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Measurement-Based Assessment of Energy Performance and Thermal Comfort in Households Under Non-Controllable Conditions

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Abstract: The current research presents a practical approach to assess energy performance and thermal comfort in households through monitoring campaigns. The campaigns are conducted in a Greek city, involving the installation of low-intrusive recording devices for hourly electricity consumption, indoor temperature, and relative humidity in different residences in winter and summer periods. The recorded indoor environmental conditions are initially compiled to the Predicted Mean Vote (PMV) index, followed by the formulation of databases of hourly electricity consumption, PMV and local outdoor climate conditions retrieved by an official source of meteorological conditions. A special algorithm for database processing was developed which takes into account the eligibility of data series, i.e., only the ones corresponding to non-zero electricity consumption are treated as eligible. First, the sequential temporal progress of energy consumption and thermal comfort is produced towards the assessment of energy-use intensity and thermal comfort patterns. Secondly, through summing of the electricity consumption within 0.5-step PMV intervals, under three outdoor temperature intervals with approximately the same number of eligible measurements, reliable interrelations of energy consumption and PMV are obtained even for residences with limited amount of measured data. It is revealed that the weekly electricity consumption ranged within 0.15–3.59 kWh/m^2 for the winter cases and within 0.29–1.72 kWh/m^2 for the summer cases. The acceptable range of $-1 \leq \text{PMV} \leq 1$ interval holds an occurrence frequency from 69.46% to 93.39% and from 37.94% to 70.31% for the winter and summer examined cases, respectively. Less resistance to discomfort conditions is observed at most of the summer examined households exhibiting the electricity peak within the $1 \leq \text{PMV} \leq 1.5$ interval, contrary to the winter cases for which the electricity peak occurred within the $-1 \leq \text{PMV} \leq -0.5$ interval. The study provides graphical relationships of PMV and electricity consumption under various outdoor temperatures paving the way for correlating thermal comfort and energy consumption.

Keywords: building energy efficiency; thermal comfort; residences; monitoring; rational use of energy

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1. Introduction

Recent recordings of climate change dictate a wide exposure of population to health risks and degradation of socio-economic conditions. In the period from 2010 to 2020,

it has been reported that the vulnerable population was subjected to a mean annual increase of heatwaves by up to 2.9 billion person-days compared to the reference period of 1986–2005 [1]. According to Ref. [1], although renewable energy penetration has grown during the last decade, CO_2 emissions annual reduction rate was only 0.6% on average during the period from 2014 to 2018. Under this performance, it would take more than 150 years to decarbonize the global energy system, a goal which is set for 2040 to restrict temperature rise below 1.5 °C as per the Paris Agreement [2]. On the other hand, the World Meteorological Organization (WMO) has stated that the global average temperature in 2023 was around 1.45 °C above the 1850–1900 average, which already challenges the limits of the Paris Agreement [3]. Regarding the future trend of climate change, under the current policies, it is estimated that by the end of the century the average global temperature will rise by 2.7 °C [4,5]. Conventional energy consumption (fossil fuels, oil, and gas) induces over 75% of global greenhouse gas (GHG) emissions [6], hence being by far the largest contributor to climate change, raising serious environmental and energy-security concerns [7]. In parallel, 39% of global GHG emissions is attributed to the building and construction sector, with around half of it being referred to the residential sector [8]. While the population worldwide is expected to increase by around 2 billion in the next 30 years [9], the intensity of building-sector environmental impact due to the increase of energy demand is expected to continue growing.

In view of the aforementioned conditions, the building sector should remain a top priority in planning novel energy efficiency strategies, with special focus on the renovation of the existing building stock which encompasses a large share of old buildings with absent or limited compliance with minimum energy performance requirements. Indicatively, in Europe, more than half of residential buildings are built before 1970 while about one-third of the stock is built between 1970 and 1990 [10]. Planning and implementing the optimal energy conservation measures in the built environment, either passive or active (including control technologies), requires both an analysis of the end-user perception over proposed interventions [11,12] and a holistic valuation of building operations related to energy performance, occupancy patterns and thermal comfort [13–15]. Knowledge on the occupants' behavior over utilizing appliances (e.g., HVACs, lighting, windows for natural ventilation, etc.) towards achieving thermal and visual comfort is decisive in valuating building energy performance [16]. The subjectivity of indoor comfort conditions' perception as well as the non-controllable end-user behavior over the energy systems, especially in residences, often leads to discrepancies between the predicted and the actual energy consumption [17], which may compromise the expected benefits of planned measures for energy efficiency improvements. Cui et al. [18] underlined that accurate simulations require detailed input parameters, including the end-user behavior. This is confirmed, for example, by Aste et al. [19], who concluded that the predicted energy consumption, obtained by dynamic energy simulation, was 1.7 times higher than the actual one in a residential complex in Italy. The synergetic impact between occupant behavior and energy performance originates on the desideratum for comfortable and healthy indoor environments. Focusing on thermal comfort assessments, the combined effect of physical and personal parameters should be taken into account; to name a few, the air temperature, relative humidity, velocity, human activity (metabolic rate), and clothing [13,20]. Perhaps the most common and widely used indicator which incorporates the physical and personal parameters is the Predicted Mean Vote (PMV) [21].

In the design process, either for new energy-efficient buildings or for the energy upgrading of existing ones, the understanding of interrelations between energy performance and comfort for the alternative design scenarios is crucial. This is because the candidate energy interventions directly influence indoor comfort conditions; hence, appropriate sim-

ulation tools which account for such interrelations and quantify the overall impacts are absolutely necessary. In this way, the designer can achieve a more holistic view of building performance for the alternative design scenarios, in terms of the energy, environmental, economic, and comfort impacts, which in turn ensures a more informed decision making towards selecting the optimal solution. For university buildings in Alicante, Galiano-Garrigós et al. [22] conducted energy calculations using the Spanish EPBD tool, namely the Cypetherm HE Plus, along with DesignBuilder simulations, for capturing energy performance, thermal comfort, and illumination aspects. Through comparisons with actual energy consumption data, they concluded that the simulated energy consumption deviates significantly, notably by around 45% higher than the actual one. In response to that challenge, Es-sakali et al. [23] developed a novel methodology for fine-tuning the simulation model set-up (using the EnergyPlus) based on extensive measurements and sensitivity analysis regarding wall thermal transmittance, glass properties, and air tightness. The methodology was applied for a building located in Benguerir in Morocco, and it was found that the selected optimal simulation model achieved a remarkable improvement of simulation accuracy concerning the hourly indoor temperature and the variable refrigerant flow (VRF) energy consumption. The latter methodology has been recently enhanced including the PMV index for thermal comfort assessments as well as visual comfort, in the framework of research concerning the impact assessment of thermochromic and electrochromic windows [24]. The approach was applied for the same building case and it was found that combining thermochromic and electrochromic coatings with optimal static glazing reaches a 26% reduction in energy consumption.

In parallel, recent research on building energy performance has demonstrated that in some cases, higher saving levels are achieved when the PMV is included in the design concept especially regarding energy management systems. For instance, in a computer simulation environment, Hong et al. [25] estimated a lowered heating and cooling energy consumption by 7.3% and 28.8%, respectively, in the case of PMV-based compared to temperature-based control. Using Computational Fluid Dynamics (CFD) techniques, another study concluded that a PMV-based controller can achieve 1.6% daily cooling energy saving [26]. In contrast, another office-case study [27], based on dynamic energy simulations, argued that the PMV-based control achieves less cooling-energy savings compared to the temperature-based one, although a remarkably more stable performance is achieved regarding the retaining of PMV within comfort level In relation to the temperature-based control. Despite the case-specificity concerning the expected energy-saving potential, there is no doubt that integrative comfort indices, which account for both physical and personal parameters, when included in the design problem, provide higher fidelity in energy-performance predictions and eventual selection of optimal retrofit measures.

As revealed in Ref. [13], the research topic referring to building energy consumption and thermal comfort gains great interest during the last five years, highlighting that building energy engineering considering thermal comfort and occupants' behavior is a cutting-edge issue in the study of the built environment. In view of stricter energy policies and standards, e.g., the transformation of existing buildings to nearly zero energy buildings (nZEBs) [28], improved energy audits and studies are required, to ensure a minimum deviation between the predicted and actual energy performance. Although dynamic building simulation tools are recognized as suitable for such purposes, the aforementioned deviation is still present in technical studies, compromising the expected impacts of energy renovations [19,29]. As pointed out in scientific literature, a critical source of this divergence is the occupants' behavior over the energy systems [13,30], especially in households [31]. On the other hand, the energy-saving potential through exploiting behavioral shifts in households can be up to 25% [32]. Occupants of residences can utilize their appliances

freely, which implies stochastic behavior, posing a great challenge in quantifying both thermal comfort and energy performance. One of the solutions responding to this challenge refers to monitoring strategies that employ low-intrusive measuring devices and feedback applications to inform the end-user. The former is related to small wireless equipment utilizing RFID and Wi-Fi for data transmission [31] ensuring occupant's acceptability and minimizing interference, while the latter refers to providing occupants' access to "live" energy consumption towards raising awareness and encouraging rational use of energy [33]. By reviewing 33 case studies worldwide involving feedback on residential energy consumption in real occupied homes, Agarwal et al. [34] concluded energy savings ranging between 5% and 20% being attributed to the energy-feedback monitoring strategy.

In the framework of previous research involving monitoring of energy consumption and thermal comfort specifically in residences, Sharmin et al. [33] presented an extensive measurement campaign in 12 apartments in a 4-storey building in Canada. They concluded useful graphical relationships among energy consumption, thermal comfort, and envelope heat flux. Instead of an integrated indicator, thermal comfort levels were assessed through the recommended ranges of air temperature and relative humidity of the ASHRAE guidelines. Lopez et al. [35] tested many thermal comfort indices through a three-year period of measurements of indoor temperature and relative humidity in three nearly-zero energy houses in France, documenting that the hourly time-step is adequate for reliable thermal-comfort estimations. Another study demonstrated remarkable energy savings and PMV-based thermal comfort improvements in the case of (internal) thermal insulation of an apartment in China, through indoor physical parameters measurements and monitoring of heating electricity consumption [36]. Aste et al. [19] exploited long-term measurements of energy consumption of a nearly-zero residential complex to explore deviations between the actual and simulated energy performance. They confirmed that the system operating profiles and user behavior are among the top causes of deviations. Recent research focuses on the development of novel Home Energy Management Systems (HEMS) to control indoor thermal comfort and minimize energy consumption through monitored indoor conditions and energy consumption [37,38]. Despite the advanced progress regarding the assessment of building energy consumption and thermal comfort, the ongoing research is mainly focused on simulated environments and, in fact, it is more focused to tertiary sector buildings such as offices and educational ones. These building uses present more stable behavioral patterns compared to residences. As admitted in Ref. [19], related studies based on actual data for residential buildings are currently scarce mainly due to the uncertainties in interpreting usage patterns of building elements and systems.

From a policy-making point of view, good knowledge on energy performance and thermal comfort of the residential building stock is again a prerequisite in order to develop appropriate strategies, technical guidelines, and funding programs that promote energy renovations. In many European Countries, the central government is competent to provide funding for energy retrofits in households. At local level, municipalities are expected to inform citizens and encourage them to undertake actions towards energy renovations of their homes. In most cases, this is achieved through capacity building, information, and awareness-raising campaigns [39]; which, however, often lack personalized information for the house owner.

Responding to the ongoing research challenge of few studies on building energy performance and thermal comfort based on actual data in real-life residential buildings, the current work presents a methodology to evaluate the relationship between indoor thermal comfort and energy consumption through the elaboration of measurements in households in Heraklion, Greece. The investigation took place in the framework of the initiative "Municipality transition towards low-carbon economy through citizen participa-

tive procedures". The latter referred to an interactive survey involving energy inspection and personalized consultation to improve residences' energy efficiency. Additionally, the municipal authority offered cost-free monitoring of electricity consumption and of indoor environmental conditions in order to inform the tenants about their house performance. Among 200 residences so far participated in the initiative, measurement surveys took place in eight houses (four in the period from October 2021 to March 2022 and another four in the period from June to September 2023). For these eight houses, the monitored database was further processed towards the extraction of weekly evolution of PMV and electricity consumption, thermal-comfort hours distribution, and graphical relationships between electricity consumption and PMV. A data-processing algorithm is developed which detects possible non-eligible measurements, i.e., the data-series corresponding to absent or zero-electricity measurements (which mean fault recordings) towards the identification of periods with missing data. Under the limitation that only the total electricity consumption was monitored in each house, the weekly evolution of PMV, outdoor temperature, and energy consumption allowed to identify possible use of energy other than electricity to satisfy thermal comfort especially during the autumn-winter period. The data-processing procedure provided electricity and PMV relationships, even for cases with limited amount of measured electricity data e.g., due to monitoring system faults, through aggregating the electricity consumption corresponding to each 0.5-step PMV interval within the PMV thermal sensation scale for different outdoor temperatures intervals with approximately the same number of eligible measurements. It is concluded that in the winter experiment, the indoor thermal comfort is better regulated, exhibiting an indoor thermal sensation from slightly cold to close-to-neutral ($-1 \leq \text{PMV} \leq 0.5$) within the range from 69.46% to 92.95% of hourly observations, with a weekly electricity consumption ranging within 0.15–3.59 kWh/m^2. On the other hand, most residences during the summer campaign present only a 37.94–48.81% occurrence frequency of thermal sensation from close-to-neutral to slightly warm ($-0.5 \leq \text{PMV} \leq 1$) with a weekly electricity consumption ranging from 0.29 to 1.72 kWh/m^2. The proposed methodology is suitable for practical houses' inspections as it consists of low-intrusive equipment including feedback for the tenant, providing useful information under non-controllable behavioral conditions. For future research, and to restrict uncertainties, it is strongly recommended to extend the measurement system including disaggregated energy recordings (per energy source and/or appliance).

2. Materials and Methods

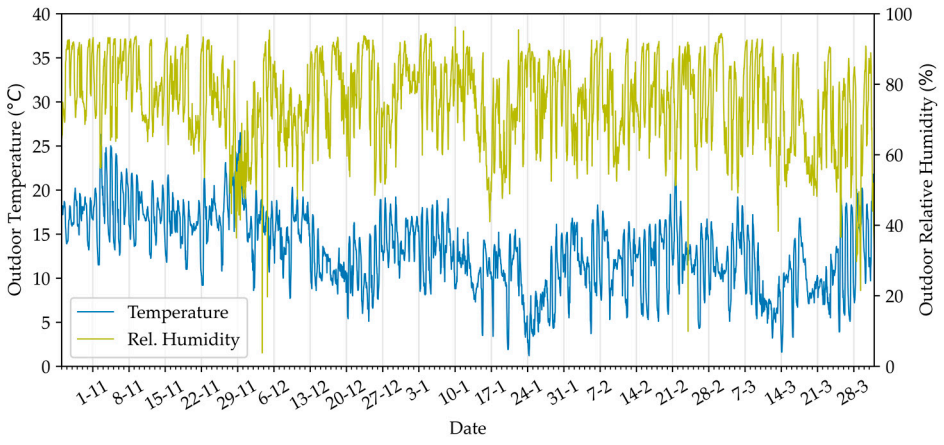
In the framework of its transition towards a low-carbon economy, the municipality of Heraklion runs a participative initiative called "Municipality transition towards low-carbon economy through citizen participative procedures", which involves intensive raising of citizen awareness to encourage upgrading their homes' energy efficiency. This action envisages energy inspections to as many households as possible and the provision of personalized recommendations on energy-upgrading solutions accompanied with potential financing resources. It was launched during the Energy Days event in September 2019 [40], which held an open call to citizens to declare their participation by completing a simple intention form. Out of 200 residences that have participated so far, 8 residences took advantage of the cost-free option (provided by the initiative) to install low-intrusive measuring devices with a feedback system in order to familiarize with their energy performance and indoor environmental conditions. Targeting at the maximum number of participating households and considering budget restrictions, the measurement system for each household was limited to only one device for electricity consumption and one for indoor air temperature and relative humidity. In recognition of the necessity to (in compliance with a previous literature review) (a) ensure acceptance of the homeowner to allow new installations,

(b) minimize interference with the measurement equipment, (c) embed a feedback system, and (d) interpret energy performance and thermal comfort, the following methodology is implemented:

- Recording of the ambient climate conditions during the period of measurements;
- Recording of typical energy-related characteristics of the measured residences and of end-user habits regarding systems' use especially the ones that regulate indoor thermal comfort;
- (i) Monitor the hourly storing of measured parameters, (ii) deploy the electricity monitoring device for total (aggregated) electricity consumption recording, and (iii) install the temperature-relative humidity device at a representative position;
- Measurement database manipulation: (i) transform environmental parameters recordings (temperature and relative humidity) to the PMV index, (ii) identify hours and periods of missing data (zero electricity consumption), and (iii) extract electricity consumption and thermal-comfort patterns.

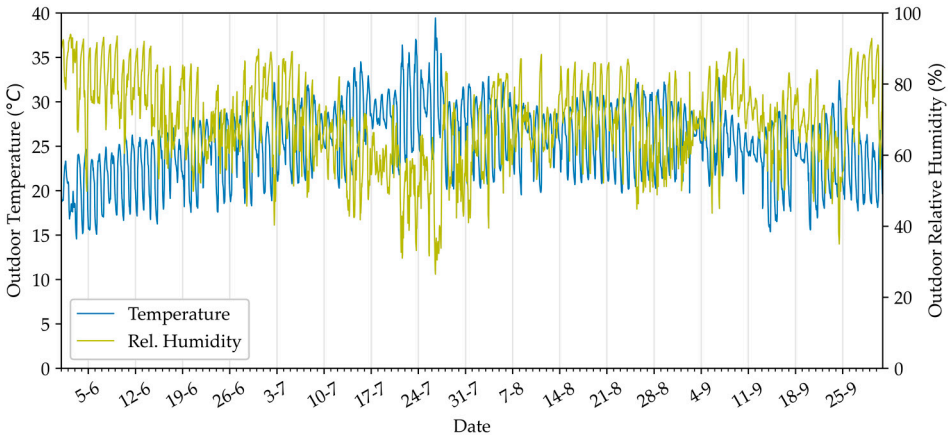
2.1. Area of the Experiment and Climatic Conditions

The monitored households are located in the City of Heraklion (Lat.: 35.3408° N; Long.: 25.1442° E) on the north shore of the island of Crete, Greece. The ground morphology ranges at low altitudes with low slopes. According to the 2021 census of the Hellenic Statistical Authority, the municipality of Heraklion is the fourth largest one in the Country in terms of population. It presented around 3% population increase compared to the 2011 census. The built environment is quite dense and the historic center is constituted by many buildings in the 2–5 story range. In its residential parts outside the historic center, there is still high building density often with a mix of multi-story apartments and low-rise homes. In terms of climatic conditions, Heraklion belongs to the CSa climatic zone as per the Köppen classification [41]. Summers are warm to hot and dry with clear skies. Due to the prevailing north–northwest winds, summer temperature rarely exceeds 32 °C. Winters are mild with moderate precipitation and temperature rarely falls below 5 °C, often being higher than 15 °C. For the purposes of the current study, hourly climatic data are retrieved from the National Observatory of Athens and specifically from the weather station located at the east part of Heraklion [42] (only 3 km from the city center). Outdoor temperature and relative humidity time series during the experimental period of October 2021 to March 2022 (winter period) and June to September 2023 (summer period), are presented in Figure 1.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Hourly outdoor temperature and relative humidity retrieved from the meteorological station during the periods of residences monitoring: (**a**) the winter period (end of October 2021 to March 2022) and (**b**) the summer period (June to September 2023).

2.2. Presentation of the Monitored Residences

As mentioned earlier, the initiative "Municipality transition towards low-carbon economy through citizen participative procedures" mainly intends to involve as many citizens as possible, without any special restrictions or criteria regarding the selection of residences. This means that all homeowners that are willing to participate are eligible, and the only criterion was that the specimen (residence) is located within the boundaries of the municipality of Heraklion. Consequently, a diverse set of residences, varying by type, envelope, systems, and occupancy, was included in the examined stock. Taking into account the restricted resources (i.e., that only one electricity monitoring device and only one for indoor air temperature and relative humidity are available for each specimen) and aiming at extracting relationships between the energy consumption and thermal comfort, eight monitored residences are showcased in the current study which presented the highest possibility of serving thermal comfort by electrical systems as per either the energy inspection or at least the occupant testimony regarding the dominant heating or cooling system. The characteristics of the selected residences, as recorded by the energy inspections and the questionnaire survey, are tabulated in Table 1.

Table 1. Information about the monitored residences.

Residence No. [1]	Winter Period (End of October 2021 to March 2022)				Summer Period (June to September 2023)			
	#8/W-1	#34/W-2	#69/W-3	#113/W-4	#5/S-1	#13/S-2	#25/S-3	#36/S-4
GENERAL INFORMATION								
Type	Apartment in multi-story building	One-floor apartment in two-story building	Single-family building	Apartment in low-rise building	2-floor apartment	Apartment in multi-story building	Apartment in multi-story building	Apartment in multi-story building
Floor area (m^2)	125	167	166	85	95	75	87	55
Year of construction	1987	2000	2006	1986	In the period 1980–1990	Before 1980	1997	2005
No. bedrooms	3	3	4	3	2	2	2	1
No. occupants	3	2	5	4	3	1	1	2
Energy interventions after construction	2 A/Cs (2011); Solar collector for DHW (2008)	Windows replacement; Solar collector for DHW; Central heat pump (2021)	Central heat pump (2013)	Windows replacement; Solar collector for DWH; energy-efficient fireplace (2004)	Solar collector (2008); Windows replacement (2013); 3 new A/Cs (2022)	Solar collector (2003); One A/C (2018); Thermal insulation (2019)	3 A/Cs (2018)	1 A/C (2023)
TECHNICAL INFORMATION								
Envelope								
Walls	Concrete-brick, insufficient insulation	Concrete-brick, insufficient insulation	Concrete-brick, insufficient insulation	Concrete-brick, insufficient insulation	Concrete-brick, in-sufficient insulation	Concrete-brick, insulated	Concrete-brick, insufficient insulation	Concrete-brick, in-sufficient insula-tion
Openings	Double glazing 6 mm, aluminum frame	Double glazing 12 mm, aluminum frame	Double glazing 12 mm, PVC frame	Double glazing 3 mm, aluminum frame	Double glazing 12 mm, PVC frame	Single glazing, Aluminum frame	Double glazing 6 mm, aluminum frame	Double glazing 12 mm, aluminum frame
Systems								
Dominant heating system/use frequency [2]	2 A/Cs/Afternoon (1 h); Evening (1 h)	Central Heat Pump/Continuous operation at fixed set-point	Central heat pump/Afternoon (3 h); Evening (3 h)	4 A/Cs/Continuous operation at fixed set-point	3 A/Cs/Continuous operation at fixed set-point	1 A/C/Continuous operation at fixed set-point	3 A/Cs/Morning hours at fixed set-point	1 A/C/Evening hours at fixed set-point

Table 1. *Cont.*

Residence No. [1]	Winter Period (End of October 2021 to March 2022)				Summer Period (June to September 2023)			
	#8/W-1	**#34/W-2**	**#69/W-3**	**#113/W-4**	**#5/S-1**	**#13/S-2**	**#25/S-3**	**#36/S-4**
Secondary heating system/use frequency [2]	Oil burner/rarely when it is too cold	N/A	N/A	Energy-efficient fireplace/Rarely when it is too cold	N/A	N/A	Electrical heater	Electrical heater/Evening (1 h)
Dominant cooling or ventilation system/use frequency [2]	2 A/Cs/Morning (1 h); Noon (2 h)	Central Heat Pump/Continuous operation at fixed set-point	5 A/Cs/Evening (4 h)	4 A/Cs/About 6 h daily	3 A/Cs/5 h daily (noon and afternoon) at fixed set-point	1 A/C/Operation during noon and afternoon hours at fixed set-point	3 A/Cs/Afternoon (1 h)	1 A/C/Only when it is too hot
Secondary cooling or ventilation system/use frequency [2]	N/A	Standing fan/Noon (3 h); Evening (3 h)	N/A	N/A	Standing fans/Rarely used when it is too hot	N/A	N/A	Standing fan/whole night
Domestic hot water	Solar collector with electrical water heater	Solar collector with electrical water heater	Solar collector with electrical water heater	Solar collector with electrical water heater	Solar collector with electrical water heater	Solar collector with electrical water	Electrical water heater (15 min in the evening)	Electrical water heater (15 min in the evening)
Lighting	Incandescent	LED	LED	LED	LED	LED	LED and Halogen	LED
Other systems	TV; Refrigerator; Clothing washer; Dish washer; Cooking equipment	TV; Refrigerator; Clothing washer; Dish washer; Cooking equipment	TV; Refrigerator; Clothing washer; Dish washer; Cooking equipment	TV; Refrigerator; Clothing washer and dryer; Dish washer; Cooking equipment	TV; Refrigerator; Clothing washer; Dish washer; Cooking equipment	TV; Refrigerator; Clothing washer; Cooking equipment	TV; Refrigerator; Clothing washer; Cooking equip-ment	TV; Refrigerator; Clothing washer; Cooking equip-ment
End-user perception and preference	Believes that the energy cost is high; Would like envelope renovation; Acknowledges ignorance over standby devices	Believes that the energy cost is realistic; Would like roof insulation; Acknowledges no energy waste	No feedback provided	Believes that the energy cost is tolerable; Would like thermal insulation and central heat pump; Acknowledges no energy waste	Believes that the energy cost is moderate; Would like shading interventions; Acknowledges ignorance over standby devices and fixtures	Believes that the energy cost is high; Would like windows replacement	Believes that the energy cost is moderate; Would like windows replacement and solar collector for DHW	Believes that the energy cost is high; Would like one A/C in the bedroom and a solar collector for DHW

[1] Numbering format: According to the order of the participant in the initiative/adopted in the current study. [2] According to occupant testimony through questionnaire.

The examined stock contains mainly apartments, and only one is a single-family building. Moreover, all residences were built before 2010 when the first technical directive for buildings energy performance (the Greek EPBD) was issued in Greece; thus, all residences, except S-2, which is subjected to a recent upgrading referring to thermal insulation, were assumed to have insufficient thermal insulation. In all cases, at least one energy upgrading intervention had already taken place especially regarding heating, cooling, and domestic hot water (DHW) systems. According to previous studies [43,44], the examined cases correspond to typical residential buildings of the Greek building stock. Focusing on the winter-period cases, electricity-based systems were declared by the occupant as dominant to regulate thermal comfort, although in some cases, secondary systems which use sources other than electricity were also recorded by the energy inspection (refer to specimens W-1 and W-4). This means that measurements of electricity only may disregard substantial amounts of energy consumed to satisfy thermal comfort; hence, appropriate treatment of the database is required to at least identify such possible divergence. On the other hand, less divergence is expected for the summer-period residences, as they all use electricity-based cooling or ventilation systems. Interestingly, only three out of the seven who responded to a user-perception questionnaire believed that their energy cost was high, and only two felt that they deviated from rational energy use, which raises concerns about the adaptability to behavioral shift recommendations.

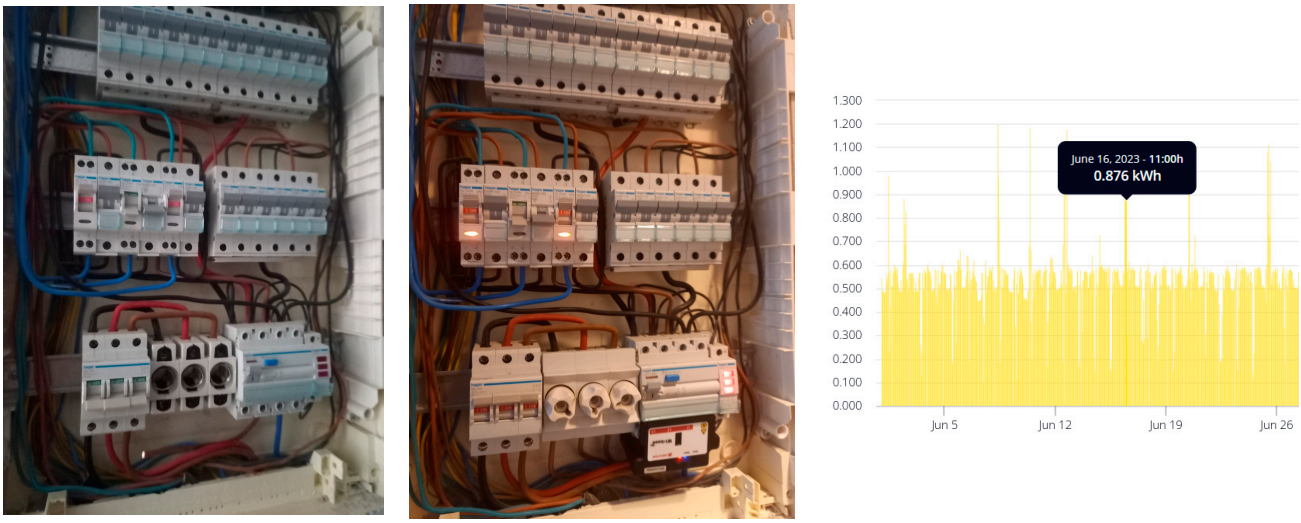
2.3. Monitoring Campaign

2.3.1. Measurement Equipment and Settings

With respect to the low-intrusive monitoring approach, in this research, the Wibeee One meter of Smilics Technologies [45] was selected. The specific meter is wireless and is adjustable to the electrical panel to measure electrical power components. It provides a hotspot to conduct the initial configuration using a mobile app from the manufacturer. Once configured, the meter sends data to the cloud, which are accessible via a cost-free Web platform (called Wibeee Nest). Among others (voltage, current, frequency, power factor, etc.), the electricity power and consumption data are recorded and stored in the cloud. Concerning feedback, near real-time visualized data are accessible via the accompanied Web app, providing dynamic graphs of electricity consumption. Moreover, retrospective monitored data may be exported at a user-defined period and time-step. The accuracy class of the meter is 2% for both voltage and current. The meter was installed on the power cut-off relay on the central electrical panel for monitoring the aggregated (total) electricity consumption. The technical specifications of the 2 W (for single-phase electrical supply) and of the 4 W (for three-phase electrical supply) Wibeee versions that were used in the current research are given in Table 2. A view of the installation and consumption visualization is provided in Figure 2. Although the measurement system is user-friendly and almost non-intrusive, a significant limitation is that it is Wi-Fi-dependent; thus, it is not suitable when no Wi-Fi is available, since in situations of internet interruption or corruption of meter syncing configuration, data are not transmitted and the measurements are lost. In the current campaign, such instances led to quite long periods of missing data, as the access to each residence for repairing the devices was not very easy (considering also the voluntary nature of the homeowners' participation).

Table 2. Technical specifications of the Wibeee devices used.

Technical Feature	Wibeee-One 2 W	Wibeee-One 4 W
Installation	Single-phase electrical supply	Three-phase electrical supply
Power supply	85–265 V L-N	85–265 V L-N
Frequency range	50–60 Hz	50–60 Hz
Power consumption	1.5–4.5 VA	1.5–4.5 VA
Nominal current	63 A	63 A
Voltage accuracy	2% (PF = 1)	2% (PF = 1)
Current accuracy	2% (PF = 1)	2% (PF = 1)
Power accuracy	4% (PF = 1)	4% (PF = 1)
Weight	18 g	52.9 g
External material	Self-extinguishing UNE 21031 90 °C V0	
Operating temperature	−10 to 45 °C	
Storage temperature	−40 to 85 °C	
Relative humidity	10–90% (non-condensing)	
Protection rating	IP20	
Communication type	Wi-Fi (IEEE 802.11)	
Communication protocol	HTTP, Modbus TCP, XML	
Frequency range	2.405–2.480 GHz	
Encryption	AES128	



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

Figure 2. Photo documentation of: (**a**) the electrical panel before meter installation; (**b**) the electrical panel after meter installation; and (**c**) monitored (hourly) data visualization in the meter accompanied Web platform at a user-defined time period (screenshot).

For thermal comfort assessments, monitoring of indoor air temperature and relative humidity (RH) is achieved using the Yowexa YMUP-20D PDF Temperature and Humidity Data Logger [46]. It is a small battery-powered (wireless) USB device (device dimensions: 95 mm × 40 mm × 17 mm) which encapsulates a sensor for temperature and RH metering, a memory for data storing with storage capacity of up to 17,280 recordings and an LCD for real-time reading of instantaneous recording. Its measuring range is −30 °C to 70 °C and 0–100%, with a ±0.5 °C and ±3%RH accuracy, for temperature and RH, respectively. Configuration regarding sampling time-step as well as database download can be obtained via the associated software PidifiX v.2.0.4, using for example a portable computer with a USB port. In the current campaign, one meter is placed in each residence, at a representative position (living room in most cases). It was set to an hourly sampling interval, in order

be able to synchronize environmental conditions, electricity measurements, and outdoor climate conditions in consolidated database reports. As far as feedback to the user is concerned and taking into account that, unlike the electricity meter, this one has no ability of "live" data transmission, at least once a month the energy inspector visited the house to download measurements and re-configure and re-install the device. Then, at least once a month, the initiative responsible sent a report of the hourly data series, including both thermal comfort (calculated PMV) and electricity measurements, to each occupant with email. Since this monitoring system is wireless and Wi-Fi-independent, it presents limited faults in data recording and data loss could occur for example due to human error during intermediate data downloads and re-configuration or due to device destruction by accident. To avoid accidents, the meters in this survey were placed at relatively isolated spots, e.g., high shelves not reachable by children, as opposed to, for example, in the center of the room, which would otherwise be considered a better position for more realistic measurements.

2.3.2. Measured Data Manipulation

First, the indoor air temperature and RH data are converted to the PMV index for thermal comfort. In accordance with the findings of previous research presented in the introduction, the PMV index is selected herein to interpret thermal comfort because it accounts for both physical and personal parameters. From a social point of view, and in the framework of regular feedback of measurements to end-users, the PMV is preferred over other thermal comfort indices because its rationale in terms of the thermal sensation scale was considered easier to understand by the occupants. According to the PMV model, apart from the indoor air temperature and relative humidity, the air velocity magnitude, the mean radiant temperature, the clothing temperature, as well as the subject's metabolic rate and clothing insulation are involved in the calculation procedure [21,47]. To account for these contributions in PMV calculations, the following assumptions are adopted:

- Indoor air velocity: A typical low value is assumed, equal to 0.15 m/s, which is suitable for indoor spaces [48];
- Subject activity level: A typical value of 1.2 met (70 W/m^2) for a relaxed person [21] is used;
- Clothing insulation: To account for possible seasonal variations, 1 clo is set for winter months (November–March), 0.5 clo is set for summer months (June–September) and 0.75 clo is set for October and May;
- Mean radiant temperature: It is estimated by means of a simple linear correlation with indoor air temperature, which was easily derived by the linear correlations of PMV with air temperature and with mean radiant temperature provided by Dyvia and Arif [49]. More specifically, in their study, they used the PMV model for indoor spaces and developed a large database of PMV values for extensive sets of personal and environmental parameters in the framework of a sensitivity analysis. Through a regression procedure they concluded the following correlations:

$$PMV = 0.2896 * T - 7.0513 \quad (1)$$

$$PMV = 0.2381 * T_{mrt} - 5.812 \quad (2)$$

where T (°C) and T_{mrt} (°C) are the indoor air temperature and mean radiant temperature, respectively. From the above equations, the one below is derived, which is used to estimate the T_{mrt} contribution in the PMV calculation:

$$T_{mrt} = 1.216 * T - 5.205 \quad (3)$$

The PMV model with the above treatments was developed in Microsoft Excel, which compiled each hourly pair of indoor air temperature and relative humidity to the PMV index. The Excel-based model contains a VBA macro which undertakes the compilation process hour-by-hour throughout the database automatically. The embedded macro also incorporates the iterative calculation process on the thermal load equation for clothing temperature calculation [21].

Finally, the monitored hourly electricity consumption (exported by the Wibeee Nest), the indoor microclimate conditions i.e., air temperature and relative humidity (downloaded from the USB meter), and the calculated PMV are consolidated into a database for each examined residence. A sample of the hourly electricity consumption and corresponding PMV for a winter and a summer residence is presented in Figure 3. To check the validity and reliability of calculations from the presently developed PMV model, the temporal variation of the PMV of the current study together with the one calculated using the CBE thermal comfort tool [47] is provided in Figure 4, along with the environmental parameters. It is seen that the PMV follows a rational trend in relation to indoor temperature and relative humidity variations, while it presents a more stable pattern (i.e., less steep change and less oscillation amplitude) in the winter case. This is also true for the associated environmental conditions, the indoor air temperature and relative humidity. Moreover, it is clearly shown that the PMV calculated herein is very close to the one obtained using the recognized CBE tool (the mean absolute error is 12.3% and 15.1% in the winter and summer case, respectively), which at least enhances the fidelity of the presently developed PMV model. Any straight line in Figures 3 and 4 corresponds to periods of absent or zero energy consumption in the dataset, which actually means faults in measurements are most likely due to Wi-Fi interruptions (refer to Section 2.3.1). To facilitate further research, the produced dataset for each residence was uploaded to the GitHub repository (refer to https://github.com/dbakirtzis/participativeinitiative (accessed on 9 January 2025)).

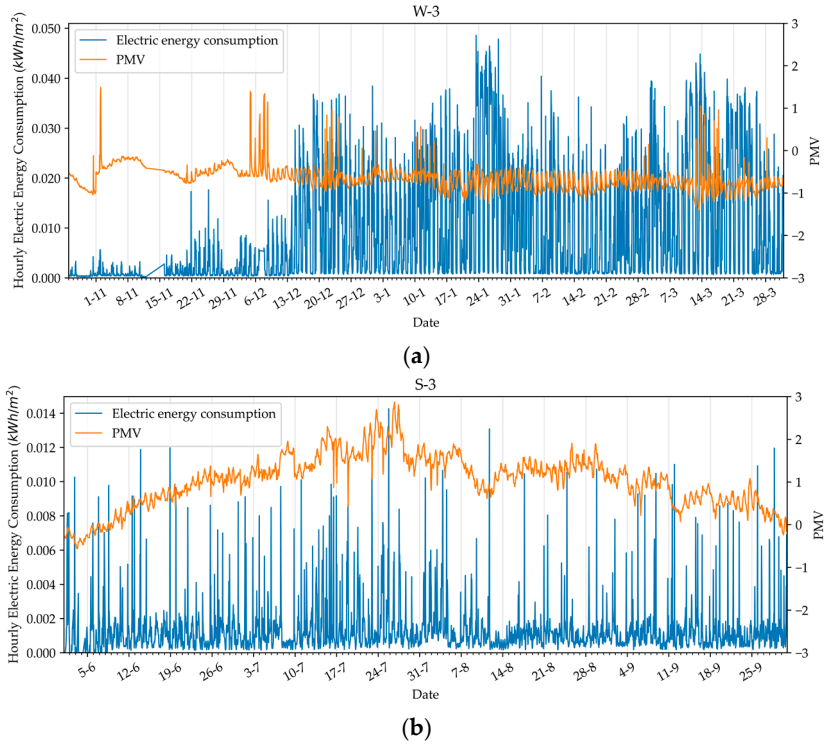


Figure 3. Hourly series of electricity consumption and PMV for the: (**a**) W-3 residence, monitored in the winter period, and (**b**) S-3 residence, monitored in the summer period.

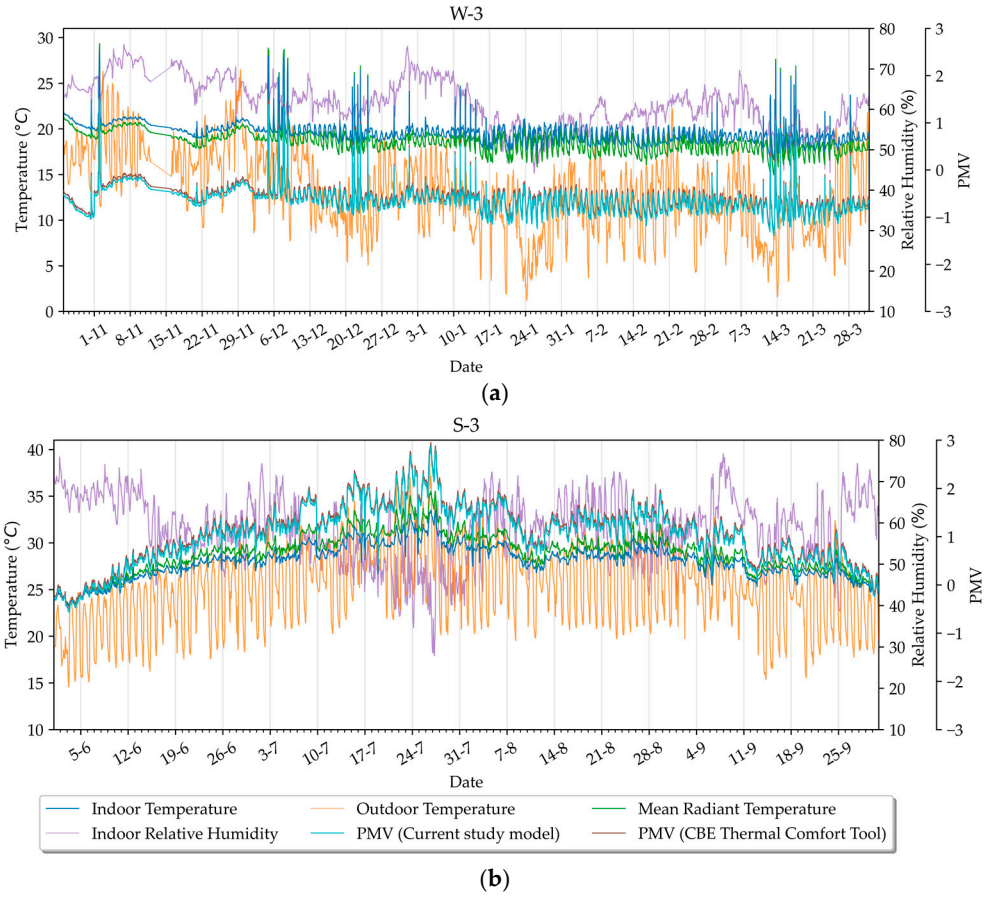


Figure 4. Temporal variation of PMV calculated by the present model and by the CBE tool along with the variation of environmental conditions for residences: (**a**) W-3 and (**b**) S-3.

To draw conclusions on energy and thermal comfort patterns, the database is further manipulated in the context of the following investigation cases for each specimen:

- Temporal progress of energy consumption and thermal comfort: Refers to the realization of the total electricity consumption and the mean PMV over specific consecutive time intervals. Considering the relatively short periods of measurements at both seasons, and to better handle possible data loss mainly due to electricity-meter deficiency, a weekly interval is adopted. The task provides a view of energy progress and thermal comfort in relation to outdoor seasonal conditions. More importantly, it allows to at least empirically recognize whether indeed the dominant electricity-powered system is used to regulate thermal comfort or if a different system is used instead. For example, in case of the winter-period studied residences, through the suggested processing, it may be derived that when the electricity consumption remains similar between the early weeks up to mid-November (followed by a warm October, common in Heraklion) and the next weeks up to February, then most likely, the occupants have either used a non-electrical system or simply kept the declared dominant system at limited use. To ensure comparable results of parameters among the week intervals, if zero or absent electricity values are detected in the database for more than 12 h within a week, then the electricity consumption is neglected in the graphical representation of parameters' weekly evolution.
- Daily electricity and thermal comfort patterns: The focus is on interpreting the energy consumption towards achieving thermal comfort and how this is distributed during the day. The task involves the extraction of the total electricity consumption for each PMV interval, particularly over a 0.5 PMV step within the measured range in

accordance with the PMV thermal sensation scale. For each PMV interval, the aggregated electricity is calculated together with the corresponding number of monitoring hours. For a typical day division, i.e., morning–noon (08.00–16.00), afternoon–evening (16.00–24.00) and nocturnal (24.00–08.00), the distribution of the hours which correspond to each PMV interval, in percentage terms, is also calculated. The suggested procedure provides the distributed use of energy to accomplish thermal comfort in parallel to the detection of the period of the day when the highest frequency of each PMV interval occurs. Consequently, at least empirically, the occupancy patterns in terms of presence and systems' use can be estimated. Data series which correspond to zero or absent electricity are neglected from the filtering process.

- Electricity consumption and thermal comfort relationships: Refers to the graphical correlation of the total electricity consumption and the PMV. Again, the distribution of energy over a 0.5 PMV step is extracted. In order to realize the influence of the outdoor temperature variations, the energy–PMV distribution extraction is conducted for three intervals of outdoor temperature. To ensure similar intervals of outdoor temperature among residences, within which only eligible data-series are used (i.e., the ones corresponding to non-zero electricity measurements), a relaxation in the number of observations among intervals is applied; namely, a maximum 5% of difference in the number of eligible recording hours. Consequently, outdoor-temperature intervals with very close numbers of monitoring hours are produced for each residence, ensuring also similar intervals and comparability among the residences.

In exploiting electricity and thermal comfort patterns and relationships, the 0.5-step discretization is chosen in order to ensure smooth electricity–PMV curves throughout the thermal-sensation scale, and in general, obtain greater detail in the results. Besides, this resolution improves precision in detecting the PMV interval, which corresponds to electricity peaks, and, more importantly, in identifying possible differences between the winter and summer cases regarding the margin of peak-electricity PMV interval from neutral conditions (PMV = 0), and thus, understanding the level of subjects' tolerance for cold and warm environments. Concerning the electricity parameter, in this study, normalized by floor area fashion is adopted. This means that in the elaboration addressed above, the aggregated electricity consumption in kWh/m^2 is obtained and presented in the results. This format is preferred in order to ensure comparability among the examined houses as well as compatibility with common building energy assessment practices in the framework of the Greek EPBD calculation methodology [50,51]. The data processing methodology described above is implemented in the open-source programming language Python v.3.11.0.

3. Results

The weekly progress of electricity consumption and thermal comfort for each residence (derived as explained in Section 2.3.2), in terms of the aggregated area-normalized electricity and average PMV, is presented in Figures 5 and 6, in the winter and summer period, respectively. On each graph, the average outdoor temperature together with the average PMV and the average and maximum electricity consumption among all residences are also depicted.

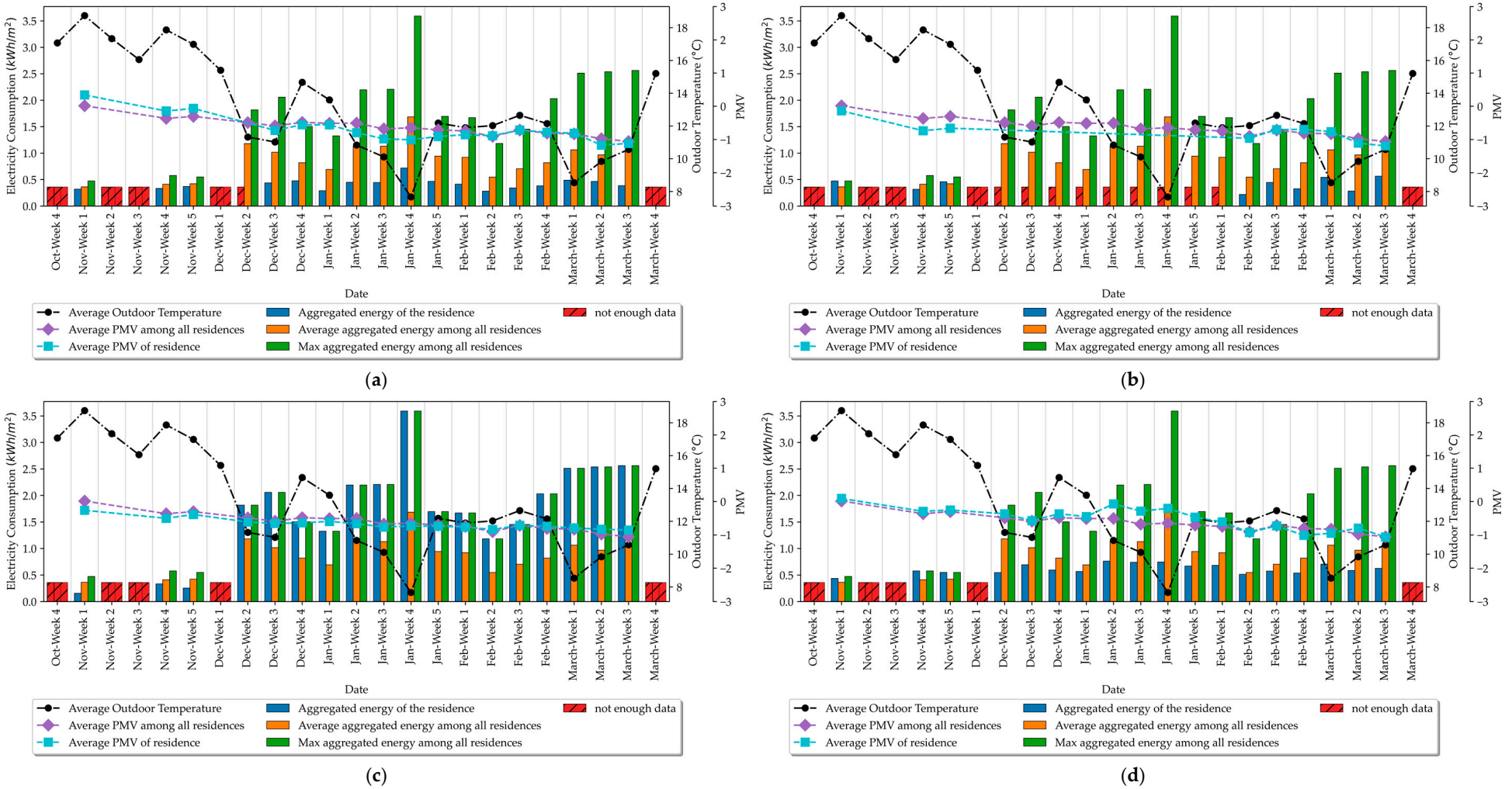


Figure 5. Weekly progress of aggregated electricity and average PMV in the winter experimental period regarding: (**a**) residence W-1; (**b**) residence W-2; (**c**) residence W-3; (**d**) residence W-4.

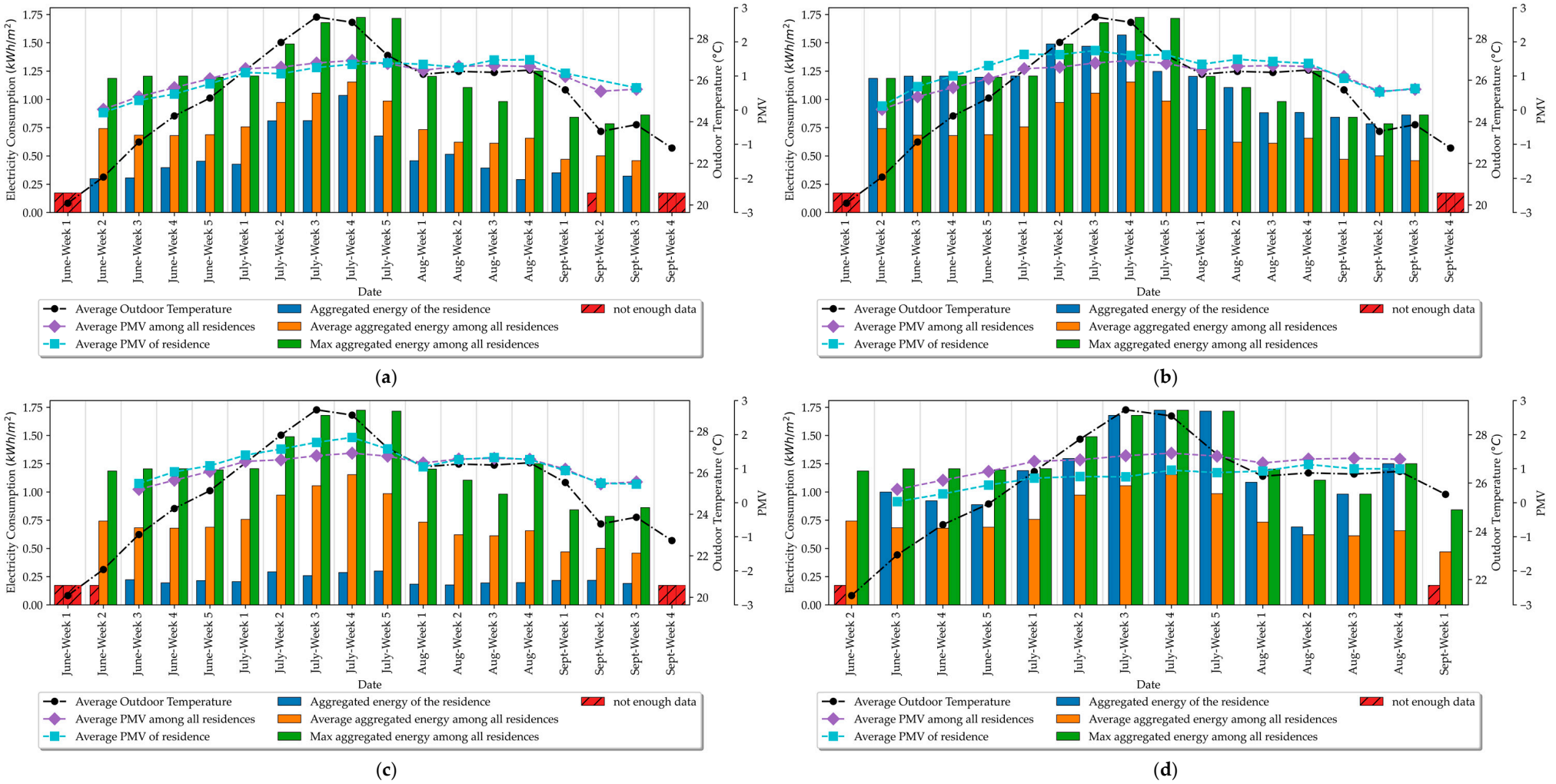


Figure 6. Weekly progress of aggregated electricity and average PMV in the summer experimental period regarding: (**a**) residence S-1; (**b**) residence S-2; (**c**) residence S-3; (**d**) residence S-4.

For the winter experiment, in Figure 5, it is noticed that in all specimens, at least 12 h of zero or absent electricity measurements occurred within at least 5 weeks (weeks with "not enough data" in the graphs). The missing data are especially tremendous in W-2, which presents not enough data during December and January. This happened because the user changed the Wi-Fi router and difficulties in Wibeee re-configuring occurred, not only from a technical point of view, but also in terms of arranging the appointment with the tenant for repairing the device. In the other cases, fewer problems occurred and the weeks with not enough data were more scattered. Fortunately, the other residences possess about three consecutive months of "healthy" data from December to March. These occasions underline the weakness of the selected meter, which despite its low intrusiveness, still depends on the compatibility and stability of the internet connection; which, in turn, implies certain amount of user interference affecting the integrity of measurements. Concerning the weekly electricity consumed, in general, it is increased in low outdoor temperatures, which means an increase in electrical equipment use, including perhaps the systems that serve thermal comfort. On the other hand, as Heraklion is usually warm in October, the heating demand in October and November is usually low. This is also confirmed by the Greek EPBD, which reported 0 and 39 heating degree days in October and November, respectively [52]. This means that the early electricity recordings in this experiment are perhaps almost solely attributed to appliances other than heating; hence, the electricity increase in the following weeks (after mid-November) corresponds to heating purposes. It is also observed that in most cases, the PMV is retained above -1, which supports the latter argument. Individually, for each winter specimen, we have the following (refer to Figure 5):

- W-1: Early recordings (until the end of November) give a weekly electricity consumption of about 0.3 kWh/m^2. In the following months, it only slightly increases, which suggests that most likely, thermal comfort is satisfied by energy sources other than electricity. According to the energy inspection, an oil burner was documented, which, however, had been declared as a secondary system by the occupant (refer to Table 1). Since the PMV is retained at tolerable levels throughout the measurement period, it becomes evident that the oil burner was most likely used despite the user feedback. In relation to mean performance of other residences, it holds lower electricity consumption. During the coldest weeks, a PMV lower than the houses' average is obtained, implying a possible sacrifice of comfort for the sake of saving energy cost.
- W-2: Surprisingly, despite a central heat pump being the only system, the electricity consumption ranges within only 0.3–0.5 kWh/m^2 at all weeks with enough data, even under low outdoor temperatures in February and March. It shows minimal increases in comparison to the early recording period. The PMV remains well above -1; thus, the space must have been conditioned. This means that an alternative system is either used or the Wibeee meter malfunctioned. As reported previously, the access to this particular household was limited, so further investigation was impossible.
- W-3: In this specimen, the use of electrical heating systems (e.g., the central heat pump reported by the tenant in Table 1) becomes clear as we are moving towards the colder months. In the buffering season (October–November), the electricity consumption ranges at around 0.3 kWh/m^2 and it peaks at 3.5 kWh/m^2 in the coldest week (4th week of January). In general, the amount of electricity consumed is analogous to the outdoor temperature. At all weeks, the PMV is above -1. This residence holds the highest electricity consumption among the examined houses. Since it amounts to a consumption similar to the rest houses in the early (buffering) period, most likely corresponding to appliances other than heating, the weekly increase may be attributed solely to the use of electrical heating systems.

- W-4: In the early recording period, this residence consumes about 0.5 kWh/m^2 on a weekly basis, which most probably refers to non-heating-related systems. Similarly to W-1 and W-2, the consumption only slightly increases as moving towards colder months. This means that the energy-efficient fireplace, declared as secondary heating system by the user, was probably used frequently. This is also evident by the mean thermal comfort conditions, as this specific residence enjoys the closest to PMV = 0 compared to the other ones.

For the summer experiment in Figure 6, it is first noticed that data of better quality are obtained, compared to the winter experiment, since the weeks with not enough data are by far less than the winter survey. For the period from the 1st week of June to the 4th week of September, only three weeks presented data loss, except for S-4, which shows data completeness but for a shorter period i.e., from the 3rd week of June until the end of August. In all cases, it is seen that the electricity consumption gradually increases as we are moving towards July, following the gradual increase of outdoor temperature. In Heraklion, May and early June present moderate outdoor temperature corresponding to low cooling energy demand. This also complies with the relevant technical directive which reports 0 and only 12 cooling degree hours in May and June, respectively [52]. Hence, the increase in electricity consumption as moving towards July is most likely due to the more frequent use of electrical cooling and/or ventilation systems.

Individually, for each residence during the summer experiment, we have the following (refer to Figure 6):

- S-1: In the early recording period (week 2 and 3 of June), the weekly electricity consumption is about 0.25 kWh/m^2 and demonstrates a max increase by 0.75 kWh/m^2 in July, when the electricity consumption peaks. This difference may be solely allocated to the mixed use of the A/Cs and ventilation standing fans reported by the occupant. The PMV is marginally held below 1 in the hottest periods; thus, it seems that the user is coping with warm conditions.
- S-2: In week 2 and 3 of June, it presents a stable electricity consumption at around 1.23 kWh/m^2 being much higher compared to S-1 and S-3 in the same period. This may be due to the much more frequent use of the cooling and other systems, considering also that only one A/C unit exists. Again, the PMV is close to 1 but during the hottest periods it even exceeds that value dictating warm sensations in the house. This happens perhaps because the construction is quite old and the heat gain might still be high despite the recent thermal insulation application (reported by the user).
- S-3: Similarly to S-1, it indicates electricity consumption at around 0.25 kWh/m^2 in the 3rd week of June; however, it remains very low throughout the experimental period. This may be justified by the fact that a very limited use of the A/C is reported while only one person lives in the apartment. On the other hand, the PMV is well above 1, which suggests that the tenant is content with warm conditions.
- S-4: It demonstrates similar trends to the S-2 above. Unlike the other cases, it holds better thermal comfort conditions (PMV closer to 0). This is perhaps because it is a more recent construction with better resistance to heat gains. In July, when the max outdoor temperature takes place, this residence holds the highest electricity consumption among all specimens.

Focusing on the distribution of energy consumption with respect to PMV and the frequency of PMV intervals over three periods of the day, the results are presented in Table 3. According to the approach described in Section 2.3.2, the following result is tabulated: over the various 0.5-step of PMV intervals, the respective aggregated electricity consumption is provided together with the frequency of PMV-interval occurrence as well as the latter's distribution over the three periods of the day, i.e., morning–noon, afternoon–evening, and

nocturnal. Concerning the winter experiment, it is seen that in all residences, the PMV intervals between −1 and 0.5 hold the highest frequency ranging from 69.46% for W-2 to 92.95% for W-3. This means that in all residences, slightly cool to almost neutral conditions prevail. In this PMV range, the highest aggregated electricity consumption also occurs, demonstrating more frequent systems' operation. Residence W-3 reaches electricity consumption as high as 26 kWh/m^2 for $-1 \leq \text{PMV} \leq -0.5$, which advocates a high contribution of the central heat pump. Referring to the daily distribution of PMV, it is observed that the neutral conditions (i.e., $-0.5 \leq \text{PMV} \leq 0.5$) present a higher occurrence frequency in the afternoon–evening hours (16.00–24.00) when the highest occupancy is anticipated. This is based on the assumption that during the morning–noon hours, members of the family might be outside for work or other activities (school, groceries, and recreation). Moreover, the nocturnal hours normally correspond to bedtime when the systems are less used and the occupant is under bedcovers. Concerning the summer experiment, contrary to the winter finding, most specimens, specifically S-1, S-2, and S-3, demonstrate higher deviation from thermal comfort, holding a frequency of PMV intervals within $-0.5 \leq \text{PMV} \leq 1$ that ranges between 37.94% (S-2) and 48.81% (S-1). This is followed by the $1 \leq \text{PMV} \leq 1.5$ interval with an occurrence frequency ranging at around 30% for all specimens. Only the S-4 gives a $-0.5 \leq \text{PMV} \leq 1$ occurrence frequency approximately 70%. Consequently, unlike the winter cases, higher deviations from thermal comfort are observed for the summer residences, advocating a higher tolerance to warm conditions. The peak electricity consumption is obtained in the $0.5 \leq \text{PMV} \leq 1$ interval for S-4 and in the $1 < \text{PMV} \leq 1.5$ interval for the others, which confirms the more intense use of cooling systems towards set-point accomplishment. The observed lag of peak electricity consumption in achieving thermal comfort also suggests that the cooling systems might be either underused or have capacity less than that required to compensate heat gains. The S-4 presents the least lag in achieving thermal comfort, which is perhaps attributed to the highest electricity consumption (7.154 kWh/m^2) corresponding to the $0.5 \leq \text{PMV} \leq 1$ interval in relation to the other houses. Regarding the daily variation, it is seen that the intervals within the range $0 \leq \text{PMV} \leq 1$ prevail in afternoon–evening and nocturnal hours, showing an almost equal distribution among all specimens, except S-4, for which the interval occurs by almost 20% more times in nocturnal hours.

Table 3. Daily PMV distribution and respective electricity consumption for the winter and summer experiments.

Residence No.	PMV Interval	Aggregated Electricity Consumption (kWh/m^2)	No. of Hours Corresponding to PMV Interval	Percentage of Hours Corresponding to PMV Interval	% of Morning–Noon Hours (Within 08:00–16:00)	% of Afternoon–Evening Hours (Within 16:00–24:00)	% of Nocturnal Hours (Within 24:00–08:00)
W-1	(−2.0, −1.5)	0.023	20	0.56%	25.00%	10.00%	65.00%
	(−1.5, −1.0)	1.787	847	23.66%	40.02%	17.83%	42.15%
	(−1.0, −0.5)	2.908	1296	36.20%	30.71%	34.49%	34.80%
	(−0.5, 0.0)	2.997	937	26.17%	30.84%	45.46%	23.69%
	(0.0, 0.5)	1.099	441	12.32%	34.69%	35.15%	30.16%
	(0.5, 1.0)	0.101	39	1.09%	23.08%	66.67%	10.26%
W-2	(−2.0, −1.5)	0.103	40	1.58%	50.00%	30.00%	20.00%
	(−1.5, −1.0)	2.695	735	28.96%	44.22%	32.79%	22.99%
	(−1.0, −0.5)	3.602	1169	46.06%	31.31%	32.34%	36.36%
	(−0.5, 0.0)	2.157	435	17.14%	22.99%	33.56%	43.45%
	(0.0, 0.5)	0.878	159	6.26%	20.75%	45.28%	33.96%

Table 3. *Cont.*

Residence No.	PMV Interval	Aggregated Electricity Consumption (kWh/m^2)	No. of Hours Corresponding to PMV Interval	Percentage of Hours Corresponding to PMV Interval	% of Morning–Noon Hours (Within 08:00–16:00)	% of Afternoon–Evening Hours (Within 16:00–24:00)	% of Nocturnal Hours (Within 24:00–08:00)
W-3	(−1.5, −1.0)	0.953	224	6.17%	44.64%	11.61%	43.75%
	(−1.0, −0.5)	26.145	2652	73.02%	35.67%	30.24%	34.09%
	(−0.5, 0.0)	4.849	710	19.55%	22.39%	50.56%	27.04%
	(0.0, 0.5)	0.181	14	0.39%	28.57%	28.57%	42.86%
	(0.5, 1.0)	0.176	16	0.44%	18.75%	56.25%	25.00%
	(1.0, 1.5)	0.120	16	0.44%	0.00%	75.00%	25.00%
W-4	(−2.0, −1.5)	0.024	5	0.14%	100.00%	0.00%	0.00%
	(−1.5, −1.0)	1.917	505	13.98%	39.80%	28.91%	31.29%
	(−1.0, −0.5)	5.421	1415	39.16%	40.78%	31.02%	28.20%
	(−0.5, 0.0)	4.217	1121	31.03%	30.33%	32.47%	37.20%
	(0.0, 0.5)	1.719	541	14.97%	14.79%	43.62%	41.59%
	(0.5, 1.0)	0.075	26	0.72%	0.00%	50.00%	50.00%
S-1	(−1.5, −1.0)	0.003	4	0.14%	50.00%	0.00%	50.00%
	(−1.0, −0.5)	0.130	70	2.41%	52.86%	2.86%	44.29%
	(−0.5, 0.0)	0.523	200	6.89%	34.00%	22.50%	43.50%
	(0.0, 0.5)	1.930	539	18.58%	41.37%	26.72%	31.91%
	(0.5, 1.0)	2.046	677	23.34%	30.28%	38.70%	31.02%
	(1.0, 1.5)	2.185	861	29.68%	35.54%	28.11%	36.35%
	(1.5, 2.0)	1.289	507	17.48%	23.08%	48.13%	28.80%
	(2.0, 2.5)	0.206	43	1.48%	16.28%	55.81%	27.91%
S-2	(−0.5, 0.0)	0.967	138	4.71%	41.30%	28.26%	30.43%
	(0.0, 0.5)	1.678	285	9.73%	34.74%	35.09%	30.18%
	(0.5, 1.0)	4.034	688	23.50%	33.28%	32.85%	33.87%
	(1.0, 1.5)	6.494	945	32.27%	34.39%	34.18%	31.43%
	(1.5, 2.0)	6.059	828	28.28%	29.23%	33.82%	36.96%
	(2.0, 2.5)	0.490	44	1.50%	54.55%	18.18%	27.27%
S-3	(−1.0, −0.5)	0.000	2	0.07%	0.00%	0.00%	100.00%
	(−0.5, 0.0)	0.191	144	5.03%	39.58%	36.81%	23.61%
	(0.0, 0.5)	0.471	379	13.23%	34.56%	23.75%	41.69%
	(0.5, 1.0)	0.907	690	24.09%	30.43%	35.51%	34.06%
	(1.0, 1.5)	1.261	1045	36.49%	32.44%	33.40%	34.16%
	(1.5, 2.0)	0.715	457	15.96%	37.64%	35.89%	26.48%
	(2.0, 2.5)	0.241	126	4.40%	35.71%	39.68%	24.60%
	(2.5, 3.0)	0.046	21	0.73%	52.38%	47.62%	0.00%
S-4	(−0.5, 0.0)	0.727	143	6.62%	32.17%	16.78%	51.05%
	(0.0, 0.5)	2.843	471	21.82%	28.66%	26.96%	44.37%
	(0.5, 1.0)	7.154	904	41.87%	29.54%	30.97%	39.49%
	(1.0, 1.5)	4.452	624	28.90%	41.67%	45.35%	12.98%
	(1.5, 2.0)	0.139	17	0.79%	64.71%	35.29%	0.00%

In the perspective of electricity consumption and thermal comfort relationships, non-zero electricity observations from the database are elaborated in terms of aggregating the hourly electricity consumption for each 0.5-step PMV interval within the thermal sensation scale from −3 to 3. In pairing with the aggregated electricity consumption, each PMV interval is represented by its average of the corresponding hourly PMV values. The results are presented in Figures 7 and 8 for the winter and summer experiment, respectively. To account for the outdoor temperature variation, the procedure is repeated for three outdoor temperature intervals with a very close number of non-zero electricity observations (i.e., the number of non-zero electricity hours deviating by not more than 5%). This means that the temperature intervals are not predefined; instead, the developed algorithm automatically detects them based on the aforementioned constraint. For this reason, the temperature intervals are not exactly the same among the examined residences (however, they are similar according to the 5% relaxation in the accounted number of observations). For both the winter and the summer cases, bell-shaped graphs are produced, indicating a max electricity consumption. On either side of the electricity peak, the consumption is reduced to close to

zero levels. As far as the winter survey is concerned, in agreement with previous outcomes, under low and moderate outdoor temperatures, the electricity consumption is maximized within the $-1 \leq \text{PMV} \leq -0.5$, and then it dramatically decreases. Consequently, there is indeed a delay in response of indoor thermal conditions to reach comfort levels. It is observed that W-1 and W-4 share a similar behavior. They hold the same order of magnitude of electricity and, interestingly, they both exhibit the least electricity consumption under the lowest outdoor temperature interval. This validates the previously reported observation that these residences use non-electrical heating systems. On the other hand, despite a central heat pump having been recorded in both the W-2 and W-3, they exhibit a difference in electricity consumption by one order of magnitude. This is because W-2 was a problematic case with a tremendous loss of data. Nevertheless, looking at the trend between these two cases, they both present the maximum consumption under the coldest ambient conditions, as anticipated. As expected, regarding the summer survey, the electricity consumption decreases as the outdoor temperature decreases, and the highest electricity is observed under the highest outdoor temperature interval, which corresponds to the intensification of cooling systems to achieve thermal comfort. Interestingly, as the outdoor temperature increases, the curve shifts to higher PMVs, which is again related to the intensification of cooling systems' use towards achieving thermal comfort. This is manifested as a lag in response of the indoor space to accomplish thermal comfort most likely due to inadequate systems' operation by means of either limited use frequency (limited use by the user) or lower capacity than that required to compensate heat gains. In comparison to the winter cases, the thermal-comfort lag is 0.5 higher in the PMV scale (the peak electricity consumption takes place mostly within the $1 \leq \text{PMV} \leq 1.5$ interval).

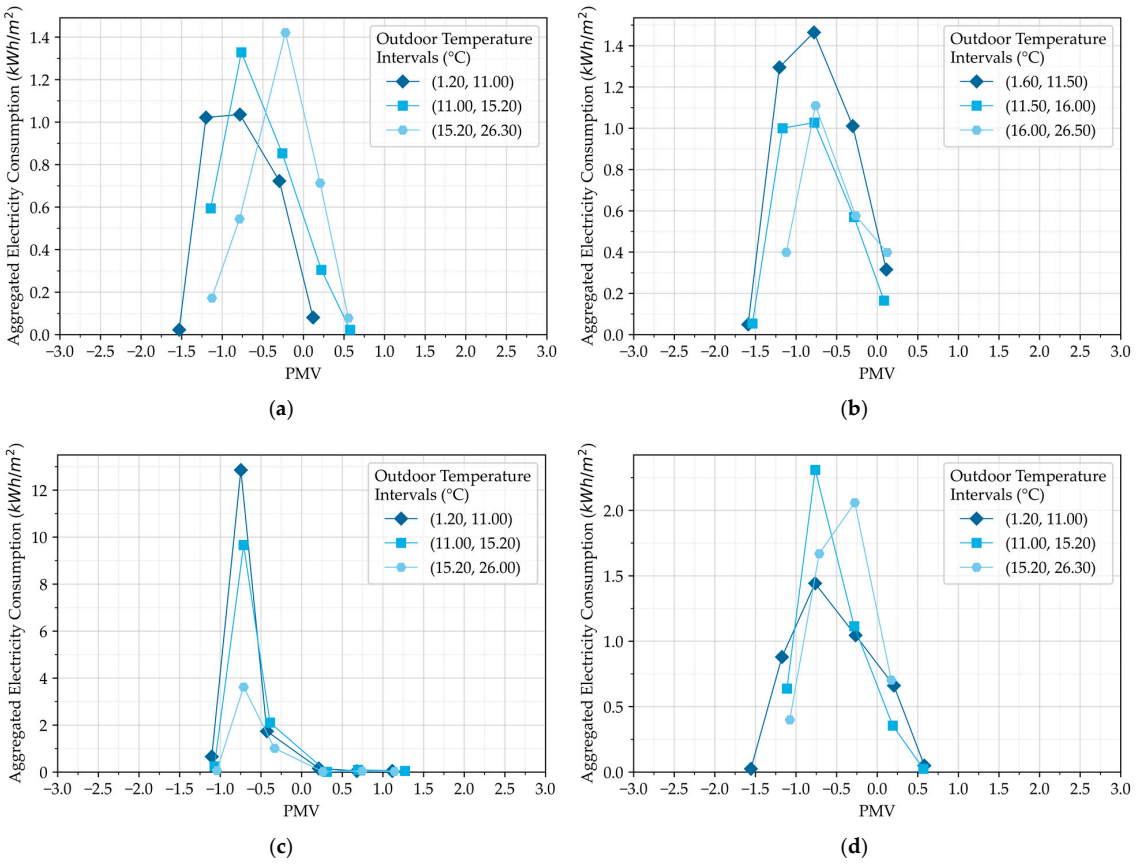


Figure 7. Aggregated electricity consumption and average PMV under different outdoor temperatures throughout the winter campaign for: (**a**) residence W-1; (**b**) residence W-2; (**c**) residence W-3; (**d**) residence W-4.

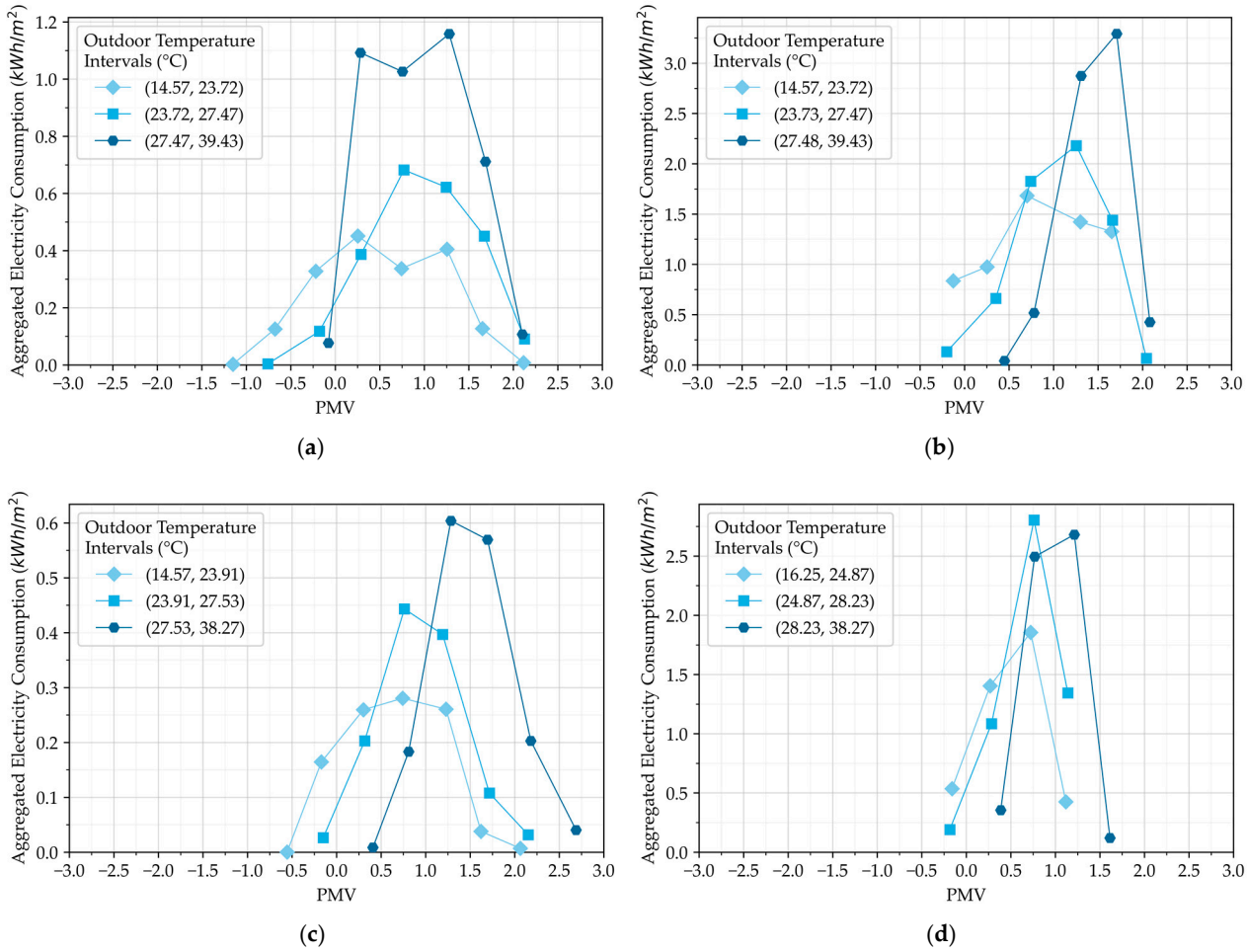


Figure 8. Aggregated electricity consumption and average PMV under different outdoor temperatures throughout the summer campaign for: (**a**) residence S-1; (**b**) residence S-2; (**c**) residence S-3; (**d**) residence S-4.

Finally, Table 4 consolidates representative results obtained by the suggested methodology. As tabulated, the summer experiment provided more complete data. However, the data manipulation process adopted herein is capable to extract conclusions even for cases with highly missing electricity data, hence providing a reliable view even for the winter cases. In the framework of the winter experiment, the minimum weekly electricity consumption ranges from 0.15 to 0.44 kWh/m^2, while the maximum one ranges from 0.56 to 3.59 kWh/m^2. Throughout the experiment, the mean PMV is in the range from -0.77 to -0.52 among all residences, corresponding to comfortable to slightly cold indoor spaces. The peak electricity consumption is calculated mostly within the $-1 \leq \text{PMV} \leq -0.5$ interval. Throughout the measurement period, the % of hours of the acceptable $-1 \leq \text{PMV} \leq 1$ interval (i.e., slightly cold to slightly warm conditions) ranges from 69.46% (W-2) to 93.39% (W-3); thus, all residences achieve an acceptable level of winter thermal comfort. Referring to the summer campaign, the minimum and maximum weekly electricity consumption among the studied residences ranged within 0.29–0.69 kWh/m^2 and 0.3–1.72 kWh/m^2, respectively. The mean PMV is calculated in the range from 0.74 to 1.19 among all specimens, corresponding to slightly warm indoor environments. The peak electricity consumption is observed mostly at $1 \leq \text{PMV} \leq 1.5$. Contrary to the winter cases, the % of hours with $-1 \leq \text{PMV} \leq 1$ ranges between 37.94% (S-2) and 51.22% (S-1) (with almost half frequency in the tighter margin $-0.5 \leq \text{PMV} \leq 0.5$) in three out of four houses. Consequently, in most cases, thermal comfort conditions deviate from the acceptable range. In terms of

comfort daily distribution, on the basis of the strictest PMV comfort margin, a mix between afternoon–evening and nocturnal hours is obtained in the winter cases, while the morning–noon and nocturnal hours possess more thermal-comfort hours in the summer cases.

Table 4. Consolidated results of residences' energy and thermal-comfort assessments.

Residence	W-1	W-2	W-3	W-4	S-1	S-2	S-3	S-4
Period of measurements (From-to)	26/10/2021–31/03/2022	26/10/2021–31/03/2022	26/10/2021–31/03/2022	26/10/2021–31/03/2022	01/06/2023–30/09/2023	01/06/2023–30/09/2023	01/06/2023–30/09/2023	09/06/2023–07/09/2023
No. of weeks with enough data	17	9	18	18	15	16	15	12
Total electricity consumption (kWh/m^2)	7.05	3.62	31.08	11.1	7.54	18.33	3.35	14.42
Mean daily electricity consumption ($kWh/m^2/d$)	0.059	0.057	0.246	0.088	0.071	0.163	0.031	0.171
Mean weekly electricity consumption (kWh/m^2)	0.414	0.402	1.726	0.616	0.502	1.145	0.223	1.201
Min weekly electricity consumption (kWh/m^2)	0.28	0.22	0.15	0.44	0.29	0.78	0.18	0.69
Max weekly electricity consumption (kWh/m^2)	0.72	0.56	3.59	0.76	1.03	1.57	0.3	1.72
Week with min electricity consumption	February Week 2	February Week 2	November Week 1	November Week 1	August Week 4	September Week 2	August Week 2	August Week 2
Week with max electricity consumption	January Week 4	March Week 3	January Week 4	January Week 2	July Week 4	July Week 4	July Week 5	July Week 4
Mean PMV throughout the experiment	−0.69	−0.77	−0.67	−0.52	0.99	1.19	1.18	0.74
Mean weekly PMV corresponding to the week with min electricity consumption	−0.89	−0.96	−0.26	0.09	1.48	0.53	1.27	1.12
Mean weekly PMV corresponding to the week with max electricity consumption	−1.01	−1.19	−0.73	−0.07	1.34	1.6	1.58	0.95
Max electricity consumption per PMV interval (kWh/m^2)	3.00	3.60	26.15	5.42	2.19	6.49	1.26	7.15
PMV interval allocated to max electricity consumption	(−0.5, 0.0)	(−1.0, −0.5)	(−1.0, −0.5)	(−1.0, −0.5)	(1.0, 1.5)	(1.0, 1.5)	(1.0, 1.5)	(0.5, 1.0)
Average PMV allocated to max electricity consumption	−0.24	−0.77	−0.72	−0.75	1.26	1.29	1.24	0.75

Table 4. *Cont.*

Residence	W-1	W-2	W-3	W-4	S-1	S-2	S-3	S-4
% of hours with $-1 \leq PMV \leq 1$	75.78%	69.46%	93.39%	85.88%	51.22%	37.94%	42.42%	70.31%
% of hours with $-0.5 \leq PMV \leq 0.5$	38.49%	23.40%	19.93%	46.00%	25.47%	14.45%	18.26%	28.44%
% morning–noon hours with $-0.5 \leq PMV \leq 0.5$	32.08%	22.39%	22.51%	25.27%	39.38%	36.88%	35.95%	29.48%
% afternoon–evening hours with $-0.5 \leq PMV \leq 0.5$	42.16%	36.70%	50.14%	36.10%	25.58%	32.86%	27.34%	24.59%
% nocturnal hours with $-0.5 \leq PMV \leq 0.5$	25.76%	40.91%	27.35%	38.63%	35.05%	30.26%	36.71%	45.93%

4. Discussion

The presented methodology provided useful results concerning the electricity use intensity in residences in relation to seasonal variations and to thermal comfort conditions. First, treating the database towards the temporal progression of electricity consumption in relation to outdoor temperature facilitates and tracing the periods of when electrical heating or cooling systems are used less, as well as the periods of enough data. In the current experiment, the total period of measurement was up to only 5 months; hence, the weekly time step was selected as the most suitable to investigate temporal progression of monitored parameters. The summer experiment provided more complete results in terms of longer periods with enough—but also consecutive—data (weeks with more than 12 h of absent or zero electricity consumption). Apart from the fact that more technical difficulties occurred (mainly Wi-Fi interruptions with limited access to repair, especially in W-2), in the winter experiment, the missing data may also be due to human errors in the installation and configuration of the electricity meter, as the involved technicians were not yet fully familiarized with the monitoring system (the winter preceded the summer experiment). In most of the examined cases in both seasons, the measurements exhibit an electricity consumption and thermal comfort pattern analogous to the outdoor temperature, as has been seen in other studies [14,33], i.e., when the outdoor temperature dictates cold or hot conditions, the electricity increases, indicating more frequent use of electrical appliances most likely including those for regulating indoor thermal comfort.

Taking into account the mild weather conditions and low heating degree days in October and November at the location of the experiment [52], it can be fairly assumed that the corresponding electricity consumption at the aforementioned early recording period refers to appliances other than (or limited) heating for the winter examined houses (refer to Figure 5). In these cases, this baseline consumption ranged at around 0.3 kWh/m^2 on a weekly basis. Looking at the propagation as moving towards the following winter months, the approach facilitates the identification of residences that most likely use non-electrical heating systems. To date, W-1 and W-4 present only a slight increase in electricity in the weeks from December to February, compared to the baseline. Considering that the mean weekly PMV is retained at acceptable levels, it can be fairly assumed that these houses use different systems for heating purposes, most likely the ones recorded as secondary in Table 1. In contrast, W-3, which uses a central heat pump, shows a clear elevation of the weekly electricity in the colder months, with the maximum elevation being from 0.15 kWh/m^2 in October to 3.59 kWh/m^2 in the fourth week of January when the minimum outdoor temperature occurs. A central heat pump was also reported for W-2, although

limited elevation in electricity is observed during February and March (when the outdoor temperature was still low) in relation to the baseline period (end of October).

As for the summer campaign, the residences S-1 and S-3 exhibit a similar electricity consumption at around 0.25 kWh/m^2 in the early recording period (in June) when a low cooling demand is expected in Heraklion [52]. However, while S-1 shows a max increase in electricity consumption of about 0.75 kWh/m^2 in July, S-3 presents practically constant weekly electricity consumption throughout the measurement period. This finding confirms the limited use of A/Cs in S-3 compared to the continuous use in S-1, as reported by the tenants and tabulated in Table 1. This, however, could be also attributed to possible longer periods of low occupancy in the former residence (considering perhaps more extended holidays in S-3). On the other hand, S-2 and S-4 show a similar trend in temporal progression of electricity consumption with a baseline weekly consumption in the early period in June at around 1 kWh/m^2, reaching its peak at around 1.6 kWh/m^2 in July when the maximum outdoor temperature occurs. Considering the similar cooling systems reported in Table 1, this elevation for both residences may be attributed to the A/Cs use for cooling purposes. Interestingly, as reported in Table 4, the minimum electricity consumption occurs in August or September, and not in June, which is assumed as the baseline. This is simply because August is the most common holiday season in Greece; hence, the minimum consumption is most likely simply due to less occupancy.

In compliance with other approaches [53,54], the current study provides the PMV daily distribution and respective electricity consumption (refer to Table 3). As long as any fault recordings are excluded according to the manipulation algorithm described in Section 2.3.2 (i.e., data series with zero or absent electricity are excluded from the processing), acceptable results are expected even for cases with extensive missing data. In all cases during the winter experiment, it is found that the PMV range from -1 to 0.5 holds the highest occurrence frequency, ranging from 69.46% to 92.95%, indicating slightly cool to almost neutral conditions. The almost neutral conditions ($-0.5 \leq$ PMV ≤ 0.5) present a higher occurrence frequency in the afternoon–evening hours (16.00–24.00), when the highest occupancy is expected. Contrary to the winter cases, S-1, S-2, and S-3 indicate higher deviation from thermal comfort, i.e., the frequency of PMV intervals within $-0.5 \leq$ PMV ≤ 1 ranges from 37.94% to 48.81%. This is followed by the $1 \leq$ PMV ≤ 1.5 interval accounting for approximately 30% of recordings for most specimens. Only the S-4 retains a $-0.5 \leq$ PMV ≤ 1 occurrence frequency at approximately 70%. The findings dictate a higher tolerance to warm conditions in relation to the cold conditions in winter. The peak electricity consumption is now obtained mostly in the $1 <$ PMV ≤ 1.5 interval presenting a higher deviation from thermal comfort compared to that occurred in the winter cases. On the basis of the consolidated results presented in Table 4, it is confirmed that the winter residences obtain better thermal comfort conditions. For the winter residences, the % of hours of $-1 \leq$ PMV ≤ 1 (i.e., slightly cold to slightly warm conditions) ranges from 69.46% (W-2) to 93.39% (W-3), whereas the % of hours of the same PMV range is only between 37.94% (S-2) and 51.22% (S-1) in three out of four houses in the summer campaign. Evidently, in the summer period, the studied households present higher deviation from thermal comfort compared to the ones in the winter experiment. Considering the uncontrollable conditions in the studied houses, the observed seasonal asymmetry could be attributed to the tolerance of the tenant with respect to habitat. To account for this aspect, Fanger and Toftum [55] have suggested the incorporation of an expectancy factor in the original PMV model based on the subject's habitat. As proposed in another study regarding an urban microclimate in Greece [41], if this alternative is adopted, then the PMV would have been better adjusted to the expected thermal sensations in the Greek context in summer. On the other hand, such a seasonal asymmetry is not anticipated in the case of more controllable heating and cooling

environments. For example, as found in Ref. [24] regarding a building with a central heat pump system with temperature control, similar margins of PMV from neutrality were observed between the winter and summer periods.

As far as the electricity consumption is concerned, the weekly electricity consumption ranges within 0.15–3.59 kWh/m^2 and 0.29–1.72 kWh/m^2 for the residences examined in the winter and summer campaign, respectively (refer to Table 4). In the former case, the mean weekly PMV ranges from -0.77 to -0.52, while in the latter case, the mean weekly PMV ranges from 0.74 to 1.19, supporting the argument that better indoor thermal comfort is achieved in the winter cases. As depicted in Figure 8, the electricity consumption in the summer cases peaks mostly within the $1 \leq \text{PMV} \leq 1.5$ interval (contrary to the winter case for which it peaks within $-1 \leq \text{PMV} \leq -0.5$, as illustrated in Figure 7). This stands for a lag in achieving indoor thermal comfort, higher in the summer case, most likely due to inadequate systems' operation by means of either limited use frequency (limited use by the user) or lower capacity than that required to compensate cooling loads. Relying on W-3, for which it is evident that heating is mostly served by the electrical central heat pump, and on either S-2 or S-4, which present a clear use of A/C or ventilation systems in summer, it may be (at least empirically) concluded that the weekly electricity consumption is slightly higher in winter compared to the summer period. Indicatively, according to Table 4, W-3 holds a mean weekly electricity consumption of 1.726 kWh/m^2, while S-2 and S-4 record, respectively, 1.145 kWh/m^2 and 1.201 kWh/m^2. It is underlined that the daily electricity consumption data in Table 4 are similar to those presented in Ref. [56], which enlists actual electricity consumption for Greek households. This supports fidelity on the electricity data presented in the current study and, eventually, the fidelity of further data processing. Complementarily to Ref. [54], which presents Energy-PMV graphical correlations but for office buildings, the current study presents electricity consumption-PMV graphs for the studied cases in Figures 7 and 8. The produced bell-shaped curves allow to identify the electricity peaks and the corresponding PMV interval in relation to the comfort zone $-0.5 \leq \text{PMV} \leq 0.5$. The graphs may be further elaborated in the framework of regression analysis towards the extraction of mathematical correlations.

An obvious limitation of the current research refers to the energy consumption measurements, which include only the total electricity consumption. Therefore, in the absence of the disaggregated electricity per end-use, the electricity part attributed to heating or cooling purposes is not precise. On the other hand, since some residences, particularly in winter, most likely use non-electrical heating systems, additional monitoring equipment (e.g., thermal energy meter) would also be useful to identify the residential end-use energy share. Another limitation refers to the uncontrollable conditions in households. In real-life cases, as presented herein, neither is access to the house limitless nor are the occupancy pattern and user's habits precisely known. In such uncontrollable environments, it is extremely difficult to capture accurately the systems' use schedule or to ensure free access for repairing possible damage or faults of the monitoring equipment. At least for practical engineering purposes, the proposed methodology tackles the aforementioned issues by relying on potential baseline energy consumption corresponding to the recording periods when the ambient conditions indicate minimal heating or cooling demand. Moreover, the possible occupancy patterns and energy consumption are also interpreted in terms of occurrence frequency of PMV intervals in relation to electricity consumption. A key advantage in this context is that the suggested algorithm provides results also for cases with high amount of missing data. Considering, however, the observed divergence from thermal comfort based on the PMV model indicates some additional possible limitations regarding the representativeness of the position of the air-temperature and RH meter, the assumptions adopted in converting these measurements to PMV, and the absence of

a survey for recording the actual thermal sensation. For future research, the following activities may be recommended:

- Enrich the energy monitoring system with thermal meters installed at the hot water network towards thermal energy monitoring in cases when boilers are recorded for space heating. In addition, electricity meters per circuit in the central electrical panel are required for disaggregated electricity measurements.
- For improved assessments of occupancy patterns and thermal comfort, a targeted questionnaire survey could be also undertaken, focusing on recording the daily routines over outdoor activities and systems' use, the personal parameters (e.g., activity and clothing), as well as the actual thermal sensation. Such a questionnaire would be completed on a daily basis by the tenant and then provided to the research team for further elaboration towards a better understanding of energy consumption, occupancy patterns, and indoor perception of thermal comfort in relation to seasonal variations.
- Conduct a sensitivity analysis to determine which factors (e.g., outdoor temperature and household occupancy) have the most significant impact on energy consumption and comfort.
- Extend the participative activity by implementing and monitoring personalized recommendations for behavioral shifts towards more active participation of tenants in practicing rational use of energy in their own homes.
- Expand the improved approach, based on the above suggestions, to additional residences and increase the research sample towards the formulation of robust recommendations for interested stakeholders (e.g., policy makers and building designers) to promote technological interventions and practices for behavioral shifts in the residential sector.

5. Conclusions

This paper presents a methodology for integrated energy and thermal comfort assessments in residential units. Low-invasive meters, including feedback measures, are installed for both the electricity consumption and the indoor air temperature and relative humidity. A specialized data processing algorithm is developed for elaborating electricity recordings and for converting the hourly measurements of indoor environmental parameters to the PMV index. To confront possible distortion of outcomes, the algorithm manipulates only eligible data series, i.e., excluding the ones that correspond to zero or absent electricity which refer to errors in measurement. Initially, the weekly propagation of electricity consumption and mean PMV is provided accounting for weeks with more than 12 h of non-zero electricity measurements as being considered of enough data to illustrate the temporal progression of energy consumption and thermal comfort. The procedure allowed to identify the potential baseline weekly energy consumption, attributed mostly to end-uses other than (or of limited) heating or cooling. The baseline, together with the PMV, allowed further understanding of the level of use of electrical heating or cooling devices throughout the experiments. To provide insight concerning the energy consumption and thermal comfort, the algorithm is extended to count the number of hours of representative PMV intervals within the thermal comfort scale and identify the occurrence frequency of comfort PMV ranges on both throughout the period of measurements and on a daily distribution fashion. Although applied to a specific case of Greek residences, the methodology is general and can be easily employed to other buildings in terms of type, use, and location. For the cases studied herein, the following conclusions are drawn:

- The acceptable range of $-1 \leq \text{PMV} \leq 1$ interval holds an occurrence frequency from 69.46% to 93.39% and from 37.94% to 70.31% for the winter and summer months in the examined cases, respectively;

- The weekly electricity consumption and mean PMV ranges within 0.15–3.59 kWh/m^2 and from -0.77 to -0.52, respectively, regarding the residences during the winter experiment (monitored from the end of October to the end of March);
- The $-1 \leq$ PMV ≤ 0.5 range holds the highest occurrence frequency, i.e., ranging from 69.46% to 92.95% of the eligible measurement hours, indicating slightly cool to almost neutral conditions in the households during the winter experiment;
- The weekly electricity consumption and the mean PMV ranges within 0.29–1.72 kWh/m^2 and from 0.74 to 1.19, respectively, concerning the residences during the summer experiment (monitored from June to September);
- In three out of the four residences during the summer campaign, the $-0.5 \leq$ PMV ≤ 1 interval ranged from 37.94% to 48.81% of the eligible measurement hours, followed by the $1 \leq$ PMV ≤ 1.5 interval accounting for approximately 30% of recording hours;
- While the electricity consumption peaks within the $-1 \leq$ PMV ≤ -0.5 interval in the winter experiment, the peak in the summer experiment is observed mostly within the $1 \leq$ PMV ≤ 1.5 interval;
- Thermal comfort is better regulated in the heating season, while in summer, higher deviation from thermal comfort is observed. This may be attributed to higher tolerance to warm conditions or inadequate cooling in terms of either systems' use frequency or less cooling capacity than that required.

It is concluded that the initiative "Municipality transition towards low-carbon economy through citizen participative procedures" is a good practice in getting the citizens involved in energy saving efforts, starting from a personalized consultation on the energy consumption and related implications of their own houses. Through the envisaged feedback measures, a more informed awareness raising is ensured making the citizen an active part of the energy transition roadmap. From a technical point of view, it is also concluded that the energy-consumption and thermal-comfort correlations provided herein contribute to the prospect of improved energy efficiency studies having the thermal comfort aspect included in residential energy rating/benchmarking and in the assessment of alternative energy renovation scenarios. This also contributes to the evaluation of households from the point of view of energy poverty, i.e., the level that they meet their energy needs. In this sense, more informed subsidy programs may be designed for residences' energy renovations under adequate and objective prioritization criteria of eligible buildings. In a broader context, the current study aligns with LEVEL(s), the new European Commission's framework for sustainable buildings which proposes an integrative way of sustainable building design, implementation, and operation, envisaging the assessment and monitoring, apart from energy performance, the indoor comfort, air quality, and circular economy principles. The presented results may further contribute to PMV-based controls in the residential sector but also in the framework of smart buildings in general. To that end, this paper directs readers to the measurements database through a publicly accessible repository (without exposing any personal information) for further investigation towards novel behavioral and technological developments in regulating energy efficiency and thermal comfort under non-controllable conditions in real-life buildings.

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Data Availability Statement: The original database used in the study is openly available in GitHub repository at https://github.com/dbakirtzis/participativeinitiative (accessed on 9 January 2025).

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