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Energy Performance of Buildings with Thermochromic Windows in Mediterranean Climates

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Abstract: This article presents comparative results on the energy performance of buildings in the Mediterranean. Many buildings in the Mediterranean exhibit low energy performance ranking. Thermochromic windows are able to improve the energy consumption by controlling the gains from sunlight. In this article, reference buildings in 15 cities around the Mediterranean are investigated. In this work, a dynamic building information modeling approach is utilized, relying on three-dimensional geometry of office buildings. Calculations of the energy demand based on computational simulations of each location were performed, for the estimation of heating and cooling loads. The presented study highlighted the need for high-resolution data for detailed simulation of thermochromic windows in buildings of Mediterranean cities. Temperature is one of the main climate parameters that affect the energy demand of buildings. However, the climate of Mediterranean cities nearby the sea may affect the energy demand. This was more pronounced in cities with arid Mediterranean climate with increased demand in air-conditioning during the summer months. On the other hand, cities with semi-arid Mediterranean climate exhibited relatively increased heating demand. With this parametric approach, the article indicates the energy saving potential of the proposed measures for each Mediterranean city. Finally, these measures can be complemented by overall building passive and active systems for higher energy reductions and increased comfort.

Keywords: thermochromic coatings; solar transmittance; solar reflectance

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1. Introduction

The Mediterranean climate is characterized by mild winters and cool summers, especially in insular areas. The temperature in winter rarely falls below 0 °C, while the temperature during summer days varies around 30 °C, due to sea wind. These winds may, however, be absent in cities near the eastern Mediterranean basin and north Africa. These mild climate conditions result to moderate heating and cooling loads of buildings in Mediterranean cities. These loads are limited during the peak winter and summer seasons, reducing the conditioning requirements during the spring and autumn [1].

Nevertheless, buildings in Mediterranean cities exhibit considerable energy consumption. A significant effort is given to improve the energy performance of residential as well as commercial buildings with a number of innovative systems.

1.1. Existing Building Energy Consumption

An important building sector includes office and school buildings, as well as the evaluation and upgrade of their energy performance. School buildings represent a high percentage of public buildings with the number of school buildings in the Mediterranean estimated at 87,000 [2]. Many schools operate at low thermal comfort, while a heating strategy is absent [3].

The introduction of possible passive measures was examined by [4,5] for warm and cold Mediterranean climates in Greece and Spain, respectively. The insulation, as well as the replacement of openings and the use of shadings were evaluated. Both reports concluded that the achieved saving can be up to 65%, while the reduction on annual CO_2 emissions can be higher than 70%. By applying passive measures in school buildings, an annual reduction of 17.7 and 15.9% in heating and cooling demand can be achieved, respectively [2].

A crucial parameter affecting the energy consumption for heating and cooling is air infiltration. The contribution of air infiltration on the total final energy specific consumption was reported between 2.43 and 16.44 kWh/m^2 for heating and between and 3.06 kWh/m^2 for cooling [6]. The consumption depends on three major parameters: (1) the location of the building whether this is built in urban, rural, high or low altitude environments, (2) the climate classification, and (3) the performance of the openings. Increasing the number of glazings can reduce the infiltration; however, this is a trade-off for the window–wall ratio, especially in the summer months in Mediterranean climates [7]. In addition, increasing the number of glazings reduces the environmental impact as reported in life-cycle assessment analyses [8]. There is, however, an optimum window–wall ratio for the best energy performance of buildings. Extensive studies limit the optimum window–wall ratio between 0.3 and 0.45 [9]. However, depending on the climate of the building's location, the optimum may vary to lower values down to 20% [10]. Changing either the number of glazings or the window–wall ratio is not always possible due to limitations related to cost or preservation of a building [11].

Reducing the window–wall ratio may increase the requirements for artificial lighting. Considering a lighting power density between 10 and 30 W/m^2, a commercial building may have annual electricity consumption between 20 and 25 kWh/m^2 [12]. This consumption can be reduced by optimizing the use of natural lighting. By adopting a building orientation that maximizes natural lighting during the day, electricity savings between 40 and 80% can be achieved in commercial buildings [13].

1.2. Reducing Energy Needs by Passive Measures

Green roofs constitute an attractive passive measure originating from traditional architecture approaches [14,15]. In Mediterranean climates, green roofs in office buildings in Cyprus [16] and residential buildings in Catania, Sicily [17] were investigated. Annual energy savings of 25% for heating and 20% for cooling were reported for the office building in Cyprus. In Sicily, the annual energy saving varied between 31 and 35% for cooling, while for heating was between 2 and 10%. Thermochromic coatings applied on building roofs were shown to decrease the energy consumption of the building by 7.7% [18], while annual energy savings up to 19% were reported for Mediterranean cities [19]. The solar reflectance of the reference thermochromic coating increased from 22 $\pm$ 4% to 47 $\pm$ 12% when titania was added. When idealized spectra are considered, a low transition temperature and a sharp hysteresis exhibit the highest energy savings [20]. The width of the hysteresis and the transmittance of thermochromic coatings can be modified by increased nitrogen flow rates during deposition [21], while the temperature of the window can be modified by controlling the incident irradiance by means of geometric concentration [22]. In addition to the thermochromic material, the matrix can be modified to obtain lower temperatures, as for example in nanocomposites and conjugated polymers that exhibit low transition temperatures down to 30 °C [23], making them promising matrices for application in windows. A temperature gradient of 6.9 °C resulting at 396 W/m^2 cooling power at 3 W/cm^2 was reported with hollow network nanoparticle nanocomposite [24], while the cooling power could be increased to 928 W/m^2 in a nanocomposite paint consisting of silica aerogel and titania nanoparticles [25].

1.3. Scope of the Study

Although thermochromic coatings exhibited considerable savings applied on roofs, their report and application as windows in buildings of Mediterranean climates is limited. Thermochromic coatings can be applied in new windows, but can be more important in existing building windows [26] with limitations in window adaptations. With this possibility in mind, we examine the performance of singly-glazed thermochromic windows in Mediterranean locations. A dynamic simulation is performed in this article to evaluate the performance of buildings with thermochromic windows. The evaluation is based on the heating and cooling energy consumption in heated and air-conditioned office buildings. The energy requirements after implementation of thermochromic windows in buildings of 15 Mediterranean cities with diverse climate conditions is evaluated and compared.

2. Methodology

2.1. Mediterranean Cities

The following cities in the Mediterranean were studied in this report. These are displayed in Figure 1. The main criteria for selection were their proximity to the Mediterranean sea and the availability of weather data. Cities as broadly as possible were chosen, across the Mediterranean coasts as well as further in continental areas.

Figure 1. Locations of the Mediterranean cities investigated in this study.

To aid the analysis of the results, the cities in this study can be grouped according to the future Köppen-Geiger classification to (a) cold semi-arid (BSk) in semi-arid cities, (b) hot-summer Mediterranean (Csa) in insular cities, and (c) dry subtropical desert (BWh) in arid cities. Accordingly:

a Jaen, Marseille, Thessaloniki, Lisboa, and Izmir share semi-arid climate,
b Cyprus, Palma, Heraklion, Cagliari, and Catania share insular climate,
c Algiers, Alexandria, Beersheva, Tripoli, and Tunis share arid climate.

Figure 2 shows the annual statistics for the evolution of the air temperature in different Mediterranean locations. It can be seen that the temperature in all cities in this study varies between −10 and 40 °C during the coldest and warmest days of the year, respectively.

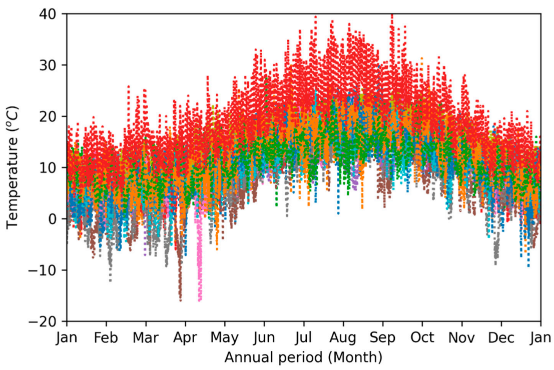

Figure 2. Annual temperature variation of the investigated Mediterranean cities.

2.2. Building Case Study

The simulations were performed on Energy Plus developed by the Lawrence Berkeley National Laboratory and the US Department of Energy. The simulation tool models the thermal and electrical loads and performs energy analysis of the entire building, enabling the user to use variable building geometries, envelope properties, lighting, heat, ventilation and air-conditioning (HVAC) systems, as well as set-point schedules. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) extreme dry- and wet-bulb temperature conditions were considered in simulations for heating and cooling design days, respectively.

In this study, an office building model with an area of 510 m^2 was considered. The window–wall ratio was 21.20% with windows distributed across all the walls of the building. This window–wall ratio is in good agreement with the 20–35% value for optimized energy performance of buildings in hot and dry regions [10,27]. Although this metric is adequate for one- and two- floor buildings, the window-to-floor-ratio should also be considered in multistory and high-rise buildings [28]. Tables 1 and 2 present the properties of the materials used in Energy Plus. Typical meteorological data were introduced to simulate the conditions of each location. To highlight the impact in energy consumption by the introduction of thermochromic windows, simulations in the absence of thermochromic coating were performed for the cities exhibiting the highest energy demand in each climate group, that is Larnaca, Tripoli, and Izmir. No dirt correction factors were applied and the windows were considered not diffusing over the solar spectrum.

Table 1. Construction materials and their properties as utilized in simulations.

Material	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (J/(kg·K)	Roughness	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Wood Shingles	0.0178	0.115	513	1255	Very Rough	0.9	0.78	0.78
Wood Decking	0.0254	0.1211	593	2510	Medium Smooth	0.9	0.78	0.78
Roof Insulation	0.2216	0.049	265	836.8	Medium Rough	0.9	0.7	0.7
Gypsum	0.0127	0.16	784.9	830	Smooth	0.9	0.92	0.92
GP01 1/2 GYPSUM	0.0127	0.16	800	1090	Smooth	0.9	0.7	0.5
Stucco	0.0253	0.6918	1858	837	Smooth	0.9	0.92	0.92
Heavyweight Concrete	0.2033	1.7296	2243	837	Medium Rough	0.9	0.65	0.65
Wall Insulation	0.0339	0.0432	91	837	Medium Rough	0.9	0.5	0.5
Heavyweight Concrete	0.1016	1.311	2240	836.8	Rough	0.9	0.7	0.7
Floor Insulation	0.0464	0.045	265	836.8	Medium Rough	0.9	0.7	0.7
MAT-CC05 8 Heavyweight Concrete	0.2032	1.311	2240	836.8	Rough	0.9	0.7	0.7
Gypsum Top	0.0127	0.16	784.9	830	Smooth	0.9	0.92	0.92
Attic Floor Insulation	0.2379	0.049	265	836.8	Medium Rough	0.9	0.7	0.7
Gypsum Bottom	0.0127	0.16	784.9	830	Smooth	0.9	0.92	0.92
Roof Membrane	0.0095	0.16	1121.3	1460	Very Rough	0.9	0.7	0.7
Metal Decking	0.0015	45.006	7680	418.4	Medium Smooth	0.9	0.7	0.3
METAL Door Medium 18Ga_1	0.0013	45.3149	7833	502.08	Smooth	0.8	0.5	0.5
METAL Door Medium 18Ga_2	0.0013	45.3149	7833	502.08	Smooth	0.8	0.5	0.5
Std Wood 6inch	0.15	0.12	540	1210	Medium Smooth	0.9	0.7	0.7
Std 1.5 MW CONCRETE	0.038	0.858	1968	836.8	Rough	0.9	0.7	0.7
Std AC02	0.0127	0.0570	288	1339	Medium Smooth	0.9	0.7	0.2
Std MAT-CC05 4 MW CONCRETE	0.1	0.858	1968	836.8	Rough	0.9	0.7	0.2
Std Very High Reflectivity Surface	0.0005	237	2702	903	Smooth	0.9	0.05	0.05
Std PW05	1.91E-02	0.115	545	1213	Medium Smooth	0.9	0.78	0.78
Std Steel_Brown_Regular	1.50E-03	44.9696	7689	418	Smooth	0.9	0.92	0.92
Std Steel_Brown_Cool	1.50E-03	44.9696	7689	418	Smooth	0.9	0.73	0.73
Plywood3/4_in	0.0191	0.115	545	1213	Medium Smooth	0.9	0.7	0.78

Table 2. Properties of glazing layers used in simulations.

Magnitude	Glass	Thermochromic Layer	Clear Acrylic Plastic	Diffusing Acrylic Plastic
Thickness (m)	0.003	0.0075	0.003	0.0022
Solar transmittance	0.2442		0.92	0.9
Front solar reflectance	0.7058		0.05	0.08
Rear solar reflectance	0.7058		0.05	0.08
Visible transmittance	0.3192		0.92	0.9
Front visible reflectance	0.6308		0.05	0.08
Rear visible reflectance	0.6308		0.05	0.08
IR Transmittance at 0°	0	0	0	0
Front IR Emissivity (2π)	0.9	0.84	0.9	0.9
Rear IR Emissivity (2π)	0.9	0.84	0.9	0.9
Conductivity (W/(m·K))	0.0199	0.6	0.9	0.9

3. Results

The monthly energy demand of the buildings studied are shown in Figures 3–5, alongside the respective temperatures and seasonal solar radiation. It is clear that the temperature profiles of each city affects the energy consumption of the building. It can be seen that the Mediterranean cities can be grouped in three categories according to their energy demand. That is (a) insular, (b) semi-arid, and (c) arid. It can be seen that the monthly energy demand in all cities during winter months varies from 4.5 to 5 MWh. There is a broader variation, however, during spring and autumn. There is increased energy demand of buildings in insular and arid climates, that can be higher by 500 W. In summer months, the energy demand of buildings in insular and arid climates can be up to 1000 W higher than in semi-arid climates. The annual energy demand of the building without thermochromic windows was increased by 104.83, 93.92, and 97.39 kWh for Larnaca, Tripoli, and Izmir, respectively.

Comparing the temperature in these cities, most of them have the warmest month in July and August. All of them have the coldest month in January. Among insular cities, it can be seen that Heraklion has the coldest winter season with the minimum temperature of −15.9 °C. This leads to an annual energy demand of 132.05 kWh/m^2, while the average annual energy demand of the locations under study was 130 kWh/m^2. Optimized thermochromic coatings applied in other Mediterranean cities yielded annual demand between 60 and 80 kWh/m^2 for south- and north-facing walls, respectively [29]. This difference in energy indicates (a) the requirement for optimization with regard to the orientation of the windows, becoming important when cost is introduced in the model, and (b) the requirement for thermochromic coatings with higher solar selectivity properties compared to the coatings utilized in this study.

Among semi-arid Mediterranean cities, in Marseille, the coldest winter with temperatures reaching minima of −15.4 °C. Tunis and Be'er Sheva have the hottest summer season with the maximum temperature of 40 °C. It can be seen that the energy demand of Tripoli peaks during June, July, and August, despite the fact that its temperature is the lowest among the investigated cities with arid climate. During these months, the energy demand increases to satisfy air-conditioning requirements and is presented in detail in the following section.

3.1. Arid Mediterranean Climates

The energy demand of the building is distributed across HVAC, lighting, and other needs including energy source equipment, that is fans and pumps.

As shown in Figure 6, the most energy demanding building in arid Mediterranean cities can be seen in Tripoli with 491.97 MJ/m^2, followed by Be'er Sheva and Alexandria with 485.32 and 483.21 MJ/m^2, respectively. Algiers and Tunis have the lowest demand among arid climate Mediterranean cities with 465.78 and 474.99 MJ/m^2, respectively. It can be seen that the use of thermochromic windows have a limited effect in lighting and other energy demands. There is, however, difference in HVAC demand of about 2% between the buildings in arid climate cities.

The heating consumption can be seen in Table 3. Algiers and Tunis have the highest consumption with 24 kW, followed by Be'er Sheva and Tripoli with 23 kW, while Alexandria has the lowest consumption with 20 kW.

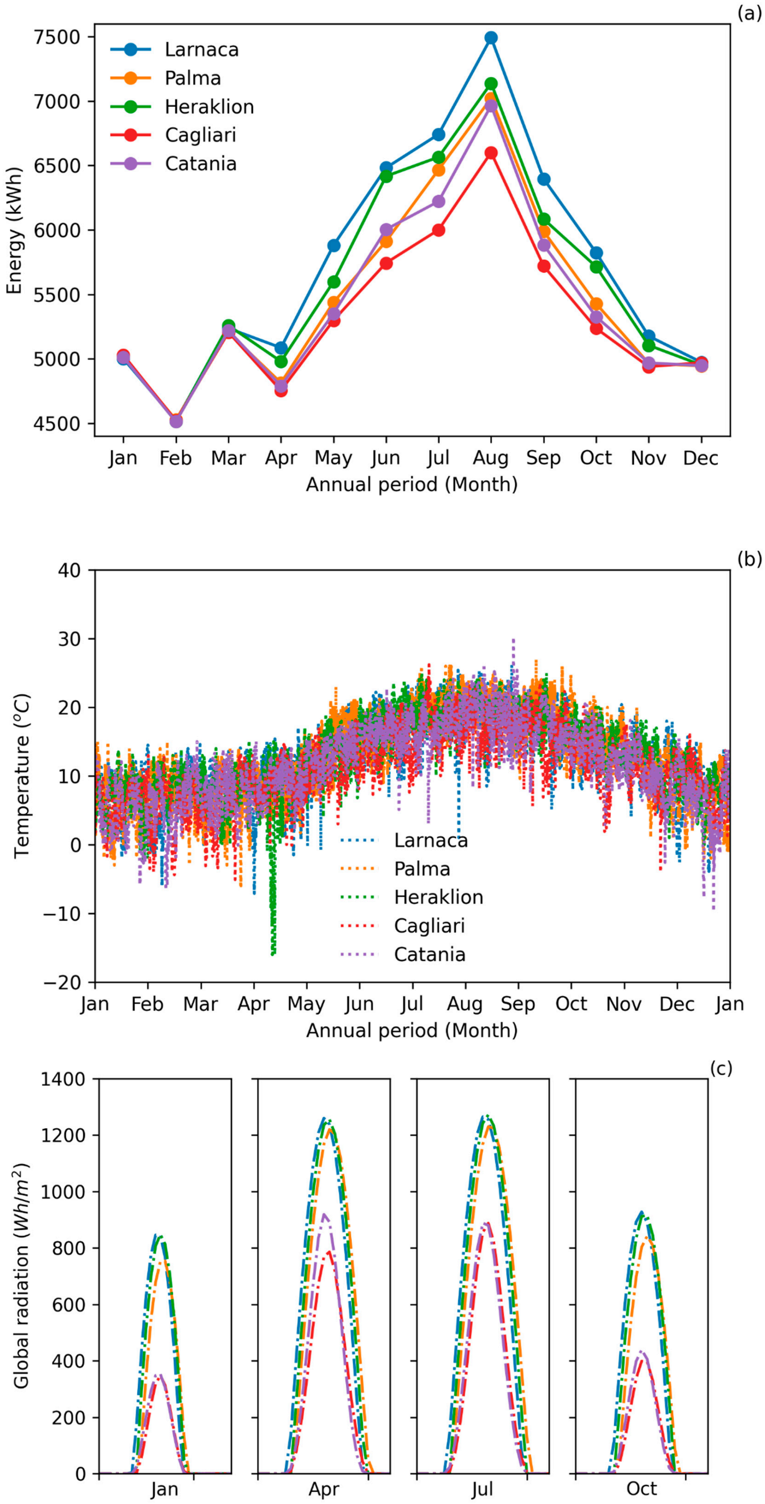

Figure 3. (**a**) Monthly energy demand of buildings, (**b**) temperature, and (**c**) seasonal global solar radiation in insular cities of the study.

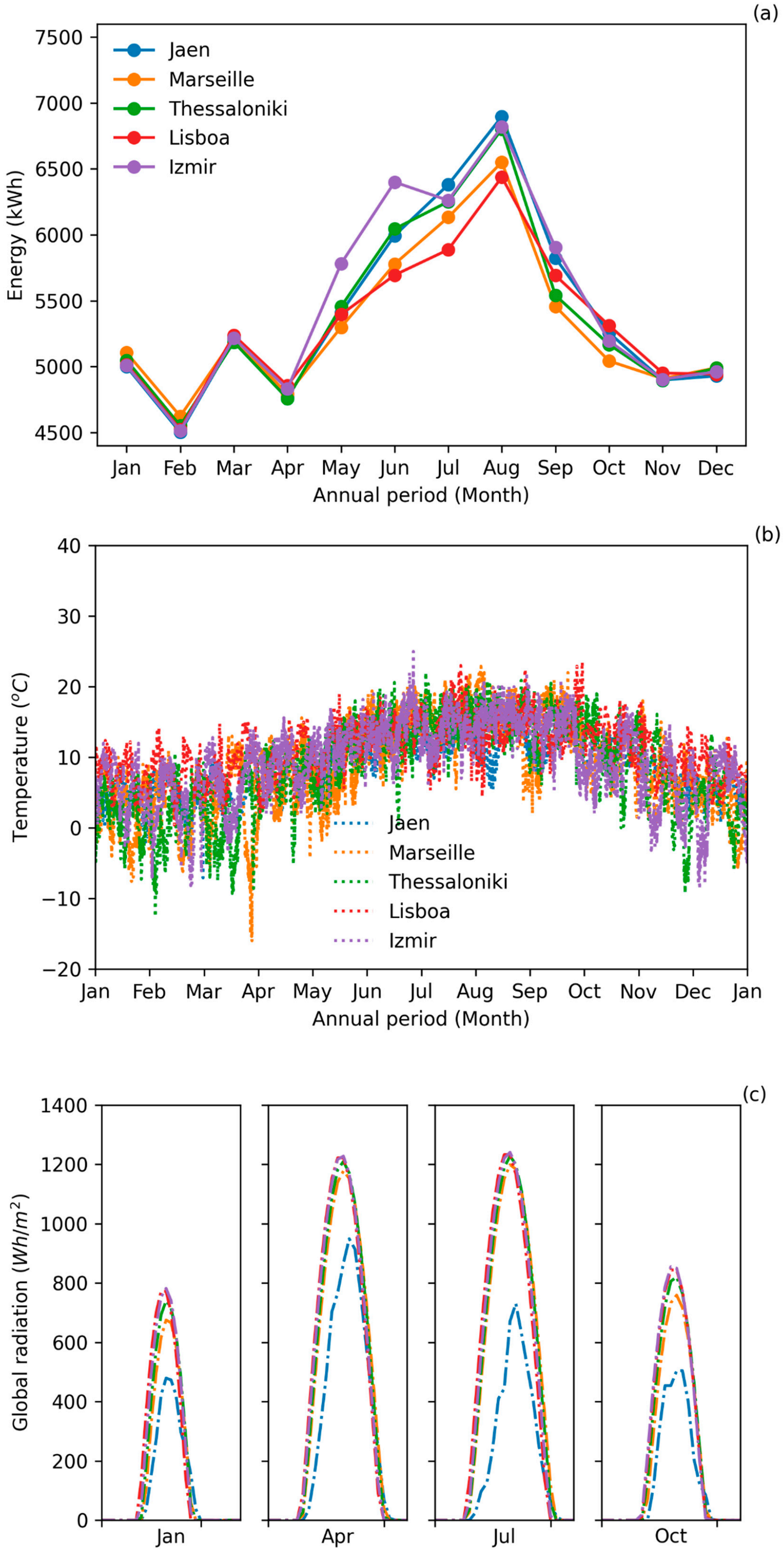

Figure 4. (**a**) Monthly energy demand of buildings, (**b**) temperature, and (**c**) seasonal global solar radiation in cities of the study with semi-arid climate.

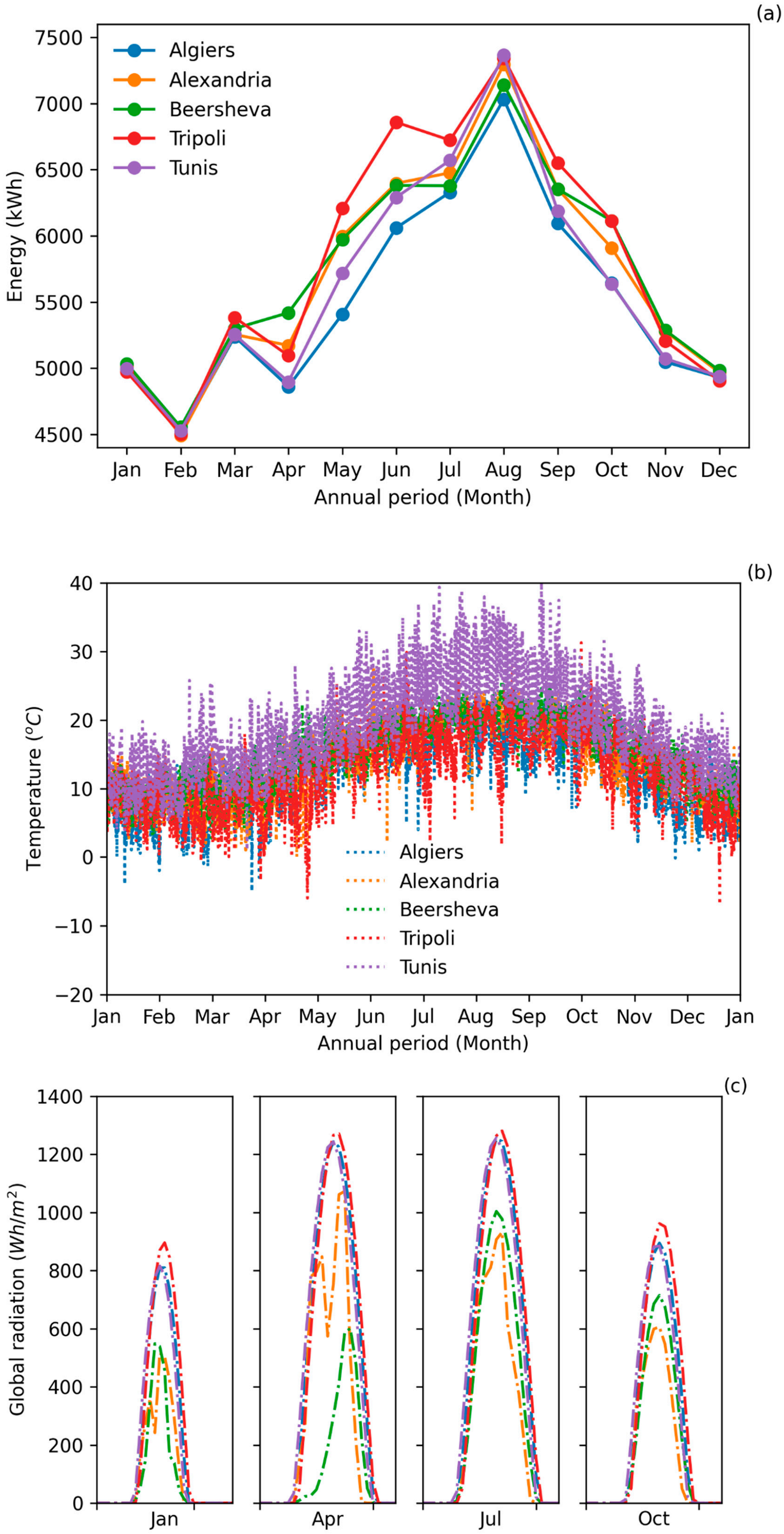

Figure 5. (**a**) Monthly energy demand of buildings, (**b**) temperature, and (**c**) seasonal global solar radiation in cities of the study with arid climate.

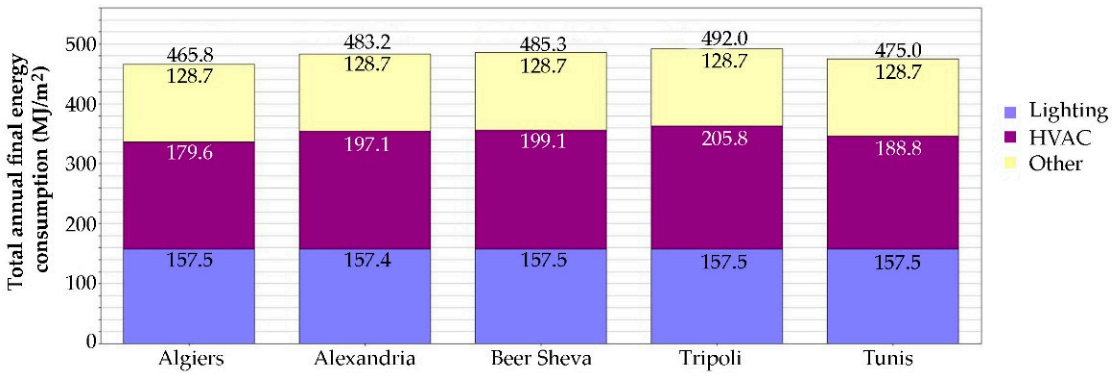

Figure 6. Annual building utility performance in arid Mediterranean climate.

Table 3. Heating consumption and hours of unmet comfort of buildings in arid climates.

City	Heating, Gas (W)	Unmet Comfort (h)
Algiers	24,854	1460
Alexandria	20,638	1085
Be'er Sheva	23,416	953
Tripoli	23,326	942
Tunis	24,067	1079

The remaining demand, shown in Figure 7, is distributed among fans (blue), cooling (purple), lighting (yellow), and other equipment (red). The demand of fans, lighting, and other equipment are the same regardless of the city. The cooling demand, however, varies considerably. Tripoli is the most demanding in cooling with 12.9 kW. Alexandria, Algiers, and Tunis require approximately 9 kW for cooling, while the least demanding of the cities is Be'er Sheva with 8.1 kW. This is in agreement with the highest energy demand depicted in Figure 5a. It can be seen that Tripoli exhibits the highest requirements among the studied cities in arid Mediterranean climate. This is largely due to the cooling requirements which are two times the cooling demand in Be'er Sheva and approximately higher by 1/3 than Algiers, Alexandria, and Tunis, see Figure 7. The extreme dry- and wet-bulb temperature conditions were utilized to simulate heating and cooling design days, respectively. This extreme scenario is commonly employed in HVAC sizing and accordingly, the demand may be overestimated due to fluctuations in local conditions. This suggests that in addition to temperature, climatic conditions such as relative humidity and wind speed may affect the energy demand of a building and should be further considered.

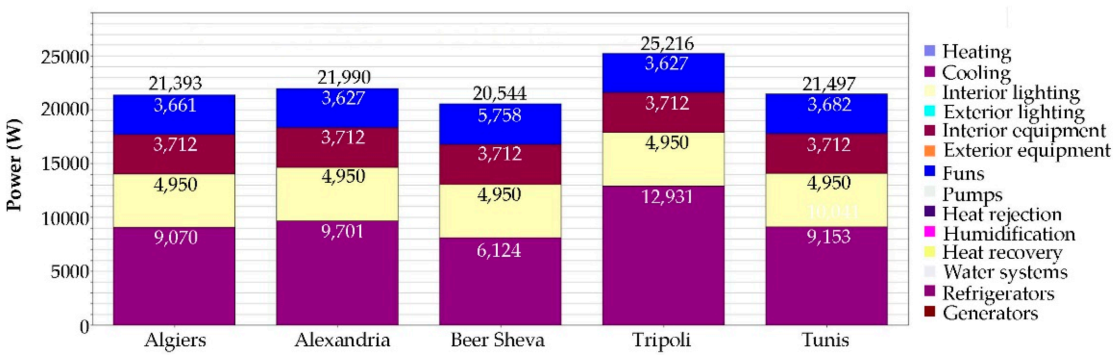

Figure 7. Demand end-use of components of buildings in arid Mediterranean climate. Components include fans (blue), cooling (purple), lighting (yellow), equipment (red).

These profiles result in several hours that comfort is not met. These hours are displayed in Table 3. In Algiers, 1460 h are not met, followed by Alexandria and Tunis with approximately 1000 h. Be'er Sheva and Tripoli share approximately 950 h of unmet comfort time.

3.2. Semi-Arid Mediterranean Climates

The most energy demanding building in semi-arid Mediterranean cities can be seen, in Figure 8, in Izmir with 219.45 MJ/m^2 followed by Jaen and Thessaloniki with 217.04 and 215.77 MJ/m^2, respectively. Marseille and Lisboa have the lowest demand among arid climate Mediterranean cities with 213 MJ/m^2. Again, lighting and other energy demand are similar; however, the demand of HVAC varies by 1% between the buildings in semi-arid Mediterranean climate cities.

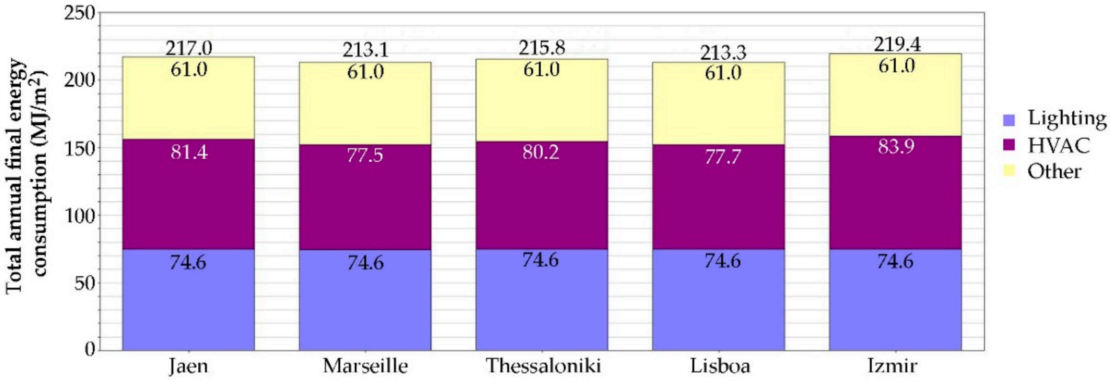

Figure 8. Annual building utility performance in semi-arid Mediterranean climate.

The heating consumption can be seen in Table 4. Jaen, Marseille, and Thessaloniki have the highest consumption with 26 kW, followed by Izmir with 24 kW and Lisboa with 23 kW.

Table 4. Heating consumption and hours of unmet comfort of buildings in semi-arid climates.

City	Heating, Gas (W)	Unmet Comfort (h)
Jaen	26,175	1185
Marseille	26,367	1930
Thessaloniki	26,320	1798
Lisboa	24,581	950
Izmir	25,331	1300

The remaining demand is shown in Figure 9. The cooling demand of Izmir is the highest with 10 kW. Jaen and Lisboa follow with 8.5 and 8.3 kW for cooling, respectively, while the least demanding cities are Marseille and Thessaloniki with 7.1 and 7.6 kW, respectively.

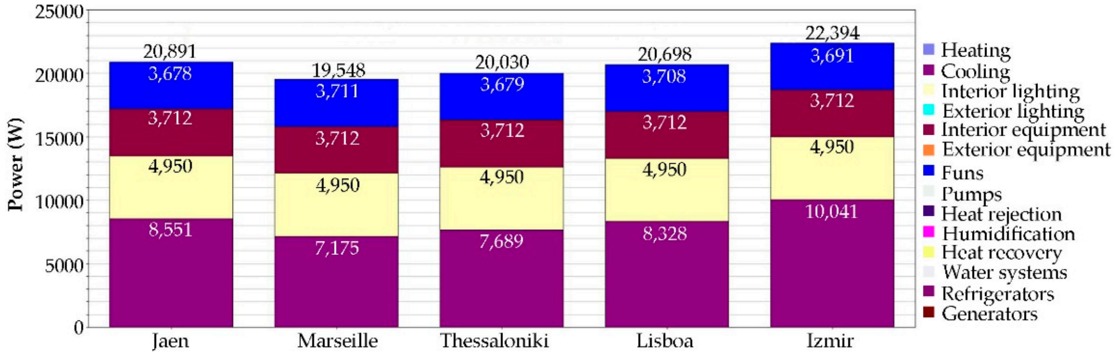

Figure 9. Demand end-use of components of buildings in semi-arid Mediterranean climate. Components include fans (blue), cooling (purple), lighting (yellow), equipment (red).

The unmet hours in this case are displayed in Table 4. In Marseille, 1930 h are not met, followed by Thessaloniki with almost 1800 h and Izmir with 1300 h. Jaen has 1185 h, while Lisboa has 950 h of unmet comfort time.

3.3. Insular Mediterranean Climates

The most energy demanding building in insular Mediterranean cities can be seen, Figure 10, in Larnaca with 484.56 MJ/m^2 followed by Heraklion and Palma with 474.28 and 462.83 MJ/m^2, respectively. Cagliari and Catania have the lowest demand among insular climate Mediterranean cities with 450 and 459 MJ/m^2. The demand of HVAC in this case varies by 3% between the buildings in semi-arid Mediterranean climate cities.

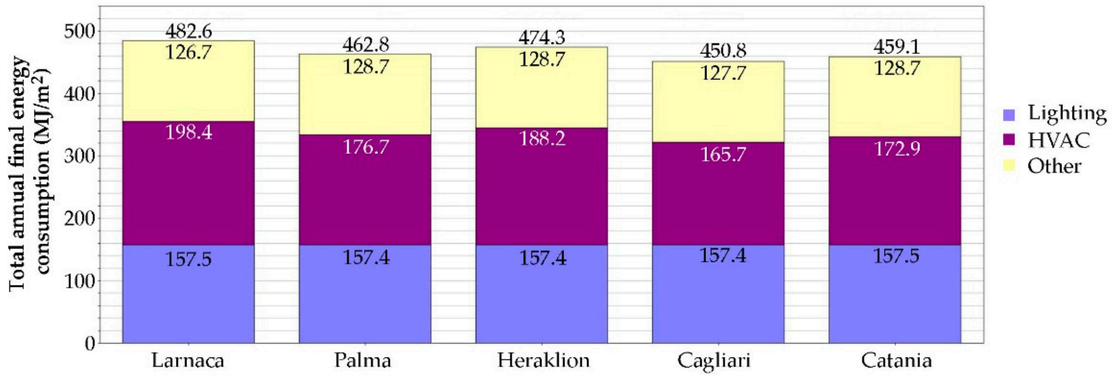

Figure 10. Annual building utility performance in insular Mediterranean climate.

The heating consumption can be seen in Table 5. Palma, Cagliari, and Catania have the highest consumption with 26 kW, followed by Heraklion and Larnaca with 25 kW.

Table 5. Heating consumption and hours of unmet comfort of buildings in insular climates.

City	Heating, Gas (W)	Unmet Comfort (h)
Larnaca	25,488	1206
Palma	26,342	2067
Heraklion	25,055	928
Cagliari	26,437	1407
Catania	26,411	1379

The remaining demand is shown in Figure 11. The cooling demand of Larnaca is the highest with nearly 10 kW. Catania has slightly lower cooling demand at 9.3 k. Palma and Heraklion follow with 8.1 kW for cooling, while the least demanding insular city of the study is Cagliari with 7 kW.

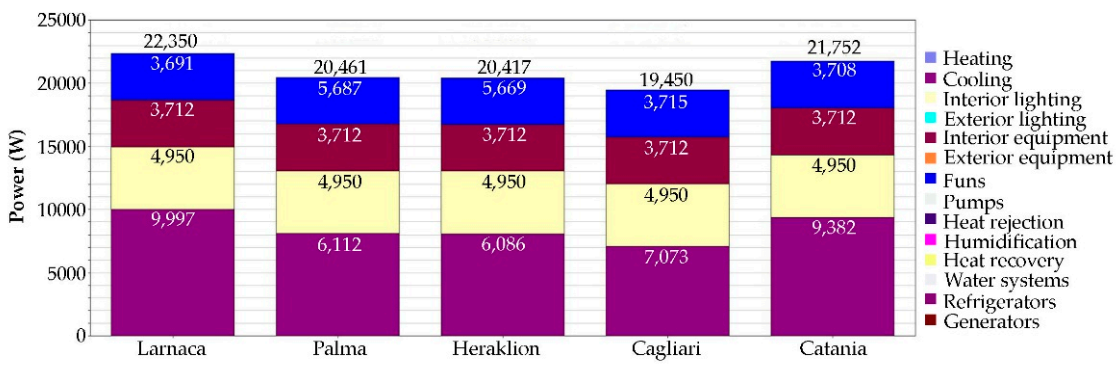

Figure 11. Demand end-use of components of buildings in insular Mediterranean climate. Components include fans (blue), cooling (purple), lighting (yellow), equipment (red).

The unmet hours in this case are displayed in Table 4. Palma has more than 2000 h unmet. Cagliari and Catania share approximately 1400 h of unmet comfort, while Larnaca follows closely with 1200 h. Finally, Heraklion has 928 h of unmet comfort time.

The HVAC equipment and the addition of thermochromic windows can optimize to a great extent the heating and cooling needs of buildings. However, in all cases there is a number of unmet hours of comfort. The number of hours was minimum in Be'er Sheva, Tripoli, Lisboa, and Heraklion. It is more likely that this is mainly due to the set of typical meteorological data used in this study and not an effect related to the local climate.

The study utilized the same building structure and construction materials. Depending on the micro-climate of each location, however, additional measures may be required to reduce the heating and cooling demand even further. Such measures can be shading as well as insulation with thermal capacity higher than what was utilized in this study. Furthermore, different thermochromic coatings with transition temperatures optimal to the peak temperatures of the location can lead to further reduction in energy consumption.

4. Conclusions

In this article, the potential for energy performance improvements in buildings was highlighted in cities sharing the Mediterranean climate. The operation of the building leads to considerable high energy consumption for space conditioning of buildings. Annual energy consumption can be reduced by introducing thermochromic windows, in particular for controlling the indoor space conditioning. The availability of high solar radiation in the Mediterranean region makes for a favorable technology for potential upgrades to zero energy buildings. The article also demonstrated the potential of energy saving in Mediterranean cities with significantly varying climate. This was highlighted by comparing the energy consumption of buildings in cities with insular, semi-arid, and arid climate.

The presented study highlighted the need for high resolution data for detailed simulation of thermochromic windows in buildings of Mediterranean cities. Temperature is one of the main climate parameters that affects the energy demand in buildings. The climate of Mediterranean cities nearby the sea may affect the energy demand. This was more pronounced in cities with arid Mediterranean climate with increased demand in air-conditioning during the summer months. On the other hand, cities with semi-arid Mediterranean climate exhibited relatively increased heating demand. It is expected that by optimally mixing and sizing energy saving systems, considerable energy savings can be achieved.

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