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Mapping the Potential of Zero-Energy Building in Greece Using Roof Photovoltaics

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Abstract: The present study investigates the incorporation of renewable rooftop photovoltaic systems in fully electrified residential buildings and estimates the zero-energy demand building potential in relation to the climatic data of Greece. Specifically, the aim of the analysis is to calculate the maximum possible number of stories and therefore the total building height for a complete transformation to zero-net-energy building. The energy analysis, which is conducted using the DesignBuilder software, focuses on single-floor up to seven-story buildings. The importance of the present work lies in the acknowledgment of the diversity of the Greek residential sector, the adherence to national energy policies, and the European goal of fully electrified buildings. The examined case studies are equipped with electrically driven air-to-air heat pumps serving the space heating and cooling demands and with an air-to-water heat pump covering the domestic hot water requirements. The investigated locations are the four main cities of Greece, Athens, Thessaloniki, Chania, and Kastoria, which represent the country's four climatic categories. The conducted analysis allows for the mapping of the zero-energy building potential for the climatic data of Greece, demonstrating the possibility of striking a positive building energy balance through the integration of on-site renewable energy sources and the production of necessary electrical energy. The novelty of the present work lies in the identification of a key factor, namely, the building height, which determines the feasibility of transforming multifamily buildings into zero-energy buildings. According to the analysis results, the critical number of stories is calculated at six for Chania, five for Athens, four for Thessaloniki, and two for Kastoria. Regarding a three-story residential building, the incorporation of a renewable photovoltaic system can result in an annual surplus electricity production of 13,741 kWh (Chania), 10,424 kWh (Athens), and 6931 kWh (Thessaloniki), and a corresponding coverage of 100% (Chania), 69.0% (Athens), 38.9% (Thessaloniki) and 0% (Kastoria).

Keywords: zero net electricity; rooftop PV systems; electrification; residential building retrofit; on-site renewable energy

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1. Introduction

The residential building sector constitutes 27.9% of the final energy consumption within the European Union, ranking as the third most significant sector in terms of energy demand [1]. For eight out of the twenty-seven European Union member states, the residential sector is characterized as the largest national energy consumer. For these member states, the energy consumption share of residencies varies from 29.3%, for the case of Germany, to 35.1% for the case of Croatia [2]. In Greece, residential energy consumption accounts for 28.8% of the nation's total final energy use [3]. Heating, cooling, and domestic hot water (DHW) preparation make up approximately 79% of households' energy usage in buildings [4].

The electrification of the building sector is strengthened by the adoption of electrically driven energy systems, for instance, heat pumps, to satisfy space heating and cooling and DHW needs [5]. Currently, only a quarter of Europe's residential sector total energy demand is electrically satisfied [1]. The contribution of renewables to electricity generation amounts to 44.2% for the European continent and 43.7% for Greece [6]. The increasing proportion of heat-pump-served buildings [7] combined with the implementation of deep retrofit initiatives aiming at the thermal performance upgrading of buildings act as key enablers for the decarbonization of Europe's energy mix [8]. Additionally, the incorporation of on-site renewable energy systems can aid in the transformation of the existing residential building stock into net-zero-energy and energy-self-sufficient buildings [9]. Zero-energy buildings are characterized by on-site renewable energy production that adequately covers its energy demand for space heating and cooling, DHW production, and electricity for appliances and lighting. Through the use of energy storage systems or the net-metering facility of the electrical grid, zero-energy buildings consume as much as or less than they produce.

Greece is characterized by a high solar potential and an available area for rooftop PV system installation of 128 km^2 [10]. The available PV rooftop installation area could potentially cover more than 30% of the country's final electricity consumption [11]. However, one of the primary obstacles hindering solar development, particularly in administrative processes such as rooftop solar installations in Greece, is the issue of grid availability [12]. Many regions in Greece are experiencing rejections of rooftop solar PV applications due to insufficient electricity grid capacity [12]. Additionally, the adoption of residential rooftop PV systems is interrupted by the relatively high investment cost [13], which according to Sagani et al. [14] is financially viable only over a minimum installed power of 5 kW. Nonetheless, the anticipated decrease in investment costs projected by the scientific community in the upcoming years, along with stable electricity prices, will gradually enhance the profitability of PV roof system installation [15]. According to Greece's energy regulation authority [16], for 2022, the installed photovoltaic power was equal to 5288 MW, while from 2011 to 2022, the PV installed capacity of Greece increased by 687%. The electricity production capability, especially at a residential level, is a driving force in the positive energy transformation of buildings and cities [17]. Regarding domestic electricity production by PVs, in 2023, Greece ranked first in Europe with a percentage (18.4%) more than double the European Union average (8.6%) and more than three times the global average (5.4%) [18]. Figure 1 illustrates the annual electricity production by PVs as well as the CO_2 emissions abated by PVs in Greece from 2013 to 2023. According to the greenhouse gas emission factors for electricity consumption given by the European Commission, for Greece, the most recent calculated emission factor for electricity consumption is 0.411 kg CO_2/kWh [19].

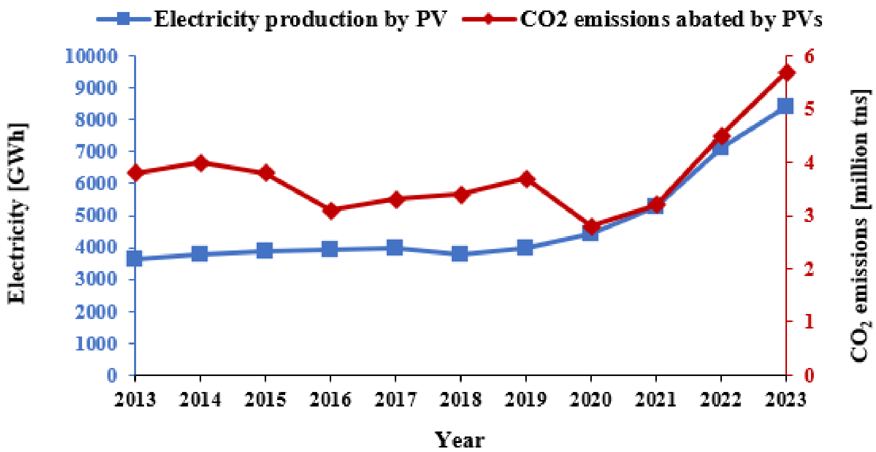


Figure 1. Electricity production by PVs and CO_2 emissions abated by PVs in Greece for 2013–2023 (data were retrieved from Refs. [18,20]).

Building height is a pivotal determinant of the potential of PV systems, impacting both energy consumption and the available area for photovoltaic deployment. The transformation of multi-story residencies into zero-net-energy buildings is a challenge that can be successfully addressed through a holistic energy efficiency improvement plan. For instance, according to the study of Bellos et al. [21], the transformation of a four-story multifamily building in Athens into a zero-energy building first requires a holistic energy renovation of the building thermal envelope and systems to restrict the overall energy demand. In another case, Dermentzis et al. [22] monitored for consecutive years two multifamily buildings in Austria equipped with electrically driven heat pumps and a rooftop PV system. They also underlined that a zero-net-electricity balance is feasible for high-efficiency building constructions, such as the Passive House standard.

Following that, Thebault and Galliard [23] investigated the integration of residential photovoltaic systems on low-, mid-, and high-rise buildings in France. They drew the conclusion that the installation of rooftop PV systems is the financially and energetically optimal strategy for low- and mid-rise buildings, whereas, for high-rise buildings, the incorporation of photovoltaics on the building façade is essential for building self-consumption and self-sufficiency. Solar potential for electrical production significantly determines the possibility of zero-energy classification in buildings. For this reason, Feng et al. [24] examined solar electricity production for the various climatic categories of Chinese cities and evaluated the integration of photovoltaic systems and the potential of achieving zero net electricity demand for multi-story family buildings. According to their analysis, the available solar irradiation and household electricity requirements are decisive factors affecting the PV rooftop performance and its sufficiency to fully serve mid-rise buildings up to seven stories in height.

Regarding the climatic conditions of Greece, researchers have investigated the incorporation of photovoltaic systems as a part of a building energy retrofit strategy. More specifically, Pallis et al. [18] examined various energy retrofit measures of a five-story office building and parametrically assessed their energy and economic performance for the four climatic categories of Greece. They concluded that the installation of photovoltaic systems is considered a cost-effective energy retrofit solution, regardless of the fuel type of building energy systems. The aforementioned conclusion is also drawn by a study by Gaglia et al. [19] regarding the national residential building sector. Other studies have focused on the energy renovation of public buildings through the integration of renewable energy systems coupled with energy storage systems [25], and the establishment of effective retrofit strategies based on the building typology [26]. Additionally, another research study by Sougkakis et al. [27] investigated the feasibility of near-zero or positive energy communities, through the examination of building-scale and community-scale retrofit action, for a case study in the city of Alexandroupolis.

The combinatorial use of photovoltaic systems and battery systems is considered a driving force toward a decarbonized and sustainable residential sector [28]. Additionally, the installation of residential capacity stands as a driving force, and subsequently the absorbed energy from the grid, which may allow for securing public grid stability. In 2019, the total installed residential capacity of battery energy storage systems was equal to nearly 2 GWh, while residential battery energy storage systems in combination with PVs accounted for approximately 7% of the total residential PV systems in operation in Europe [29]. Despite the increasing adaptation of battery energy storage systems, the market potential remains enormous, particularly considering that over 90% of European buildings still lack solar systems [29].

The most popular and commercially available battery systems are the lithium-ion and sodium–nickel chloride batteries [30]. Regarding lithium-ion batteries, according to Liu et al. [31], their superiority over other battery configuration choices lies in their long lifespan, their ability to perform effective charge and discharge cycles, and the fact that they are an appropriate option for off-grid systems. For instance, Forrousso et al. [32], parametrically investigated the sizing of a lithium-ion battery system for various climatic conditions in Morocco, to design a zero-net-energy building and maximize the load coverage factor and the energy autonomy. Additionally, Orth et al. [30] examined 26 lithium-ion battery configurations to determine the sizing, conversion, control, and standby losses in residential-scale use. They identified a significant potential for enhancement in residential PV battery systems, especially with regard to conversion efficiency and standby power consumption. Moreover, Chreim et al. [33] investigated the advantages of individual and shared renewable energy systems integrated with appropriate battery storage systems. They underlined that the sizing parameter is crucial for the optimum performance and economic efficiency of the system, which can be compromised due to the shortage of available solutions in the market.

The present analysis investigates the incorporation of PV roof systems in a typical building typology for a variable number of stories in four different locations. For this purpose, the DesignBuilder software [34] is used for yearly building energy simulation, in combination with accurate weather data extracted from the PVGIS tool, namely, the incident solar irradiation on the PV modules, for the calculation of electricity production by the PV system [35]. The aim of this study is to define the maximum number of stories that allow the transformation of a fully electrified building into a zero-energy building, an issue that has not been resolved for the residential building sector of Greece. The examined building locations are the cities of Chania, Athens, Thessaloniki, and Kastoria, which represent the four different Mediterranean climatic categories of Greece. The examined building is equipped with electrically driven air-to-air heat pumps that serve the building's heating and cooling demands and an air-to-water heat pump for the satisfaction of DHW requirements. The conducted analysis allows for mapping the zero-energy building potential based on climatic data for Greece and introduces the possibility of positive electricity production through the integration of on-site renewable energy sources. The present study can serve as a valuable guideline for the identification of Greece's potential to increase the number of zero-energy buildings and achieve European goals for the decarbonization and electrification of the residential sector. Additionally, the present study takes into consideration the versatility of Greek buildings, the wide range in the number of story levels, as well as the national energy standards. Lastly, the outputs of the present study can serve as a useful guideline for cities with similar climatic conditions and contribute to the correlation between zero-energy potential and climate types.

2. Materials and Methods

2.1. Description of Building

We examine a variable-story building, with the number of stories varying from one to seven, designed and analyzed in DesignBuilder software [34]. The simulation analysis is conducted for an entire year with a six-minute simulation step. Air temperature is set as the control temperature for the operation of the building space heating and cooling energy systems, while the selected solution algorithm is the conduction transfer function. According to the national building inventory [36], the main categories in which buildings are distributed in Greece are single-story buildings (50.5%), two story-buildings (33.3%), low-rise buildings with three to five stories (13.2%), and mid-rise buildings with over six stories (2%). Figure 2a–d depict the case of a three-story building and its geometry in the four directions of the horizon. Every story consists of two apartments with the same area of 75 m^2 and a common space area of 10 m^2, as depicted in Figure 2e, serving the communication between floors. The building is characterized by a rectangular shape of 16 m in length and 10 m in width, a flat roof, and no basement. The windows' total area represents 20% of the building's outer surface, with the greatest window area being located on the south side in the form of doors with floor-length windows. The entire south side has a 16 m length balcony of 1 m width that serves as an overhang for shading purposes. Additionally, on the east and west sides, the windows are also shaded either with a small balcony or an overhang of 0.6 m width.

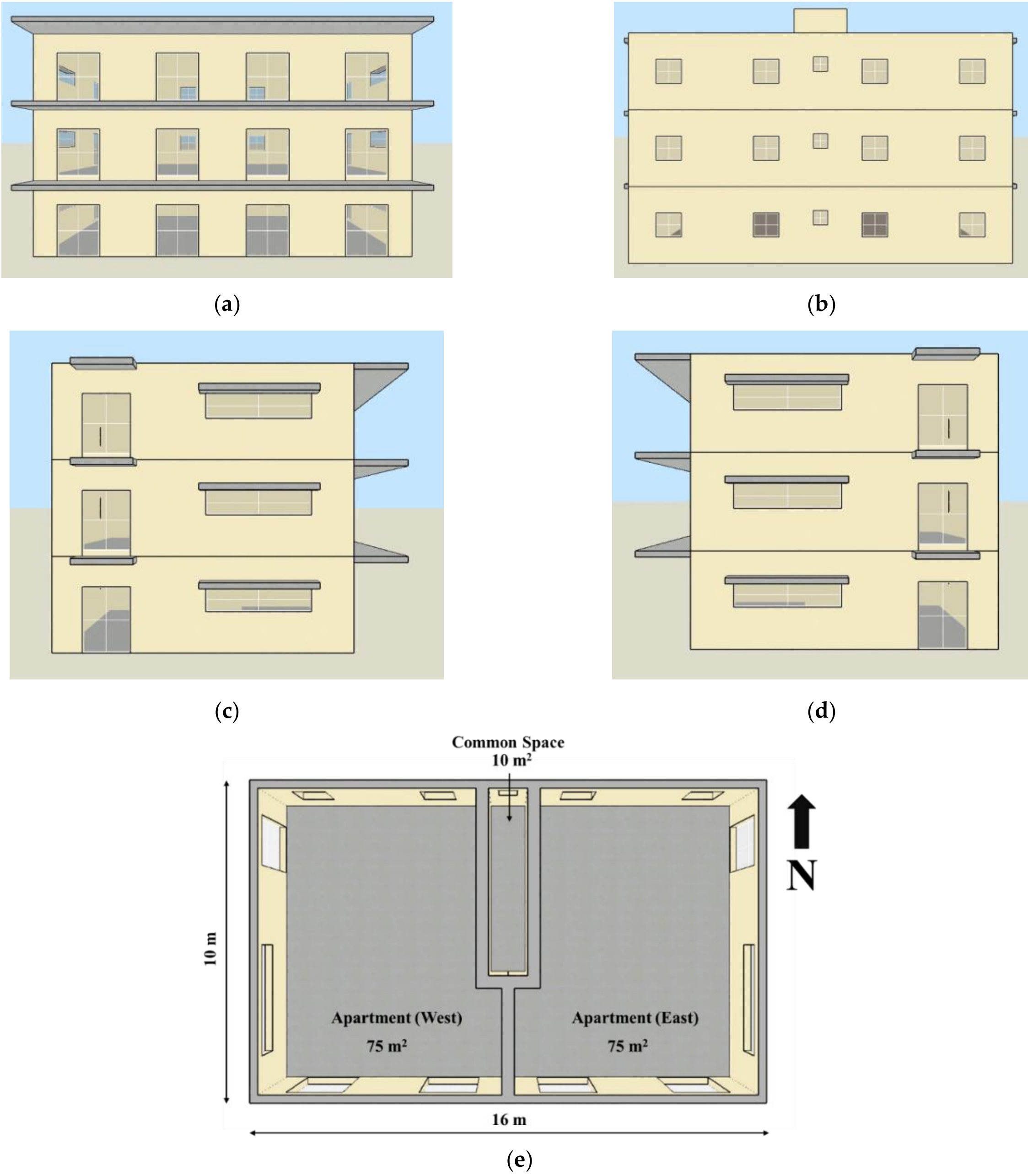


Figure 2. Depiction of the examined topology for the case of the three-story building: (**a**) south side, (**b**) north side, (**c**) west side, (**d**) east side, (**e**) plan view.

The building construction is composed of reinforced concrete, with double brick layered walls. Also, the insulation material used is expanded polystyrene with a thermal conductivity value of 0.045 W/mK, while the windows are air-filled double-glazed. The thermal properties of the building constructions are determined by national regulations according to the climatic category of the examined location. Specifically, the national technical guidelines determine the maximum allowed thermal transmittance values of the building's external walls, roof ground slab, and windows, which are given in Table 1 [37]. In Table 2, the mean thermal transmittance value of the entire building thermal envelope is presented according to the number of floors and city [37]. Additionally, the ratio of the total outer surface to volume and the percentage of the window area are given. The total solar transmittance value of the windows is considered to be 0.6 for every location. Additionally, the solar absorptance and emittance values are considered to be 0.6 and 0.8, respectively, for the external surface of the entire building envelope for every city [37].

Table 1. Total thermal transmittance value (U-value) of the building construction per city.

Building Construction	Chania (Zone A)	Athens (Zone B)	Thessaloniki (Zone C)	Kastoria (Zone D)
External walls	0.55	0.45	0.40	0.35
Roof slab	0.45	0.40	0.35	0.30
Ground slab	1.10	0.80	0.65	0.60
Windows	2.80	2.60	2.40	2.20

Table 2. Mean thermal transmittance value (U-value) of the building per number of floors and city, total outer surface-to-volume ratio, and window area ratio.

Floors	Mean U-Value [W/m^{2}K]				Outer Surface/Volume [m^2/m^3]	Window Area [%]
	Chania	Athens	Thessaloniki	Kastoria		
1	0.67	0.56	0.50	0.44	0.95	27.4
2	0.76	0.65	0.57	0.51	0.64	40.8
3	0.80	0.69	0.62	0.56	0.53	48.8
4	0.84	0.72	0.65	0.58	0.48	54.0
5	0.86	0.75	0.67	0.60	0.45	57.8
6	0.88	0.76	0.69	0.62	0.43	60.6
7	0.89	0.78	0.70	0.63	0.41	62.8

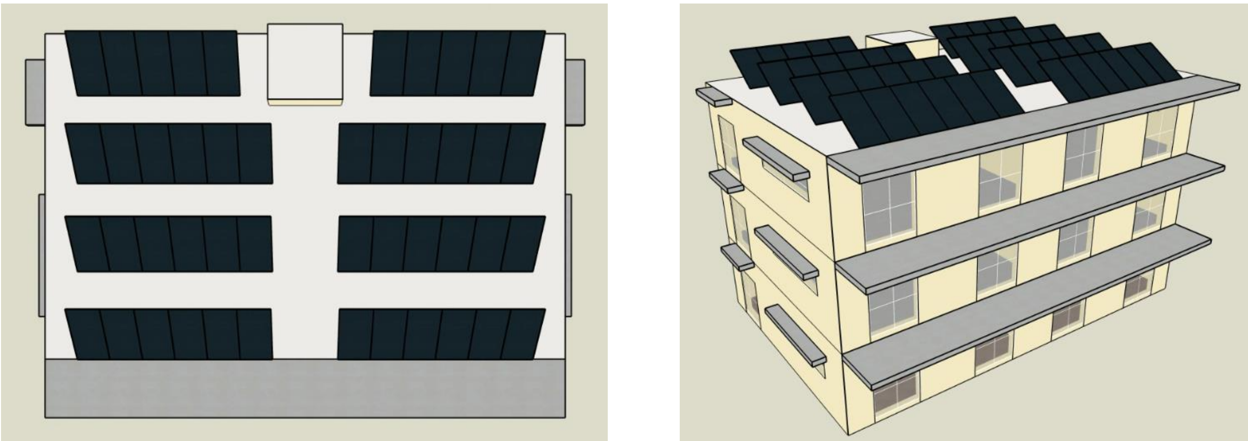
Every apartment is occupied by a three-member family with an occupant load of 80 W [37] and a daily occupancy factor of 75% [38]. The lighting and appliance equipment are characterized by specific loads of 4 W/m^2 and 2 W/m^2 and a mean operating daily factor of 50% [38]. These loads are calculated for the total gross area of the building, which is 160 m^2 per story. Every apartment is served by a reversible unitary air-to-air heat pump and an air source heat pump for the domestic hot water demand. The temperature setpoint for the heating season is set to 20 °C and for the cooling season to 26 °C. The common spaces are not equipped with a heating and cooling system and therefore the gross treated floor area per story corresponds to 150 m^2. The daily demand for domestic hot water (DHW) is set to 50 L per person at a serving temperature of 45 °C. Table 3 summarizes the building's operating data.

Table 3. Building operating parameters.

Parameters	Values
Gross treated floor area per story [m^2]	150
Occupancy [persons/apartment]	3
Occupant load [W/person]	80
Lighting specific load [W/m^2]	4
Lighting operation fraction [%]	50
Appliances specific load [W/m^2]	2
Appliances operation fraction [%]	50
DHW daily demand [liters/person]	50
DHW temperature set-point [°C]	45
Heating temperature set-point [°C]	20
Heating temperature set-point [°C]	26
Nominal COP/EER for heating/cooling mode	4.0

The modeling of the building energy systems is based on the DesignBuilder performance curves [34]. Regarding the heating and cooling energy system, the selected heating, ventilation, and air conditioning (HVAC) template is a unitary air-to-air heat pump with a nominal coefficient of performance (COP) and a nominal energy efficiency ratio of 4.0 for the heating and cooling modes, respectively. The nominal heating and cooling capacity of the heat pump is auto-sized to effectively serve the heating and cooling needs for every examined location. The DHW analysis is executed with the HVAC template of the water heater heat pump, with a selected nominal COP of 4.0 [39].

The building rooftop is covered by a solar photovoltaic system for electricity production. The examined photovoltaic technology comprises monocrystalline cells with a module surface area of 1.94 m^2 and a nominal electricity generation of 360 W [40]. In Table 4, the technical characteristics of the examined photovoltaic modules are given. The photovoltaic panels are installed with an azimuth angle of 0°, direction to the south, and the optimal per-city slope, as given in Table 5. The maximum possible installed nominal electrical power is calculated at 16.56 kW, as depicted in Figure 3. The electrical losses of the conversion of the variable direct current output of the PV solar panels into a utility frequency alternating current are set to 5%.



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

Figure 3. (**a**) Plan view and (**b**) axonometric view of the roof photovoltaic system at the maximum installed power in the case of a three-story building.

Table 4. Technical characteristics of examined photovoltaic panel system.

Parameters	Values
Maximum power, P_{max} [W]	360
Open-circuit voltage, V_{oc} [V]	47.2
Short-circuit current, I_{sc} [A]	9.79
Voltage at point of maximum power, V_{mpp} [V]	38.9
Current at point of maximum power, I_{mpp} [A]	9.26
Module reference efficiency, η [%]	18.5
Module length [m]	1.956
Module width [m]	0.922
Nominal operating cell temperature [°C]	44
Temperature coefficient of P_{max} [%/°C]	−0.39
Temperature coefficient of V_{oc} [%/°C]	−0.29
Temperature coefficient of I_{sc} [%/°C]	0.05

Table 5. Basic climatic parameters of each examined location.

City	HDDs	CDDs	Mean Yearly Temperature [°C]	Mean Yearly Water Temperature [°C]	Horizontal Irradiation [kWh/m²]	Optimum PV Panel Slope [°]	Maximum PV Panel Irradiation [kWh/m²]
Chania	648	308	18.3	18.6	1831	28	2009
Athens	1041	588	18.0	17.8	1833	33	2081
Thessaloniki	1793	314	15.0	15.6	1648	35	1904
Kastoria	2726	134	11.6	13.7	1580	34	1808

2.2. Climatic Conditions

The present study examines a multifamily building of typical reinforced concrete-brick construction in the environmental conditions of four main Greek cities, which represent the four climatic categories of Greece. Table 5 gives the basic climatic parameters of the four examined cities extracted from the PVGIS tool [35], including the heating degree days (HDDs) and cooling degree days (CDDs), the yearly mean air temperature, the yearly mean water temperature, and the yearly specific horizontal irradiation. Regarding the installation of photovoltaic panels, the optimum PV panel slope is also given, as well as the respective yearly specific in-plane irradiation. Additionally, in Appendix A, the average daily ambient air temperature and the total solar daily irradiation are illustrated in Figure A1 for each of the four examined cities.

2.3. Simulation Strategy

The present analysis investigates the installation of a roof photovoltaic system for a typical building construction with one to seven stories in height. The building is located in one of four different Greek cities, which represent the four different climatic categories of Greece. The energy systems serving the building space heating and cooling and the DHW preparation are electrically driven and therefore the building produces no on-site carbon emissions. The aim of this study is to define the maximum number of stories that the photovoltaic system can fully serve or, in other words, the maximum number of stories for which the building presents zero net electricity demand. Validation evidence proving the credibility of the models used in the present study was given in Ref. [39]. Additionally, regarding the simulation of the photovoltaic models and the electricity production, the calculations of the DesignBuilder [34] software have been compared to the results provided by the PVGIS tool [35], demonstrating deviations of less than 1.0%.

2.4. Basic Mathematical Formulation

The thermal transmittance (U-value) of the building constructions is calculated as [37]

$$U = \frac{1}{h_{out} + \sum \frac{t_i}{k_i} + h_{in}} \quad (1)$$

where (k) stands for thermal conductivity [W/m·K] and (i) represents the material layers that each building construction comprises. The coefficients of convective heat transfer are selected from ISO 6946:2017 [41] and the national technical guidelines [37]. For instance, for the horizontal roof construction, the convective heat transfer coefficient is equal to h_{in} = 7.7 W/m^{2}K for the internal surface, and to h_{out} = 25 W/m^{2}K [41] for the external surface.

The coefficient of performance (COP) of the unitary reversible heat pump for the heating mode is calculated as the proportion of the heat pump's instantaneous heating thermal power input to electricity consumption:

$$COP = \frac{Q_{heat}}{P_{el_{heat}}} \quad (2)$$

Similarly, the energy efficiency ratio (EER) of the cooling mode is calculated by the proportion of the instantaneous cooling thermal power to electricity consumption:

$$EER = \frac{Q_{cool}}{P_{el_{cool}}} \tag{3}$$

The seasonal coefficient of performance (SCOP) and seasonal energy efficiency ratio (SEER) represent the yearly average COP and EER values of the unitary heat pump operation and are calculated based on the corresponding yearly energy loads.

$$SCOP = \frac{E_{heat}}{E_{el_{heat}}} \tag{4}$$

$$SEER = \frac{E_{cool}}{E_{el_{cool}}} \tag{5}$$

The building is fully electrified because its energy needs for space heating and cooling, DHW, lighting, and appliances are all electrically satisfied. The building adheres to the net metering billing mechanism and therefore all the electricity produced by its PV system is considered to be firstly exploited for the building's own energy needs. The building's total gross demand for electricity ($E_{el,gross}$) is calculated as the sum of its electricity demand for space heating and cooling, DHW preparation, lighting, and appliances needs.

$$E_{el_{gross}} = E_{el_{heat}} + E_{el_{cool}} + E_{el_{DHW}} + E_{el_{lighting}} + E_{el_{appliances}} \tag{6}$$

The net electricity demand ($E_{el,net}$) is calculated by subtracting the PV-generated electricity (E_{PV}) from the gross electricity demand:

$$E_{el_{net}} = E_{el_{gross}} - E_{PV} \tag{7}$$

3. Results

3.1. Energy Analysis of the Examined Buildings in Different Locations

This section presents the calculations regarding the thermal loads and energy behavior of the examined building typology for a variable number of floors (one to seven floors) and for the four Greek cities of Chania, Athens, Thessaloniki, and Kastoria. Specifically, Figures 4–7 illustrate the specific heating and cooling energy demand according to the number of floors and the specific electricity demand for heating and cooling according to the number of floors for the four examined locations. Also, in Appendix B, the thermal analysis calculations for each city are given in tables.

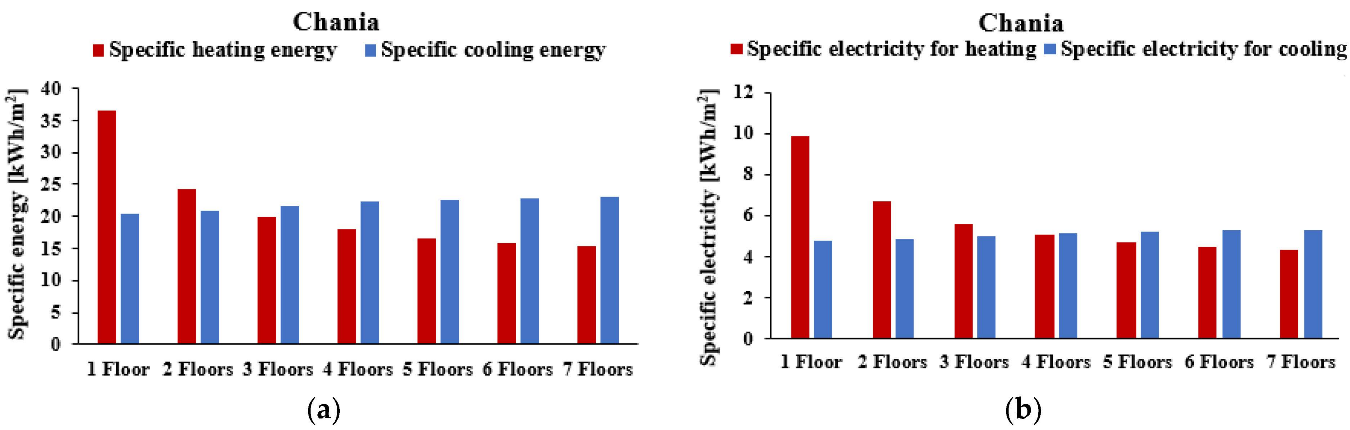


Figure 4. (**a**) Specific heating and cooling energy demand, and (**b**) specific electricity demand for heating and cooling, for the city of Chania.

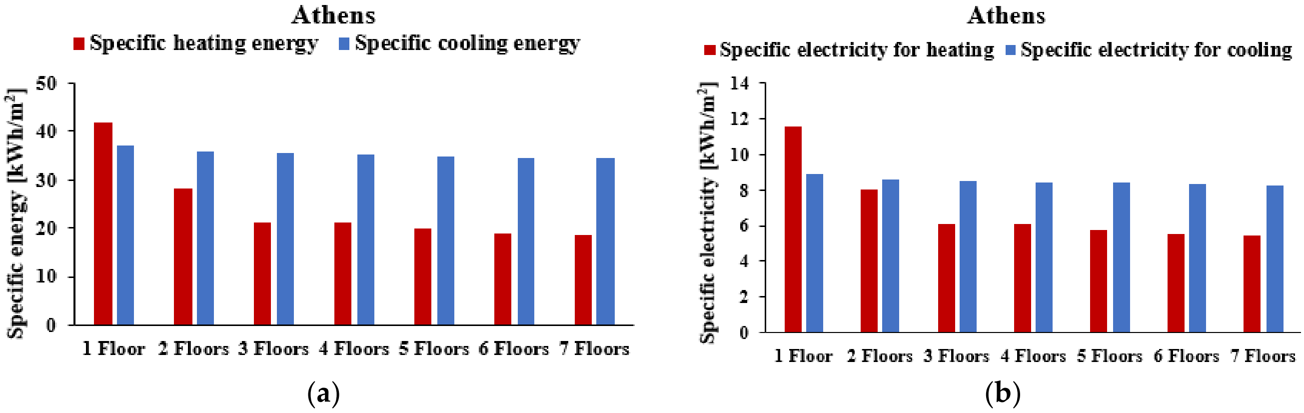


Figure 5. (**a**) Specific heating and cooling energy demand, and (**b**) specific electricity demand for heating and cooling, for the city of Athens.

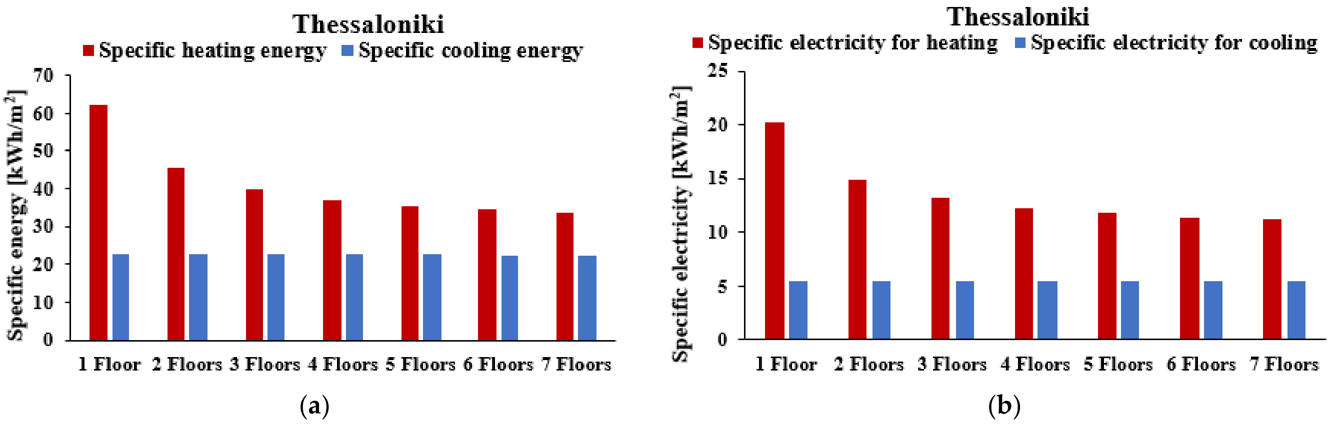


Figure 6. (**a**) Specific heating and cooling energy demand, and (**b**) specific electricity demand for heating and cooling, for the city of Thessaloniki.

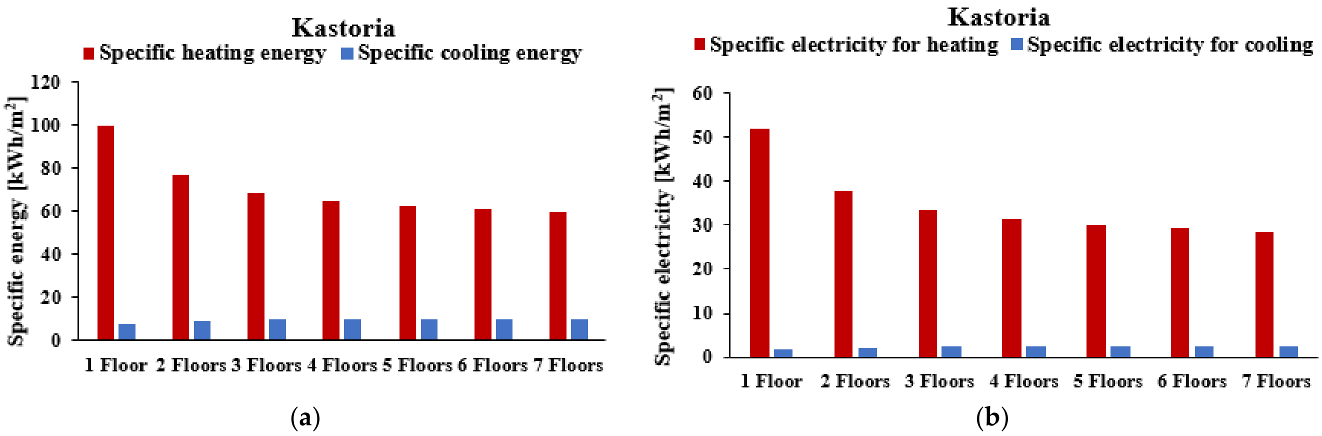


Figure 7. (**a**) Specific heating and cooling energy demand, and (**b**) specific electricity demand for heating and cooling, for the city of Kastoria.

Firstly, for the climatic conditions of Chania, the city with the highest yearly average ambient air temperature (18.3 °C) and lowest HDDs among all examined locations, the specific heating energy demand is given in Figure 4, which presents ranges between 15.32 kWh/m^2 for the case of the seven-story building and 36.39 kWh/m^2 for the case of the single-story building. The electricity demand for heating is calculated as between 4.33 kWh/m^2 and 9.86 kWh/m^2. For the case of Chania, the mean COP of the unitary air-to-air heat pumps is calculated as 3.59. The specific cooling energy demand varies between 20.44 kWh/m^2 for the case of the single-story building and 22.97 kWh/m^2 for the case of the seven-story building. It is observed that the specific cooling energy demand presents a reverse behavior in contrast to the specific energy demand for heating, namely, that the increase in the number of floors leads to an increase in the specific energy demand for cooling and to a decrease in the specific energy demand for heating. This is explained by the fact that the ratio of the window area to the building's total outer surface increases with the addition of stories. Specifically, for the case of a single-story building, the respective ratio is 27.4%, while for the seven-story building, it reaches 62.8%. This fact, in combination with the high total solar irradiation observed in Chania, has an adverse effect on the building's cooling energy demand but a positive result regarding the heating energy demand. The specific electricity demand for cooling varies between 4.75 kW/m^2 for the case of the single-story building and 5.29 kWh/m^2 for the case of the seven-story building. The mean EER of the unitary air-to-air heat pumps is calculated at 4.33.

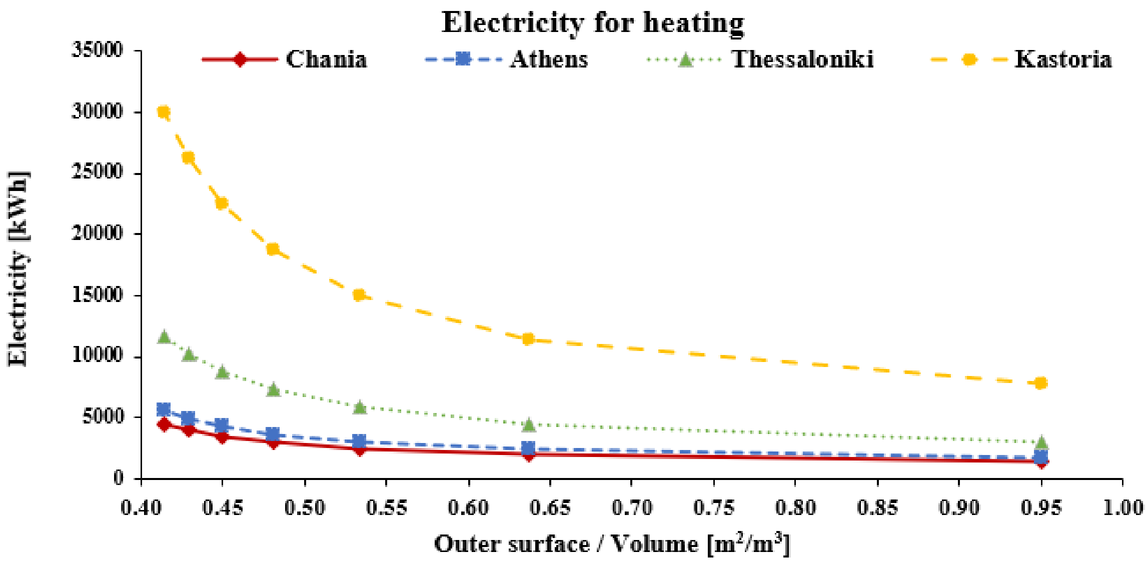
For the case of Athens, both the heating and cooling energy demand are increased, as depicted in Figure 5, in comparison with the thermal loads of Chania. Specifically, the specific heating energy demand varies between 18.69 kWh/m^2 for the seven-story building and 41.73 kWh/m^2 for the single-story building. The electricity demand for heating is calculated as 5.42 kWh/m^2 for the seven-story building and peaks at 11.58 kWh/m^2 for the case of a single floor. The mean COP value for the heat pump heating mode in Athens is 3.51. This value is slightly decreased in contrast to Chania, which is a result we expected. Athens is characterized by the highest CDDs among all examined locations and therefore demonstrates the highest energy demand for space cooling. Precisely, the specific cooling energy demand for the city of Athens is found to vary between 34.41 kWh/m^2 for the seven-story building and 37.09 kWh/m^2 for a single floor. The electricity demand for cooling is calculated to vary between 8.92 kWh/m^2 and 8.30 kWh/m^2. The mean EER value for the heat pump's cooling mode is 4.15.

For the city of Thessaloniki, as shown in Figure 6, the annual average ambient air temperature is 3.0 K and 3.3 K lower than the respective values of Athens and Chania. The specific heating energy demand varies between 18.69 kWh/m^2 for the seven-story building and 41.73 kWh/m^2 for the single-story building, while the corresponding electricity demand for heating is calculated to be in the range of between 11.58 kWh/m^2 and 5.42 kWh/m^2. For the city of Thessaloniki, the mean COP value of the unitary heat pump heating mode is 3.04, which is distinctively lower in comparison to the cities of Chania and Athens. The specific cooling energy demand for the city of Thessaloniki is between 22.49 kWh/m^2 for a seven-story building and 22.77 kWh/m^2 for a single-story building. These results are comparable with the corresponding values for Chania, which was anticipated because both cities demonstrate similar values of CDDs. The electricity demand for cooling for Thessaloniki is calculated as between 5.41 kWh/m^2 and 5.45 kWh/m^2, presenting almost no fluctuation. The mean EER value regarding the cooling mode of the air-to-air heat pumps is 4.16.

Following that, Figure 7 illustrates the thermal energy load calculations for the city of Kastoria, which presents the coldest climatic conditions among the examined locations. Firstly, the specific heating energy demand is calculated as 59.94 kWh/m^2 for the seven-story building and 99.28 kWh/m^2 for the most energy-demanding case of the single-story building. The respective specific electricity demand for heating is in the range of between 28.60 kWh/m^2 and 51.83 kWh/m^2, and the mean COP value is 2.05. On the other hand, the specific cooling energy is significantly lower, since Kastoria demonstrates the mildest summer conditions among all examined locations Specifically, for a single-story building, the specific cooling energy demand is 7.87 kWh/m^2, while for the most energy-demanding case of seven stories, it is 10.07 kWh/m^2. The corresponding specific electricity demands are 1.93 kWh/m^2 and 2.44 kWh/m^2, while the mean EER value is 4.11. Conclusively, the case of the three-story building and the city of Athens, for which the electricity demand for heating/cooling is equal to 6.10/8.51 kWh/m^2, is taken as a reference to facilitate a comparison among all examined locations. The variations in electricity demand for heating/cooling are equal to −8.52%/−41.13% (Chania), 115.41%/−36.08% (Thessaloniki), and 448.52%/−72.74% (Kastoria).

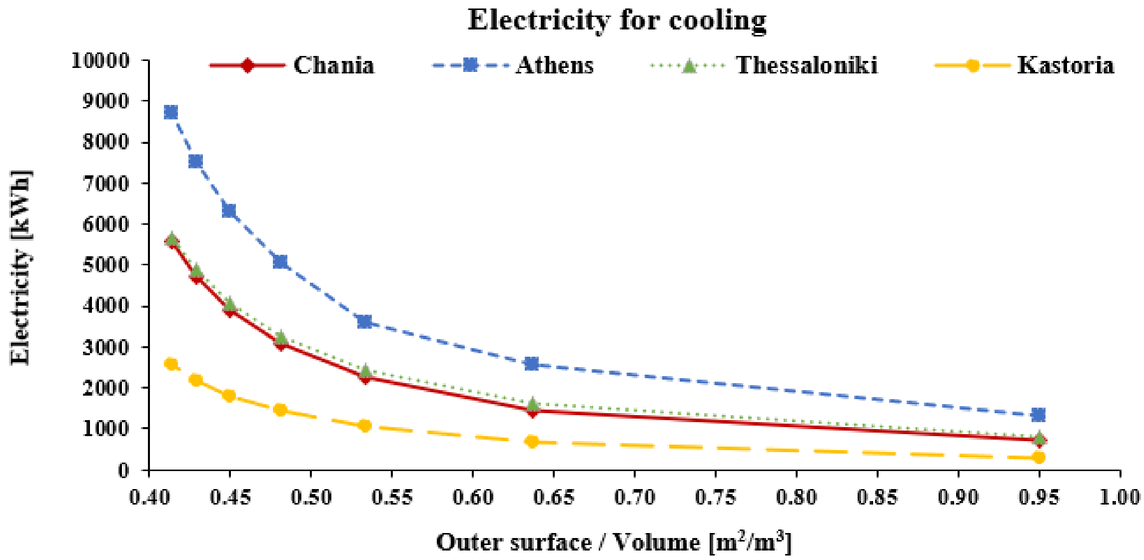
Figure 8 compares and contrasts the electricity demands for heating and cooling, as well as the aggregated electricity demand for both heating and cooling. The electricity demand values are presented in relation to a building's geometrical parameter, which concerns the ratio of its total outer surface, namely the surfaces of external walls, the roof, and the ground slab, divided by its volume. The greatest value of 0.95 m^2/m^3 corresponds to the single-story building, while the lowest value of 0.41 m^2/m^3 corresponds to the seven-story building. According to Figure 8a, the building with the highest energy demand during the heating season is located in Kastoria, with electricity consumption ranging from 7774 kWh to 30,034 kWh. The second most energy-demanding city is Thessaloniki, with an electricity demand for heating in the range of 3037 kWh to 11,759 kWh. Athens ranks third, with its electricity usage for heating falling between 1737 kWh and 5686 kWh. Chania follows closely with a demand ranging from 2014 kWh to 4545 kWh.

On the other hand, according to Figure 8b, Athens is characterized by the highest electricity demand for cooling, ranging from 1338 kWh to 8711 kWh. Following this, the electricity usage for cooling in the cases of Thessaloniki and Chania is similar, ranging from 817 kWh to 5680 kWh for Thessaloniki and from 712 kWh to 5559 kWh for Chania. Lastly, for the city of Kastoria, the electricity demand for cooling varies from 289 kWh to 10,104 kWh. Figure 8c illustrates the aggregation of electricity demand for both heating and cooling, highlighting Kastoria as the most energy-demanding case study. This figure allows a direct comparison among the four examined locations and the number of stories. Regarding the case of the single-story building, the total electricity demand for heating and cooling ranges from 2191 kWh (Chania) to 8063 kWh (Kastoria), a difference that is equivalent to a 368% increase. Conversely, as the number of stories increases, the disparity between the most and least energy-demanding locations diminishes. Specifically, for Chania, the total electricity demand is calculated at 10,104 kWh, compared to 32,599 kWh for Kastoria, resulting in a more moderate 323% increase. This result highlights the fact that single-story buildings are the most vulnerable to ambient conditions. However, as the number of stories increases, the impact of the ambient conditions is slightly mitigated.



(a)

Figure 8. *Cont.*



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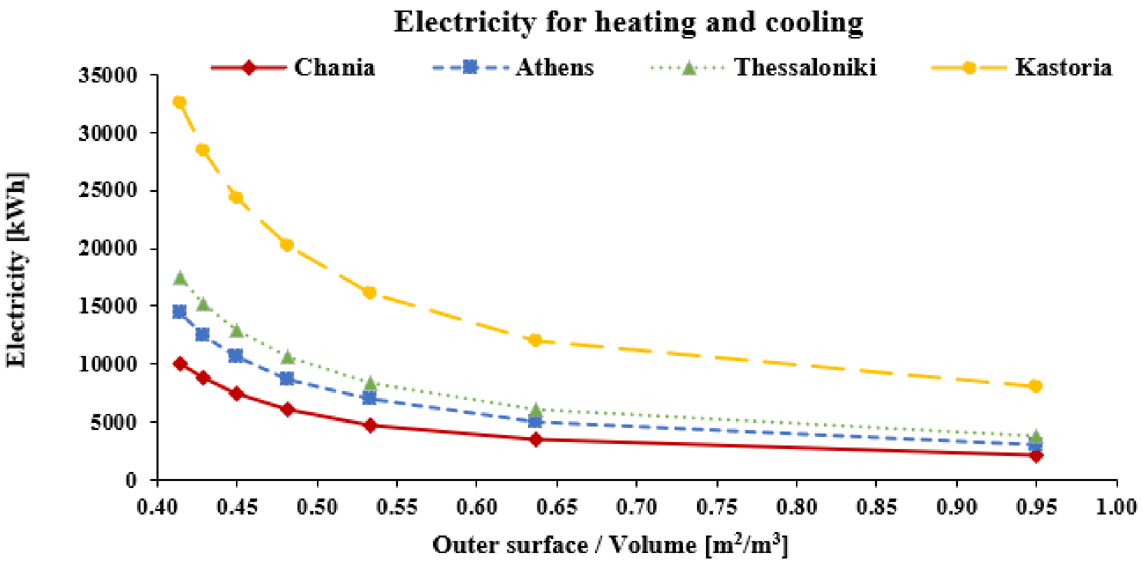


(**c**)

Figure 8. (**a**) Electricity demand for heating, (**b**) electricity demand for cooling, and (**c**) electricity demand for both heating and cooling, for the four examined locations.

Regarding the energy demand for the preparation of domestic hot water, Figure 9 depicts the energy input required per floor per city, as well as the necessary electricity demand. These values are presented according to the number of floors because it is considered that every floor is occupied by a specific number of people. The deviations between the DHW energy demand per city are due to the difference in the yearly mean water temperature of water. Precisely, according to Table 5, the mean yearly water temperature is equal to 18.6 °C (Chania), 17.8 °C (Athens), 15.6 °C (Thessaloniki), and 13.7 °C (Kastoria). According to Figure 9, for the city of Chania, the DHW energy demand is calculated as 3248 kWh per floor, for Athens as 3338 kWh per floor, for Thessaloniki as 3603 kWh per floor, and for Kastoria as 3847 kWh per floor. The corresponding electricity demand for DHW preparation is equal to 902 kWh per floor for Chania, 951 kWh per floor for Athens, 1185 kWh per floor for Thessaloniki, and 1895 kWh per floor for Kastoria.

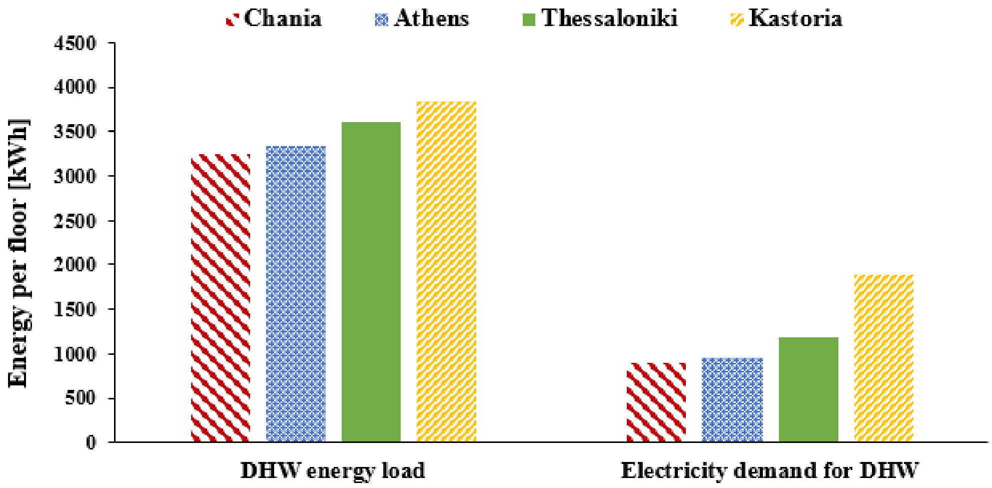


Figure 9. DHW energy load and electricity demand per floor for the four examined locations.

3.2. Analysis of PV Electrical Production Potential

In this section, the potential of the electricity production of the roof photovoltaic system is analyzed for each of the four examined locations. The installation of rooftop PVs is investigated with the aim of transforming low- and mid-rise multifamily buildings into zero-net-energy buildings. The dense urbanization of Greek cities, especially Athens, highlights the roof area as the only available building area for the installation of on-site renewable energy systems. The dense urban development in combination with the complex architecture of the Greek building sector, characterized by a lack of uniformity and the abundancy of balconies and semi-closed spaces [42], mean building-integrated—for instance, façade-integrated—photovoltaic systems are not appropriate solutions.

The yearly specific horizontal irradiation, as well as the optimum titled angle of the PV panels, are equal to 1831 kWh/m^2 and 28° (Chania), 1833 kWh/m^2 and 33° (Athens), 1648 kWh/m^2 and 35° (Thessaloniki), and 1580 kWh/m^2 and 34° (Kastoria), according to Table 5. The entire roof is equipped with PV panels of nominal power equal to 16.56 kW. Figure 10 presents the maximum electricity production in contrast to the gross electricity demand for a number of total floors and locations. This figure allows us to identify the maximum number of floors that can be fully served by the PV system and lead to a zero net electricity demand or positive electricity production. Specifically, for the city of Chania, the electricity production by the PV system is 27,098 kWh, for Athens, it is 25,521 kWh, for Thessaloniki, it is 24,730 kWh, and for Kastoria, it is 24,638 kWh. The calculated electricity production can fully satisfy the electrical requirements of a six-story building in Chania, a five-story building in Athens, a four-story building in Thessaloniki, and a two-story building in Kastoria. Following on from this, Figure 11a illustrates the surplus electricity production per number of floors per city, and Figure 11b the specific positive electricity production per one floor with the considered floor area of 150 m^2. More specifically, according to Figure 11, for the critical number of floors, the positive electricity production is calculated at 1155 kWh or 7.7 kWh/m^2 (Chania, six floors), 354 kWh or 3.36 kWh/m^2 (Athens, five floors), 1517 kWh or 10.11 kWh/m^2 (Thessaloniki, four floors), and 4885 kWh or 32.57 kWh/m^2 (Kastoria, two floors). Additionally, Table 6 summarizes the gross electricity demand, including the electricity demand for space heating and cooling, DHW preparation, lighting, and appliances needs, as well as the surplus electricity production per number of floors and location. It should be noted that the integration of the photovoltaic system into the building rooftop and its shading effect on the rooftop are taken into consideration during the thermal analysis to effectively calculate the building energy demand for heating and cooling. PV modules operate as shading components that decrease the amount of solar irradiation intercepted by the building rooftop and therefore alleviate solar heat gains for the building interior.

Table 6. Gross electricity demand and positive electricity production per city and number of floors.

Parameters	Number of Floors						
	1	2	3	4	5	6	7
				Chania			
Gross electricity demand [kWh]	5054	9188	13,358	17,544	21,741	25,943	30,147
Electrical positivity [kWh]	22,044	17,910	13,741	9554	5357	1155	0
				Athens			
Gross electricity demand [kWh]	5987	10,808	15,097	20,380	25,167	29,955	34,781
Electrical positivity [kWh]	19,534	14,713	10,424	5141	354	0	0
				Thessaloniki			
Gross electricity demand [kWh]	7000	12,395	17,799	23,213	28,624	34,043	39,462
Electrical positivity [kWh]	17,730	12,334	6931	1517	0	0	0
				Kastoria			
Gross electricity demand [kWh]	11,919	19,753	27,667	35,594	43,615	51,595	59,592
Electrical positivity [kWh]	12,719	4885	0	0	0	0	0

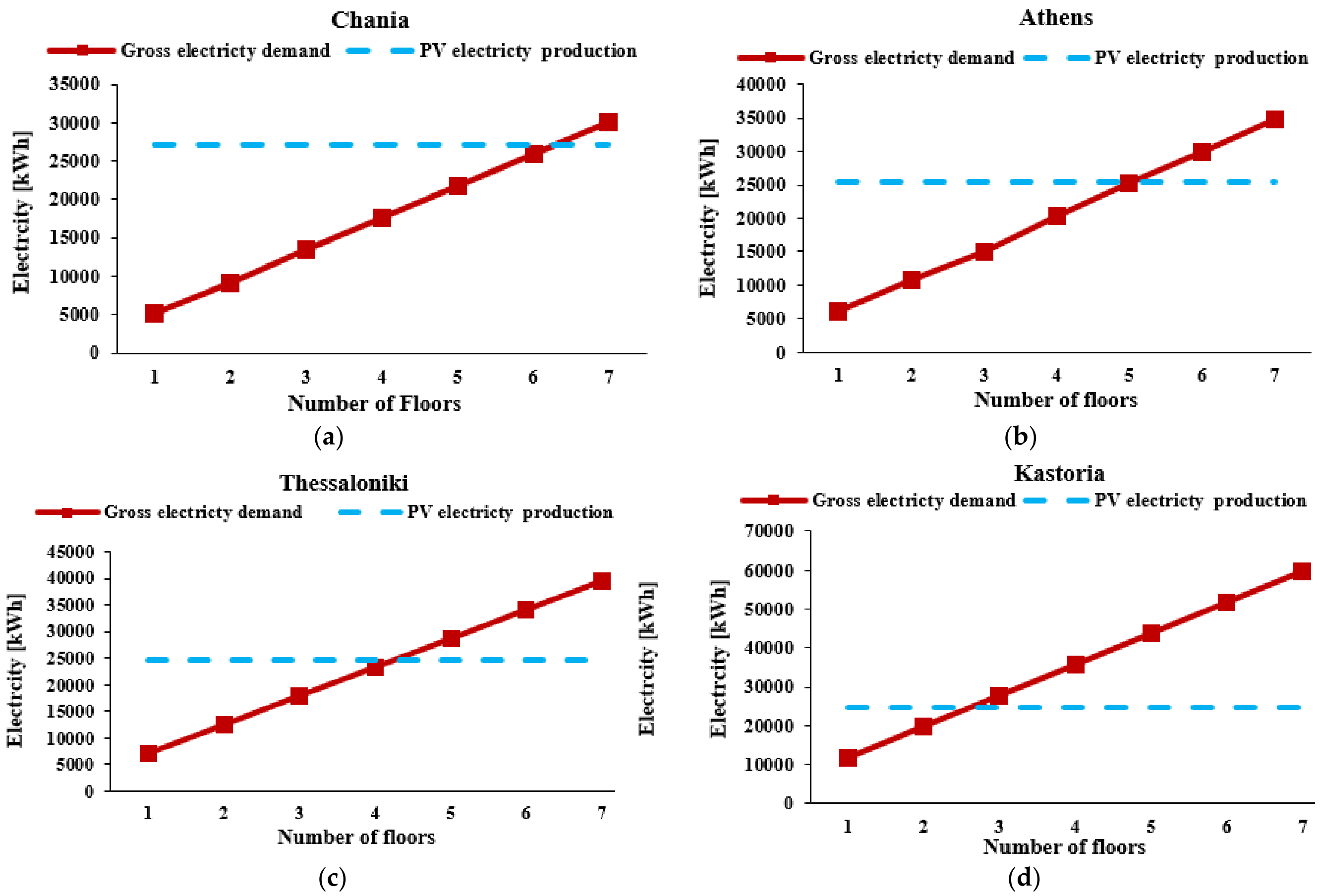
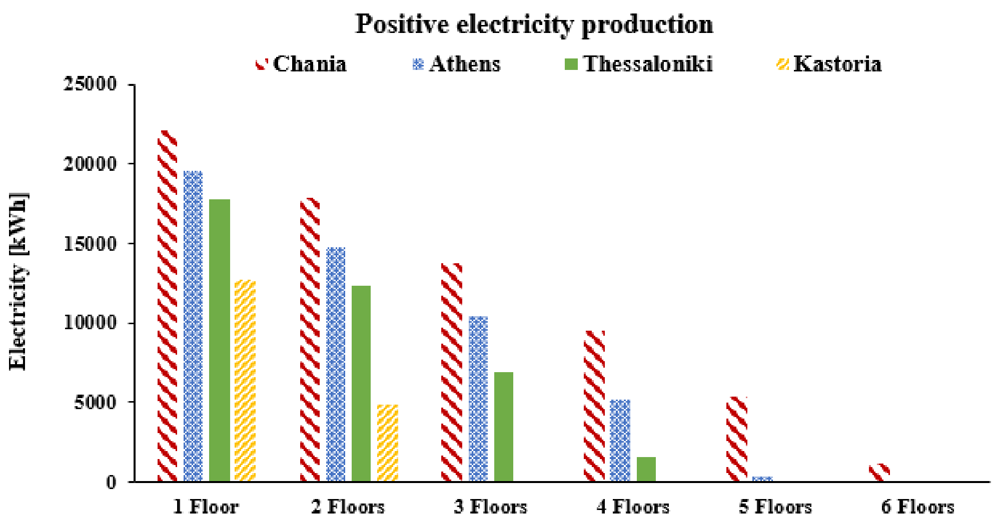


Figure 10. Gross electricity demand per number of floors and maximum PV electricity production for the cities of (**a**) Athens, (**b**) Athens, (**c**) Thessaloniki, and (**d**) Kastoria.



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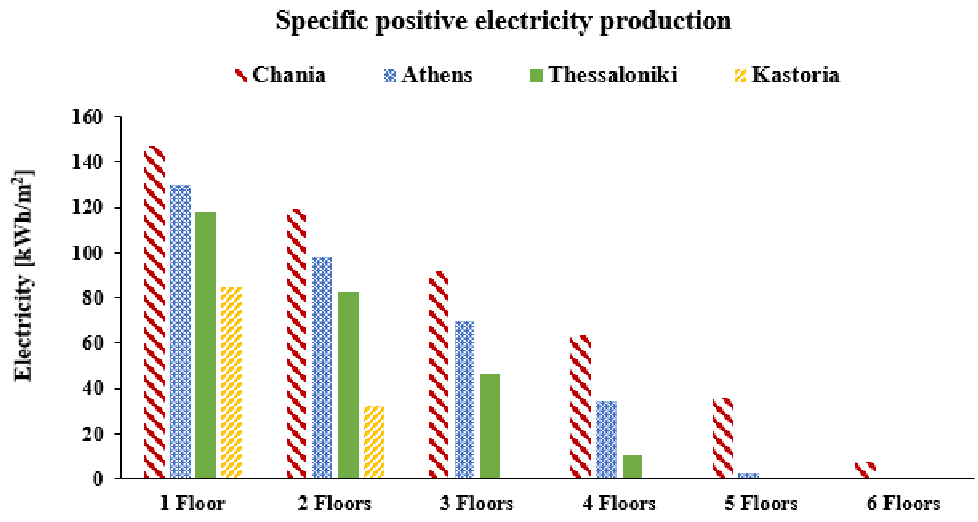

(**b**)

Figure 11. (**a**) Positive electricity production and (**b**) specific positive electricity production per one-floor area.

4. Discussion

Positive energy districts (PEDs) are urban areas of positive energy equilibrium, comprising highly efficient buildings and integrated renewable energy systems for energy production [43]. The concept of positive energy buildings lies in the need to create sustainable cities, with a low carbon footprint, able to positively contribute to the energy supply of their surroundings. Addressing the challenges of converting a city to an energy-self-sufficient and sustainable urban environment requires the adoption of multiple, custom-made solutions that apply not only to city-scale restrictions but also to the national energy mix and energy strategy for security and resilience [44]. Despite the indisputable advantages of positive energy districts, their development is restricted to a research level, with only a few case studies within projects with European funding being applied [45].

Regarding the case of Greece, currently, three cities are engaged in international projects of developing exemplar energy districts utilizing concepts of sustainable energy deployment: Heraklion [46], Trikala [47], and Thessaloniki [48]. The located efforts contribute to the country's successful implementation of its national energy and climate plan goal, setting a cornerstone for future urban development goals. As in the majority of similar positive energy district projects [45], the transformation of a city's building stock into ZEBs is a pivotal element for the feasibility of a PED [17]. It has been proven that the combinational adoption of passive or building envelope retrofitting techniques, as well as the installation of highly efficient active energy systems, supports PEDs as an achievable and economically viable target [49]. In that direction, innovative building materials with advanced thermal and optical properties, highly efficient energy systems for heating, cooling, and domestic hot water production, renewable energy systems for energy production, as well as energy storage systems need to be appropriately utilized to enhance buildings and subsequently a city's energy performance and footprint.

In this study, the parameter of a building's height or number of stories was investigated concerning the transformation potential into zero-net-energy buildings. Greece is characterized by an old, energy-consuming building stock with immense potential for energy savings [50]. According to the thermal analysis results, the mean annual specific energy demand of a residential building was calculated for heating at 20.92 kWh/m^2 (Chania), 24.29 kWh/m^2 (Athens), 41.21 kWh/m^2 (Thessaloniki), and 70.35 kWh/m^2 (Kastoria), and for cooling at 21.95 kWh/m^2 (Chania), 35.32 kWh/m^2 (Athens), 22.62 kWh/m^2 (Thessaloniki), and 9.48 kWh/m^2 (Kastoria). These results are corroborated by various studies that examine the thermal performance of residential buildings in the Mediterranean climate. For instance, in a study by Ascione et al. [49], two three-floor villas equipped with a reversible air-source electric heat pump with a nominal COP/EER equal to 2.2 and 2.0 are examined for the climatic conditions of Greece and South Italy. For the newly constructed villa in Greece, the annual specific electricity demand for heating/cooling is 20.0 kWh/m^2/ 34.0 kWh/m^2, while for the ancient villa in South Italy, the corresponding values are 60.0 kWh/m^2 and 17.0 kWh/m^2. Furthermore, in a previous study concerning a flat roof single-family property in Athens, the specific energy demand for heating was found to range between 18.09 kWh/m^2 and 31.02 kWh/m^2, while for cooling, it was between 31.65 kWh/m^2 and 37.21 kWh/m^2 [39]. Regarding the colder Mediterranean climate of Barcelona, the yearly specific heating demand for a mid-rise multifamily building ranges between 28.0 kWh/m^2 and 68.0 kWh/m^2, while the specific cooling energy demand is between 1.0 kWh/m^2 and 6.0 kWh/m^2 [51]. Finally, the specific heating/cooling energy demands for a deeply renovated four-story multifamily building in Athens are found to be 11.0 kWh/m^2 and 24.4 kWh/m^2, respectively [21]. In the latter study, a photovoltaic system is installed on an available rooftop area of 160 m^2, converting the multifamily building into an energy-positive building with a yearly electricity production of 24.4 MWh or 152.4 kWh per m^2 of available rooftop area. In the present study and for the case of Athens, the respective figures were found to be 25.5 MWh and 159.5 kWh per m^2 of available rooftop area.

Despite the fact that low-rise buildings are the most energy-consuming type of residential buildings [52], they are characterized by an analogically larger available rooftop area for the installation of photovoltaic systems for energy production in comparison to mid- or high-rise buildings. In other words, the analogy of available rooftop area for electricity-production exploitation in comparison to the total treated floor area of a building is a key factor for its successful transformation into a zero-energy building. This aspect poses a question and a serious challenge of whether cities of high population and building density can be successfully converted into PEDs. Comprehensive research regarding the role of the number of building stories in impacting the feasibility of creating positive energy districts needs to be conducted.

Developing the equipment of the building sector with electrically driven heat pumps is proven to be a necessary step towards the decarbonization of the sector and the increase in its energy efficiency. In contrast to carbon-fueled energy systems, heat pumps, characterized by a high coefficient of performance, when combined with the enhancement of a building's thermal behavior, result in the restricted consumption of electrical energy. The necessary electricity can be derived from on-site electricity production through the installation of a renewable photovoltaic system on a building rooftop, securing a building's energy autonomy and low energy footprint.

The present work focused on four main cities of Greece, which represent the country's four distinct climatic categories. According to the present study's results, the coverage of the available rooftop area with a photovoltaic system can satisfy the yearly electricity demand of a variable number of stories of a multifamily building. The critical number of stories is directly connected to the meteorological conditions of a building's location, and the findings of the present study can be useful inputs for a future study in which a correlation between the zero-energy potential of multi-story residencies and climate types could be identified. Regarding the outputs of the present study, the maximum number of stories is six for the moderate winter and summer conditions of the city of Chania, characterized by a mean yearly ambient temperature of 18.3 °C and an annual PV in-plane solar irradiation of 1999.3 kWh. For cooling-dominant Athens, where the mean yearly ambient temperature and annual PV in-plane solar irradiation are equal to 18.0 °C and 2070.3 kWh, respectively, the maximum height of a zero-energy building is five stories. For the colder climates of Thessaloniki and Kastoria, where the mean ambient temperature and annual PV-incident irradiation are 15.0 °C and 11.6 °C and 1905.9 kWh and 1789.9 kWh, respectively, the maximum multifamily building height is calculated at four or two stories. These results can be used as a guideline for cities that demonstrate similar climatic characteristics, namely, similar cooling and heating degree days, yearly solar irradiation, and ambient temperature, as well as the PV electricity production potential.

The widespread and successful integration of photovoltaic renewable systems in Greece's national energy mix concerns both smaller- as well as larger-scale installations. In this direction, the Greek Ministry of Environment and Energy issued a public call with its EUR 238 million subsidy program (from 20% to 100% of the investment cost) for rooftop photovoltaics that either support household applications combined with a storage system, or professional farmers with or without the combination of a storage system, for self-consumption with the application of net metering [53]. Regarding large-scale electricity production and storage projects, Greece has committed to completing by mid-2025 two important constructions of photovoltaic units with an individual capacity of 252 MW, in combination with integrated molten-salt thermal storage units, an extra-high-voltage substation, and a 309 MW photovoltaic unit with an integrated lithium-ion battery energy storage system [54]. These projects are predicted to increase the annual net renewable electrical energy in Greece by 1.2 TWh, increasing the country's capacity in energy storage and thereby enhancing grid stability and availability [54]. Additionally, two important European Union-funded projects of grid interconnections between Greece's mainland and islands (Cyclades and Crete) are being realized to combat grid unreliability and high electricity costs [55]. Lastly, two important cornerstones in the substantial improvement of Greece's electrical grid should inarguably involve upgrade works to the current infrastructure as well as the liberation of the national electricity market [56].

5. Conclusions

The present analysis has investigated the integration of rooftop photovoltaic systems for on-site electricity production and the transformation of residential buildings into zero-net-energy buildings. For this purpose, low- and mid-rise residential buildings of one to seven stories were simulated for the four climatic categories of Greece. The aim of the study was to identify the zero-net-energy potential of residencies in Greece by taking into consideration the variability of the residential sector and the national energy efficiency guidelines. The conclusions drawn in this study are summarized below:

- Full electrification can be achieved through the installation of electrically driven air-to-air heat pumps for serving space heating and cooling and of an air source heat pump for domestic hot water preparation. The energy performance of the energy systems, as well as the heating, cooling, and domestic hot water energy demand, are mainly determined by the climatic conditions of a location.
- For Athens and the case of the three-story building, the gross electricity demand is calculated at 33.55 kWh/m^2, representing an 11.5% increase compared to Chania.

Conversely, for Thessaloniki, the total electricity demand is 17.9% higher than in Athens, and for Kastoria, it is 83.3% higher than in Athens.

- Zero-net-energy building transformation is feasible for fully electrified low-rise, up-to-two-story, multifamily buildings in each of the four climatic categories of Greece.
- The installation of photovoltaic systems on the available rooftop space of multifamily buildings can successfully satisfy the overall electricity demand of up to six stories for Chania, up to five stories for Athens, up to four for Thessaloniki, and up to two for Kastoria.
- Positive electricity production is restricted with the increase in stories. Greater electricity production is achieved for the milder climatic conditions of Chania, with Athens, Thessaloniki, and, lastly, Kastoria following.

The installation of rooftop PV is an effective solution for the achievement of energy self-sufficiency in buildings. Additionally, for the densely developed main cities of Greece, rooftops are the only option for successfully integrating photovoltaic systems into the building envelope without diminishing their energy performance due to uncontrolled shading from closely placed neighboring buildings. In a future study, the zero-net-energy transformation of high-rise residential buildings needs to be addressed. For the respective case, alternative photovoltaic solutions in combination with stricter and energy-efficient standards need to be examined. Addressing these issues is of pivotal importance to the development of positive energy building stocks, which is a prerequisite for positive energy cities.

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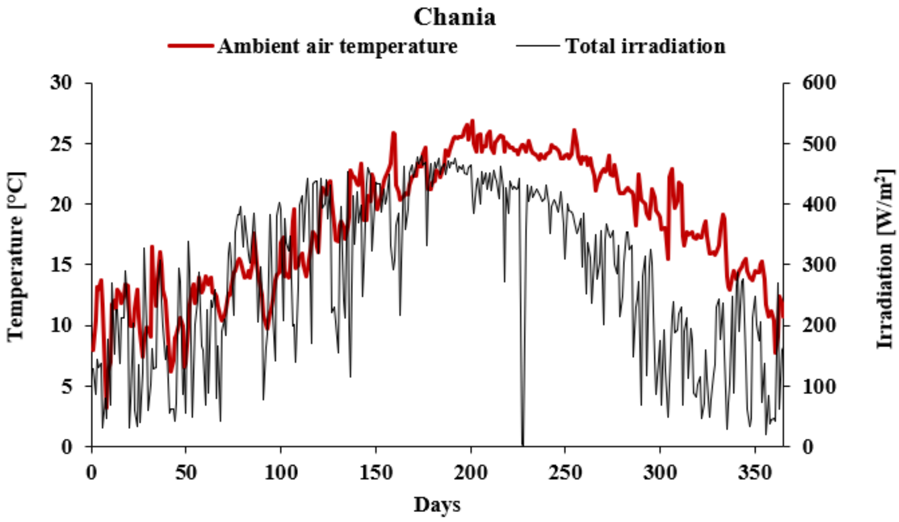
Nomenclature

h_{in}	Inside convection coefficient, W/m^{2}K
h_{out}	Outside convection coefficient, W/m^{2}K
I	Current, A
k	Thermal conductivity, W/mK
P_{el}	Electrical power, W
Q	Load, W
t	Thickness of construction layers, m
U-value	Thermal transmittance value, W/m^{2}K
V	Voltage, V
Subscripts and superscripts	
max	Maximum
mpp	Maximum power point
heat	Heating
cool	Cooling
oc	Open circuit
sc	Short-circuit
Abbreviations	
CDDs	Cooling degree days
COP	Coefficient of performance for heating mode
DHW	Domestic hot water
EER	Energy efficiency ratio for cooling mode
HDDs	Heating degree days

HVAC	Heating, ventilation, and air conditioning
PED	Positive energy district
SCOP	Seasonal coefficient of performance for heating mode
SEER	Seasonal energy efficiency ratio for cooling mode

Appendix A. Weather Data

This appendix includes the basic weather data of the examined locations. Figure A1 depicts the ambient temperature and the total solar irradiation on the horizontal surface, while Figure A2 illustrates the monthly PV in-plane solar irradiation for the four studied locations.



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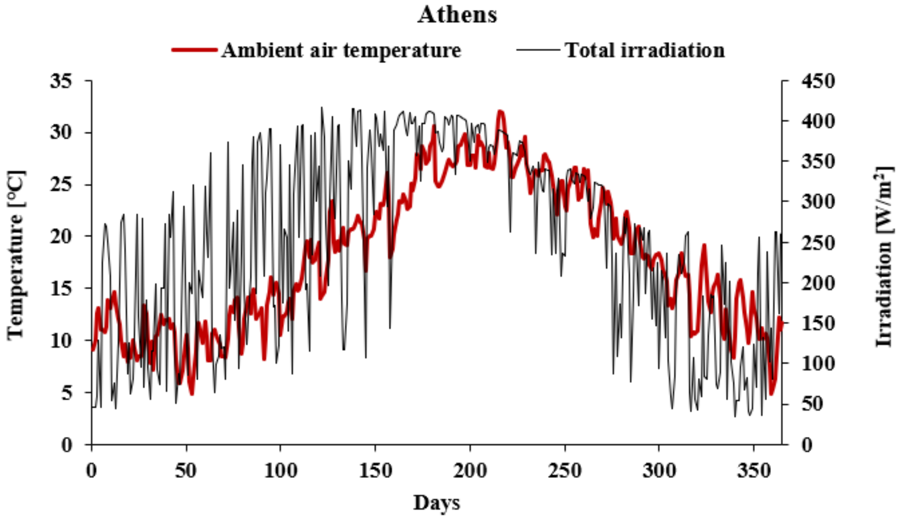

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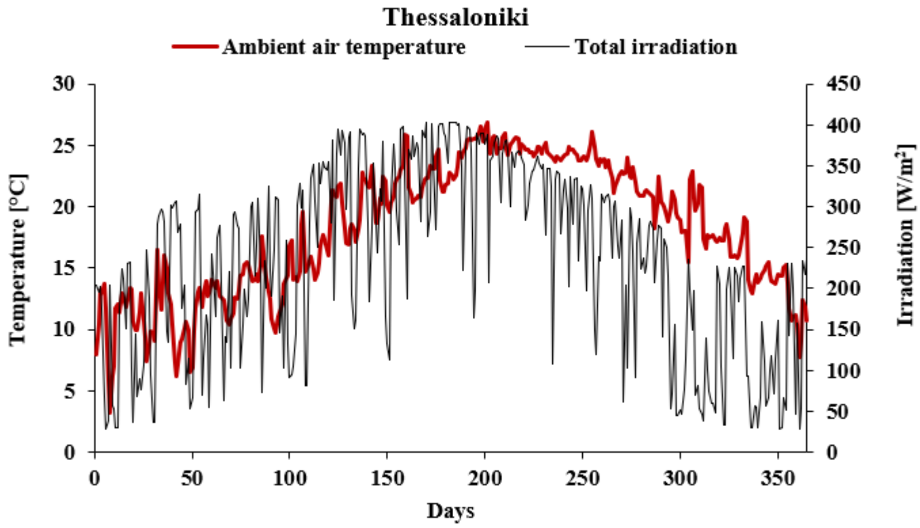
Figure A1. *Cont*.



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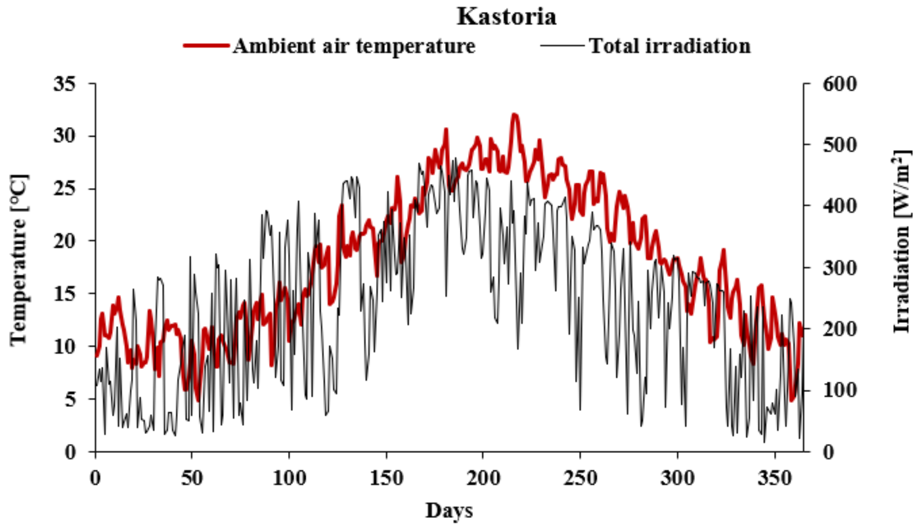

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Figure A1. Average daily ambient air temperature and total solar irradiation for the cities of (**a**) Chania, (**b**) Athens, (**c**) Thessaloniki, and (**d**) Kastoria.

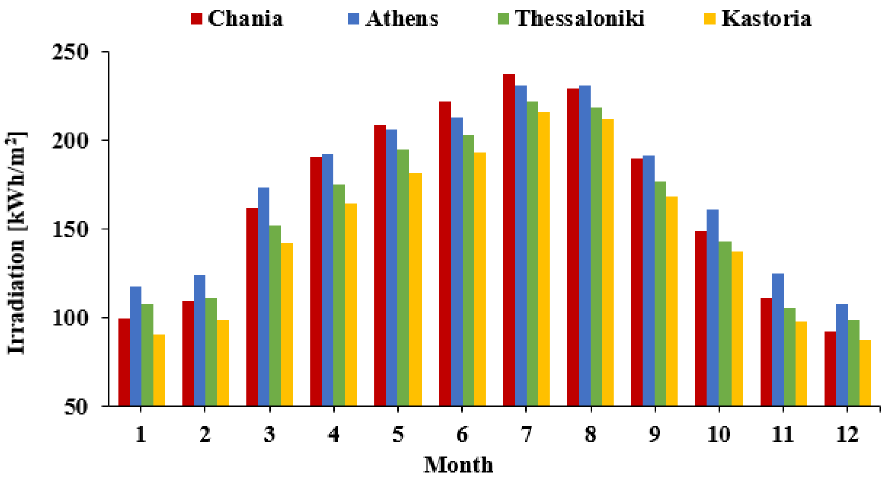

Figure A2. Monthly PV in-plane solar irradiation for the four examined cities.

Appendix B. Thermal Analysis Results

This appendix includes the calculation results of the thermal analysis simulations for every number of stories and for each of the four examined locations, given in Tables A1–A4. These results are also included in Figures 3–6.

Table A1. Thermal analysis calculations for the city of Chania.

Number of Stories	Specific Heating Energy [kWh/m^2]	Specific Cooling Energy [kWh/m^2]	Specific Electricity for Heating [kWh/m^2]	Specific Electricity for Cooling [kWh/m^2]
1	36.39	20.44	9.86	4.75
2	24.27	20.87	6.71	4.83
3	20.01	21.71	5.58	5.01
4	17.91	22.23	5.02	5.13
5	16.67	22.59	4.69	5.21
6	15.87	22.81	4.48	5.26
7	15.32	22.97	4.33	5.29

Table A2. Thermal analysis calculations for the city of Athens.

Number of Stories	Specific Heating Energy [kWh/m^2]	Specific Cooling Energy [kWh/m^2]	Specific Electricity for Heating [kWh/m^2]	Specific Electricity for Cooling [kWh/m^2]
1	41.73	37.09	11.58	8.92
2	28.22	35.75	8.00	8.61
3	21.32	35.39	6.10	8.51
4	21.22	35.04	6.11	8.45
5	19.87	34.86	5.74	8.41
6	18.99	34.71	5.50	8.37
7	18.69	34.41	5.42	8.30

Table A3. Thermal analysis calculations for the city of Thessaloniki.

Number of Stories	Specific Heating Energy [kWh/m^2]	Specific Cooling Energy [kWh/m^2]	Specific Electricity for Heating [kWh/m^2]	Specific Electricity for Cooling [kWh/m^2]
1	61.98	22.77	20.25	5.45
2	45.66	22.64	14.91	5.43
3	39.97	22.66	13.14	5.44
4	37.17	22.64	12.27	5.44
5	35.52	22.59	11.76	5.43
6	34.45	22.55	11.43	5.42
7	33.71	22.49	11.20	5.41

Table A4. Thermal analysis calculations for the city of Kastoria.

Number of Stories	Specific Heating Energy [kWh/m^2]	Specific Cooling Energy [kWh/m^2]	Specific Electricity for Heating [kWh/m^2]	Specific Electricity for Cooling [kWh/m^2]
1	99.28	7.87	51.83	1.93
2	76.48	9.07	37.93	2.21
3	68.62	9.56	33.46	2.32
4	64.73	9.82	31.23	2.39
5	62.45	9.93	30.04	2.41
6	60.97	10.02	29.19	2.43
7	59.94	10.07	28.60	2.44

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