2/year)				Space Heating Energy Demand Associated to the Whole Office Building (kWh/m^2/year)			
Case study	Tabriz	Teheran	Yazd	Bandar Abbas	Tabriz	Teheran	Yazd	Bandar Abbas
Case NS	36.7	60.0	83.6	134.1	110.7	66.3	50.8	6.8
Case EW	50.6	76.8	99.4	146.7	109.4	65.0	48.9	6.5
Case rNS	23.3	42.8	62.2	113.2	99.1	61.3	45.4	6.7
Case rEW	26.6	47.5	67.2	116.5	97.1	59.6	43.2	6.4

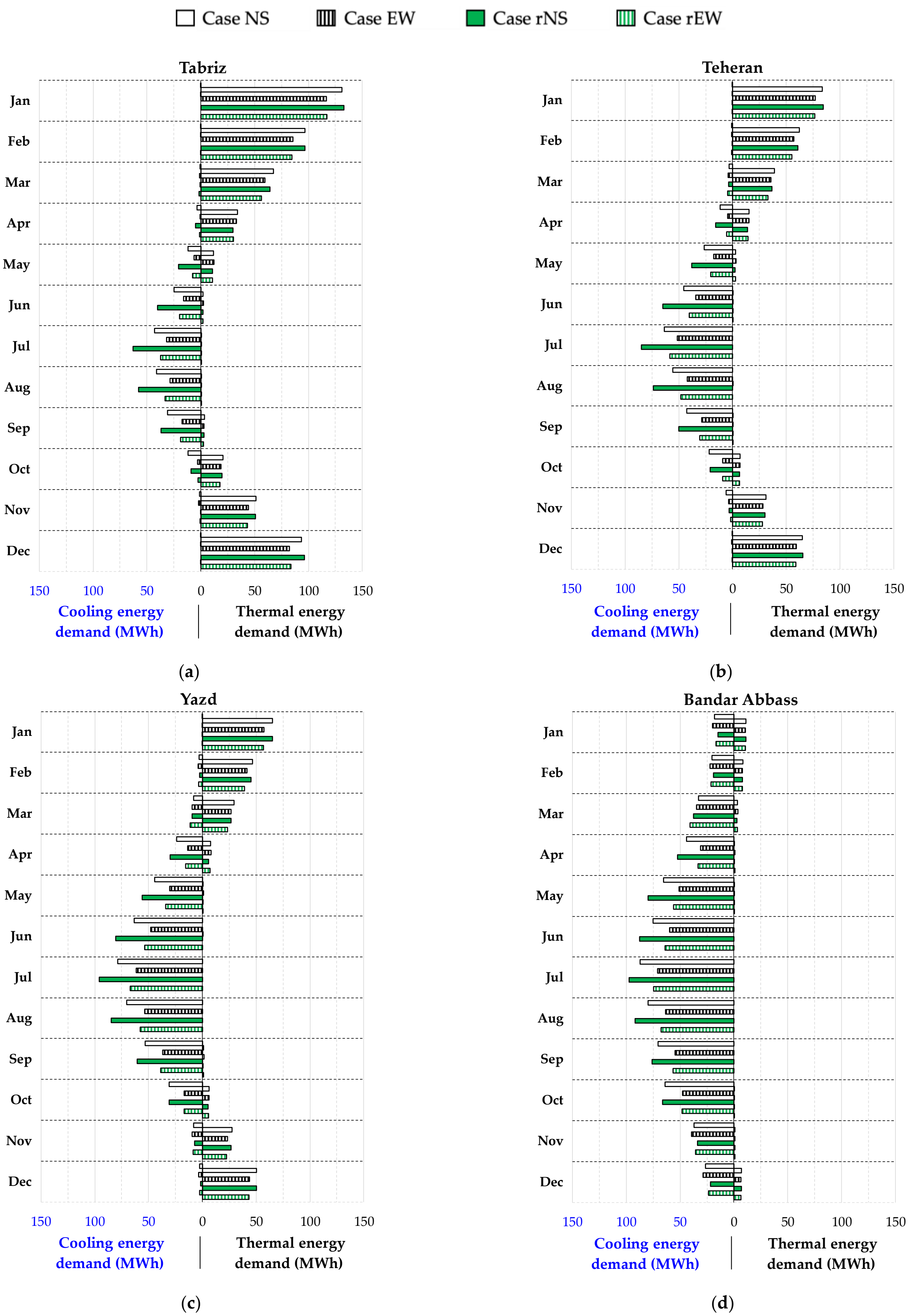


Figure 8. Energy flows in varied locations: (**a**) Tabriz, (**b**) Teheran, (**c**) Yazd, and (**d**) Bandar Abbas.

The simulation results shown in Figures 7 and 8, as well as Table 6, indicate that:

- all the proposed cases (cases rNS and rEW, Table 5) allow for saving primary energy consumption and reducing carbon dioxide equivalent emissions with respect to the reference cases for each considered location (cases NS and EW, Table 5);
- in all the locations, the best results are returned, in terms of reduction of both primary energy consumption and CO_2 equivalent emissions, when the main facades of the building are oriented east-west (cases rEW, Table 5) in comparison to the reference cases (cases EW, Table 5);
- the *PES* varies between a minimum of 7.7% in Bandar Abbas (case rNS-Ba) and a maximum of 13.6% in Yazd (case rEW-Ya);
- the values of ΔCO_2 vary from a minimum of 25.8 $\mathrm{Mg_{CO_2,eq}}$ (case rNS-Ba) and a maximum of 45.5 $\mathrm{Mg_{CO_2,eq}}$ (case rEW-Ya);
- considering the north-south orientation, the best values of *PES* (10.0%) and ΔCO_2 (31.8 $\mathrm{Mg_{CO_2,eq}}$) are returned by the retrofit case in Yazd (case rNS-Ya), thanks to an important reduction of both the thermal and cooling energy demand with respect to the reference case, of about 10.7%, and 25.6% respectively. Indeed, the case rNS-Ya returned the best results in terms of reduction of the annual specific total (cooling and thermal) energy demand of about 26.8 kWh/m^2/year (see Table 6);
- considering the east-west orientation, the best values of *PES* (13.6%) and ΔCO_2 (45.5 $\mathrm{Mg_{CO_2,eq}}$) are returned by the retrofit case in Yazd (case rEW-Ya), thanks to an important reduction of both the thermal and cooling energy demand with respect to the reference case, of about 11.7% and 32.4%, respectively. Indeed, the case rEW-Ya return the best results in terms of reduction of the annual specific total (cooling and thermal) energy demand of about 37.9 kWh/m^2/year (see Table 6);
- concerning the reduction of cooling energy demand, the best results for both east-west and north-south orientation cases are achieved in Yazd, equal to 32.2 kWh/m^2/year and 21.4 kWh/m^2/year, respectively; the worst results for both north-south and east-west orientation cases are returned in Tabriz, equal to 13.4 kWh/m^2/year and 24.0 kWh/m^2/year, respectively;
- concerning the reduction of thermal energy demand, the best results for east-west and north-south orientation cases are achieved in Tabriz, equal to 12.3 kWh/m^2/year and 11.6 kWh/m^2/year, respectively. In comparison, the worst results for both north-south (0.08 kWh/m^2/year) and east-west (0.12 kWh/m^2/year) orientation cases are returned in Bandar Abbas.

Finally, Figure 9 reports the *SPB* period (Equation (7)) upon varying the case study (Table 5) and the incentives hypotheses.

Figure 9 highlights that:

- with respect to the building orientation, the east-west oriented cases return, on average, values of *SPB* period almost 30 years lower than those calculated for the north-south oriented cases;
- in general, the worst results are returned in Bandar Abbass (106.7 years), when the building is north-south oriented, and no incentives are taken into account ($I_{0\%}$), while the best results are calculated in case rEW-Ya (48.8 years, in Yazd) considering the most significant amount of hypothesized incentive ($I_{20\%}$);
- in all the considered locations, the installation of the *SS* facade systems on the buildings that are north-south oriented (cases rNS, Table 5) returned unacceptable values of *SPB* period ranging between 69.6 years (case rNS-Ya with $I_{20\%}$) and 106.8 years (case rNS-Ba with $I_{0\%}$);
- in all the considered locations, the installation of the *SS* facade systems on the building east-west oriented (cases rEW, Table 5) returned, while still high, more acceptable values of *SPB* period ranging between 48.8 years (case rEW-Ya with $I_{20\%}$) and 73.9 years (case rEW-Ba with $I_{0\%}$).

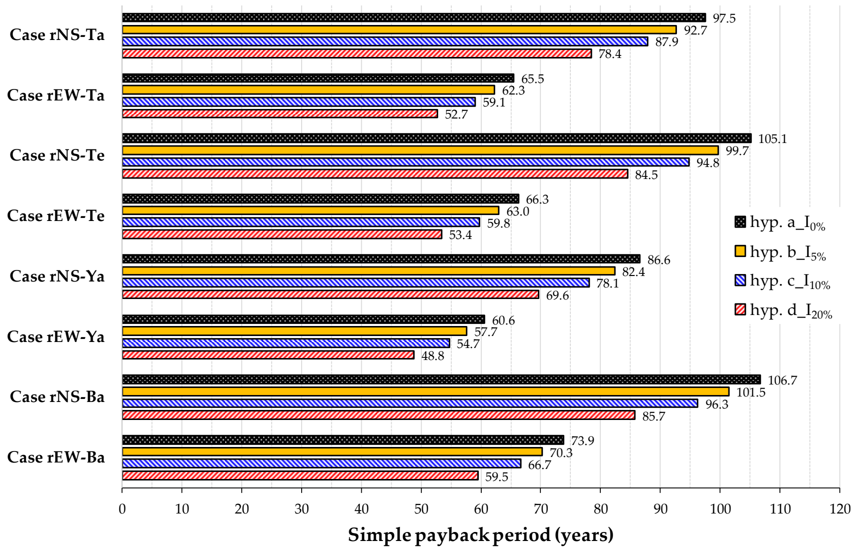


Figure 9. Simple payback period according to case study and incentives' hypotheses.

4. Discussion: Limitations and Comments for Future Research

This section tries to give a broader perspective to the achieved numerical results, along with a comment on the economic analysis, which may deserve a more articulated consideration.

As reported in the literature review, there are a limited number of research activities about *SS* facade systems, or ventilated facades in general, in the Iranian context. Other than the achieved benefits, it is important to assess the general considerations that stand out when considering this type of system across the varied Iranian climate.

In terms of reducing energy consumption and emissions, the results achieved by the *SS* facade system presented in this research seem to be in line with those achieved by Zomorodian et al. [30] and Mahdavinejad & Mohammadi [28] in Teheran. However, as stated by the same authors, the impact of these particular passive systems seems to be quite low compared to retrofit design which involves active systems or more intrusive renovations. Arguably, when considering the advantages of the *SS* facade systems, the analysis should also focus on the architectural value of the building. In previous works [17,31,32], the authors have investigated the use of *SS* facade systems, in particular where historical or old buildings represent the building stock, where *SS* structures may be the only feasible retrofit solution, both for short and long term renovations, thanks to their non-invasiveness and lightness. In these cases, *SS* facade systems can provide energy and environmental benefits while also providing for an increase in the building's value.

Another consideration, particularly in the perspective of future research, is the design of the *SS* facade system and first of all the orientation of the retrofit facades and the control logic of the *SS* components (inlet and outlet shutters, movable sections, etc.). In this regard, very few works consider the behavior of the *SS* facade system across a whole year, mainly focusing on the cooling season and the response to high solar radiation levels. However, this work highlighted how it is possible to achieve good results also in the heating season when the control logics are designed to exploit the advantages of the materials or components in the *SS* external layer. Indeed, these topics, related to the implementation of new materials and components as external layer, as well as to the development of proper and more effective control logics (i.e., based on the external vertical solar radiation or illuminance levels), are at the same time a current limitation and a reference for future research. With the rapid development of new materials (especially in plastic and low-impact materials) or the use of local materials (usually more affordable and easily available), there is a need to develop new methodologies (design, modeling, and control) able to assess their impact when integrated into these construction systems. Future research may also investigate installing this kind of passive system in locations or orientations, such as Nordic regions, where traditionally low or no benefits were achieved.

Finally, the economic analysis highlighted similar concerns about the feasibility of installing a *SS* facade system in the Iranian panorama. As also stated in [30], the payback period is quite long, and the economic impact should be evaluated on the whole architectural design, also considering the added aesthetic value and attractiveness. However, the results achieved in this research reveal the need for a more robust approach to energy policies and government incentives in Iran. Indeed, there is now an evident gap between developed and emergent nations in terms of promoting and adopting energy policies [12]. Usually, the policies are introduced applying national or international directives about new approaches (such as thermal building envelope regulation, renewable energy sources, internal market regulation for penetration of efficient technologies and higher environmental standards). In Iran, the first energy-related policy was introduced in the early 1990s and updated in 2005, as a voluntary policy for all buildings, but it has been poorly adopted, mainly due to socio-economic obstacles [13]. In this regard, the strategies to overcome these obstacles could involve:

- regularly enforcing the adoption of the policy for all new buildings and renovations;
- financially assisting the construction of buildings able to reach a certain performance threshold, instead of focusing on prescriptive limitations;
- financially assisting the renovation of the existing building stock, prioritizing passive approaches and system enhancements;
- setting up an energy performance label system, in order to give the tools to buyers and renters to assess the quality of a building;
- publicly encouraging the consumers in adoption of new technologies.

Notably, these strategies could merge into national policies that aim at developing the required economic tools, while also providing the necessary educational bases for an easier common understanding of the benefits. Indeed, the first and main obstacle for the government is the economic planning for these incentive policies. Examples from around the world show good success in providing the necessary funding to owners and construction agencies, mainly by:

- guaranteeing a direct capital grant for owners or buyers, where the amount is proportional to the achieved building energy performance;
- guaranteeing an indirect grant, by lowering the owners' taxes proportionally to the cost of renovations;
- guaranteeing an indirect grant, by lowering utility charges proportionally to the achieved performances of renovations.

Future research may investigate more complex economic scenarios and incentives, while also accounting for a more comprehensive assessment of the economic impact of all the *SS* facade system components across their whole life cycle.

5. Conclusions

In the last decade, Iranian primary energy consumption has increased, and the most significant energy demand is related to use in buildings. In order to acknowledge the problems of energy efficiency, indoor comfort, and sustainability, several systems and methodologies have been proposed, highlighting the use and optimization of passive systems for the buildings' facades. In this research, the evaluation of the energy, environmental and economic effects of the refurbishment of an existing office building by means of a passive retrofit action, in terms of reduction of primary energy consumption, carbon dioxide equivalent emissions, operating costs, and simple payback period has been carried out upon varying both weather conditions (Tabriz, Teheran, Yazd, and Bandar Abbas) and orientation of the building (north-south and east-west orientation of the two main facades under consideration). The analyses were carried out through the simulation software TRNSYS 18 using a numerical model validated by the authors of a second-skin system integrating a tensile material. In particular, an office building was considered, consisting of geometries defined by the literature and thermophysical characteristics of the envelope typical of the Iranian building stock. The passive retrofit actions involved seasonal control of the second-skin system, fully exploiting the characteristics of the tensile material. The thermal transmittance threshold values suggested by the Iranian building code were also considered. In order to further develop the economic analysis, three different incentive policies were hypothesized and suggested to promote the endorsement of energy efficiency measures on existing buildings.

The results returned by the numerical simulation highlight that the building in the east-west orientation achieves the best results in terms of *PES* and ΔCO_2. In particular, the simulation returned the maximum values of *PES* and ΔCO_2 in Yazd (equal to 13.6% and 45.5 $Mg_{CO_2,eq}$, respectively). Indeed, the east-west oriented building in Yazd returned the best results in terms of reduction of the annual specific total (cooling and thermal) energy demand of about 37.9 kWh/m^2/year. In addition, the use of the proposed second-skin system as a retrofit solution allowed for a reduction of both specific space cooling (up to 32.2 kWh/m^2/year) and heating (up to 12.3 kWh/m^2/year) energy demand.

Concerning the economic analysis, the east-west oriented cases return, on average, values of simple payback period almost 30 years lower than those calculated for the north-south oriented cases; this result seems to highlight a favorable orientation for building in Iran, which may also suggest a guideline for new building construction. However, the analysis also underlines two main issues: (i) on the one hand, there is a need for investigating more innovative materials, also considering their local availability and efficacy, and (ii) on the other, there is a need for government policies to incentive the refurbishment of the existing building stock on a large scale and with a better economic return. Successful policies have been applied around the world: (i) direct capital grant for improving the building energy efficiency, (ii) tax deductions in the function of the cost of renovations as well as (iii) incentives for the operating costs, thereby promoting the penetration of innovative and more efficient systems.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Latin letters	
BEC	Building Energy Code
CC	Capital Costs
COP	Coefficient of Performance (-)
E	Energy (kWh)
EER	Energy Efficiency Ratio (-)
EHP	Electric Heat Pump
EPS	Expanded PolyStyrene
EW-Ta/EW-Te/EW-Ya/EW-Ba	reference case in East-West orientation in Tabriz/Teheran/Yazd/Bandar Abbass
h	hours
HVAC	Heating, Ventilation and Air Conditioning
I	Incentive for retrofit action
IEA	International Energy Agency
IRR	Iranian Rial
LPD	Lighting Power Density (-)
m	mass (kg)
NS -Ta/NS -Te/NS -Ya/NS -Ba	reference case in North-South orientation in Tabriz/Teheran/Yazd/Bandar Abbass
OC	Operating Costs
PC	Proposed Case
PES	Primary Energy Saving
PVC	PolyVinyl Chloride
RC	Reference Case
rEW-Ta/rEW-Te/rEW-Ya/rEW-Ba	retrofit case in East-West orientation in Tabriz/Teheran/Yazd/Bandar Abbass
rNS -Ta/rNS -Te/rNS -Ya/rNS -Ba	retrofit case in North-South orientation in Tabriz/Teheran/Yazd/Bandar Abbass
s	thickness
SS	Second-Skin
T	Temperature
U	transmittance value (m^2K/W)
USD	US Dollar ($)
WD	Work Days
WE	Week-Ends
WWR	Windows-to-Wall Ratio
Greek letters	
Δ	difference
η	efficiency (%)
λ	thermal conductivity (W/mK)
Subscripts/Superscripts	
avg	average
cool	cooling
el	electricity
I	Incentive for retrofit action
indoor	indoor air
min	minimum
max	maximum
p	primary energy
PC	Proposed Case
PP	Power Plant
RC	Reference Case
th	thermal
w	window
X%	percentage of the retrofit capital costs

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