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Analysis of thermal energy storage tanks and PV panels combinations in different buildings controlled through model predictive control

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Abstract

The present study analyses the performance of a heating system controlled by a model predictive control strategy, where the impact of different combinations of thermal energy storage tank volumes and installed PV power capacities are analysed. The novelty of the paper lies in studying both economic and energy impacts of each equipment combination in different locations, buildings, and indoor occupancy schedules. The payback period, the reduction of the electricity grid consumption, and the behaviour of the coefficient of performance of the heat pump are studied in detail for all cases. Results point out that from an economic point of view, to invest in a thermal energy storage tank provides shorter payback periods in comparison to scenarios with PV panels, due to the high price of the solar elements. However, the energy performance analysis highlighted that the use of PV panels contributes to achieve up to 34%, 54%, and 90% of reduction of the electricity grid consumption in Helsinki, Strasbourg, and Athens, respectively. Finally, it is worth noting that the increase of the thermal energy storage volume improves the coefficient of performance of the heat pump.

Keywords: Thermal energy storage; model predictive control; building energy management; occupancy patterns

Nomenclature

E	electrical energy, kWh
price	electricity price from the grid, €/kWh
$\dot{Q}$	thermal power, kW
act	Boolean variable to activate and deactivate
T	temperature, ºC
H	horizon, time slot
N	number of prediction horizon
P	power capacity of the PV panels, kWp
V	volume of the TES tank, l
PB	payback, years
PoI	annual percentage of electricity price increasing, %
cost	electricity cost from the grid, €
a	period until the initial investment is recovered, years
I_0	initial investment, €
b	sum of cash flows at the end of year, €
F_t	cash flow of the year in which the investment is recovered, €

Greek Symbols

δ	delta time, s

Subscripts

out	outdoor
imp	impulsion
n	year
j	simulation time step
g	electricity grid
HP	heat pump
WT	water tank
PV	photovoltaic
HP-H	directing from heat pump to house
HP-WT	directing from heat pump to water tank
WT-H	directing from water tank to house

Abbreviations

TES	thermal energy storage
HVAC	heating, ventilation, and air conditioning

MPC	model predictive control
RBC	rule-based control
HP	heat pump
WT	water tank
ToU	time-of-use
HDD	heating degree day
COP	coefficient of performance
ICA	inner control algorithm

1. Introduction

According to the annual report of the World Economic Forum [1], climate change is one of the major global risks for our society. The United Nations highlighted climate action among their seventeen sustainable development goals framed within the 2030 Agenda, that calls all countries to promote prosperity while protecting the planet [2]. Due to the high rate of the energy production coming from fossil fuels, the accelerated global warming and problems arising from climate change became bigger during last years [3]. Following the current energy consumption behaviour without changing the energy sources is drawing a very worrying scenario from a global perspective. Therefore, experts have established the target to maintain the world temperature rise below to 2 ºC for 2050 compared to preindustrial levels [4]. Higher heating and cooling needs in some parts of the world contributed to this increase of energy consumption, driven by both a larger number of population and an improvement in the comfort requirements.

According to the European Commission, during the year 2019 in Europe, residential and service sectors represented 288 Mtoe (27%) and 154 Mtoe (14%) of the final energy consumption, respectively [5]. Thus, to reduce energy consumption coming from fossil fuels in these sectors is a key point to fight against climate change, since both amount to around 40% of the total final consumption.

An increasing of the energy efficiency in both equipment and processes can represent an important contribution to tackle this problem [6]. Also, a higher share of renewable energy sources can push to reduce energy production from fossil fuels, while energy requirements of the society are fully covered [7]. Although the use of renewable energy resources increased every year during last decade, the influence of the sector is still far to become crucial to overcome the climate change problem [8]. To increase the significance of renewables in the building sector, the easiest system to adapt to its characteristics is solar energy. Its capacity to be installed on the roof and to operate together with the electricity grid, considering the on-time necessities of the occupants make solar PV panels a suitable option for this kind of energy service. However, the main drawback to fully exploit the potential of PV panels is the mismatching between energy production and its consumption, which makes necessary another complementary technology to overcome this limitation. In that sense, researchers pointed out to thermal energy storage (TES) as one of the best options to mitigate this energy mismatching [9]. Its capacity to store energy at any time helped to promote solar PV panels integration and to encourage the users to take advantage of this clean energy source. However, there are strong limitations related to the implementation of this kind of systems, since the building sector has some particularities that need to be studied in more detail:

- **Occupancy schedule:** The aforementioned mismatching between the power generation from renewables and the building energy utilization is mainly due to the highly variable consumption patterns of the occupants [10]. The influence of the occupancy schedule in the heating, ventilation, and air conditioning (HVAC) operation was highlighted by Jung and Jazizadeh [11] and they found out high energy savings potential in a good occupancy assessment. Following this approach, this topic was undertaken by Guerra Santin et al. [12], where the energy required for space heating in a residential framework considering the influence of the occupancy was analysed. They noticed a 4.2% of variation in energy use for heating, due to the behaviour of the occupants. However, authors pointed out that this percentage could be larger, depending on both the type of building and the schedule that its occupants follows. Therefore, it is crucial to analyse which is the effect of the occupancy schedule in the energy consumption, taking into account a more exhaustive occupancy schedule variability such as the ones find in office and service buildings. In this way, Burak Gunay et al. [13] developed a sensitivity analysis for different types of buildings, where the influence of the occupancy schedule was evaluated. Authors highlighted its significance and they concluded that both the shape of the daily occupancy profile and the peak occupancy levels are two key parameters to determine the optimum operation of the HVAC systems. All this said, occupancy profile analysis and reliable prediction represents a key variable also affecting the energy efficiency performance of retrofit and optimization strategies, including both passive and active solutions [14,15]. As it is well-known, these occupancy variations are difficult to predict and control, since their profiles oscillate depending on the type of building, but also on non-physical parameters such as psychological, sociological, demographic patterns, and awareness levels [16]. Thus, to identify a control strategy able to tackle the fluctuations in occupancy parameters can contribute to obtain both more energy and economic savings. This analysis was carried out by Naylor et al. [17], which reviewed the main techniques to reduce the building energy use, considering different occupancy data. The authors pointed out model predictive control (MPC) strategies as an option with a big potential to obtain significant energy savings. Following the same line, the behaviour of MPC to control indoor spaces through HVAC equipment, considering different occupancy schedules, was analysed by Mirakhorli and Dong [18]. The authors identified the capacity of MPC to manage the possible disturbances generated for the occupancy when controlling the building climate system and its benefits against a traditional control strategy and a rule-based control (RBC) method. Another study of the impact of the occupancy schedule upon the HVAC performance was carried out by Yu and Pavlak [19]. The authors assessed an MPC strategy with a day-ahead horizon that took into account uncertainty in the occupancy patterns of three office buildings. Promising results were obtained from this study and the MPC strategy designed by the authors performed a good managing of the system. Similarly, Lee et al. [20] analysed the impact of occupancy variations in commercial buildings environment upon the capacity of an MPC strategy, obtaining encouraging savings. Nevertheless, the comparison was developed without analysing other occupancy profiles as residential buildings and offices. Therefore, all authors agree that a good solution to tackle the energy consumption that implies a strong variance in the occupancy profile of a building can be dealt with occupancy aware MPC strategies. However, more occupancy profiles should be evaluated to know the real capacity of MPC in different types of buildings.

- **Location:** Another crucial aspect to consider when implementing a renewable energy system with TES is the influence in the energy consumption caused by the building location. As it was stated by Pérez-Lombard et al. [21], one of the key factors to accurately determine the energy use of a specific building lies in a good assessment of its location and the weather conditions of such a place. This idea was also supported by Zhao and Magoulès [22], which identified the outdoor temperature and the solar radiation of a site as two variables that must be considered to define the weather profile of a region. Thus, it is necessary to discover a control strategy able to deal with different weather parameters to overcome the variations that different locations can introduce. Focusing on this idea, a further assessment was carried out by Tarragona et al. [23] in a heating system with both PV panels and TES. This system was controlled through an MPC strategy and authors analysed its behaviour in seventeen different locations with distinct weather conditions. The study demonstrated a robust performance of the controller in all climates and it turned out to be the one which obtained highest economic savings against the other employed control strategies. Therefore, other than the occupancy schedules MPC also appeared as a good option to manage the weather parameters given by different locations.

Overall, in the literature some authors studied the behaviour of MPC, emphasizing the ability of this control strategy to manage HVAC systems with TES in specific occupancy schedules [24,25] and certain locations [26,27]. In fact, it was demonstrated that its implementation significantly contributes to integrate renewable energy resources, to exploit the capacity given by the TES systems, and to reduce the peak demand [28-30]. Nevertheless, a global perspective of the influence of both PV panels and TES could be obtained, as well as a better knowledge of the robustness of MPC. Following this research path, a first approach was done by D'Ettorre et al. [31], where a correlation between the storage capacity of a TES system and some technical parameters of the MPC strategy was found. Also, Bechtel et al. [32] highlighted the importance to develop a good parametrization of TES tanks to fully exploit the HVAC capacity in systems controlled by an MPC strategy. However, the evaluation of the capacity of both elements PV panels and TES remains to be performed in multiple building types and weather conditions.

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The present paper tackles the importance to determine the influence of both building occupancy schedule and location upon the performance of a heating system. Demand variations due to occupancy profiles or weather conditions can have a great impact in the possibilities to include renewable energy sources. Therefore, to assess the chance to increase the renewable energy harvesting while the final energy cost is reduced in different working conditions is a challenge to contribute in the renewable energy deployment. This evaluation should be carried out adapting the size of the physical elements of the system to the environmental conditions, to be able to exploit the whole capacity of the equipment, without oversizing the system. The key variable identified in HVAC systems with renewable energy sources and TES was the relation between the renewable power production and the TES storage capacity. So far, a very good option to obtain a good trade-off between these two aspects was to include an MPC strategy upon the HVAC operation. The ability of the strategy to deal with all energy fluxes contributes to a very good management of the HVAC equipment, renewable energy sources, and TES tanks. However, to the knowledge of the authors there are no works in the literature that tackled this issue. Therefore, considering this framework, the novelty of this paper lies in analysing both economic and energetic impact of different PV panels and TES tank combinations available in the market upon a heating system adapted to distinct working scenarios and controlled by an MPC strategy. These different operation conditions defined a wide range of heterogeneous requirements in terms of heating demand, which highly variated depending on the scenario. In that sense, the employed occupancy profiles in this study were a residential apartment, an office building, and a hotel. Then, regarding the different climates, they were represented by three locations: Helsinki (cold), Strasbourg (temperate), and Athens (hot).

2. Methodology

2.1. Overview

A scheme of the main stages followed during the development of the study is shown in Figure 1. The first step was the selection of both buildings and climates employed to develop the heating simulations that were run later in the EnergyPlus software. After that, three steps were done in parallel: the selection of the PV panels and TES tank models, the sizing of the heat pump for all studied climates, and the import of the electricity price data, which followed a time-of-use (ToU) tariff structure. Later on, simulations for all cases were run with an MPC strategy, which aimed to reduce the electricity cost. To do that, the control strategy decided to switch-on the heat pump using either electricity that came from the PV panels or electricity from the grid during off-peak periods. Moreover, taking advantage of the TES tank, the system could store such an energy for future consumption hours. However, when the TES tank was discharged and no cheap electricity was available, the heating requirements of the buildings were supplied running the heat pump with electricity of the on-peak period. Finally, considering this system operation, an economic evaluation and an energy analysis of the impact of both PV panels and TES tank were carried out.

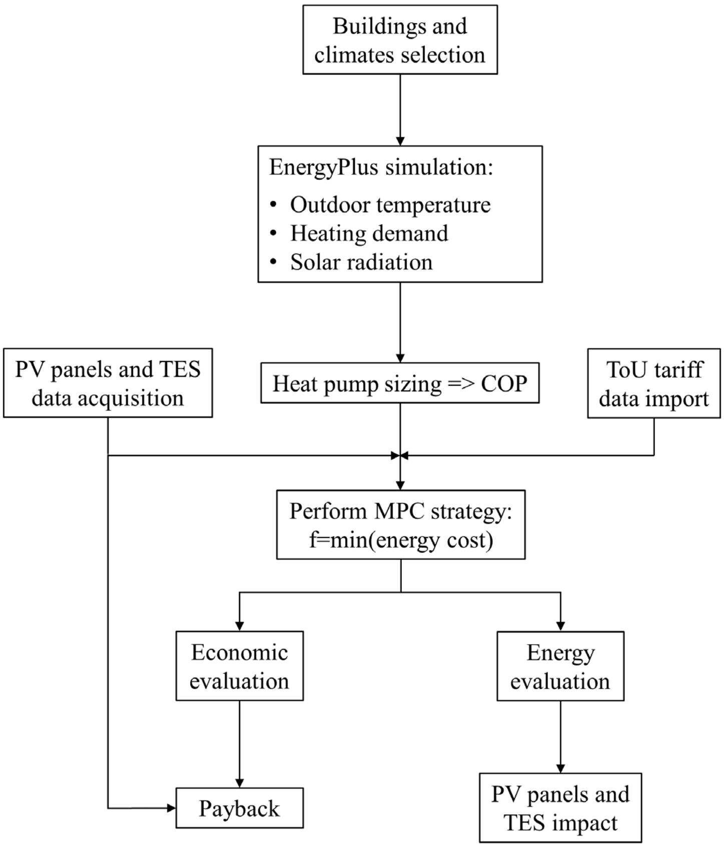


Figure 1. Workflow of the study.

2.2. Buildings description and weather data

Three representative building options were selected to perform this study: a residential apartment, an office building, and a hotel, in order to consider different typologies of occupancy schedules. It is worth noting that all simulations were run with EnergyPlus [33] and the building data and characteristics were imported from Halverson et al. [34], aiming to obtain the heating demand for all cases. Along the analysis, the same construction and window features were considered for the three types of buildings. These construction details can be seen Table 1. However, in all buildings, both occupancy and infiltration were assessed considering a determined fraction for each type of building or space, depending on the time of the day. On the one hand, the occupancy fraction provided the ratio of people who were in the building at each hour. On the other hand, the infiltration fraction gave the ratio of air changes per hour (ACH) due to the air infiltration through the building envelope (including doors and fenestration), upon the total air renovation of the building [35].

Table 1. Wall, roof, window, and floor details.

Exterior wall	
Construction type	Steel frame
R-value ($m^2 \cdot K/W$)	2.10
Roof	
Construction type	Insulation entirely above deck
R-value ($m^2 \cdot K/W$)	2.79
Window	
U-Factor ($W/m^2 \cdot K$)	5.84
Solar heat gain coefficient	0.39
Visible transmittance	0.22
Floor	
Floor type	Mass floor
Construction	4 in slab w/carpet
R-value ($m^2 \cdot K/W$)	0.54

2.2.1. Domestic

The building selected to simulate the domestic schedule was a multifamily mid-rise apartment of four floors, which both shape and scheme can be seen in Figure 2. The building area is 782 m^2, being 3128 m^2 the total floor area of the four floors and the window-to-wall ratio for all orientations is 20%.

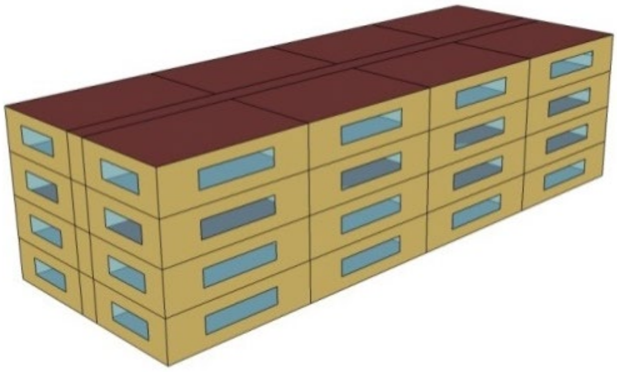


Figure 2. Scheme of the domestic building.

The heating set point considered in this building was constant at 21 ºC during the whole day, as well as the infiltration fraction, which was 1 ACH along the 24 hours. However, the occupancy fraction varied depending on the hour, as it is shown in Table 2. It is worth noting that the value of people in the building on which depends this occupancy fraction is 2.5 people/100 m^2.

Table 2. Occupancy fraction of the domestic building.

Hour	**Occupancy [Fraction]**
0	1
1	1
2	1
3	1
4	1
5	1
6	1
7	0.85
8	0.39
9	0.25
10	0.25
11	0.25
12	0.25
13	0.25
14	0.25
15	0.25
16	0.30
17	0.52
18	0.87
19	0.87
20	0.87
21	1
22	1
23	1

2.2.2. Office

A scheme of the building selected to analyse the influence of the office schedule is shown in Figure 3. The window fraction is higher than the domestic building, since in this case it is 33% facing all directions. Regarding the building characteristics, it has an area of 1650 m^2, summing a total floor area of 4950 m^2 considering the three floors.

To have a better understanding of the energy requirements of this building, Table 3 shows its hourly heating set point, its occupancy behaviour, and its infiltration fraction. All these parameters changed, depending on both day and hour. It is worth noting that the value of people in the building on which depends this occupancy fraction is 5.4 people/100 m^2.

Table 3. Heating set point, occupancy fraction, and infiltration fraction of the office building.

Hour	**Heating set point [ºC]**			**Occupancy [Fraction]**			**Infiltration [ACH]**		
	Weekday	**Saturday**	**Sun, Holidays, Other**	**Weekday**	**Saturday**	**Sun, Holidays, Other**	**Weekday, Summer design**	**Saturday, Winter design**	**Sun, Holidays, Other**
0	15.6	15.6	15.6	0	0	0	1	1	1
1	15.6	15.6	15.6	0	0	0	1	1	1
2	15.6	15.6	15.6	0	0	0	1	1	1
3	15.6	15.6	15.6	0	0	0	1	1	1
4	15.6	15.6	15.6	0	0	0	1	1	1
5	17.8	17.8	15.6	0	0	0	1	1	1
6	20	20	15.6	0.1	0.1	0.05	0.25	0.25	1
7	21	21	15.6	0.2	0.1	0.05	0.25	0.25	1
8	21	21	15.6	0.95	0.3	0.05	0.25	0.25	1
9	21	21	15.6	0.95	0.3	0.05	0.25	0.25	1
10	21	21	15.6	0.95	0.3	0.05	0.25	0.25	1
11	21	21	15.6	0.95	0.3	0.05	0.25	0.25	1
12	21	21	15.6	0.5	0.1	0.05	0.25	0.25	1
13	21	21	15.6	0.95	0.1	0.05	0.25	0.25	1
14	21	21	15.6	0.95	0.1	0.05	0.25	0.25	1
15	21	21	15.6	0.95	0.1	0.05	0.25	0.25	1
16	21	21	15.6	0.95	0.1	0.05	0.25	0.25	1
17	21	15.6	15.6	0.3	0.05	0.05	0.25	0.25	1
18	21	15.6	15.6	0.1	0.05	0	0.25	1	1
19	21	15.6	15.6	0.1	0	0	0.25	1	1
20	21	15.6	15.6	0.1	0	0	0.25	1	1
21	21	15.6	15.6	0.1	0	0	0.25	1	1
22	15.6	15.6	15.6	0.05	0	0	1	1	1
23	15.6	15.6	15.6	0.05	0	0	1	1	1

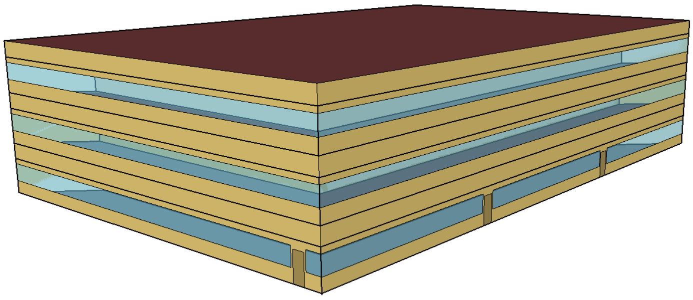


Figure 3. Scheme of the office building.

2.2.3. Service

The building selected to represent the service schedule is a hotel (Figure 4), for lodging purposes. It has an area of 990 m^2 and 4 floors, resulting in a total area of 3960 m^2. Its total window-to-wall ratio is 10.9% (3.1% to South, 11.4% to East, 4% to North, and 15.2% to West).

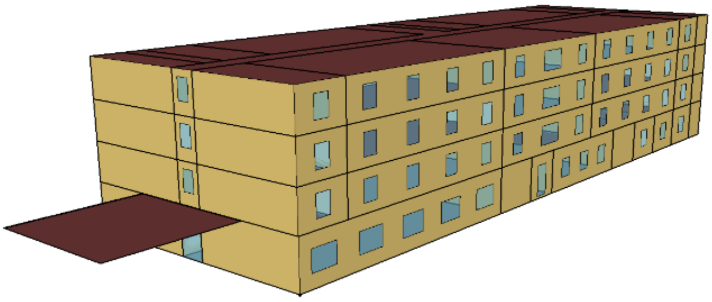


Figure 4. Scheme of the service building.

The service schedule has a higher complexity than domestic and office since there are more thermal spaces to be controlled. These thermal areas are divided in guest rooms, which can be vacant or rented, common areas, and semi-heated spaces, which are mainly the storage rooms and the stairs. In Table 4, the heating set point of such different areas is explained.

Concerning the occupancy schedule of all the presented areas, Table 5 shows the occupancy fraction of all the space types in the hotel. It should be mentioned that the lobby, the office, the meeting room, and the employee lounge are all considered as common areas. Finally, it is worth noting that the infiltration fraction is 0.25 ACH the 24 hours in all hotel areas during the whole year and the value of people in the building on which depends this occupancy fraction is 6.5 people/100 m^2.

Table 4. Heating set point of the service building.

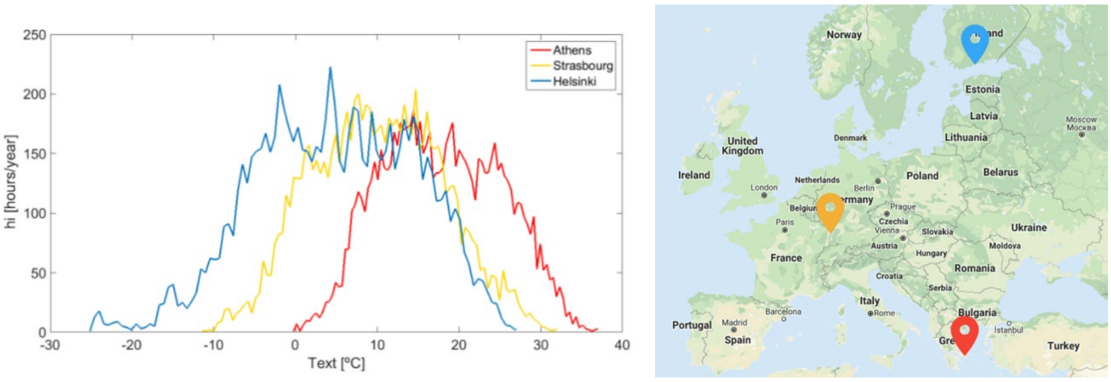
Hour	**Heating set point [ºC]**							
	Vacant Guest Room		**Rented Guest Room**		**Common Area**		**Semi-Heated areas (storage rooms/stairs)**	
	Weekday	**Weekend, Holidays**	**Weekday**	**Weekend, Holidays**	**Weekday**	**Weekend, Holidays**	**Weekday**	**Weekend, Holidays**
0	19	19	21	21	21	21	7	7
1	19	19	21	21	21	21	7	7
2	19	19	21	21	21	21	7	7
3	19	19	21	21	21	21	7	7
4	19	19	21	21	21	21	7	7
5	19	19	21	21	21	21	7	7
6	19	19	21	21	21	21	7	7
7	19	19	21	21	21	21	7	7
8	19	19	21	21	21	21	7	7
9	19	19	21	21	21	21	7	7
10	19	19	21	21	21	21	7	7
11	19	19	21	21	21	21	7	7
12	19	19	21	21	21	21	7	7
13	19	19	21	21	21	21	7	7
14	19	19	21	21	21	21	7	7
15	19	19	21	21	21	21	7	7
16	19	19	21	21	21	21	7	7
17	19	19	21	21	21	21	7	7
18	19	19	21	21	21	21	7	7
19	19	19	21	21	21	21	7	7
20	19	19	21	21	21	21	7	7
21	19	19	21	21	21	21	7	7
22	19	19	21	21	21	21	7	7
23	19	19	21	21	21	21	7	7

Table 5. Occupancy fraction of the service building.

Hour	Occupancy [Fraction]									
	Guest Room		Lobby		Office		Meeting Room		Employee Lounge	
	Week day	Weekend, Holidays	Week day	Weekend, Holidays	Week day	Weekend, Holidays	Week day	Weekend, Holidays	Week day	Weekend, Holidays
0	1	1	0.1	0.1	0.2	0.2	0	0	0	0
1	1	1	0.1	0.1	0.2	0.2	0	0	0	0
2	1	1	0.1	0.1	0.2	0.2	0	0	0	0
3	1	1	0.1	0.1	0.2	0.2	0	0	0	0
4	1	1	0.1	0.1	0.2	0.2	0	0	0	0
5	1	1	0.3	0.1	0.2	0.2	0	0	0.1	0.05
6	0.77	0.77	0.7	0.3	0.3	0.2	0	0	0.1	0.05
7	0.43	0.53	0.7	0.7	0.4	0.3	0.05	0.05	0.2	0.05
8	0.43	0.53	0.7	0.7	1	0.5	0.5	0.5	0.2	0.1
9	0.2	0.3	0.7	0.7	1	0.5	0.5	0.5	0.2	0.1
10	0.2	0.3	0.2	0.2	1	0.5	0.2	0.2	0.2	0.1
11	0.2	0.3	0.2	0.2	1	0.5	0.2	0.2	0.2	0.1
12	0.2	0.3	0.2	0.2	0.5	0.5	0.05	0.05	0.7	0.2
13	0.2	0.3	0.2	0.2	1	0.5	0.5	0.5	0.2	0.1
14	0.2	0.3	0.2	0.2	1	0.5	0.5	0.5	0.2	0.1
15	0.31	0.3	0.2	0.2	1	0.5	0.2	0.2	0.2	0.1
16	0.54	0.3	0.4	0.2	1	0.5	0.2	0.2	0.2	0.1
17	0.54	0.53	0.4	0.2	0.4	0.3	0.2	0.2	0.2	0.1
18	0.54	0.54	0.2	0.2	0.3	0.2	0.05	0.05	0.1	0.05
19	0.77	0.65	0.2	0.2	0.2	0.2	0.05	0.05	0.1	0.05
20	0.77	0.65	0.2	0.2	0.2	0.2	0	0	0	0
21	0.89	0.77	0.2	0.2	0.2	0.2	0	0	0	0
22	1	0.77	0.1	0.1	0.2	0.2	0	0	0	0
23	1	0.77	0.1	0.1	0.2	0.2	0	0	0	0

2.2.4 Weather data

To analyse the impact of the weather conditions in the heating demand profile and, consequently, to study the influence of both PV panels power capacity and TES tank volume for all cases, three different climates were chosen to simulate the presented building types. These locations are Helsinki (cold climate), Strasbourg (temperate climate), and Athens (hot climate) [36]. In Figure 5a, the frequency distribution of the outdoor temperature in the three cities is shown. Moreover, to give more detail about the geographical location of the three cities, Figure 5b shows a map, specifying the three positions, following the colour scale employed in the graph (Figure 5a). To have a better understanding of the weather conditions in all studied climates, the annual heating degree days (HDD), as well as the yearly sum of horizontal global irradiation [37] are detailed for each location in Table 6.



(a) (b)

Figure 5. Frequency distribution of external temperatures of all the studied climates (a) and their location (b).

Table 6. Annual heating degree days and yearly sum of horizontal global irradiation for each climate.

Location	**Annual HDD [ºC·day/year]**	**Yearly sum of horizontal global irradiation [kWh/m^2]**
Helsinki	5742	935
Strasbourg	3733	1215
Athens	1750	1972

2.3. PV panels and TES tank volumes

To evaluate both, PV panels power capacity and volume of the TES tank, different commercial models were selected to analyse the savings that can be obtained using all the combinations in the considered climates and type of buildings. To have more detail about PV panels employed in this study, Table 7 shows their main technical features. Moreover, it is worth noting that a service lifetime of 25 years of PV-modules was considered.

Table 7. Technical data of the PV panels [38].

Length x Width x Height [mm]	1660 x 990 x 50
Number of cells	60
Rated power [W]	285.00
Rated voltage [V]	31.30
Rated current [A]	9.10

Regarding the financial data of equipment, Table 8 presents the price of PV panels considered in this study while Table 9 details the different volumes of the TES tank and their price. The thermal storage media selected for this study was water, since it is the most common material used to store sensible energy and it contributes to an easiest integration of solar energy systems in buildings [39].

Table 8. Power capacity of the PV panels and their price.

P [kW_p]	**Price [€]**
5	9464
10	17410
20	31516

Table 9. Volumes of the TES tank and their price.

V [L]	**Price [€]**
1000	2136
2000	3213
3000	4484
4000	6145
5000	6604
6000	8605
8000	10472
10000	11699

2.4. Heat pump features

To be more accurate in the heat pump design, the coefficient of performance (COP) was adapted to all climates, depending on both the peak power of the heating demand and the minimum outdoor temperature in each place. In that sense, the heat pump was simulated using the detailed performance maps generated by Corberán et al. [40] using IMST-ART software which contains an accurate physical model. Due to the hard-computational cost of the MPC algorithm, it was necessary to narrow the involved variables in the process and only consider the most significant. For this reason, the selected independent variables were the supply water temperature (condenser outlet) and the outdoor air temperature. The model assumed a typical 5 ºC water temperature difference across the condenser, a mean fan speed of 60%, and a constant compressor speed at 50 Hz. At every time step, the heat pump was assumed to deliver the heating rate required by each building. For each location and building, the heat pump was sized linearly for the maximum annual heating load. Two supply temperatures were considered; 40 ºC in case the heat pump delivers heat directly to the building or 55 ºC in case it heats up the TES tank.

Finally, the COP was correlated with the outdoor air temperature and introduced in the overall model with the MPC strategy. The COP for every location is given by Equations ((1)-(6)), obtained through the aforementioned performance maps [40]. Since the COP is the relation between the heating power and the compressor consumption, for any time step where the heating rate is known, the compressor consumption can be hereby calculated by the model.

$$COP_{Helsinki\,(T_{imp}=40°C)} = 0.0008 \cdot {T_{out}}^{2}[°C] + 0.1 \cdot T_{out}[°C] + 3.8449 \tag{1}$$

$$COP_{Helsinki\,(T_{imp}=55°C)} = 0.0003 \cdot {T_{out}}^{2}[°C] + 0.0731 \cdot T_{out}[°C] + 2.5524 \tag{2}$$

$$COP_{Strasbourg\,(T_{imp}=40°C)} = 0.001 \cdot {T_{out}}^{2}[°C] + 0.0973 \cdot T_{out}[°C] + 3.837 \tag{3}$$

$$COP_{Strasbourg\,(T_{imp}=55°C)} = 0.0004 \cdot {T_{out}}^{2}[°C] + 0.0717 \cdot T_{out}[°C] + 2.5482 \tag{4}$$

$$COP_{Athens\,(T_{imp}=40°C)} = 0.0013 \cdot {T_{out}}^{2}[°C] + 0.0917 \cdot T_{out}[°C] + 3.8601 \tag{5}$$

$$COP_{Athens\,(T_{imp}=55°C)} = 0.0005 \cdot {T_{out}}^{2}[°C] + 0.0694 \cdot T_{out}[°C] + 2.5578 \tag{6}$$

2.5. Time-of-use tariff

To analyse the peak load shifting ability of the studied heating system controlled by an MPC strategy, a ToU tariff structure with two periods of billing was selected. Aiming to carry out the comparison with the same electricity price conditions, although this study employed three different locations, the profile of the electricity cost was the same in all scenarios. To do that, the price of the variable term of the electricity tariff used in this study was imported from Red Eléctrica de España [41] along one year. Additionally, an annual increment of 1% in that electricity price was applied in the economic analysis to consider the inflation rate as it was established in Equation (7):

$$price_n = price_{n-1} \cdot PoI \tag{7}$$

where n is the year, $price_n$ indicates the cost of the electricity, and PoI is the increase in electricity price per unit.

The hourly price distribution of the selected electricity tariff is shown in Table 10. It is worth noting that the change between winter and summer schedule takes place the day when the time changes from summertime to wintertime and the other way around.

Table 10. Time-of use tariff description.

Period of billing	Season schedule	Hourly schedule	Price [€/kWh]
On-peak	Winter	From 12h to 22h	0.165
	Summer	From 13h to 23h	
Off-peak	Winter	From 22h to 12h	0.086
	Summer	From 23h to 13h	

2.6. MPC strategy

The employed MPC strategy was designed following the formulation stated by Tarragona et al. [42]. The good performance showed by the strategy when managing a heating system with constant PV panels surface and TES tank volume pushed the authors to employ it in the present study, to further analyse the economic and energetic possibilities of such a control strategy. To have more detail about its way of working, Figure 6 shows a scheme depicting the operation of the selected MPC strategy and its variables management, considering inputs and outputs obtained after processing all the control decisions.

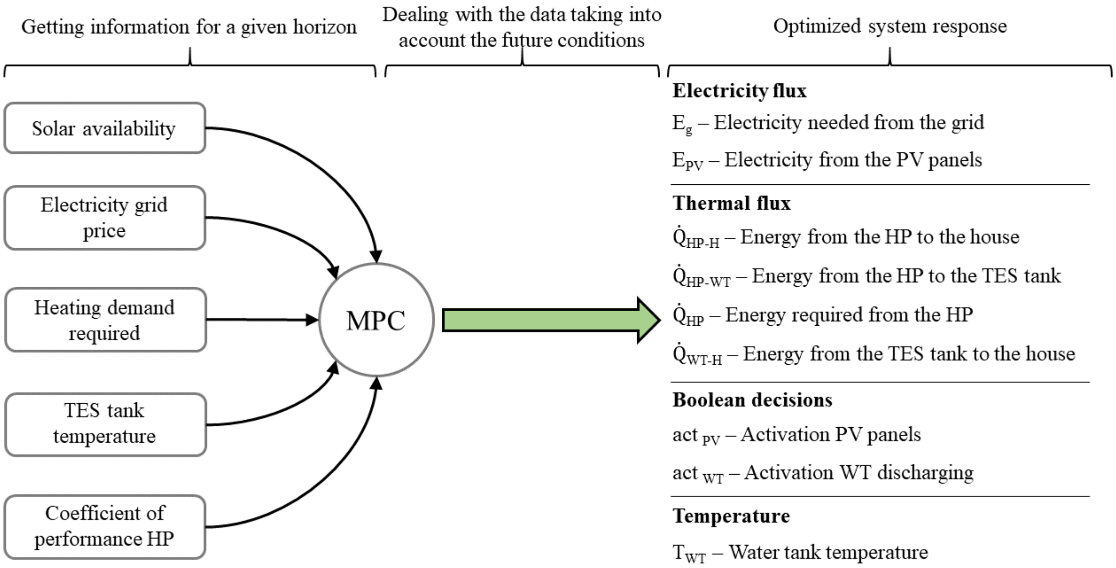


Figure 6. Operation scheme of the MPC strategy [42].

The inputs analysed by the MPC strategy are the following:

- The solar availability that depends on both the building location and the power capacity of the PV panels in each case.
- The hourly electricity prices.

- The heating demand required by the building that varies in function of the location and the building type.
- The TES tank temperature that defines its state of charge, which depends on the tank volume.
- The COP of the heat pump, which can fluctuate considering both the building location and the heat pump operation, since it can supply either the TES tank or directly to the building.

All these inputs are taken using a time step (δ) of 1 hour and they are analysed by the MPC controller with a horizon (H) of 24 hours, since it was demonstrated that longer horizons did not increase the savings in the final results [42]. Therefore, considering these two control principles, the prediction horizon slots (N) of the formulated MPC strategy is defined in Equation (8):

$$N = \frac{H}{\delta} \tag{8}$$

As it is well-known, MPC optimizes a control process, either minimizing or maximizing a specific function. In the present case study, the objective function to minimize can be seen in Equation (9):

$$cost = min \sum_{j=0}^{N-1} E_{g,i} \cdot price_{g,i} \tag{9}$$

being $cost$ the electricity cost from the grid, E_g the amount of electricity purchased from the grid, and $price_g$ the hourly grid electricity price.

Regarding the MPC outputs, Figure 6 details all the system responses after being optimized. On the one hand, there are the energy fluxes that can be either electrical or thermal. In case of electrical, MPC optimizes the amount of electricity needed from both electricity grid and PV panels. Focusing on the thermal fluxes, MPC analyses the energy that must be produced by the heat pump to be delivered either to the building or to the TES tank. Then, the controller also calculates the amount of thermal energy that needs to be supplied from the TES tank to the building. On the other hand, MPC indicates the Boolean decisions that are taken by the control strategy, considering the heating requirements of the system for the next hours. Finally, the temperature of the water TES tank is also delivered by MPC, to continue analysing the system operation.

Moreover, the employed MPC strategy created by Tarragona et al. [42] was designed with two levels of actuation: high-level and low-level. Specifically, the high-level controller operates as the one explained in this section so far. However, the low-level controller was designed with the main goal to correct possible deviations obtained during the operation of the high-level controller. This low-level controller was called inner control algorithm (ICA) by the authors and its settings were: δ of 5 minutes and a H of 1 hour. The detail of its operation is shown in the flowchart depicted in Figure 7, where the responses that the ICA explored in all cases are explained. As it can be seen, first, the ICA checked if there is any mismatching between heating demand requirements and thermal energy supply. On the one hand, in case there was a part of the demand without supplying, the ICA verifies if the energy provided by PV panels was enough to cover this mismatching. If not, the ICA covers the demand with the energy stored in the TES tank. Finally, if it remains any shortfall of thermal energy to supply the heating energy required by the building, the ICA uses the electricity grid. On the other hand, in case the high-level controller predicted a higher demand that what it finally is, the first step of the ICA is to check the energy availability to be delivered through the TES tank and to switch-off the heat pump if necessary. If it is not possible, the heat pump would adapt its energy deliver to the new heating requirements.

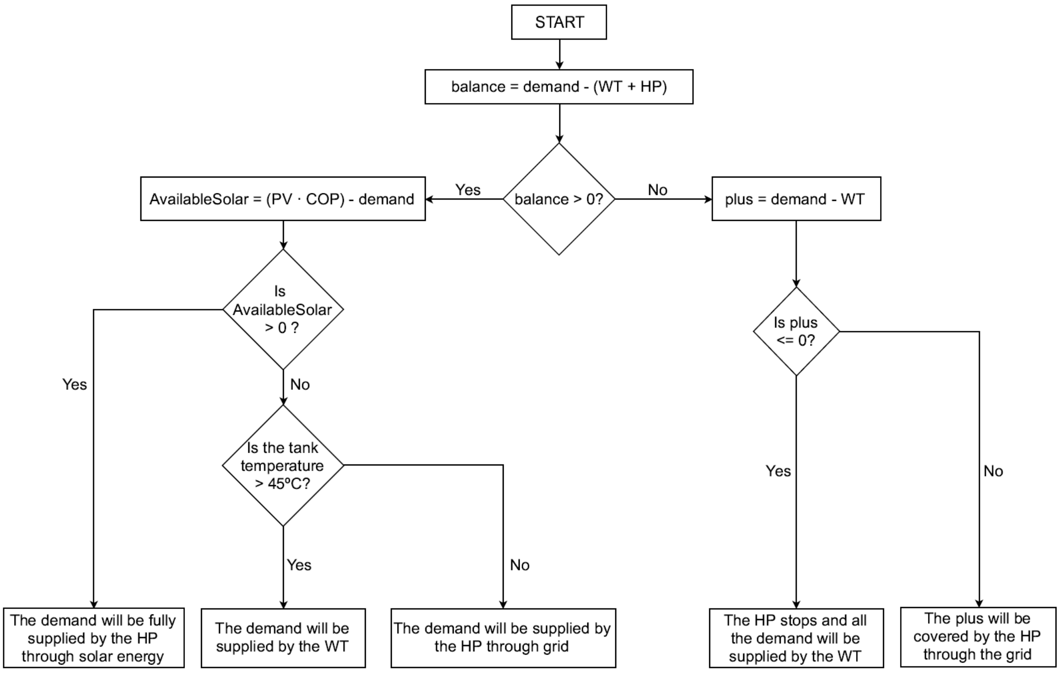


Figure 7. Inner control algorithm flowchart [42].

2.7. Case studies

2.7.1. Economic evaluation

The economical assessment carried out in this study was focused on analysing the payback (PB) of each PV panels and TES tank combination. The PB is a metric used in financial studies to assess the time that it takes to receive the same amount that was invested. In this framework, this study evaluated the economic savings achieved through a combination of PV panels and TES tank in comparison to the case where the heating system was controlled by the MPC strategy, but without neither of these two technologies. Then, Equation (10) was used to calculate this PB period that all studied combinations needed to recover the initial investment, considering the variable price of the electricity:

$$PB = a + \frac{I_0 - b}{Ft} \tag{10}$$

where a is the number of the preceding year until the initial investment is recovered, I_0 is the initial investment, b is the sum of the cash flows until the end of year a, and F_t is the cash flow of the year in which the investment is recovered.

2.7.2. Energy evaluation

Regarding the energy evaluation of the system operation, the main goal was to identify which was the influence of both PV panels and TES tank on the final energy consumption. This analysis was focused on analysing the following aspects:

- First, it was studied the capacity of the TES tank to reduce the heating supply coming directly from the heat pump to the building. MPC decides to store energy in the TES tank during solar energy surpluses, when the system can operate in off-peak periods, or when the weather conditions contribute to run the heat pump with high-efficiency operation. Therefore, to assess the use of the TES tank became a key performance indicator.
- Second, the MPC strategy should be able to exploit as much as possible the energy provided by PV panels. Therefore, the impact of PV panels to reduce the electricity grid consumption was another key performance indicator evaluated in this study.
- Third, the last key performance indicator analysed in this study was the behaviour of the COP with different TES tank volumes and PV power capacities.

3. Results and discussion

3.1. Analysis of the heating demands

Simulations of all buildings were carried out with EnergyPlus engine. To illustrate the heating demand in the three considered occupancy schedules, Figure 8 shows the heating demand profile of four representative winter days in Strasbourg. As it can be seen, the figure is divided in three graphs, which depict the hourly evolution of the heating demand and the different behaviour among the three studied occupancies. In the domestic schedule, the main energy consumption peaks were located at night, since it is the time with more concurrency in the apartments. In contrast, the office building presented a repeating pattern consumption profile, with high peaks before beginning the workday. Finally, the profile in the hotel (service building) did not followed a pattern of heating consumption and it presented different peaks and valleys in some hours of the day. This behaviour was due to the multiple occupancy options that can be derived from the amount of rooms that were rented or the occupancy variance in the common areas of the building (Section 2.2.3).

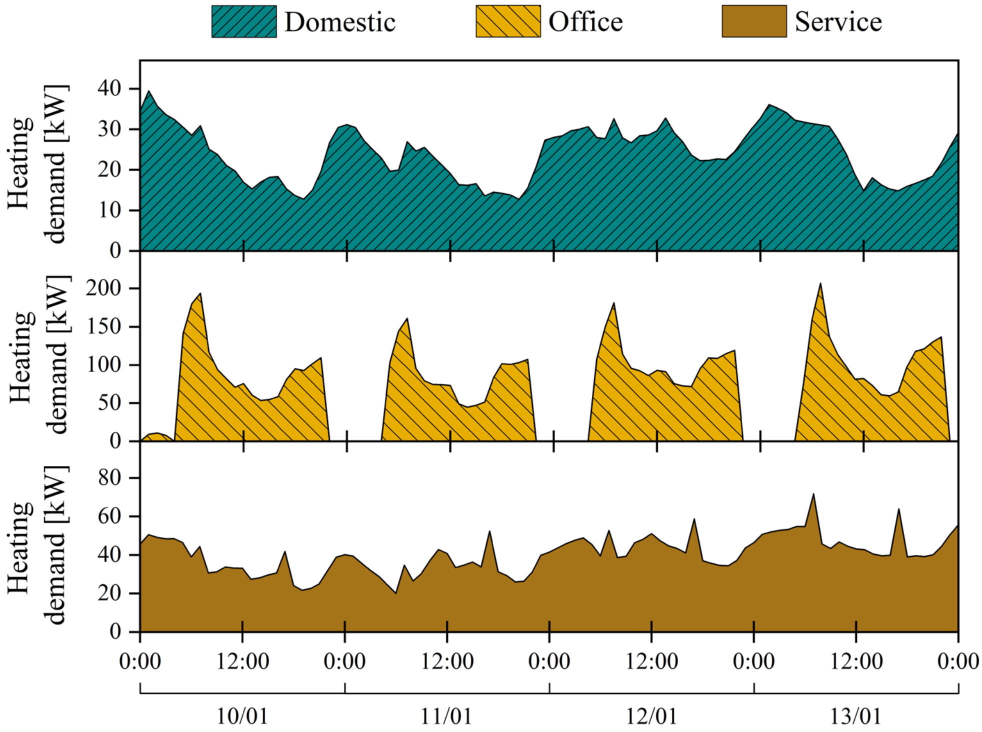


Figure 8. Heating demand profile of four representative winter days for the three studied occupancy schedules in Strasbourg.

Then, to have an overview of the differences among the three types of buildings located in the three studied climates, Table 11 details the peak load demand and the annual heating consumption of each case. As it can be seen, the office schedule is by far the one with a higher peak load demand, followed by the service and the domestic schedules, respectively. The same tendency happened in the annual heating consumption, which the office schedule stands out in comparison to the other two. Therefore, in terms of occupancy schedule, the three buildings showed remarkable differences in their energy consumption profiles.

Table 11. Peak load demand and annual heating consumption of the studied schedules.

	Peak load demand [kW]			**Annual heating consumption [kWh_{th}]**		
Location	**Domestic**	**Office**	**Service**	**Domestic**	**Office**	**Service**
Helsinki	75	330	165	$1.84 \cdot 10^6$	$4.56 \cdot 10^6$	$3.32 \cdot 10^6$
Strasbourg	54	311	104	$0.86 \cdot 10^6$	$2.47 \cdot 10^6$	$1.58 \cdot 10^6$
Athens	25	208	45	$0.17 \cdot 10^6$	$0.65 \cdot 10^6$	$0.31 \cdot 10^6$

Regarding the climate influence, as expected, Helsinki is the place that requires more energy to supply the heating needs. However, focusing on the peak load demand, the variance between Helsinki and Strasbourg results smaller, especially in the office schedule. This effect should be considered during the MPC operation and its energy management, because its ability to mitigate peak loads using PV panels and TES is crucial to achieve both energy and economic savings. Thus, to investigate the influence of PV panels power capacity and TES volume becomes essential to tackle the multiple energy cases, to analyse the robustness of MPC, and to assess the system performance with each combination.

3.2. Economic assessment of the system operation

The aim of this section is to evaluate the economic results that were obtained from the simulations carried out through the designed MPC strategy with different combinations of PV panels and TES tanks. The desirability of all investments was directly related to the PB period, meaning that the shorter PB the more attractive the investment was. In that sense, this PB evaluation was carried out in all locations and occupancy schedules, to find out which was the economic impact of both PV panels and TES. Moreover, it was contemplated the scenario with only TES, to assess which was the influence of the high price of PV panels. A representative case of this assessment is shown in Figure 9, where the PB period for all locations is depicted for the domestic schedule.

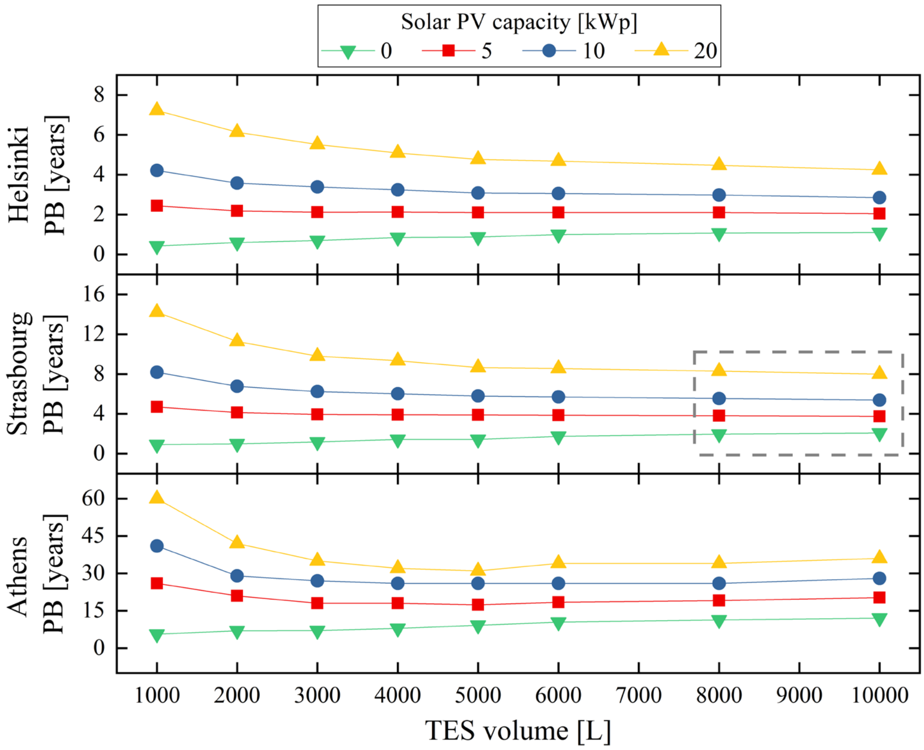


Figure 9. Payback evolution of the domestic schedule in function of both PV panels and TES capacities.

Overall, in all locations the best PB period was obtained in the scenario without PV panels. The low price of TES tanks contributed to recover the initial investment very fast, ranging between 1 and 3 years in cold and temperate climates. In contrast, the high cost of PV panels made their integration to the heating system a long-term investment, being 5, 8, and 36 years the PB period for the case with 20 kW_p of PV panels and 10000 L of TES tank in Helsinki, Strasbourg, and Athens, respectively. However, there are some aspects that should be considered in this economic analysis.

On the one hand, to combine a small TES tank with big PV power capacities achieved the worst PB periods in all locations. Large PV power capacities drove to obtain solar energy surpluses that MPC decided to store in the TES tank. In that sense, the bigger the TES tank the higher capacity to take advantage of the solar energy that cannot be consumed on-time by the building. Helsinki and Strasbourg demonstrated this behaviour, reaching the best PB period for 20 kW_p of PV panels with a TES tank of 10000 L. Moreover, it is worth noting the region highlighted with a dashed rectangle in the Strasbourg graph. It shows a convergence tendency where to invest only in a TES tank became more expensive for large volumes and to increase both PV power capacity and TES tank volume increased the investment profitability, due to the advantage to join both technologies.

On the other hand, it should be highlighted the good PB periods obtained with only a TES tank, especially in a hot climate as Athens. Its low annual heating demand (Table 11) allowed MPC to take advantage of the off-peak electricity periods to obtain significant economic savings and to recover the initial investment of the TES tank. However, although the high solar radiation in Athens, PV panels could not produce enough energy to overcome the high price of the equipment.

Additionally, another important aspect to consider in the economic assessment was the influence of the electricity price upon the final energy cost. As it was stated in Section 2.5, in this study, the price of the electricity in Spain was used in all simulations as a reference price. However, the electricity cost was different in each European country [43]. Therefore, a sensitivity analysis was carried out to evaluate the variation of such a price, considering the cost range among all European countries and establishing the cost of the electricity in Spain as the reference. Then, from this reference, higher and lower prices were taken into account with a maximum price 30% larger than Spain and a minimum 50% smaller.

The sensitivity analysis was developed in the three studied climates, since the energy demands between them were very different. Moreover, to obtain a wider perspective of the study was crucial to evaluate different scenarios of TES tanks and PV panels configurations together with the electricity price variation. In that sense, Figures 10, 11, and 12 illustrate the annual energy cost variation in Helsinki, Strasbourg, and Athens, respectively, depending on the variation of the electricity price and the energy equipment scenario. Overall, in the three locations the cost of the electricity had a strong effect in the annual energy cost, especially in the case without TES tank neither PV panels. However, this influence dropped as different TES tanks and PV panels were considered in the system operation. As it can be seen, in the scenario with a TES tank of 10000 L and 20 kW_p of PV panels, the influence of the electricity price was much smaller than in previous scenarios, meaning that to operate with the proper size of TES tank and PV panels reduced the dependence of the system on the electricity price.

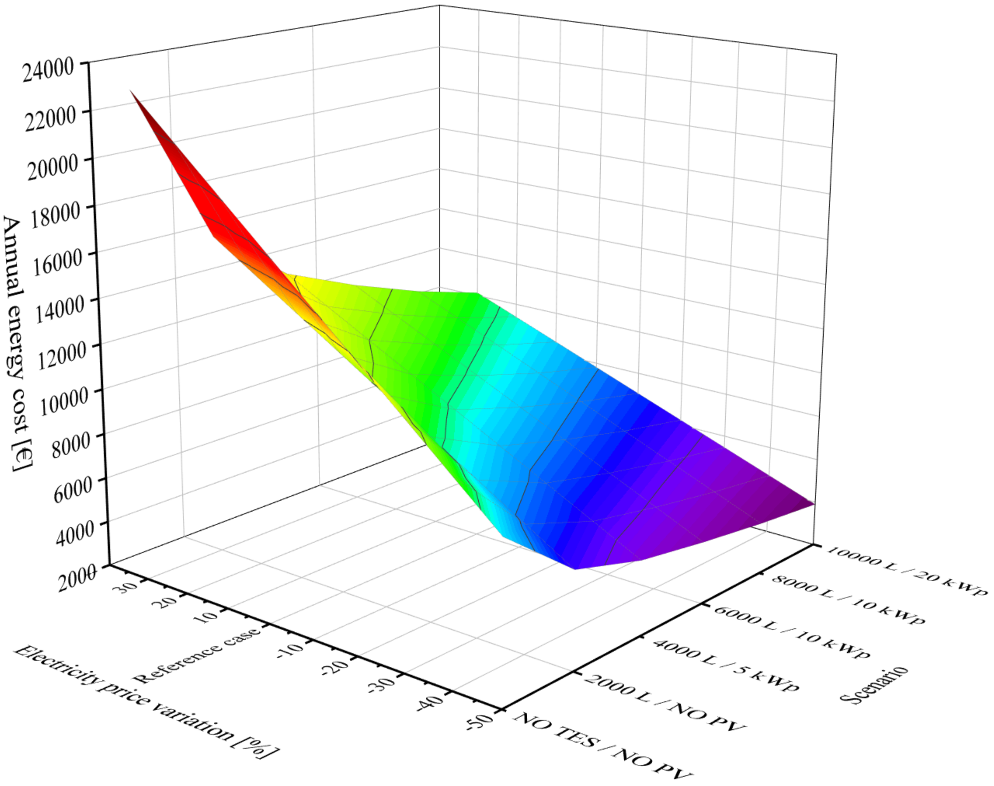


Figure 10. Annual energy cost variation in Helsinki depending on the electricity price and the scenario.

Focusing on the case of Helsinki (Figure 10) in more detail, although the annual energy cost was high, the ability of the MPC strategy combined with the use of TES and PV panels were able to reduce the cost even in the case with the highest electricity price. However, the price of the electricity upon the annual energy cost was crucial, since the case with a electricity cost reduction of 50% without TES neither PV panels obtained the same annual energy cost as the reference case (electricity price of Spain) with a TES tank of 10000 L and 20 kW_p of PV panels power capacity.

Regarding the case of Strasbourg (Figure 11), due to the lower heating requirements of this location, the capacity of the studied system was exploited even more than in Helsinki, overcoming the electricity price variation easier. In comparison to Helsinki, the smoother slope of the scenario with 10000 L and 20 kW_p in Strasbourg, in function of the ratio of variation of the electricity price, depicts that the MPC strategy could take advantage of the TES and the PV panels during many hours, giving grid independence to the system.

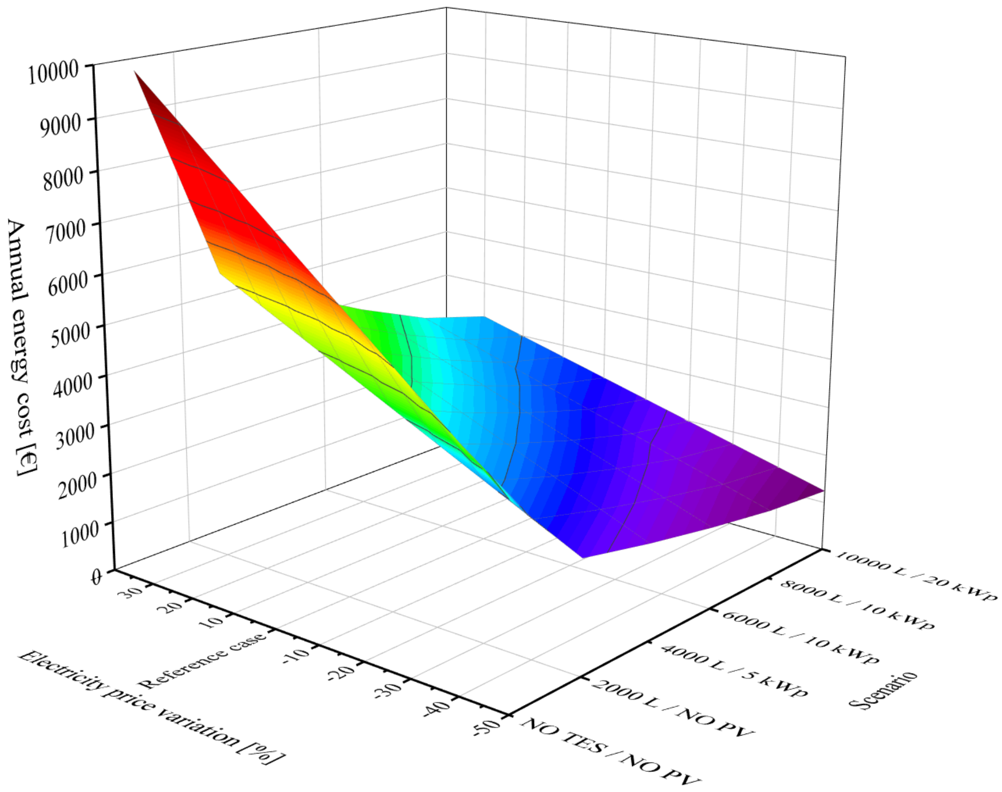


Figure 11. Annual energy cost variation in Strasbourg depending on the electricity price and the scenario.

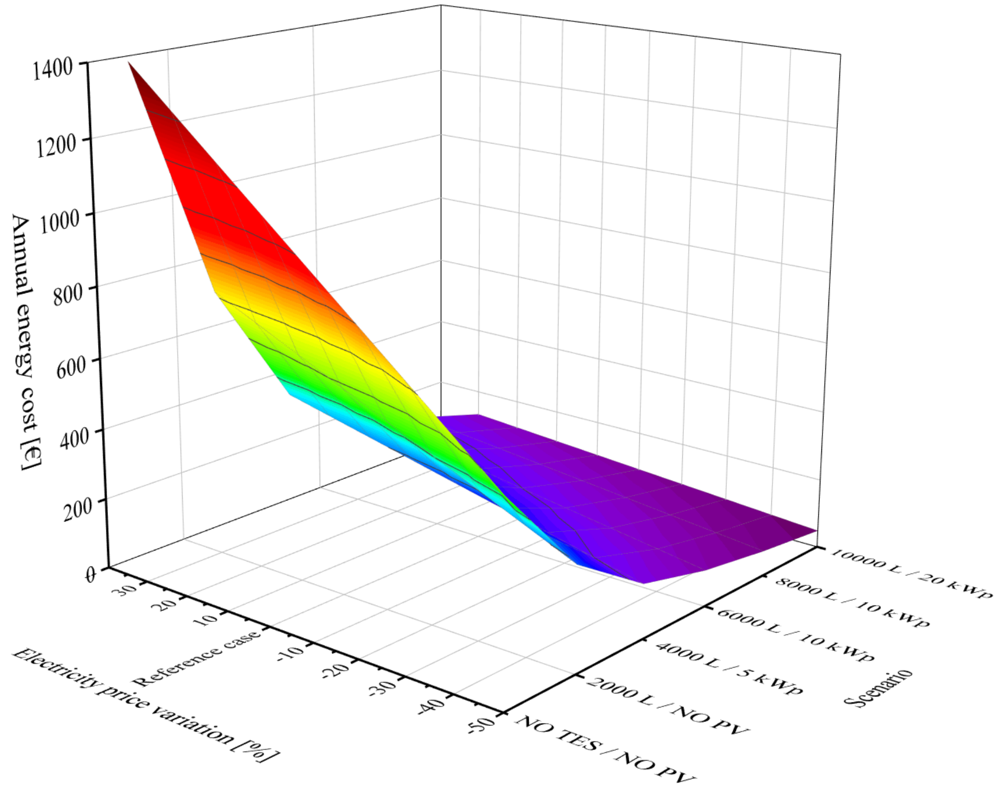


Figure 12. Annual energy cost variation in Athens depending on the electricity price and the scenario.

Finally, due to the low heating demand, the climate of Athens was not really sensitive to the price of the electricity. Moreover, as it can be seen in Figure 12, to install TES and PV panels to compensate the electricity price variation was useless, since the annual energy cost was small in such a location. Therefore, from an economic point of view, large TES and PV panels power capacities were not needed in Athens. To install a TES tank of 4000 L together with 5 kW_p of PV panels were enough to achieve both very important cost reductions and flexibility to overcome electricity price variations.

3.3. Energy assessment of the system operation

The energy assessment was divided in the study of the heating system behaviour from two different points of view:

- The thermal impact of the TES tank upon the heating demand supplying.
- The final electricity consumption considering the influence of PV panels.

On the one hand, to evaluate the impact of the TES tank in the three occupancy schedules, the volume of all the studied tanks was divided by the building area that is heated in each type of schedule: 2118 m^2 in the block apartment, 4950 m^2 in the office, and 3725 m^2 in the hotel. Regarding the MPC operation analysed in previous works [23,42], it should be highlighted that the control strategy decided to store thermal energy in the TES tank when the heat pump could operate through solar energy surpluses, using electricity from the grid during off-peak periods, or when the MPC identified high performance hours of the heat pump due to favourable weather conditions that improved its COP. Therefore, the energy stored in the TES tank by MPC aimed to reduce the grid consumption during high cost hours or when the heat pump performance is low. In that sense, to use the proper volume of the TES tank was crucial in all cases to take advantage of the maximum low-cost heating energy.

Therefore, in this study, it was assessed for all locations and schedules the percentage of incidence of the TES tank upon the final heating energy consumption. This percentage was evaluated considering the part of total heating that was covered through energy previously stored in the TES tank, which reduced the ratio of direct supplying done by the heat pump. A representative case of this analysis is shown in Figure 13, where it can be seen a heat map that depicts the impact of both heat pump and TES tank on the heating supply for different TES tank volumes. The analysis was framed in Strasbourg and the power of the PV panels to study the behaviour of the TES tank was considered constant at 5 kW_p for all storage volumes.

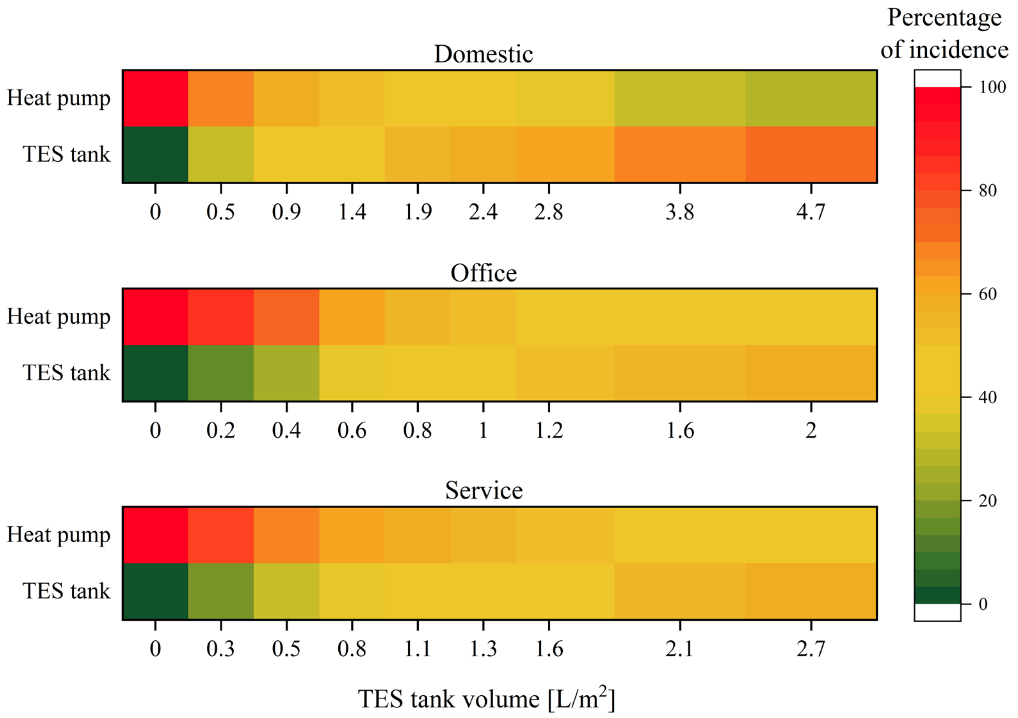


Figure 13. Influence of the TES tank volume upon heating demand supplying in Strasbourg.

As it can be seen, due to heating areas variation among the three schedules, the domestic storage volume assigned to each square meter was higher in comparison to office and service buildings. However, the impact of the tank in the heating supply presented the same tendency in all studied occupancies. The demonstration of that is illustrated in the comparison between the office and the service plots, where the incidence of the TES tank reached around 60% even considering that the heating demand profiles between buildings were different. Moreover, another aspect to remark is that the TES tank overcame the peaks in the heating consumption, which were very sharp in the office, as it was shown in Figure 8. Therefore, this means that MPC was able to manage the schedule variances among the three studied occupancy patterns, adapting the TES tank operation to the heating requirements of each type of building. This fact demonstrated that the optimal size of the tank was not strongly linked to the occupancy schedule, since MPC compensated it through its control decisions. In contrast, the volume of the TES tank per square meter was identified as crucial to fully exploit the MPC ability.

Focusing on the impact of the climate upon the TES tank size, it was studied the percentage of incidence of both TES tank and heat pump for all the studied locations. In this analysis, the PV power capacity was also constant at 5 kW_p, to be able to assess the real impact of the TES tank. Results of the study are shown in Table 12. As expected, increasing the size of the TES tank in all cities drove to a higher use of this system. Regarding to Helsinki, its high annual heating energy demand (Table 11) did not allow to overcome a 60% of the TES tank use. Higher volumes should be studied to increase the incidence of the storage to the global heating energy supplying. In Strasbourg, although the percentage of incidence of the TES tank was higher than Helsinki and it achieved a 73%, its maximum potential was not reached. This maximum potential was obtained in the hotter conditions of Athens. In this case, the TES tank reached its maximum at 8000 L, showing the same TES tank influence for higher volumes. Therefore, it was demonstrated that weather conditions must be considered to size the TES tank. The ability of MPC to take advantage of storing thermal energy during high performance hours, could achieve 90% of impact in the final heating supply if the TES tank was big enough.

Table 12. Impact of different TES tank volumes upon the incidence of both TES tank and heat pump in all locations for the domestic schedule.

TES tank volume [L]	**Helsinki (cold)**		**Strasbourg (temperate)**		**Athens (hot)**	
	Percentage of incidence		**Percentage of incidence**		**Percentage of incidence**	
	TES tank	**Heat pump**	**TES tank**	**Heat pump**	**TES tank**	**Heat pump**
1000	19.9	80.1	30.7	69.3	60.3	39.7
2000	31.5	68.5	41.2	58.8	73.5	26.5
3000	37.2	62.8	48.2	51.8	81.2	18.8
4000	42.3	57.7	53.7	46.3	84.7	15.3
5000	46.0	54.0	58.3	41.7	86.7	13.3
6000	50.3	49.7	62.6	37.4	87.7	12.3
8000	55.7	44.3	68.6	31.4	90.4	9.6
10000	60.3	39.7	73.2	26.8	89.3	10.7

On the other hand, it was evaluated the potential of PV panels to reduce the electricity consumption from the grid. To develop the assessment, it was considered the scenario with a TES tank volume of 10000 L and it was compared the performance of all PV panels capacities in the three studied locations. Overall, results showed in Table 13 point out that MPC can obtain significant energy benefits using PV panels in the studied system. Although the low solar radiation of Helsinki, near to 35% of electricity grid savings could be obtained with the maximum studied capacity. In Strasbourg, where the annual heating consumption is lower than Helsinki and the solar radiation is higher, PV panels could reduce more than half the grid consumption. Finally, Athens obtained between 83% and 90% of electricity grid savings, taking advantage of both high solar radiation and low heating requirements. Therefore, to install PV panels with TES allowed MPC to increase the ratio of solar energy use, while the amount of electricity bought from the grid was diminished.

Table 13. Impact of different PV power capacities in the reduction of the electricity grid.

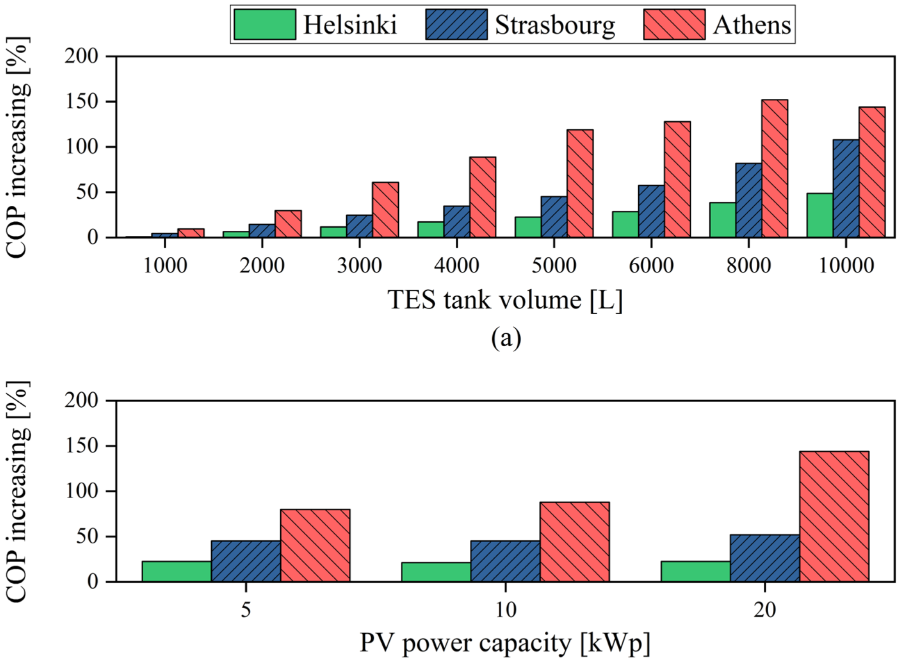
PV power capacity [kW$_p$]	Reduction of the electricity grid consumption [%]		
	Helsinki (cold)	**Strasbourg (temperate)**	**Athens (hot)**
5	31.3	49.1	83.0
10	32.6	51.5	84.3
20	34.5	54.8	90.2

Finally, to analyse the ability of MPC to manage the studied heating system it was considered essential to assess which was the impact of both TES tank volume and PV power capacity upon the mean COP of the heat pump. The aim of this analysis was to assess which was the capacity of the MPC strategy to take advantage of different combination of equipment sizes, to switch-on the heat pump during higher performance hours. To do that, it was compared the increasing of the COP against a case without TES tank neither PV panels (base case). Table 14 details the mean COP of the base case for all locations. Then, the comparison between this mean COP and the one obtained after adding PV panels and TES within the system operation is depicted in the double-graph of Figure 14, which illustrates the percentage of increasing of each combination. In Figure 14a, is shown the COP increasing in function of the TES tank volume, where all TES tank volumes were studied for the same PV panels capacity (5 kW$_p$). Moreover, the COP increasing depending on the PV power capacity is shown in Figure 14b for a constant TES tank volume of 5000 L, as a representative case.

Table 14. Mean COP of the base case in all locations.

Locations	Mean COP in the base case
Helsinki	1.4
Strasbourg	2.3
Athens	2.8

As it can be seen in Figure 14a, there was a significant growth of the COP in all locations when the volume of the TES tank was increased. Although in Helsinki the low external temperatures hamper the heat pump performance, to employ a TES tank of 10000 L improved the COP a 50%, due to the efficient energy management conducted by the MPC strategy. This performance enhancement was even larger in Strasbourg, where the COP achieved a 100% of increasing with the same volume (10000L) in comparison to the base case. In the case of Athens, MPC could run the heat pump during high performance hours and the COP growth reached the top at 145% for a TES tank of 8000 L. In contrast, due to an excess of TES volume the COP started to decrease, since to heat up an extra volume of water produced performance losses.



(a)

(b)

Figure 14. Increasing rate of the COP, depending on the TES tank volume (a) or the PV power capacity (b).

Regarding to the impact of the PV power capacity on the COP illustrated in Figure 14b, it is worth noting that part of the initial improvement is due to the TES tank (5000 L). Therefore, the real increasing of the COP was evaluated considering the variation obtained comparing the increasing of 5 kW_p, against 10 kW_p and 20 kW_p. In that sense, results from Helsinki showed the same increasing ratio in all PV power capacities. No variations in the COP were identified when more PV panels were added to the system operation. Strasbourg performed the same tendency of Helsinki, with a little variation of a 6% with 20 kW_P. In contrast, Athens improved till 145% the heat pump performance with 20 kW_p, in comparison to the 80% increasing showed in the reference case (5 kW_p).

Therefore, results pointed out that to increase the TES tank volume contributed to increase the COP of the heat pump, improving the global performance of the heating system. However, to increase the PV power capacity only improved the COP in the hot climate, since cold and temperate climates performed the same COP results for the three studied PV capacities.

4. Conclusions

This study presented an evaluation of the impact of different combinations of TES tanks and PV panels upon the economic and energetic performance of an MPC strategy, which managed a heating system in various occupancy schedules and locations. Overall, it was demonstrated that the variability in the heating energy profiles due to different occupancy patterns was successfully managed by the MPC strategy. The capability of the controller to predict the future energy demand, the solar radiation, and the external temperature reduced the impact of the schedule on the heating system performance. Moreover, the influence of the energy consumption derived by the building location was identified as a key parameter to consider.

From an economic point of view, to install only a TES tank obtained the smallest PB periods in all climates, especially with a TES tank of 1000 L. The high price of PV panels hampered their options to obtain shorter PB periods in comparison of using only a TES tank, due to the ability of MPC to switch-on the heat pump during off-peak periods and to store such an energy in the TES tank to consume it when the electricity is expensive. However, coupling high PV power capacities with a big TES tank reduced the PB period compared to invest in PV panels with small tank volumes.

From an energy point of view, to increase the TES tank volume provided energy benefits in all cases. The ability of MPC to run the heat pump during high-performance hours made the heating system more efficient, since the COP increased, while the on-time consumption supplied by the heat pump was reduced. The main reason was that the heat pump was switched-off by the MPC controller during periods with low outdoor temperatures, which improved its performance. This was proved with a growth in the COP of 50% (Helsinki), 100% (Strasbourg), and 145% (Athens) when the TES tank volume of the system was increased. Focusing on the impact of PV panels, more power capacity reduced the electricity grid consumption, but did not improve the performance of the heat pump unless the studied climate was sunny. Therefore, the peak load shifting capacity of the MPC strategy, together with a good sizing of the equipment, represented an important reduction of the dependence on the electricity grid during on-peak periods.

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