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# DYNAMIC SIMULATION AND ANALYSIS OF A PASSIVE HOUSE CASE STUDY WITH DIRECT PV SYSTEM FOR HEATING AND DOMESTIC HOT WATER PRODUCTION

**CANDIDATO:**
**Elisa Venturi**

**RELATORE:**
**Chiar.mo Prof. Ing. Gian Luca Morini**

**CORRELATORI:**
**Dr.-Ing. Fabian Ochs**
**Dr.-Ing. Georgios Dermentzis**
**Ing. Mara Magni**

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# DYNAMIC SIMULATION AND ANALYSIS OF A PASSIVE HOUSE CASE STUDY WITH DIRECT PV SYSTEM FOR HEATING AND DOMESTIC HOT WATER PRODUCTION

Elisa Venturi,

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Master Thesis

Supervisors:
- Prof. Ing. Gian Luca Morini
- Dr.-Ing. Fabian Ochs
- Dr.-Ing. Georgios Dermentzis
- Ing. Mara Magni

Institute for Material Technology

Unit of Energy Efficient Building

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## EXTENDED ABSTRACT

In this master thesis, different heating systems for space heating and domestic hot water (DHW) preparation are investigated with respect to their energy efficiency. In particular, a case study of a multi-storey Passive House (called An-der-Lan) is analysed by means of dynamic building and system simulations.

The investigated building is a Passive House with an electric heating and DHW preparation system. It represents a case study to investigate this concept for cost effective and efficient buildings. Through the flat-wise electric heating and DHW preparation system, distribution losses can be avoided while in the same time due to the simple installation, the investment costs can be kept at minimum levels. However, the inefficient electric heating leads to high electricity demand and correspondingly high operation costs. Therefore, all the south façade of the building is equipped with a large photovoltaic (PV) field to compensate for that.

Nearly zero energy building (nZEB) according to the Energy Performance of Building Directive (EPBD) is the required building standard from 2021 on. Each State member of the European Union developed its own definition of nZEB and requirements to accomplish that concept nZEBs. Hence, it is difficult to compare the ambition level of different member states (in contrast to the Passive House requirements). Exemplarily, the Italian and Austrian implementations of the EPBD were analysed.

Dynamic simulations are performed using the integration of several software. All data about the building are read from PHPP (Passive House Planning Package), which is a tool used for design and certification of Passive Houses. This algorithm uses monthly energy balance. Data are then read by the CarnotUIBK, which is a model in MATLAB Simulink environment, developed by the University of Innsbruck, in order to simulate the behaviour of the building. Finally, blocksets from the CARNOT library (developed by the Solar Institute Jülich, Germany) are assembled in Simulink in order to model the additional systems. These are: heating emission system, DHW production system, photovoltaic (PV) system and a heat pump (HP). For parametrizing the HP model, data are acquired from the software of Galletti company (Selmac Galletti).

For sake of simplicity, the first part of dynamic simulations focuses on the comparison of the UA and RC models for a simple office located in Rome. This is a case study from the project IEA SHC T56 – System Simulation Models. In particular, attention is put on the influence of the thermal capacity. Assuming the RC model as the reference case, variants of the UA model with different percentages of the thermal capacity are simulated, in order to find out the most

similar to the RC model. Several quantities are evaluated and compared between the two models. Based on the considered quantity, the UA model that is more similar to the RC model changes. For this building, the UA model with 25% of the original thermal mass (which is 132 $\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$, that correspond to the value of a standard medium weight building in PHPP) could be considered as the best approximation of the more detailed RC model. The same investigation is carried out for the An-der-Lan building. In this case, it is not possible to identify the best UA model, because for every considered quantity, the minimum difference between the UA and RC model is got for a different percentage of the thermal mass. Moreover, simulation times for the simple single zone model case (office) are compared. The RC model is the one with the longest time. For example, the simulation time for the RC model is 6 times higher than the required time from the UA model with 25% of the capacitance. However, this major simulation effort is considered acceptable in order to get more realistic results.

The second part of dynamic simulation focuses on the comparison among different systems for heating and DHW preparation. The realized system is direct electric heating with radiant heaters and flat-wise DHW preparation with electric boilers. Here it is denoted as the reference all electric Case1 and it is compared against alternative solutions. Case2 is based on a central heat pump system: both heating and DHW production are supplied by an air/water heat pump. For these two main cases, several variants are studied. The first variant concerns the DHW storage volumes: a smaller and a bigger volume than the base case, are introduced. Furthermore, the variation of the area of PV panels is investigated. Different design of PV panels and different orientations are considered. A sensitivity analysis study is conducted. When variants on the storage volumes are considered, PV system is at the reference case and vice versa. Finally, Case3 and Case4 are a mix of the previous two cases. Case3 assumes heating by heat pump and electric boiler for DHW, while Case4 assumes direct electric heating and a heat pump for DHW preparation.

Results show that Case2 is the best in terms of electric energy required from the grid, although it is the system with the highest thermal losses. This proofs the convenience of a heat pump compared to the electric system, which is less energy efficient. Furthermore, the PV system only in the south façade is not sufficient to cover the energy required in neither of the two main cases. Only for few days in a year, electric energy can be supplied to the grid.

Finally, annual, monthly, daily, hourly and 10 minutes balances are compared. Results show the importance of smaller time step in balances between required and produced energy, in order to have more precise results.

# EXTENTED ABSTRACT

In questa tesi, diversi sistemi per il riscaldamento e la produzione di acqua calda sanitaria (ACS) sono studiati in riferimento alla loro efficienza energetica. In particolare, è analizzato un edificio caso studio, che rispetta i requisiti di Passive House (denominato An-der-Lan), tramite strumenti di simulazione dinamica di edifici e impianti.

L'edificio studiato è una Passive House dotata di un sistema elettrico per il riscaldamento e la produzione di ACS. Questo rappresenta un caso studio per investigare il concetto di convenienza economica ed efficienza degli edifici. Grazie alla produzione elettrica di calore per il riscaldamento dell'edificio e la produzione di ACS, si evitano perdite di distribuzione e allo stesso tempo, grazie alla semplicità di installazione, i costi di investimento possono essere mantenuti al minimo. Ma a causa dell'inefficienza del sistema, la richiesta energetica è elevata e di conseguenza lo sono i costi operativi. Quindi, per compensare la richiesta energetica, su tutta la facciata dell'edificio esposta a sud è stato installato un impianto fotovoltaico (PV).

Gli edifici a energia quasi zero (nZEB) rappresentano lo standard richiesto dal 2021 in poi dalla Direttiva Europea "Energy Performance of Building Directive" (EPBD). Ogni Stato membro dell'Unione Europea ha sviluppato la propria definizione di nZEB e i propri requisiti da soddisfare per raggiungere questo concetto. Risulta quindi difficile paragonare i Decreti di ogni Stato (al contrario dei requisiti delle Passive House). A titolo d'esempio, la Direttiva italiana e austriaca di recepimento e applicazione dell'EPBD sono state analizzate.

Sono condotte simulazioni dinamiche grazie all'integrazione di diversi software. Tutti i dati dell'edificio sono letti dal PHPP (Passive House Planning Package), il quale è uno strumento per la progettazione e la certificazione delle Passive House. Il PHPP usa bilanci energetici su base mensile. I dati sono in seguito letti da CarnotUIBK, modello in ambiente MATLAB Simulink, sviluppato dall'Università di Innsbruck, per simulare il comportamento dinamico dell'edificio. Infine, blocchi della libreria CARNOT (sviluppata dal Solar Institute di Jülich, Germania) sono assemblati in Simulink per modellare i sistemi aggiuntivi. Questi sono: il sistema per il riscaldamento, il sistema per la produzione di ACS, il sistema fotovoltaico e la pompa di calore (HP). Per la parametrizzazione della HP, i dati sono acquisiti dal software dell'azienda Galletti (Selmac Galletti).

Per semplicità, la prima parte delle simulazioni dinamiche si concentra sul paragone tra i modelli UA e RC per un semplice ufficio situato a Roma. Questo è un edificio caso studio del progetto IEA SHC T56 – System Simulation Models. In particolare, l'attenzione si concentra sull'influenza della capacità termica. Assumendo il modello RC come il caso di riferimento, sono simulate varianti del modello UA con diverse percentuali di capacità, al fine di trovare la

più simile al modello RC. Sono considerate varie grandezze e in seguito i loro valori sono paragonati tra i due modelli. In base alla grandezza considerata, il modello UA più simile al RC cambia. Per questo edificio, il modello UA con il 25% della capacità termica originale (che è $132\,\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$, che corrisponde al valore standard per un edificio con un peso medio nel PHPP) può essere considerato la migliore approssimazione del modello RC (che è il modello più dettagliato). Lo stesso studio è condotto per l'edificio An-der-Lan. In questo caso non è possibile identificare il migliore modello UA in quanto, per ogni grandezza considerata, la minima differenza tra il modello UA e il modello RC si ottiene per una diversa percentuale della capacità termica. Inoltre, sono confrontati i tempi di simulazione per il caso del semplice edificio a una sola zona termica. Il modello RC risulta quello con il maggior tempo computazionale. Per esempio, esso risulta 6 volte maggiore del tempo richiesto dal modello UA con il 25% di capacità. In ogni caso, questo maggiore sforzo computazionale è considerato accettabile al fine di ottenere risultati più realistici.

La seconda parte di simulazioni dinamiche si concentra sul confronto tra diversi sistemi per il riscaldamento e la produzione di ACS. Il sistema reale, assunto come caso di riferimento e chiamato Case1, è composto da riscaldamento elettrico tramite corpi radianti e produzione di ACS tramite boiler con resistenze elettriche. Questo è confrontato con soluzioni alternative. Il Case2 si basa su un sistema centralizzato a pompa di calore: sia il riscaldamento che la produzione di ACS sono alimentati da una pompa di calore aria/acqua. Per questi due casi principali, diverse varianti sono studiate. La prima variante riguarda gli accumuli per l'ACS: un volume minore e uno maggiore, rispetto al caso base, sono considerati. Inoltre, è studiata la variazione dell'area dei pannelli PV. Diversi design e diversi orientamenti sono considerati. È condotta un'analisi di sensitività. Quando si considerano le varianti dell'accumulo di ACS, il PV è mantenuto al caso di riferimento e viceversa. Infine, il Case3 e il Case4 sono una via di mezzo dei casi precedenti. Il Case3 prevede il riscaldamento da HP e produzione elettrica di ACS, mentre il Case4 consiste in riscaldamento elettrico e ACS fornita da HP.

I risultati mostrano che il Case2 è il migliore in termini di energia elettrica richiesta dalla rete, sebbene sia il sistema con le maggiori perdite termiche. Questo prova la convenienza della HP rispetto al caso elettrico, che è il meno efficiente. Inoltre, l'impianto PV sulla facciata a sud non risulta sufficiente a coprire la richiesta energetica in nessuno dei due casi principali. Infatti solo per pochi giorni in un anno, l'energia elettrica può essere fornita alla rete.

Infine, bilanci energetici annuali, mensili, giornalieri, orari e ogni 10 minuti sono confrontati. I risultati mostrano l'importanza di piccoli time step nei bilanci tra energia richiesta e prodotta, al fine di ottenere risultati più precisi

# SUMMARY

## *LIST OF SYMBOLS AND UNITS*

| | | |
|---|---|---|
| A | Total internal floor area | $\left[\mathrm{m^2}\right]$ |
| C | Capacity | $\left[\frac{\mathrm{J}}{\mathrm{m^3\ K}}\right]$ |
| $c_p$ | Specific heat capacity at constant pressure | $\left[\frac{\mathrm{J}}{\mathrm{kg\ K}}\right]$ |
| $E$ | Electric energy | [Wh] |
| EEB | Final energy demand | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2 year}}\right]$ |
| EP | Energy Performance Index | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2}}\right]$ |
| $E_r$ | Relative error | [-] |
| f | Conversion Factor | [-] |
| $f_{GEE}$ | Total energy efficiency factor | [-] |
| $HBW_{Ref}$ | Reference space heating demand | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2 year}}\right]$ |
| $H'_T$ | Average coefficient of global heat exchange for transmission per unit of dispersing surface | $\left[\frac{\mathrm{W}}{\mathrm{m^2}}\right]$ |
| $HTEB_{Ref}$ | Reference heating technology energy demand | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2 year}}\right]$ |
| I | Current | [A] |
| ℓc | Shape factor | [-] |
| $\dot{m}$ | Mass flow | $\left[\frac{\mathrm{kg}}{\mathrm{s}}\right]$ |
| $N$ | Exponent of the radiator | [-] |
| n | Number of elements | [-] |
| P | Power | [W] |
| $PEB_{HEB}$ | Primary energy demand | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2 year}}\right]$ |
| $Q$ | Thermal power | [W] |
| Q | Requested thermal energy (according to the Italian Interministerial Decree) | $\left[\frac{\mathrm{kWh}}{\mathrm{m^2 \cdot year}}\right]$ |
| T | Absolute temperature | [K] |
| U | Thermal Transmittance | $\left[\frac{\mathrm{W}}{\mathrm{m^2 K}}\right]$ |
| V | Voltage | [V] |

## *LIST OF GREEK LETTERS AND UNITS*

| | | |
|---|---|---|
| η | Efficiency | [-] |
| Δ | Difference | [-] |
| θ | Relative temperature | [°C] |
| ρ | Density | $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$ |

## *LIST OF SUBSCRIPTS*

| | |
|---|---|
| *10 min* | 10 minutes balance |
| A | Ambient air indoor |
| amb | Ambient air outdoor |
| *annual* | Annual |
| *building* | Required from the building |
| C | Cooling |
| c | Convective |
| $CO_2$ | $CO_2$ |
| DHW | Domestic Hot Water |
| el | Element |
| energy_cool | Energy through the cooling system |
| energy_heat | Energy through the heating system |
| energy_trans | Energy through walls and windows |
| energy_vent | Energy due to ventilation |
| gl | Global |
| *grid* | Required from the grid |
| H | Heating |
| in | Inside |
| inf | Infiltration |
| intgains | Gains |
| L | Lighting |
| limit | Limit |
| max | Maximum |
| mpp | Maximum power point |

| | |
|---|---|
| nd | Needed |
| oc | Open circuit |
| out | Outside |
| P,nren | Primary no-renewable energy |
| P,ren | Primary renewable energy |
| P,tot | Total primary energy |
| PE | To determine the PEB |
| PE, ern | Renewable portion of the PEB |
| PE, n ern | Non-renewable portion of the PEB |
| PV | Photovoltaic |
| R | Radiator |
| r | Radiative |
| s | Sensitive |
| sc | Short circuit |
| spec | Specific |
| Tground | Transmission through the ground |
| tot | Total |
| trans | transmission |
| Twalls | Transmission through wall |
| Twind | Transmission through windows |
| u | Useful |
| V | Ventilation |
| vent | Ventilation |
| ventmech | Mechanical ventilation |
| W | Water |

## *LIST OF ABBREVIATIONS*

| | |
|---|---|
| 3D | Three Dimensional |
| A | Annex |
| AC | Alternate Current |
| AEA | Austrian Energy Agency |
| BIPV | Building Integrated PhotoVoltaics |
| BPS | Building Performance Simulation |
| CARNOT | Conventional And Renewable eNergy systems OpTimization Blockset |
| COP | Coefficient Of Performance |
| CTI | Italian Thermotechnical Committee |
| DC | Direct Current |
| DH | District Heating |
| DHW | Domestic Hot Water |
| e7 | Energy Markets Analysis |
| EH | Electric Heating |
| ENEA | National Agency For New Technologies And Energy |
| EPBD | Energy Performance Of Building Directive |
| ERA | European Research Area |
| EU | European Union |
| HP | Heat Pump |
| HPP | Heat Pump Programme |
| HVAC | Heating, Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| IEA | International Energy Agency |
| LCoE | Levelized Cost Of Electricity |
| MATLAB | MATrix LABoratory |
| nZEB | Nearly Zero Energy Building |
| NZEB | Net Zero Energy Building |
| OIB | Austrian Institute Of Construction Engineering |
| PHPP | Passive House Planning Package |
| PI | Proportional-Integrator |

| | |
|---|---|
| PV | Photovoltaic |
| RMS | Root mean square |
| RSE | Energy Research Company |
| SaLüH | Renovation for ventilation, heating and hot water |
| SHC | Solar Heating and Cooling programme |
| SPF | Seasonal Performance Factor |
| ST | Solar Thermal |
| STC | Standard Test Conditions |
| T | Task |
| THB | Thermo-Hydraulics Bus |
| WDB | Weather Boundary Condition |
| ZEL | Zero Energy Level |

# 1 PROJECT INTRODUCTION

## 1.1 LITERATURE OVERVIEW

The European Union (EU) is focused on limiting building environmental impact through specific policy actions, a clear example is the recast of the Energy Performance of Buildings Directive (EPBD) (European Commission, 2018). One relevant regulatory obligation of the EPBD recast is that all new buildings have to be nearly zero-energy buildings (nZEBs) by the end of 2020. The definition of nZEB is up to each Member State, but the common aspect is a very high energy performance with renewable production to cover the remaining energy needs in a building. Moreover, Member States should draft a cost-optimal methodology. The aim is to obtain both an energy convenience and a cost convenience in the new building construction.

As D'agostino and Parker (2018) highlighted, a cost-effective nZEB is achievable in many states with the optimization of some key factors such as thermal insulation, airtightness, home energy management system along with photovoltaics (PV), and class A++ for appliances and lighting. In the optimized cases, the natural gas consumption for space and water heating was reduced approximately by 70.

For more economic solutions in some cases, a shift from an nZEB to a zero emission neighbourhoods can be meaningful. The installation of grid connected renewable energy sources at a local or regional level instead of a single building could be more efficient and economic (Good et al., 2016).

A similar concept of nZEB is the Net Zero Energy Building (NZEB) accounting often for annual electricity balance between on-site renewables and grid. An example is an efficient technical system entirely based on heat pump combined with the maximum possible PV installed in a highly insulated building (Becchio et al, 2015). In that case also, the economic benefits of considering a region or a state instead of a single building were discussed. Introducing the levelized cost of electricity (LCoE), it has been shown in a simulation study that the cost of energy from PV was more expensive than the grid electricity for a single building

(Hirvonen et al. 2016). Therefore, it is confirmed the need of incentives. Then, a system of PV combined with heat pump (HP) or direct electric heating (EH) shows an LCoE lower than the grid. However, the same trend is not confirmed for a PV system coupled with district heating (DH). In any case, it was highlighted that the zero energy level (ZEL) was directly proportional to the PV capacity for all heating systems. Another interesting outcome was that the use of a thermal storage of 200 l was able to increase the self-consumption of PV. Self-consumption values for the heat pump were increased by 20 - 40%, while with direct electric was increased by 15% - 70% when storage was utilized. With EH, a small storage gave relatively much larger benefits than a large one. Below 2 kW PV capacity, the storage size was not important, due to the small amount of excess power. Larger storages increased the demand for grid electricity during times of low insolation.

Another study declares that a combination of PV and HP is more cost effective compared to PV and battery. Indeed, optimal operation of an HP enabled an average saving of 7% of the electricity cost under conventional operation. This can greatly contribute to the expansion of PV. Although the introduction of a 2 kWh to 4 kWh battery enabled a cost saving of 100 to 300 USD per year, the investment was not recovered within the lifetime of the battery (assuming current prices) (Iwafune et al., (2017).

Finally, a comparison between a solar thermal (ST) system and a PV system coupled with an HP has been presented in considering two multi-family houses. The yield of a solar thermal system (including storage and distribution losses) was compared to that of a heat pump system and PV. It was indicated that small solar thermal systems are generally favourable compared to PV from the energetic point of view. For air-/water heat-pumps with commonly lower seasonal performance factor (SPF) larger solar thermal system are beneficial. The economics strongly depends on the development of the PV system costs. Trends indicate an advantage of PV over ST even if low volatile electricity prices (i.e. seasonal fluctuation) are considered. The system complexity increases in case of solar and heat pump systems. Hence, for a decision for or against ST, it should be considered that the maintenance effort might be over-proportional high for small ST systems (Ochs et al., 2014).

## 1.2 AN-DER-LAN BUILDING AND THE CONCEPT OF PASSIVE HOUSE

The project analysed in this work is about a new building in the so called An-der-Lan project. From now on, for sake of simplicity, it will be referred as the An-der-Lan building.

The building has been constructed under the requirements of the Passive House standard. Passive House is a building standard that is truly energy efficient, comfortable and affordable at the same time. A Passive House is designed to have an energy demand that is as low as possible. The combination of Passive House with renewable sources of energy represents a suitable solution to move to low/zero carbon buildings. Indeed, with such a low amount of required energy, it is easier to meet the subsequent demand by renewable sources (Passive House Institute, 2018).

The An-der-Lan building is a new small residential complex with 14 flats situated in Innsbruck, Austria (Figure 1.1).

The owner is the Innsbruck's real estate company (IIG) and it will be used by the association “psycho-social care service of Tyrol”. The Association will accompany the mentally ill, which after a stay in the clinic, should be offered a temporary assisted living environment with a therapeutic offer as assistance on the way to the independent life.

*Figure 1.1: Building of the An-der-Lan project*

In this study, the Passive House case study An-der-Lan building is simulated with the dynamic tool MATLAB Simulink. Electric system is modelled to provide heat for the space heating and domestic hot water (DHW). A PV system is modelled to provide electric power. A comparison of electric source with PV system and HP with PV system is carried out in order to evaluate which can be the more energy convenient. Indeed, the study has the purpose to investigate which can be the best way to have self-consume of the power coming from the PV system, requiring as less as possible energy from the grid. This is a more precise approach to the problem, compared to the no-dynamic tools. Indeed, monitoring the behaviour of the whole building system every few minutes for a year allows to have more detailed and realist results compared to static tool. The main risk of the latter is to overrate the actual useful power from the PV system, as the request and production of energy are not coincident.

In Chapter 2 the concept of energy efficient building according the European Union is illustrated. Moreover, the nZEB requirements according the Italian and Austrian Decrees are presented. Chapter 3 presents the detailed description of the two considered buildings. The first is a simple single zone office, the second is the An-der-Lan building. In particular, there is the description of its systems in the reference case, the alternative solutions considered and all the variants taken into account in this project. Theoretical description of the UA and RC models is illustrated in Chapter 4. Moreover, in this chapter adopted tools in simulation models are shown. In particular, all the blocksets used in MATLAB Simulink models are presented too. In Chapter 5 results for different models (UA and RC) are illustrated and discussed. The same method is applied for the results obtained from the An-der-Lan building simulations. Moreover, a sensitivity analysis is presented. Furthermore, the comparison among alternative systems are discussed. Comparison among different time step balances is conducted too. Finally, in Chapter 6 conclusion and possible future development are exposed.

# 2 NZEB IN THE CURRENT LANDSCAPE

## 2.1 ENERGY EFFICIENCY BUILDING FOR EUROPEAN COMMISSION

Buildings are responsible for approximately 40% of energy consumption and 36% of $CO_2$ emissions in the EU. Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of building stock is energy inefficient, while only 0.4-1.2% (depending on the country) of building stock is renovated each year. Therefore, more renovation of existing buildings has the potential to lead to significant energy savings, which could reduce the EU's total energy consumption by 5-6% and lower $CO_2$ emissions by about 5%.

Improving the energy efficiency of buildings can also generate other economic, social and environmental benefits. Furthermore, energy performance of buildings also has a major impact on the affordability of housing and energy poverty. Energy savings and efficiency improvement of the housing stock would enable many households to escape energy poverty (European Commission: Energy Efficiency, Building, 2018).

The 2010 Energy Performance of Buildings Directive (EPBD) and the 2012 Energy Efficiency Directive are the EU's main legislation promoting the improvement of the energy performance of buildings within the EU and providing a stable environment for investment decisions to be taken.

### 2.1.1 The Energy Performance of Buildings Directive (EPBD, 2010)

The EPBD is the European Union's main legislative instrument aiming to promote the improvement of the energy performance of buildings within the Community. It was inspired by the Kyoto Protocol which commits the EU and all its parties by setting binding emission reduction targets.

The so-called "EPBD recast" was the replacement of the Directive 2002/91/EC. It was approved on 19 May 2010 and entered into force on 18 June 2010.

This version of the EPBD broadened its focus on Nearly Zero-Energy Buildings (nZEB), cost optimal levels of minimum energy performance requirements as well as improved policies.

According to the recast:

- All new buildings must be nearly zero-energy buildings by 31 December 2020 (public buildings by 31 December 2018)
- Energy performance certificates must be issued when a building is sold or rented, and they must also be included in all advertisements for the sale or rental of buildings
- EU countries must establish inspection schemes for heating and air conditioning systems or put in place measures with equivalent effect
- EU countries must set cost-optimal minimum energy performance requirements for new buildings, for the major renovation of existing buildings, and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls and so on)
- EU countries must draw up lists of national financial measures to improve the energy efficiency of buildings.

The last two points represent the idea that minimum requirements have to be defined through an economic analysis too. The rules for performing this analysis have been set by the Commission and form the “cost-optimal methodology”, which must be applied by each Member State to make a comparison against the current requirements and, in the future, whenever the requirements are updated.

### 2.1.2 The Energy Efficiency Directive (2012)

The Energy Efficiency Directive establishes a set of binding measures to help the EU reach its 20% energy efficiency target by 2020 (Europe 2020). Under the Directive, all EU countries are required to use energy more efficiently at all stages of the energy chain, from production to final consumption.

Buildings under the Energy Efficiency Directive should respect the following points:

- EU countries must make energy efficient renovations to at least 3% of the total floor area of buildings owned and occupied by central government
- EU governments should only purchase buildings which are highly energy efficient
- EU countries must draw up long-term national building renovation strategies which can be included in their National Energy Efficiency Action Plans.

On 30 November 2016 the Commission proposed an update for both the Directives. The aim is to accelerate building renovation, to help promote the use of smart technology in building and a new target of 30% of energy efficiency for 2030.

To support this aim, the Commission also published the EU Building Stock Observatory. This is a new buildings database that monitors the energy performance of buildings across Europe, tracking many different aspects.

In the end, the European Commission draws its attention to certificates and financing renovations too.

## 2.2 EUROPE 2020 AND HORIZON 2020

Europe 2020 is a 10-year strategy proposed by the European Commission on 3 March 2010 for advancement of the economy of the European Union. It aims at "*smart, sustainable, inclusive growth*" with greater coordination of national and European policy. It follows the Lisbon Strategy for the period 2000–2010.

The strategy identifies five headline targets the European Union should take to boost growth and employment. One of these is exactly about the energy landscape: reduction of greenhouse gas emission, increase of renewable energy and increase of energy efficiency. One of the implementing tools of the Europe 2020 strategy is Horizon 2020 (European Commission: Europe 2020 Strategy, 2018).

Horizon 2020, also named "FP8", is the eighth of the Framework Programmes for Research and Technological Development. These are funding programmes created by the European Union/European Commission to support and foster research in the European Research Area (ERA). Horizon 2020 provides grants to research and innovation projects through open and competitive calls for proposals. Horizon 2020 supports Open access to research results, in order to create greater efficiency, improve transparency and accelerate innovation (Framework Programmes for Research and Technological Development, 2018).

## 2.3 NZEB ITALIA

### *ITALIAN DEFINITION OF NEAR ZERO ENERGY BUILDING (NZEB)*

In Italy, the EPBD has been implemented with the Legislative Decree 4 June 2013, n.63, converted with modifies in the law of the 3rd August 2013, n.90. Here the nZEB is defined. The definition is the following: "*A Nearly Zero Energy Building is a building with a great performance, which is evaluated based on the requirements for new buildings and additional requirements about renewable sources. Energy needs are very low, or nearly zero, and mostly covered by renewable sources. The requirements are all referred to the reference building*" (Decreto Interministeriale del 26 Giugno 2015, 2015).

The "reference building" was born in the Interministerial Decree of June 26, 2015 for building energy certification. The purpose of this operation is to provide a general reference to calculate the value of primary energy limit that new buildings or those undergoing major renovation must comply. The reference building is defined by the Decree as a virtual building identical to the planned one in terms of geometry (shape, volumes, floor area, surfaces of constructive elements and components), orientation, territorial location, destination of use and situation to the contour. On the other hand, thermal characteristics and energy parameters are determined by the Decree, based on the climatic zone of the site. For all not defined input data and parameters, real building values are used.

Regarding the building shell, there are precise transmittance values within which it is necessary to undergo, these change according to the housing element considered, to the climate zone and the date of the operation (in the case of residential in fact limits are different between 2015 and 2021). In the Decree is specified that all these values are inclusive of thermal bridges.

As regards the technical installations, instead, the building of reference shall be deemed to be equipped with the same energy production plants of the real building. In the regulation are provided values concerning winter heating, summer cooling, production of domestic hot water, of electricity on- site, of mechanical ventilation and lighting.

The Decree defines that it must be refer to UNI/TS 11300 for the calculation of the requested thermal energy in winter ($Q_{H,nd}\left[\frac{kWh}{m^2\cdot year}\right]$) and in summer ($Q_{C,nd}\left[\frac{kWh}{m^2\cdot year}\right]$). Moreover, for space heating and cooling, reference building parameters must be used, while regarding the domestic hot water, the required thermal energy ($Q_{W,nd}\left[\frac{kWh}{m^2\cdot year}\right]$) is equal to that of the real building.

Consequently, to carry out any work on the building, there must a comparison with the parameters proposed by the Decree regarding the reference building.

Different requirements must be satisfied if different intervention types are taken into account.

### *PARAMETERS OF ITALIAN NZEB*

Five requests have to be satisfied in order to obtain a nZEB.

1. The average coefficient of global heat exchange for transmission per unit of dispersing surface ($H'_T \left[\frac{W}{m^2}\right]$) must be less than the maximum allowable value reported in Table 2.1, depending on the climate of the area and the ratio surface/volume $\left(\frac{S}{V}\left[\frac{1}{m}\right]\right)$:

*Table 2.1: Maximum allowable $H'_T$ values*

| **Shape ratio** $\left(\frac{S}{V}\right)\left[\frac{1}{m}\right]$ | **Climatic zone** | | | | |
|---|---|---|---|---|---|
| | **A and B** | **C** | **D** | **E** | **F** |
| $\left(\frac{S}{V}\right) \geq \mathbf{0.7}$ | 0.58 | 0.55 | 0.53 | 0.50 | 0.48 |
| $\mathbf{0.4} \leq \left(\frac{S}{V}\right) < \mathbf{0.7}$ | 0.63 | 0.60 | 0.58 | 0.55 | 0.53 |
| $\left(\frac{S}{V}\right) < \mathbf{0.4}$ | 0.80 | 0.80 | 0.80 | 0.75 | 0.70 |

2. The ratio between the solar summer equivalent area of the windowed components and the area of the useful surface ($\frac{Asol,est}{Asup,useful}$ [−]) must be lower than the corresponding limit value. This is 0.030 for residential building and 0.040 for all other buildings.

3. The energy performance indexes $EP_{H,nd}$, $EP_{C,nd}$ and $EP_{gl}$ must be lower than the values of the corresponding limit indexes calculated for the reference building ($EP_{H,nd,limit}$, $EP_{C,nd,limit}$ and $EP_{gl,limit}$).
   These parameters represent:
   - $EP_{H,nd}$ is the energy performance index for winter conditioning $\left[\frac{kWh}{m^2}\right]$
   - $EP_{C,nd}$ [kWh/m$^2$] is the energy performance index for summer conditioning, including humidity control $\left[\frac{kWh}{m^2}\right]$

- $EP_{gl}$ is the global energy performance index, expressed in total primary energy $\left[\frac{\mathrm{kWh}}{\mathrm{m}^2}\right]$. Sometimes this parameter can be also indicated as $EP_{gl,tot}$ for the building and $EP_{gl,tot,limit}$ for the reference building.
- $EP_{H,nd,limit}$, $EP_{C,nd,limit}$ and $EP_{gl,limit}$ (or $EP_{gl,tot,limit}$) are the same quantities, but referred to the reference building $\left[\frac{\mathrm{kWh}}{\mathrm{m}^2}\right]$

All these parameters are calculated as the ratio between the needed energy [kWh] and the surface of the apartment [m$^2$]. In particular, they are obtained from Equation 2.1-2.3:

$$EP_{H,nd} = \frac{Q_H}{S_u} \tag{2.1}$$

$$EP_{C,nd} = \frac{Q_C}{S_u} \tag{2.2}$$

$$EP_{gl,nd} = EP_{H,nd} + EP_{C,nd} + EP_{W,nd} + EP_{V,nd} + EP_{L,nd} \tag{2.3}$$

Where:

$$EP_{W,nd} = \frac{Q_{W,nd}}{S_u} \tag{2.4}$$

$$EP_{V,nd} = \frac{Q_{V,nd}}{S_u} \tag{2.5}$$

$$EP_{L,nd} = \frac{Q_{L,nd}}{S_u} \tag{2.6}$$

$Q_{W,nd}$, $Q_{V,nd}$, $Q_{L,nd}$ are the energy demand respectively for domestic hot water, ventilation and lighting and they all are assumed equal to values of the real building.

The energy demands (Q) for heating and cooling are calculated considering the thermal transmittance of the reference building. These values vary based on the element (vertical external wall, vertical internal wall, roof, etc.) and the climatic zone. Limit values for structures toward outside or not conditioned rooms are shown in Table 2.2.

*Table 2.2: U-value limits for structures toward outside or no-conditioned room, based on the type of structure and climatic zone, according to the Interministerial Decree of June 26, 2015*

| | $\mathbf{U}\left[\frac{W}{m^2K}\right]$ | | | |
|---|---|---|---|---|
| **Climatic zone** | **Opaque vertical structures** | **Opaque horizontal or sloping coverage structures** | **Opaque horizontal floor structures** | **Transparent and opaque windows (fixtures included)** |
| **A and B** | 0.43 | 0.35 | 0.44 | 3.00 |
| **C** | 0.34 | 0.33 | 0.38 | 2.20 |
| **D** | 0.29 | 0.26 | 0.29 | 1.80 |
| **E** | 0.26 | 0.22 | 0.26 | 1.40 |
| **F** | 0.24 | 0.20 | 0.24 | 1.10 |

Furthermore, thermal transmittance U of opaque vertical and horizontal structure of separation between buildings or neighbour estate must be lower than 0.8 $\frac{W}{m^2K}$ for every climatic zone. The total solar factor transmission value (ggl+sh) for the windowed components with orientation from east to west passing to the south must be lower than 0.35 for every climatic zone.

4. The efficiencies of average seasonal efficiency of heating ($\eta_H$), of average seasonal efficiency of hot water production ($\eta_W$) and of average seasonal efficiency of cooling ($\eta_C$) must be higher than the values of the corresponding efficiencies indicated for the building of reference ($\eta_{H,limit}$, $\eta_{W,limit}$, and $\eta_{C,limit}$). These limits are listed in the Table 2.3 and 2.4.

*Table 2.3: Efficiencies for the subsystem of utilization performance*

| Subsystem of utilization performance | H | C | W |
|---|---|---|---|
| **Water distribution** | 0.81 | 0.81 | 0.70 |
| **Air distribution** | 0.83 | 0.83 | - |
| **Mix distribution** | 0.82 | 0.82 | - |

*Table 2.4: Efficiencies for subsystem of power-generating*

| Subsystem of power-generating | Thermal energy production | | | Electric energy production on-site |
|---|---|---|---|---|
| | **H** | **C** | **W** | |
| **Liquid fuel power-unit** | 0.82 | - | 0.80 | - |
| **Gas fuel power-unit** | 0.95 | - | 0.85 | - |
| **Solid fuel power-unit** | 0.72 | - | 0.70 | - |
| **Solid biomass power-unit** | 0.72 | - | 0.65 | - |
| **Liquid biomass power-unit** | 0.82 | - | 0.75 | - |
| **Vapour compression heat pump with electric engine** | 3.00 | 2.50 | 2.50 | - |
| **Vapour compression chiller with electric engine** | - | 2.50 | - | - |
| **Absorption heat pump** | 1.20 | 2.50 | 1.10 | - |
| **Chiller with indirect flame** | | $0.60 * \eta_{gn}$ | - | - |
| **Chiller with direct flame** | - | 0.60 | - | - |
| **Vapour compression heat pump with endothermic engine** | 1.15 | 1 | 1.05 | - |
| **Cogeneration** | 0.55 | - | 0.55 | 0.25 |
| **Electric heating (resistance)** | 1.00 | - | - | - |
| **District heating** | 0.97 | - | - | 0.1 |
| **District cooling** | - | 0.97 | - | - |
| **Thermal solar system** | 0.3 | - | 0.3 | - |
| **Photovoltaic system** | - | - | - | - |

5. In accordance with the Legislative Decree No. 28/2011 remain the limits on thermal renewable.

   Specifically, the plants for the production of thermal energy must guarantee the respect of the cover, through the use of renewable sources, of 50% $EP_W$ and 50% ($EP_H + EP_C + EP_W$).

### *ITALIAN CONVERSION FACTORS*

For the purposes of building classification, the calculation of not renewable primary energy is made applying the appropriate conversion factors in primary no-renewable energy.

The conversion factor in total primary energy is $f_{P,tot}$ and it is calculated according to Equation (2.7):

$$f_{P,tot} = f_{P,nren} + f_{P,ren} \tag{2.7}$$

Where:

- $f_{P,nren}$: conversion factor in primary no-renewable energy
- $f_{P,ren}$: conversion factor in primary renewable energy

These factors are indicated in Table 2.5:

*Table 2.5: Conversion factors*

| **Energetic vector** | $f_{P,nren}$ | $f_{P,ren}$ | $f_{P,tot}$ |
|---|---|---|---|
| **Natural gas** | 1.50 | 0 | 1.05 |
| **GPL** | 1.50 | 0 | 1.05 |
| **Diesel and oil fuel** | 1.07 | 0 | 1.07 |
| **Coal** | 1.10 | 0 | 1.10 |
| **Solid biomass** | 0.20 | 0.80 | 1 |
| **Liquid and gas biomass** | 0.40 | 0.6 | 1 |
| **Electric energy from the grid** | 1.95 | 0.47 | 2.42 |
| **District heating** | 1.5 | 0 | 1.5 |
| **Urban waste** | 0.2 | 0.2 | 0.4 |
| **District cooling** | 0.5 | 0 | 0.5 |
| **Electric energy from solar thermal system** | 0 | 1.00 | 1.00 |
| **Electric energy from photovoltaic system** | 0 | 1.00 | 1.00 |
| **Free cooling** | 0 | 1.00 | 1.00 |
| **Heat pump** | 0 | 1.00 | 1.00 |

### ***ITALIAN COST-OPTIMAL METHODOLOGY***

In Italy, to pursue the cost-optimal methodology, the Ministry of Economic Development has set up a working group including Energy Research Company (RSE), National Agency for New Technologies and Energy (ENEA) and Italian Thermotechnical Committee (CTI). The last step in this methodology was to compare the optimal levels with the requirements currently in force. Comparison showed that in almost all the buildings, it is more cost-effective to exceed the minimum legal requirements and construct higher-performance buildings than those required by the current law. This will allow to obtain not only energy savings but also cost savings during the building's useful life.

## 2.4 NZEB AUSTRIA

### *AUSTRIAN DEFINITION OF NEARLY ZERO ENERGY BUILDING (NZEB)*

The Austrian nZEB is defined in the Austrian Institute of Construction Engineering (OIB) Guideline 6 (Österreichisches Institut für Bautechnik, 2018). The definition is "*A nZEB is an energy efficient building with a good thermally insulated envelope and an environment-friendly heating system, which is not attached to a specific building concept, e.g., 'Passive House'* ".

### *PARAMETERS OF AUSTRIAN NZEB*

Austrian nZEBs are defined by four indicators or parameters. The minimum energy performance requirements on these four indicators are related to the Austrian reference climate. In addition to these parameters, other requirements have to satisfied. These concern renewable share, heat-transferring components, technical building system and maximum coverable electricity required.

Independently from requirements, every new building or existing building in case of renovation has to respect the limit on the U values, defined in the OIB Guideline 6 (Table 2.6). The same values will also apply for the NZEB 2020 buildings as well.

*Table 2.6: Minimum requirements for U-values*

| **Building elements** | **U** $\left[\frac{W}{m^2K}\right]$ |
|---|---|
| **Exterior wall** | 0.35 |
| **Roof** | 0.2 |
| **Window** | 1.4 |
| **Floor** | 0.4 |

1. The four main indicators are:
    - Reference space heating demand ($HBW_{Ref}$ $\left[\frac{kWh}{m^2a}\right]$);
    - Final energy demand (EEB $\left[\frac{kWh}{m^2a}\right]$);
    - Total energy efficiency factor ($f_{GEE}$ [-]);
    - Primary energy demand ($PEB_{HEB}$ $\left[\frac{kWh}{m^2a}\right]$);

These parameters have to respect the requests shown in the Table 2.7. The table shows that the national plan indicates a stepwise tightening of the requirements towards 2020. In particular, compliance with minimum requirements can be achieved by two methods:

- Through tightened requirements on space heating demand ($HBW_{Ref}$), which means better building envelope in order to reduce the heating/cooling energy needed, and not considering the $f_{GEE}$. This is reflected in the formula for NZEB 2020 buildings $10 \times (1 + 3{,}0 / \ell c)$ where $\ell c$ is the characteristic length (usually known as the building's 'shape factor');
- Through installation of a more energy efficient technical system for heating and DHW. The total energy efficiency factor ($f_{GEE}$) reflects the type of energy use and production

*Table 2.7: Main indicators for Austrian nZEB*

| | **$HBW_{Ref}$** | **EEB** | **$f_{GEE}$** | **$PEB_{HEB}$** |
|---|---|---|---|---|
| **Currently in force** | $14 \times (1 + 3{,}0 / \ell_c)$ | by means of $HTEB_{Ref}$ | | 41 |
| | or | | | |
| | $16 \times (1 + 3{,}0 / \ell_c)$ | | 0,85 | |
| **By entry into force of OIB-RL6:2019** | $12 \times (1 + 3{,}0 / \ell_c)$ | by means of $HTEB_{Ref}$ | | |
| | or | | | |
| | $16 \times (1 + 3{,}0 / \ell_c)$ | | 0,80 | |
| **From 01/01/2021** | $10 \times (1 + 3{,}0 / \ell_c)$ | by means of $HTEB_{Ref}$ | | |
| | or | | | |
| | $14 \times (1 + 3{,}0 / \ell_c)$ | | 0,75 | |

Where $HTEB_{Ref}$ is the reference heating technology energy demand.

2. Requirements for the renewable share

The requirement of minimum levels of energy from renewable sources in the case of new construction and renovation of a building is fulfilled if at least one of the following points from (a) or (b):

a. Use of renewable sources outside the system boundaries "building":
   It is required that at least 50% of heat demand for space heating and hot water is covered by renewable source, in compliance with the requirements of the applicable maximum heating energy demand. The mentioned renewable source can be: biomass, heat pump, district heating from a heating plant on basis if renewable or district heating from high efficiency cogeneration.

b. Use of renewable sources on-site or nearby:
   - There are through active measures, such as by solar thermal energy, net income on-site or in the vicinity of at least 10% of the energy requirement for hot water;
   - There are through active measures, such as by photovoltaic, net income on-site or in the vicinity of at least 10% of the energy requirement for household current or to generate operating current;
   - There are through active measures, such as by heat recovery, net income on-site or in the vicinity of at least 10% of the energy requirements for space heating;
   - A combination of the three previous possibilities to reduce the maximum permissible final energy demand or the maximum permissible total energy efficiency factor $f_{GEE}$ by at least 5% through a combination of measures of solar thermal energy, photovoltaics, heat recovery or efficiency gains.

3. Requirements for heat-transferring components:

The U value of walls must not exceed the values shown in Table 2.8.

*Table 2.8: Limits of U-values foe each type of wall*

| Component | U $\left[\frac{W}{m^2K}\right]$ |
|---|---|
| **Wall against outside air** | 0.35 |
| **Wall against unheated or not developed attic rooms** | 0.35 |
| **Wall against unheated, frost-free parts of building (except lofts)** | 0.60 |
| **Walls earth touched** | 0.40 |
| **Walls (partition walls) between residential or operating units or conditioned staircase** | 0.90 |
| **Walls against other structures at land or building site boundaries** | 0.50 |
| **Walls on small surfaces against outside air** | 0.70 |
| **Walls (partition walls) within residential and business units** | - |
| **Windows, window doors, glazed doors each in residential buildings against outside air** | 1.40 |
| **Windows, window doors, glazed doors each in non-residential buildings against outside air** | 1.70 |
| **Other transparent components vertical against outside air** | 1.70 |
| **Other transparent components horizontal or inclined to outside air** | 2.00 |
| **Other transparent components vertical against unheated building parts** | 2.50 |
| **Roof window against outside air** | 1.70 |
| **Doors unglazed, against outside air** | 1.70 |
| **Doors unglazed, against unheated building parts** | 2.50 |
| **Gates Rolling doors, sectional doors like against outside air** | 2.50 |
| **Inner doors** | - |
| **Ceilings and roofs in each case against outside air and against roof areas (ventilated or uninsulated)** | 0.20 |
| **Ceilings against unheated building parts** | 0.40 |
| **Ceilings against separate living and operating units** | 0.90 |
| **Ceilings within residential and operational units** | - |
| **Ceilings over outdoor air (for example over passages, parking decks)** | 0.20 |
| **Ceilings against garages** | 0.30 |
| **Floors touched the ground** | 0.40 |

4. Requirements for parts of the technical building system

To limit heat dissipation, the heat distribution systems for space heating have to follow the technical measures illustrated in Table 2.9:

*Table 2.9:Limits of technical measured for distribution system*

| **Type of cables** | **Minimum insulation thickness** $\left[\frac{W}{m\,K}\right]$ |
|---|---|
| **Lines in non-conditioned rooms** | 2/3 of the pipe diameter, however, at most 100 mm |
| **for cables in walls and ceiling openings, in the intersection of lines, at central Cable network distributors** | 1/3 of the pipe diameter, however, at most 50 mm |
| **Cables in conditioned rooms** | 1/3 of the pipe diameter, however, at most 50 mm |
| **Cables in the floor construction** | 6 mm (can be omitted when laying in the Impact sound insulation in ceilings against conditioned Spaces, of course without Reduction of footfall sound insulation) |
| **Stubs** | no requirements |

5. Maximum coverable electricity required

The following electricity demand shares are considered to be covered by photovoltaic electricity (Table 2.10):

*Table 2.10: Required percentage of photovoltaic electricity*

| Components | Coverable portion |
|---|---|
| **Space heating, heat supply (heat)** | 25 % |
| **Space heating, power supply(aux.)** | 75% |
| **Hot water, heat supply (heat)** | 50 % |
| **Hot water, power supply (aux.)** | 75 % |
| **Cooling energy requirement** | 25 % |
| **Household Electricity / Electricity consumption** | 75% |
| **Solar thermal energy, auxiliary energy (aux.)** | 100 % |
| **Lighting energy demand** | 0 % |
| **Humidifying energy demand** | 0 % |

## *AUSTRIAN CONVERSION FACTOR*

The conversion factors used to determine the PEB ($f_{PE}$), the non-renewable portion of the PEB ($f_{PE,\ n.ern.}$), the renewable share of PEB ($f_{PE,\ ern.}$) and $CO_2$ ($f_{CO2}$) are shown in Table 2.11.

*Table 2.11: Austrian conversion factors*

| Energy carrier | $f_{PE}$ [-] | $f_{PE,n.ern.}$ [-] | $f_{PE,ern.}$ [-] | $f_{CO2}\left[\frac{g}{kWh}\right]$ |
|---|---|---|---|---|
| **Coal** | 1.46 | 1.46 | 0.00 | 337 |
| **Oil** | 1.23 | 1.23 | 0.01 | 311 |
| **Gas** | 1.17 | 1.16 | 0.00 | 236 |
| **Biomass** | 1.08 | 0.06 | 1.02 | 4 |
| **Electricity (Austrian mix)** | 1.91 | 1.32 | 0.59 | 276 |
| **District heating from renewable energy source** | 1.60 | 0.28 | 1.32 | 51 |
| **District heating from non-renewable energy source** | 1.52 | 1.38 | 0.14 | 291 |
| **District heating from high efficient cogeneration (default value)** | 0.94 | 0.19 | 0.75 | 28 |
| **District heating from high efficient cogeneration (best value)** | ≥ 0.30 | according to individual certification | | |

### *AUSTRIA COST-OPTIMAL METHODOLOGY*

The calculation of cost-optimality in order to define NZEBs 2020 was carried out by OIB in March 2013. This calculation was based on three surveys conducted by the Austrian Energy Agency (AEA), the Energy Markets Analysis (e7) and the Technical University of Vienna.

To calculate cost-optimality, virtual buildings were chosen, which represented four different building categories, namely:

- single-family house;
- multi-family house;
- multi-storey residential building;
- office or commercial building (non-residential building with natural ventilation).

The calculation of the cost-optimality included the calculation of 4 parameters:

- space heating demand $\left[\frac{\mathrm{kWh}}{\mathrm{m}^2\ \mathrm{a}}\right]$
- primary energy demand $\left[\frac{\mathrm{kWh}}{\mathrm{m}^2\ \mathrm{a}}\right]$
- $CO_2$ emissions $\left[\frac{\mathrm{kg}}{\mathrm{m}^2\ \mathrm{a}}\right]$, (according to the conversion factors in the OIB Guidelines)
- total energy efficiency factor ($f_{GEE}$)

The calculation of the cost-optimality consisted of a comparison between the value of the energy savings achieved using the different improvement packages and the costs that are directly and indirectly related to those energy efficiency measures alone.

Based on the outcomes of the cost-optimality methodology, the requirements for achieving NZEB levels – for both residential and non-residential buildings – were defined.

# 3 BUILDINGS AND BOUNDARY CONDITIONS

## 3.1 SIMPLE OFFICE

One of the first topic to investigate is to understand which could be the best possible way to simulate a building, taking into account both the accuracy and the effort to do it. For this purpose, a very simple office is considered (Figure 3.1). The office is from the project IEA SHC T56 – System Simulation Models (SHC Solar Heating and Cooling Programme - International Energy Agency, 2018)

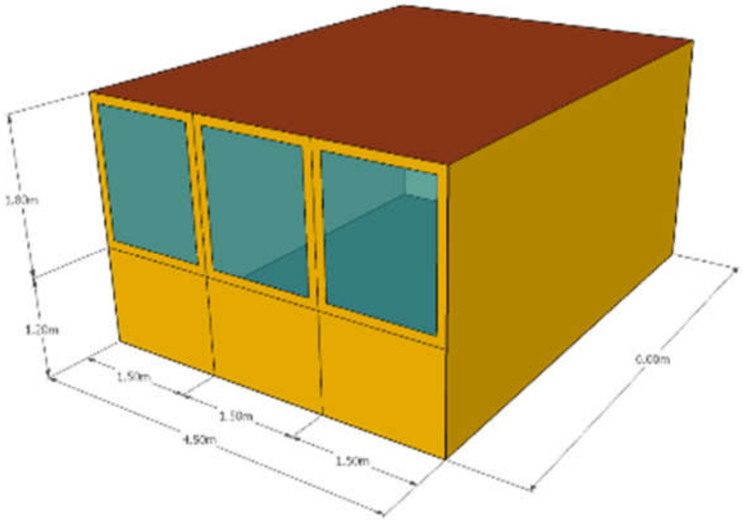

*Figure .3.1: Sketch of the office taken into account*

All the walls are adiabatic except for the south façade, which is through the external environment. This characteristic was simulated by setting the temperature in the other virtual rooms equal to the one in the office. The main wall has three windows with shadings. The simple office is located in Rome, Italy. Climate data are assumed from Meteonorm (Meteonorm Software, 2018) and are shown in Table 3.1, 3.2 and 3.3.

*Table 3.1: Main data climate, according to Meteonorm*

| | |
|---|---|
| **Latitude** | 41.9° |
| **Longitude** | 12.5° |
| **Altitude** | 1 m |

*Table 3.2: Average monthly temperature [°C] , according to Meteonorm*

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8.9 | 10.0 | 12.6 | 14.6 | 19.1 | 23.1 | 26.3 | 26.4 | 22.8 | 18.1 | 12.4 | 9.4 |

*Table 3.3: Average monthly irradiation* $\left[\frac{kWh}{m^2\ month}\right]$*, according to Meteonorm*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nord** | 12 | 18 | 26 | 32 | 46 | 52 | 48 | 39 | 28 | 22 | 15 | 12 |
| **Est** | 38 | 47 | 75 | 94 | 109 | 116 | 121 | 107 | 84 | 65 | 42 | 35 |
| **South** | 104 | 98 | 122 | 107 | 95 | 89 | 100 | 117 | 125 | 127 | 104 | 100 |
| **West** | 40 | 46 | 77 | 88 | 115 | 112 | 119 | 114 | 89 | 64 | 41 | 36 |
| **Horizontal** | 58 | 73 | 122 | 154 | 192 | 202 | 216 | 189 | 142 | 101 | 63 | 50 |

## 3.2 AN-DER-LAN BUILDING

The case study of a multi-storey Passive House is located in Innsbruck, Austria. Therefore, the climate data for Innsbruck are considered. Table 3.4 shows latitude, longitude and altitude.

*Table 3.4: Main data climate, according to Meteonorm*

| | |
|---|---|
| **Latitude** | 47.267° |
| **Longitude** | 11.4° |
| **Altitude** | 582 m |

Table 3.5 shows average monthly temperature [°C].

*Table 3.5: Average monthly temperature, according to Meteonorm*

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -2.5 | 0.2 | 5.2 | 9.9 | 14.3 | 17.6 | 19.3 | 18.5 | 15.2 | 9.6 | 4.1 | -0.9 |

Table 3.6 shows the average monthly values of irradiation along different orientation $\left[\frac{\text{kWh}}{\text{m}^2\ \text{month}}\right]$.

*Table 3.6: Average monthly irradiation, according to Meteonorm*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nord** | 8 | 13 | 21 | 26 | 36 | 39 | 39 | 30 | 22 | 16 | 10 | 7 |
| **Est** | 22 | 34 | 60 | 72 | 91 | 85 | 92 | 79 | 61 | 45 | 25 | 16 |
| **South** | 74 | 81 | 103 | 87 | 83 | 73 | 79 | 84 | 87 | 95 | 72 | 55 |
| **West** | 26 | 36 | 62 | 71 | 79 | 77 | 9 | 74 | 61 | 50 | 29 | 19 |
| **Horizontal** | 37 | 55 | 97 | 120 | 148 | 146 | 151 | 133 | 99 | 73 | 41 | 28 |

The building has been built on a total area of 810 $\text{m}^2$, it is composed by six storeys and a basement. The total area is of 1053 $\text{m}^2$

Each floor is 3 m high. Since the roof is sloped, the fourth and the five floors have different area. Geometrical values for each floor are shown in Table 3.7

*Table 3.7: Geometrical properties of each floor*

| | Height [m] | Area [$\text{m}^2$] | Volume [$\text{m}^3$] |
|---|---|---|---|
| **Basement** | 3.00 | 175 | 525 |
| **Ground floor** | 3.00 | 200 | 395 |
| **First floor** | 3.00 | 181 | 543 |
| **Second floor** | 3.00 | 181 | 543 |
| **Third floor** | 3.00 | 147 | 440 |
| **Fourth floor** | 3.00 | 103 | 308 |
| **Fifth floor** | 3.00 | 66 | 199 |
| **Total** | 21.00 | 1053 | 3615 |

Moreover, each storey has a different planimetry. Table 3.8 shows the spaces included in each floor. It has to emphasized that each apartment has a bathroom and a kitchen.

*Table 3.8: Rooms in each floor*

| | |
|---|---|
| **Basement** | Therapy room with kitchen, basement, storage room, 2 technical rooms, 3 WCs, 2 showers, 2 changing rooms |
| **Ground floor** | Living room, storage closet, office, conference room, WC, equipment room, waste room, terrace |
| **First floor** | 4 apartments |
| **Second floor** | 4 apartments |
| **Third floor** | 4 apartments |
| **Fourth floor** | 2 apartments, WC, shower, changing room |
| **Fifth floor** | Therapy room, WC, shower |

There are 25 different walls, considering orientation, stratigraphy and tilt. Internal walls are not considered, since the whole building is considered as a unique thermal zone. Moreover, thermal bridges are not taken into account. For the sake of simplicity, they are gathered in 10 different walls. Table 3.9 shows the characteristics of the considered walls.

*Table 3.9: Properties of the walls*

| | **Type of wall** | **Orientation** | **Orientation angle [°]** | **Slope [°]** | **Area $[m^2]$** | **U-value** $\left[\frac{W}{m^2K}\right]$ | **Thickness [m]** |
|---|---|---|---|---|---|---|---|
| **1** | Outside wall | South | 176 | 90 | 285.2 | 0.125 | 0.453 |
| **2** | Floor | Horizontal | 90 | 180 | 280.8 | 0.170 | 0.600 |
| **3** | Outside wall | North | 0 | 90 | 148.1 | 0.125 | 0.453 |
| **4** | Outside wall | East | 113 | 90 | 144.1 | 0.125 | 0.453 |
| **5** | Roof | North | 0 | 59 | 188.0 | 0.166 | 0.463 |
| **6** | Outside wall | West | 299 | 90 | 95.9 | 0.125 | 0.453 |
| **7** | Roof | Horizontal | 342 | 0 | 82.2 | 0.109 | 0.558 |
| **8** | Roof | West | 299 | 59 | 119.0 | 0.166 | 0.463 |
| **9** | Earth retaining wall | - | - | 90 | 225.6 | 0.199 | 0.513 |
| **10** | Roof | Horizontal | 133 | 0 | 41.5 | 0.171 | 0.523 |

There are 10 different type of windows, considering type of glass and wall in which they are applied. For the sake of simplicity, they are gathered in 5 different windows. Table 3.10 shows the properties of the windows.

*Table 3.10: Properties of the windows*

| | **Orientation** | **Orientation angle [°]** | **Slope [°]** | **$U_g$ $\left[\frac{W}{m^2K}\right]$** | **$U_f$ $\left[\frac{W}{m^2K}\right]$** | **g- value [-]** | **Total area [m$^2$]** |
|---|---|---|---|---|---|---|---|
| **1** | South | 176 | 90 | 0.52 | 0.90 | 0.54 | 47.88 |
| **2** | South | 176 | 90 | 0.60 | 0.85 | 0.54 | 41.15 |
| **3** | East | 113 | 90 | 0.52 | 0.90 | 0.54 | 40.14 |
| **4** | West | 299 | 90 | 0.52 | 0.90 | 0.54 | 26.99 |
| **5** | North | 0 | 90 | 0.52 | 0.90 | 0.54 | 23.03 |

### 3.2.1 Photovoltaic system

A distinctive point of the building is the wide photovoltaic (PV) system. This covers the whole south façade of the building. Rectangular panels with different sizes are installed. Table 3.11 shows the amount of panels mounted on the façade.

*Table 3.11: PV system in the South facade*

| **Type** | **Panel's dimensions [m x m]** | **Panel's area [m$^2$]** | **Number of panels** | **Total area [m$^2$]** |
|---|---|---|---|---|
| **1** | 0.995 x 1.700 | 1.69 | 108 | 182.7 |
| **2** | 0.995 x 2.017 | 2.01 | 7 | 14.0 |
| **3** | 0.995 x 1.520 | 1.51 | 7 | 10.6 |

This numbers are based on the plan draw.

Since the average of area between the bigger and smaller panels (type 2 and 3) is equal to the medium surface (type 1), for sake of simplicity only characteristics of the type 1 panels are considered. Therefore, all panels are assumed as type 1 panels.

Technical data of the PV panels are show in Table 3.12

*Table 3.12: Technical data of the PV system*

| **Cell type** | Monocrystalline silicon |
|---|---|
| **Maximum power ($P_{max}$) [W]** | 220 |
| **MPP voltage ($V_{mpp}$) [V]** | 29.1 |
| **MPP voltage ($I_{mpp}$) [A]** | 7.56 |
| **Open circuit voltage ($V_{oc}$) [V]** | 36.0 |
| **Short circuit current [A]** | 8.10 |
| **Temperature coefficients:** | |
| **NOCT [°C]** | 45 ± 3 |
| **$P_{max}$ $\left[\frac{\%}{^\circ C}\right]$** | - 0.41 |
| **$V_{oc}$ $\left[\frac{\%}{^\circ C}\right]$** | - 0.30 |
| **$I_{sc}$ $\left[\frac{\%}{^\circ C}\right]$** | 0.03 |
| **Inverter properties:** | |
| **Nominal power [W]** | 9000 |
| **Overload** | 1.2 |
| **Efficiency [%]** | 0.90 |
| **Standby power consumption** | 0 |

### 3.2.2 Heating system

In the building the heating system is an electric system. This means that electric resistances are giving heating to the room, in order to maintain the desired set point temperature, that is 20 °C. This system allows to not have dedicated room for heating technology and no distribution – ascending pipes. This also means that the distribution losses are avoided. The only losses to consider are the thermal loss through the boiler surface and the distribution losses from the boiler to the sinks. Actually, the latter are not taken into account in the comparison between different systems, since they are produced in any case.

In each room electric surfaces of different size are installed. Emitters in each floor are shown in Table 3.13.

*Table 3.13: Emitters for each floor*

| Floor | Emitters | Total nominal power [W] |
|---|---|---|
| **Basement** | 4 x 500 W<br>2 x 750 W | 3500 |
| **Ground floor** | 1 x 250 W<br>2 x 500 W<br>2 x 750 W | 2750 |
| **First floor** | 4 x 250 W<br>1 x 1000 W<br>3 x 1250 W | 5750 |
| **Second floor** | 4 x 250 W<br>1 x 1000 W<br>3 x 1250 W | 5750 |
| **Third floor** | 1 x 50 W<br>3 x 250 W<br>3 x 1000 W<br>1 x 1250 W | 5050 |
| **Fourth floor** | 2 x 250 W<br>1 x 500 W<br>3 x 1000 W | 4000 |
| **Fifth floor** | 1 x 250 W<br>1 x 1000 W<br>1 x 1250 W | 2500 |

Therefore, the total power installed for the heating system is 29.3 kW.

Furthermore, the ventilation system is assumed constant during the year. The monthly energy required is supposed equal to 0.480 kWh.

### 3.2.3 Domestic hot water preparation system

The system for the preparation of the DHW is electric too. This means that electric resistance heats water content into a boiler. In the bathroom of each apartment a boiler of 50 litres is installed. So there are totally 14 boilers of 50 litres capacitance. Moreover, for the common area, three boilers of 12 litres are provided. Technical data about boiler are shown in Table 3.14.

*Table 3.14: Technical data of the boilers*

| | **Apartment boiler** | **Common area boiler** |
|---|---|---|
| **Water volume [l]** | 50 | 120 |
| **Volume [m$^3$]** | 0.05 | 0.12 |
| **Diameter [m]** | 0.273 | 0.369 |
| **Height [m]** | 0.854 | 1.122 |
| **Nominal electric power [W]** | 3000 | 3000 |
| **Energy class** | B | B |
| **Thermal transmittance** $\left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right]$ | 1.059 | 0.789 |
| **U A** $\left[\frac{\mathrm{W}}{\mathrm{K}}\right]$ | 0.9 | 1.2 |
| **Water conductivity** $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$ | 0.6 | 0.6 |

For both boilers the required temperature of the water after the boiler is 60 °C in order to avoid the Legionella risk. After, the water is mixed with water from the tap (at averagely 10 °C) in order to obtain the desired mass flow at 48 °C.

The DHW profile are esteemed based on the IEA SHC & HPP T44/A38 (Haller et al., 2013).

Since the study presented in the document refers to a family, trends are scaled down in the more truthfully possible way. Different trends are assumed for the apartment boilers and for the common area boilers and different water requested are considered. In any case, daily profiles are considered and kept unchanged for all the days of the year. In particular, two different profiles are assumed for the apartments, they are called A1 and A2 (half of the apartments follows trend A1 and the half the trend A2). While for the three common boiler are assumed three different profiles, called C1, C2 and C3. The apartment profiles are assumed for one person. C1 profile is assumed for 24 persons (14 patients and 10 operators during the day), while C2 and C3 profile are assumed for 5 persons (only working and not living in the building). The DHW profiles are illustrated in Table 3.15.

*Table 3.15: DHW profiles*

| Time | A1 | A2 | C1 | C2 | C3 |
|---|---|---|---|---|---|
| **7.00** | | | Floor clean. | | |
| **7.15** | Shower | Small tapping | | Shower | |
| **7.30** | | | | | Small tapping |
| **8.00** | | | Small tapping | | |
| **8.30** | | Small tapping | | | |
| **8.45** | | | | | Small tapping |
| **9.00** | Small tapping | | | | |
| **9.15** | | | | Small tapping | |
| **10.00** | | | Small tapping | | |
| **10.30** | | Small tapping | | | |
| **10.45** | | | | | Small tapping |
| **11.00** | Small tapping | | | | |
| **11.15** | | | | Small tapping | |
| **12.00** | Small tapping | Small tapping | Small tapping | | |
| **12.15** | | | | Small tapping | Small tapping |
| **12.45** | | | Dish wash. | | |
| **14.00** | | | Small tapping | | |
| **14.30** | | Small tapping | | | |
| **14.45** | | | | | Small tapping |
| **15.00** | Small tapping | | | | |
| **15.15** | | | | Small tapping | |
| **16.00** | | | Small tapping | | |
| **16.30** | | Small tapping | | | |
| **16.45** | | | | | Small tapping |
| **17.00** | Small tapping | | | | |
| **17.15** | | | | Small tapping | |
| **18.00** | | | Small tapping | | |
| **19.00** | Small tapping | Small tapping | Small tapping | | |
| **19.15** | | | | Small tapping | Small tapping |
| **20.30** | | | Dish wash. | | |

| | | | | | |
|---|---|---|---|---|---|
| **20.45** | | | Household | | |
| **21.00** | | | Household | | |
| **21.15** | Small tapping | Shower | | Small tapping | Shower |
| **21.30** | | | Shower | | |

Where each tap corresponds to the values shown in Table 3.16.

*Table 3.16: Characteristics of the tapping*

| Name | $Q_{DHW}$ [kWh] | Flow rate $\left[\frac{l}{h}\right]$ | Time [min] |
|---|---|---|---|
| **Dish wash.** | 0.300 | 240 | 5 |
| **Floor clean.** | 0.100 | 240 | 5 |
| **Household** | 0.100 | 240 | 5 |
| **Shower** | 1.315 | 600 | 5 |
| **Small tapping** | 0.100 | 240 | 1 |

### 3.2.4 Internal gains

Internal gains include people and appliances in the building. They are an advantage during the winter, but a disadvantage for the comfort during the summer. Moreover, appliances consume electric power, so they have to add to the heating and DHW system in the electric balances.

It is assumed the presence in the An-der-Lan building of 14 patients and 10 operators. Only five of them stay in the building during the night. It is expected that people won't do particular movement, so a power of 80 $\frac{\mathrm{W}}{\mathrm{person}}$ is considered.

Regarding the appliances, the profile is estimated based on the SaLüH! project (Universität Innsbruck, 2018). Since data are referred to apartments for three people family, values are scale down. In particular, the daily profile is considered the same for all days of the year. The electricity rate required by appliances is estimated in same way and shown in Table 3.17.

*Table 3.17: Required electric power for appliances [W]*

| **Time [h]** | **Kitchen** | **Apartments** | **Common Areas** | **Total** |
|---|---|---|---|---|
| **00.00** | 1573 | 941 | 847 | 3360 |
| **01.00** | 473 | 284 | 239 | 996 |
| **02.00** | 250 | 149 | 126 | 525 |
| **03.00** | 250 | 149 | 126 | 525 |
| **04.00** | 251 | 149 | 126 | 526 |
| **05.00** | 251 | 149 | 126 | 526 |
| **06.00** | 250 | 149 | 126 | 525 |
| **07.00** | 1874 | 1027 | 865 | 3767 |
| **08.00** | 2225 | 1186 | 999 | 4410 |
| **09.00** | 2001 | 1102 | 928 | 4031 |
| **10.00** | 246 | 147 | 123 | 516 |
| **11.00** | 239 | 147 | 123 | 509 |
| **12.00** | 1306 | 609 | 513 | 2429 |
| **13.00** | 307 | 125 | 105 | 537 |
| **14.00** | 694 | 259 | 218 | 1171 |
| **15.00** | 531 | 304 | 256 | 1091 |
| **16.00** | 505 | 319 | 269 | 1092 |
| **17.00** | 506 | 318 | 267 | 1091 |
| **18.00** | 899 | 407 | 346 | 1653 |
| **19.00** | 850 | 399 | 399 | 1648 |
| **20.00** | 2726 | 1467 | 1758 | 5951 |
| **21.00** | 1794 | 995 | 1275 | 4065 |
| **22.00** | 1715 | 998 | 1351 | 4064 |
| **23.00** | 1886 | 1107 | 1285 | 4278 |

Figure 3.2 shows daily profile of electric power required for DHW preparation and appliances, Indeed, these profiles are assumed to be in the same way every day of the year.

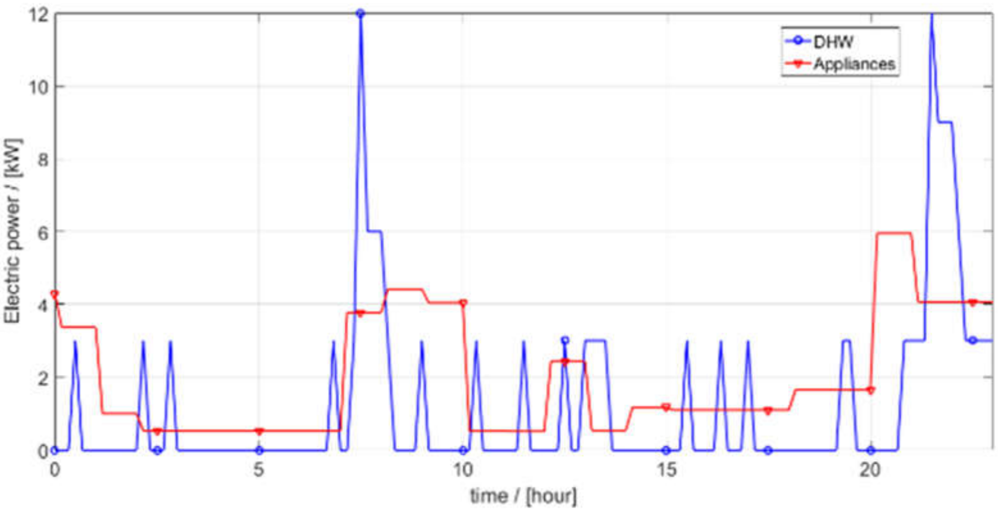

*Figure 3.2: Daily electric power profile for DHW and appliances*

## 3.3 ALTERNATIVE CASE FOR AN-DER-LAN BUILDING

As an alternative at the whole electric system, an air/water heat pump (HP) is take into account. This source of energy provides thermal energy to space heating, DHW preparation system or both depending on the considered case. Indeed, four main cases are evaluated, but in each of them, building, internal gains and ventilation system are the same. Table 3.18 illustrates system's characteristics for each case.

*Table 3.18: Considered cases*

| | **Description** | **Heating** | **DHW** |
|---|---|---|---|
| **Case 1** | All electric (real case) | Electric | Electric |
| **Case 2** | All HP | HP | HP |
| **Case 3** | HP + electric | HP | Electric |
| **Case 4** | Electric + HP | Electric | HP |

### 3.3.1 Air/Water Heat pump

Model HWMC029H0 from Galletti company is the considered heat pump. Based on air temperature, water temperature and frequency, technical data are evaluated thank to software Selmac Galletti (Galletti). Considered air temperature is from -15 to 21 °C every 3 °C. Possible water temperatures in/out are 30-35 °C, 40-45 °C, 55-60 °C. Minimum frequency is 30 Hz and the maximum frequency is 110 Hz, intermediate frequencies are possible every 10 Hz. Set relative humidity is 70% and distance in free field is 5 m.

Figure 3.3 and 3.4 show respectively the trend of the coefficient of performance (COP) and the heating power delivered by the heat pump, based on the air and water temperatures, at the minimum and maximum frequencies. COP values include fan power, but exclude power needed for defrost cycles.

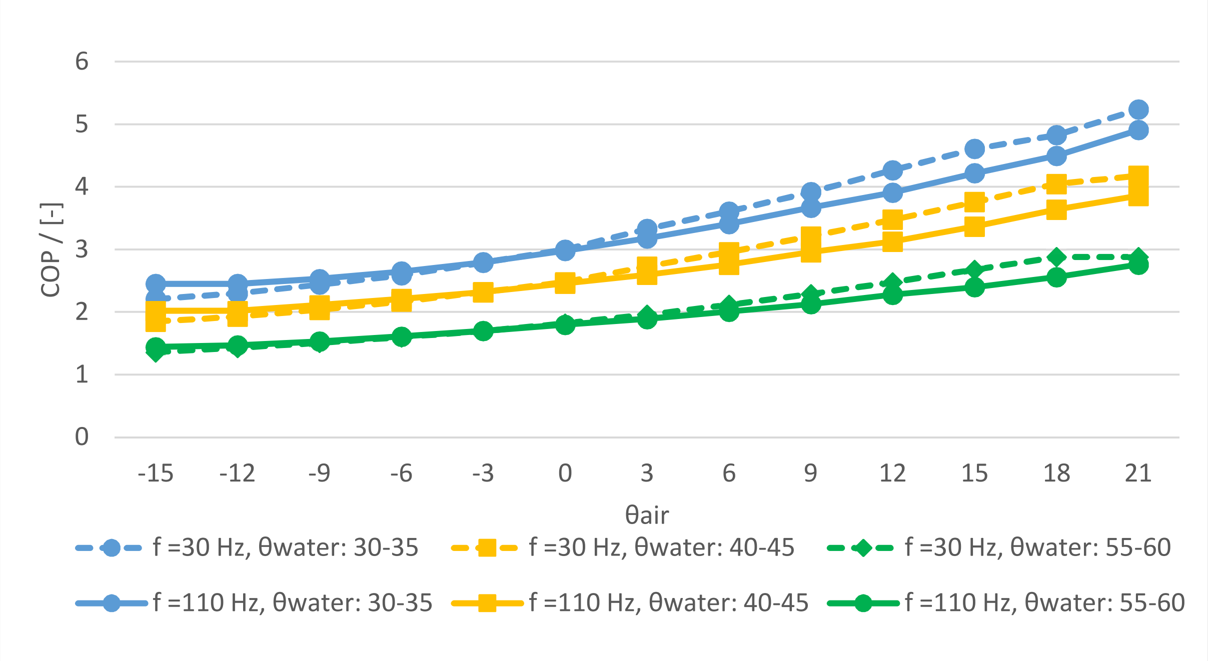

*Figure 3.3: COP Heat Pump at minimum and maximum frequency, according to Selmac Galletti*

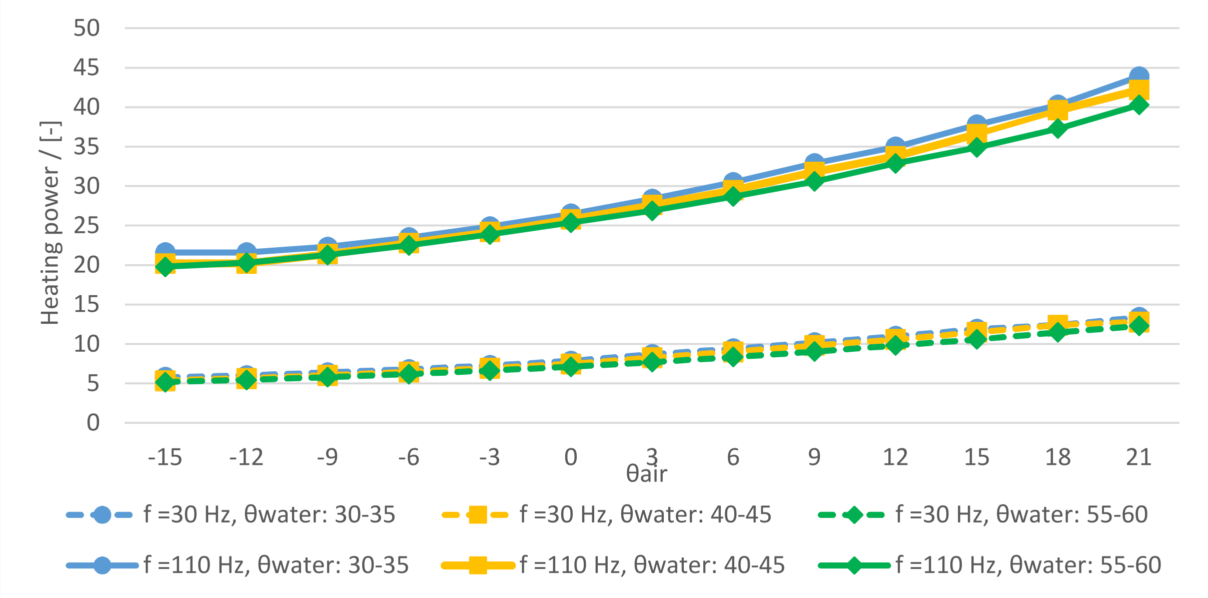

*Figure 3.4: Thermal power Heat pump at min and max frequency, according to Selmac Galletti*

Heat pump always works at the maximum frequency when it is serving the DHW system. In Case 2, where both heating and DHW are provided by the heat pump, the priority is always to the DHW. This behaviour doesn't affect in an important way the heating system, thanks to the intrinsic capacitance of heaters.

The defrost function is taken into account too. This function helps the heat pump to avoid ice formation on it, but it requires electric power while no heat is provided to the system. Truthfully, during this operation heat is taken away from the system because the defrost function is based on an inversion of the whole cycle. This means that the internal ambient (that should be heated) is used as the heat source, while the external ambient (that should be the source) is instead heated.
Defrost cycle turns on when the evaporator temperature is below 0 °C for two hours, even not consecutive. In the defrost operation mode, the heat pump works at the maximum frequency and provides to the external ambient 24 kW. This means that this power is subtracted at the indoor side. The defrost function lasts 10 minutes. From the moment that the normal operation mode is back, the count of the two hours for the evaporator temperature restarts from zero.

Finally, in case of the adoption of the heat pump, the monthly electric energy for the ventilation and the circulation pumps is equal to 0.514 kWh.

### 3.3.2 Radiator

Since the heat pump uses electric power to heat water, different heating bodies have to be taken into account. Low temperature radiators are considered because the building is a Passive House. Indeed, lower thermal power is required compared to a standard building. Hence, radiators with standard size, but lower temperature, can be installed. Moreover, this is a convenient design choice for the heat pump because it has better performance when low temperatures are required. Low temperature radiators available on the market are considered. Technical data are shown in Table 3.19.

*Table 3.19: Technical data of radiator*

| **Water-in temperature [°C]** | 55 |
|---|---|
| **Water-out temperature [°C]** | 45 |
| **Water content** $\left[\frac{\text{l}}{\text{element}}\right]$ | 0.45 |
| **Weight** $\left[\frac{\text{kg}}{\text{element}}\right]$ | 2.24 |
| **Power** $\left[\frac{\text{W}}{\text{element}}\right]$ | 173.6 |
| **Exponent** | 1.3545 |

In order to evaluate how many elements have to provided ($n_{el}$), Equation (3.1) is used.

$$Qair = \left(\frac{T_R - T_A}{\Delta T}\right)^N P_{el}\, n_{el} \tag{3.1}$$

Where:

- $Qair$ is the thermal power given to the ambient
- $T_R$ is the average temperature of the radiator
- $T_A$ is the ambient air temperature
- $\Delta T$ is the standard temperature difference of 50 K
- $N$ is the exponent that characterizes the radiator
- $P_{el}$ is the emitted power for each element of the radiator
- $n_{el}$ is the number of elements of the radiator

Therefore, elements needed for each room are evaluated. They are shown in Table 3.20.

*Table 3.20: Radiators for each floor*

| Floor | Number of radiators and elements |
|---|---|
| **Basement** | 2 radiators with 9 elements<br>4 radiators with 6 elements |
| **Ground floor** | 2 radiators with 9 elements<br>2 radiators with 6 elements<br>1 radiator with 3 elements |
| **First floor** | 3 radiators with 15 elements<br>1 radiator with 12 elements<br>4 radiators with 3 elements |
| **Second floor** | 3 radiators with 15 elements<br>1 radiator with 12 elements<br>4 radiators with 3 elements |
| **Third floor** | 1 radiator with 15 elements<br>3 radiators with 12 elements<br>3 radiators with 3 elements<br>1 radiator with 1 elements |
| **Fourth floor** | 3 radiators with 12 elements<br>1 radiator with 6 elements<br>2 radiators with 3 elements |
| **Fifth floor** | 1 radiator with 15 elements<br>1 radiator with 12 elements<br>1 radiator with 13 elements |

Therefore, there is a total of 431 elements.

Since the thermal power given to the air must be equal to the thermal power in the radiator, the needed mass flow ($\dot{m}$) in each radiator is calculated according with the Equation (3.2).

$$\dot{Q}w = \dot{m}\, c_p\, (T_{in} - T_{out}) \tag{3.2}$$

Where:

- $\dot{Q}w$ is the thermal power exchanged by the water in the radiator
- $\dot{m}$ is the needed mass flow in the
- $c_p$ is the specific heat capacity at constant pressure of the water
- $T_{in}$ is the water-in temperature in the radiator
- $T_{out}$ is the water-out temperature from the radiator

In particular, since all the building is modelled as a unique thermal zone, the radiator is assumed to be one, too. This means that a unique radiator with the sum of all the evaluated elements is implemented in the simulations.

### 3.3.3 Boiler

When the heating system is provided by heat pump, it needs a boiler too. This boiler work as a capacitance, so that the heat required by the ambient doesn't have to be produced immediately by the heat pump, but hot water previously heated (and stocked into the boiler) can be used. At the same time, when the DHW production is sustained by the heat pump, different boiler has to be taken into account. Indeed, in this cases, singular boilers aren't used anymore as in the base case, but a centralised boiler is used. Storage's data are illustrated in Table 3.21.

*Table 3.21: Technical data of storage for space heating served by heat pump*

| | |
|---|---|
| **Water capacity [l]** | 1000 |
| **Volume [m$^3$]** | 1.179 |
| **Diameter [m]** | 0.85 |
| **Height [m]** | 2.078 |
| **Energy class** | B |
| **Thermal transmittance** $\left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right]$ | 2.4 |
| **U A** $\left[\frac{\mathrm{W}}{\mathrm{K}}\right]$ | 6.737 |

The UA value takes into account both the losses through the boiler and losses through the pipe. In particular, the considered pipes are from the boiler in the basement until the apartments. Pipe losses in each apartment are not considered because they are equal at the electric case. Hence the aim of the study is the comparison between different energy sources, distribution losses in the apartments are not considered because they don't affect the comparison. Therefore, using a heat pump, additional losses are caused by the distribution losses.

For Case1 and Case2, variants on the photovoltaic system and on the DHW storage volume (illustrated in Chapter 3.4) are considered.

## 3.4 SENSITIVITY ANALYSIS STUDY OF AN-DER-LAN BUILDING

### 3.4.1 PV variants

In order to evaluate the importance of the PV system, different variants are considered. The area and the orientation are the changing factors. The first variant is the reference case (so the real case) as descripted in section 3.2.1. Technical data of the PV panels are the same of the real case. Size of PV panels are the same as the reference case for variants 2 and 4. It has to emphasized that the west façade has a part vertical and a part sloped. Variants that assume PV in the west façade, have PV panels in both parts. Obviously, they produced different electric power due to the different solar irradiation they receive from the sun. Table 3.22 illustrates the PV area assumed in every variant.

*Table 3.22: PV surface assumed in every variant*

| | **Number of panels** | | | **Area [m$^2$]** | | | |
|---|---|---|---|---|---|---|---|
| **Variant (name)** | **South** | **East** | **West** | **South** | **East** | **West** | **Total** |
| **1<br>(PV_Sp Reference case)** | 108 Type1<br>7 Type2<br>7 Type3 | - | - | 182.7<br>14.1<br>10.6 | - | - | 207.3 |
| **2<br>(PV_SEWp)** | 108 Type1<br>8 Type2<br>7 Type3 | 61 Type1 | 76 Type1<br>1 Type2<br>1 Type3 | 182.7<br>16.1<br>10.6 | 103.2 | 129.6<br>2.0<br>1.5 | |
| **3<br>(PV_Si)** | 156.8 | | | 267 | - | - | 267 |
| **4<br>(PV_SEWi)** | 156.8 | 77.1 | 103 | 267 | 131.5 | 175.1 | 573.6 |
| **5<br>(PV_Sr)** | See below Table 3.23 | - | - | 250.3 | - | - | 250.3 |

The second variant is called PV_SEWp because PV panels are considered in the three orientation (South, East and West) with normal shape panels (from catalogue as in the reference case). The third variant is called PV_Si because PV surface is only on the South façade and an ideal PV installation in consider. Ideal means that the PV surface is equal to the wall area excluding only the windows. In order to perform simulations, the number of panels is needed. Therefore, it is evaluated as the ratio between the total area and the area of a Type 1 PV panel (see section 3.2.1). The fourth variant (PV_SEWi) bases on the same concept of the third, but applied in the tree orientation. Finally, the fifth variant is called PV_Sr because it represents the case in which all the PV panels installed in reality, would be actually working. This variant has the purpose to investigate how different would be the power from the PV system if all the panels would be functional. Indeed, some of them are installed only for esthetical purpose. For example, panels with a squared shape or cut rectangular are installed. These particular shapes are shows in Figure 3.5. Differences between second and fifth variants are the gap between consecutive panels and missing triangle surfaces along the sloped roof.

*Figure 3.5: Example of particular shape of some of the PV panels*

More specifically, area and number of panels considered in this variant are illustrated in Table 3.23.

*Table 3.23: PV system if every real panel would be connected*

| Type | Panel's dimensions [m x m] | Panel's area [$m^2$] | Number of panels | Total area [$m^2$] |
|---|---|---|---|---|
| **1** | 0.995 x 1.700 | 1.69 | 108 | 182.68 |
| **2** | 0.995 x 2.017 | 2.01 | 7 | 14.05 |
| **3** | 0.995 x 1.520 | 1.51 | 7 | 10.59 |
| **4** | 0.995 x 0.995 | 0.99 | 4 | 3.96 |
| **5** | 0.995 x 0.680 | 0.68 | 1 | 0.68 |
| **6** | 0.680 x 2.017 | 1.37 | 12 | 16.46 |
| **7** | 0.680 x 1.700 | 1.16 | 9 | 10.40 |
| **8** | 0.680 x 1.520 | 1.03 | 1 | 1.03 |
| **9** | Sum of the particular shape | - | - | 10.45 |

### 3.4.2 DHW storage variants

In order to evaluate the effects due to the boiler volume serving the DHW system, different sizes of boilers are taken into account. This method is applied both to Case1 (electric DHW preparation) and Case2 (heat pump serving DHW preparation). Three variant are taken into account: the first one is the reference case, the second one assumes a minor storage, while the third assumes a bigger storage.

Since the electric DHW preparation system is a decentralized system, variants are applied at each storage simultaneously. Particularly, different sizes are assumed both for apartments and common areas boilers. Table 3.24 shows the three variants for apartments boiler, while Table 3.25 shows variant for the common areas boiler.

*Table 3.24: Variants for apartments storage for electric DHW preparation system*

| | **Variant (name and description)** | | |
|---|---|---|---|
| | **Variant 1**<br>**(V50: reference case)** | **Variant 2**<br>**(V30: minor boiler)** | **Variant 3**<br>**(V80: major boiler)** |
| **Water volume [l]** | 50 | 30 | 80 |
| **Volume [$m^3$]** | 0.05 | 0.03 | 0.08 |
| **Diameter [m]** | 0.273 | 0.253 | 0.328 |
| **Height [m]** | 0.854 | 0.597 | 0.947 |
| **Energy class** | B | B | B |
| **Thermal transmittance** $\left[\frac{W}{m^2K}\right]$ | 1.059 | 1.91 | 0.874 |
| **U A** $\left[\frac{W}{K}\right]$ | 0.9 | 0.8 | 1 |

*Table 3.25: Variants for common areas storage for electric DHW preparation system*

| | **Variant (name and description)** | | |
|---|---|---|---|
| | **Variant 1**<br>**(V120: reference case)** | **Variant 2**<br>**(V100: minor boiler)** | **Variant 3**<br>**(V150: major boiler)** |
| **Water volume [l]** | 120 | 100 | 150 |
| **Volume [$m^3$]** | 0.12 | 0.10 | 0.15 |
| **Diameter [m]** | 0.369 | 0.253 | 0.63 |
| **0.375** | 1.122 | 0.966 | 1.358 |
| **Energy class** | B | B | B |
| **Thermal transmittance** $\left[\frac{W}{m^2K}\right]$ | 0.789 | 0.841 | 0.659 |
| **U A** $\left[\frac{W}{K}\right]$ | 1.2 | 1.1 | 1.2 |

In case of heat pump serving the DHW preparation system, since the system is centralised, only a storage is assumed. Therefore, different volumes compared to the electric case have to be taken into account to simulate variants. Table 3.26 shows technical data for each variant of centralised boiler for DHW preparation.

*Table 3.26: Volume variants for DHW system served by heat pump*

| | **Variant (name and description)** | | |
|---|---|---|---|
| | **Variant 1**<br>**(V1000: reference case)** | **Variant 2**<br>**(V750: minor boiler)** | **Variant 3**<br>**(V1250: major boiler)** |
| **Water capacity [l]** | 1000 | 750 | 1250 |
| **Volume [m$^3$]** | 1.179 | 0.886 | 1.503 |
| **Diameter [m]** | 0.85 | 0.75 | 0.95 |
| **Height [m]** | 2.078 | 2.005 | 2.120 |
| **Energy class** | B | B | B |
| **Thermal transmittance** $\left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right]$ | 1.995 | 2.250 | 1.727 |
| **U A** $\left[\frac{\mathrm{W}}{\mathrm{K}}\right]$ | 2.4 | 2.1 | 2.6 |

To summarise, all considered cases with relative variants are shown in Table 3.27.

*Table 3.27: Cases and variants taken into account*

| | Description | Boiler Volume Variant | PV Variant |
|---|---|---|---|
| **Case1** | Electric heating,<br>Electric DHW | V30, V100 | PV_Sp (reference case) |
| | | V50, V120 (reference case) | |
| | | V80, V150 | |
| | | V50, V120 (reference case) | PV_Sp (reference case) |
| | | | PV_SEWp |
| | | | PV_Si |
| | | | PV_SEWi |
| | | | PV_Sr |
| **Case2** | HP heating,<br>HP DHW | V7500 | PV_Sp (reference case) |
| | | V1000 (reference case) | |
| | | V1250 | |
| | | V1000 (reference case) | PV_Sp (reference case) |
| | | | PV_SEWp |
| | | | PV_Si |
| | | | PV_SEWi |
| | | | PV_Sr |
| **Case3** | HP heating,<br>Electric DHW | V50, V120 (reference case) | PV_Sp (reference case) |
| **Case4** | Electric heating,<br>HP DHW | V1000 (reference case) | PV_Sp (reference case) |

# 4 MODELS

## 4.1 BUILDING PERFORMANCE SIMULATION

Significant energy savings can be achieved in buildings if they are properly designed, constructed and operated. For this reason, building energy efficiency can provide key solutions to energy shortages, carbon emissions and their serious threat to our living environment. Improvements on building envelope and ventilation can play an important role in reducing space heating and cooling consumption levels (Shoubi et al., 2015).

In this scenario, building simulation is an important tool. Building performance simulation (BPS, formerly known as building energy simulation or building energy modelling) is the use of software to predict performance aspects of a building. The objective is to create a virtual model that is sufficiently accurate to form a useful representation of the actual building. BPS forecasts the various energy and mass flows within a building, in order to evaluate one or several performance aspects using computer simulation.

From a physical point of view, a building is a very complex system, influenced by a wide range of parameters. BPS is a technology of considerable potential that provides the ability to quantify and compare the relative cost and performance attributes of a proposed design in a realistic manner and at relatively low effort and cost. Energy demand, indoor environmental quality (including thermal and visual comfort, indoor air quality and moisture phenomena), Heating, Ventilation and Air Conditioning (HVAC) and renewable system performance, urban level modelling, building automation, and operational optimization are important aspects of BPS.

Over the last six decades, numerous BPS computer programs have been developed. The core tools in the field of BPS are multi-domain, dynamic, whole-building simulation tools, which provide users with key indicators such as heating and cooling load, energy demand, temperature trends, humidity, thermal and visual comfort indicators, air pollutants, ecological impact and costs (Wikipedia, 2018). In particular, in this work MATLAB Simulink (MATLAB, 2016) with Carnot library (Solar Institute Juelich) was used to simulate different case studies. CARNOT is a toolbox extension for MATLAB Simulink developed by Aachen University (Germany). It is a tool for the calculation and simulation of the thermal components of HVAC systems with regards to conventional and regenerative elements. The CARNOT Toolbox is a library of typical components of these systems and it is organized in Blocksets like the Simulink Library itself.

## 4.2 IMPLEMENTATION OF THE SIMULATION MODELS

In this work all simulations are run with the same method.

Firstly, data are taken from the Passive House Planning Package (PHPP). The PHPP is a software programme created by the Passive House Institute. The programme is a series of interlinked worksheets that work in commonly available spreadsheet applications such as Microsoft Excel and OpenOffice Calc. The PHPP is at once a design, verification and certification tool (Burrel, 2015). It is based on a collection of clearly defined building physics algorithms. When the required information is entered, monthly results are produced. And it continues to be developed as the Passivhaus Standard evolves and the world progresses towards a renewable energy future.

In their turn, values entered in the PHPP, have been taken starting from AutoCAD plants, then implemented in SketchUp.

Later, CarnotUIBK is used in order to simulate the building. CarnotUIBK is a Simulink model created by Innsbruck University, Unit for Energy Efficient Building( (Universität Innsbruck, 2018). CarnotUIBK is capable to read data of the building from the PHPP and use them in order to launch simulation. All results are saved in order to develop post processing studies.

CarnotUIBK has a simple heating system. Since, the main topic of this study is the comparison of different systems, they are all added to the CarnotUIBK. In order to model the additional systems, CARNOT blocksets are joined and connected. The concept of the library CARNOT is similar to the Simulink standard library. The models are organized in so called subsets that contain the components of conventional and renewable heating systems. The program performs simultaneous calculation of heat transfer and hydraulics. New systems configurations can be created entirely by mouse operations, just drag-and-drop the respective blocks from the library. Interconnection of the blocks is done by lines that represent vectors of the physical properties. In the same way completely new models of components can be included (Wemhöner et al., 2000).

More specifically, Chapter 4.5 illustrates how models are created.

## 4.3 SELECTION OF THE APPROPRIATE SIMULATION MODEL: UA AND RC

An investigation between UA model and RC model is made. These are two possible approaches to the simulation. They consider walls in different ways and, as a consequence, they provide different results.

### 4.3.1 UA model

The UA model is a one-node model. This implies that all the equations and the balance are referred to this node and, as a consequence, only one temperature is obtained. This temperature is generally called sensitive temperature ($\theta_s$). There is only one capacitance for wall and air, indeed this capacitance is obtained by the sum of the product of mass and specific heat of air, walls and furniture. All gains and losses depend on the sensitive temperature.

### 4.3.2 RC model

On the contrary of the UA model, in the RC model the air has his own capacitance and the wall too. There are two nodes: radiative and convective. As a consequence, two temperatures are obtained: the radiative temperature ($\theta_r$) and the convective temperature ($\theta_c$). Also in this case it is evaluated the sensitive temperature $\theta_s$, but this time it is an average between the radiative and the convective temperature. This is often a weighted average, based on the considered contribution. In particular, the convective node is the air node and it represents the trend of the air in the room. This means that it is considered that all the air in the room is at the same temperature, which is the convective temperature $\theta_c$. On the other hand, the radiative node is more difficult to be represented. This is due to the fact that it represents a mean of the temperature of all the walls that constitute the room envelope. It is considered that all the walls exchange radiative energy, as they “can see each other but they are not in contact with each other”. Every surface of the wall has its own temperature and each of them contributes to the radiative temperature in the same way.

The evaluation of the radiative temperature is possible through the electrotechnical analogy. As is well known, three resistances connected in a star model can be considered in a delta model, thanks to appropriate functions. Obviously, this can be seen in the other way around. Therefore, three wall connected in a delta model can be transformed in a star model (Figure 4.1).

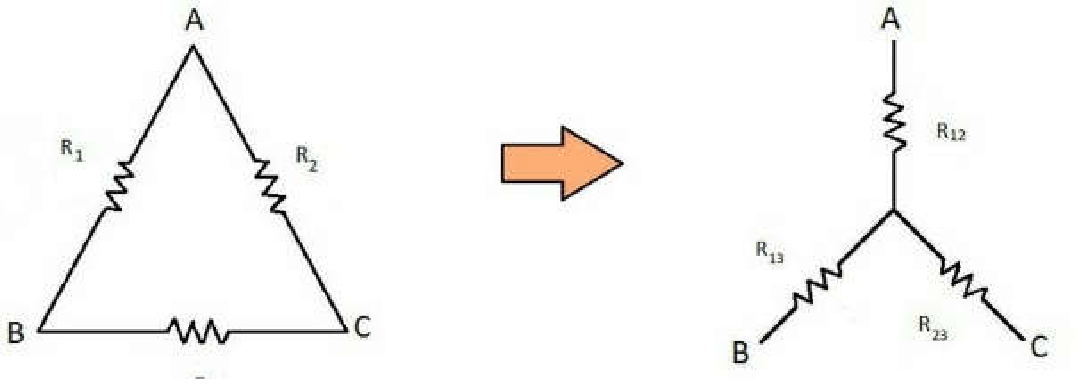

*Figure 4.1: Delta to star model*

Moreover, it has been demonstrated that the same concept can be applied with more than three walls, with an acceptable error (Feist, 1994).

For sake of simplicity, a wall can be seen as a resistance and two capacities (one on the external and one on the internal side of the wall). Each side of the wall exchanges thermal power through irradiation and convection. Particularly, these exchanges with the internal environment take place with the convective node and with the radiative node. This reasoning can be applied to all the other walls and that is how a RC model works. The co-existence of the two temperatures obviously affects the thermal power balances. For example, transmission losses depend on both nodes (they are evaluated on the basis of both $\theta_r$ and $\theta_c$), while ventilation depends on the convective node (it is evaluated through $\theta_c$). Moreover, there are gains, as internal gains, solar gains and gains form the HVAC. These gains are split between the radiative node and the convective node on the basis of the system used. In the simplest models they can be equally shared between the two nodes. But, for a more faithful representation, realistic radiative and convective share factors are introduced. Thanks to these, each energy contribution is shared with its own percentage. Factors depend on absorbance factor of the walls, surfaces' temperatures, emission factors of the structures, type of heating system, etc (Magni, 2015).

## 4.4 THE INFLUENCE OF THE THERMAL MASS

### 4.4.1 Description of the thermal mass

The capacity is also called thermal mass. This is a property of the mass of the building, which enables it to store heat, providing "inertia" against temperature fluctuations. It is sometimes known as the thermal flywheel effect.

The thermal storage capacity of a material is evaluated according Equation (4.1). This is also known as the volumetric specific heat capacity $\left[\frac{\mathrm{J}}{\mathrm{m^3\,K}}\right]$.

$$C = \rho c_p \tag{4.1}$$

Where:

- ρ is the density $\left[\frac{\mathrm{kg}}{\mathrm{m^3}}\right]$
- $c_p$ is the specific heat capacity at constant pressure $\left[\frac{\mathrm{J}}{\mathrm{kg\,K}}\right]$

The volumetric specific heat capacity therefore describes how much heat or energy a cubic meter of material [$\mathrm{m^3}$] can store for a one-degree rise in temperature [K].

The specific thermal capacity describes the active thermal mass per unit floor area $\left[\frac{\mathrm{kWh}}{\mathrm{m^2K}}\right]$ and this is the reference value used for thermal mass in PHPP. The term "active" or "effective" thermal mass refers to thermal mass which is located inside the insulation layer of a building and it has an impact on the dynamics of the internal temperature (McLeod & Hopfe, 2015). The specific thermal capacity ($C_{spec}$ in PHPP, $\left[\frac{\mathrm{kWh}}{\mathrm{m^2K}}\right]$) can be calculated according to Equation (4.2):

$$C_{spec} = \frac{\sum C\,V}{A} \tag{4.2}$$

Where:

- C is volumetric specific of each material $\left[\frac{\mathrm{kWh}}{\mathrm{m^3K}}\right]$
- V is the volume of each material [$\mathrm{m^3}$]
- A is total internal floor area [$\mathrm{m^2}$]

A range of default thermal capacity values are provided in PHPP for different construction types. More specifically, in the PHPP the specific capacity is evaluated with the following equation:

$$60 + n(heavy) \cdot 24 \tag{4.3}$$

Where $n(heavy)$ is:

- 0 for lightweight building
- 3 for mixed
- 6 for massive

Consequently, the specific capacity is equal to:

- $60\,\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$ for lightweight building
- $132\,\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$ for mixed
- $204\,\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$ for massive

This should emphasise that the value of the specific capacity is just an approximation value.

This subdivision follows the idea that construction types can broadly be categorised as lightweight, medium weight or heavyweight constructions, according to the level of available thermal mass. Heavyweight constructions tend to inherently have a high thermal mass, though materials with a high thermal mass may be built into lightweight constructions.

In practice, adding thermal mass within the insulated building envelope helps to dampen the extremes of daily internal temperature cycles, thus making the average internal temperature more stable and the building typically more comfortable to inhabit. Thermal mass is particularly important for comfort in temperate and warmer climates which receive marked swings in the diurnal temperature range as a result of relatively high solar loads. Thermal mass also plays an important role in building with high internal gains, where they can be used during the night.

In the RC model, the convective node has a capacitance. The radiative node has no capacitance, but usually a transfer function is introduced in order to avoid numeric errors.

As already said in section 4.3.1 the node in the UA model includes both air and wall characteristics. This brings to have approximate results and therefore it is interesting to evaluate how much the difference is. In particular, it can be important to investigate how much of the capacity really affects the temperature development and therefore, the heat exchange. Indeed, usually only the first part of the wall is taken into account in order to consider this capacitive behaviour. For this reason, the RC model is assumed as the reference. The same UA model is then considered with different percentages of the capacitance. Later on, all these models are compared with the RC one.

### 4.4.2 Studies on the thermal mass

In the case of the simple office (described in section 3.1), the PHPP shows a capacitance for a medium building, so of 132 $\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$.

The control of the heating system is on the sensible temperature. The percentage of the capacitance considered are: 1%, 10%, 20%, 25%, 35%, 50% and 75% respect at capacitance in the UA model (132 $\frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$). In order to evaluate the best case, are evaluated the root mean square and relative error for several quantities and different periods of the year.

The root mean square (RMS) is evaluated through a MATLAB function. This value is calculated in the following way:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{4.4}$$

Where:

- $x_i$ is the value from the UA model
- $\bar{x}$ is the value from the RC model (as reference)

The relative error ($E_r$) is evaluated with the Equation (4.5)

$$E_r = \frac{x_{UA} - x_{RC}}{x_{RC}} \tag{4.5}$$

Where:

- $x_{UA}$ is the value from the UA model
- $x_{RC}$ is the value from the RC model (as reference)

Finally, the simulation times needed are evaluated and compared.

A parallel study is made for the An-der-Lan building. The initial value of specific capacity in the PHPP is the massive one, so 204 $\frac{\mathrm{Wh}}{\mathrm{m^2\ K}}$. The applied method is the same for the office, meaning that new UA models with different capacity are created and then compared with the RC model.

The percentage of the capacitance considered are: 25%, 50%, 75%, 100%, 125%, 150%, 175%, 200%, 400%, 600%, 800% and 1000% respect at the capacitance in the UA model (204 $\frac{\mathrm{Wh}}{\mathrm{m^2\ K}}$).

## 4.5 SIMULATION TOOLS FOR THE AN-DER-LAN BUILDING

In this project, all the building is simplified as a unique thermal zone. This means that the power introduced through the heating system is the sum of the power for each real zone. Therefore, the temperature inside the building is assumed to be the same for all the rooms.

The sample time assumed for the simulation is 600 seconds, the preruntime is three months. The sample time is the period between a balance and the following one. The preruntime is the period of simulation before the actual one, in order to start the simulation from realistic data.

### 4.5.1 Model for the PV system

The photovoltaic system is composed mainly by three CARNOT blocksets: Radiation_on_Inclined_Surface, PV_Generator and Inverter. The first two need as input the vector of the weather boundary condition (WDB) and the position of the panels (Fixed_Surface). Figure 4.2 shows the implemented Simulink model.

The PV_Generator block allows the calculation of the power produced in direct current (DC) by the panels, based on the following parameters:

- Peak power of each panel at Standard Test Conditions (STC) [W]
- Temperature coefficient of $P_{\mathrm{max}}$ $\left[\frac{1}{\mathrm{K}}\right]$
- Number of panels
- Efficiency of generator field (losses in diodes, power mismatch, dirt)

In particular, in this work the PV_Generator block from CARNOT is modified in order to consider the effect the integration of PV panels in the façade. This characteristic, indeed, affects the panels' temperature and so their performance. The effect of building integrated photovoltaics (BIPV) is considered based on a study by Nordmann and Clavadetscher (Nordmann & Clavadetscher, 2003). They found out that the difference between panel and ambient temperature is proportional to the irradiation on the surface. In the present study, the proportional coefficient is set to 62 $\frac{\text{m}^2\,\text{K}}{\text{kW}}$. This leads to a yield reduction of 4% (compared to a free standing PV system), which is in accordance to the results of Poulek et al. (2018).

The Inverter block needs as input the DC power product by the PV panel and gives as output the power in alternate current (AC). Moreover, the parameters to be set are the nominal power, the efficiency value and the stand-by power of the inverter.

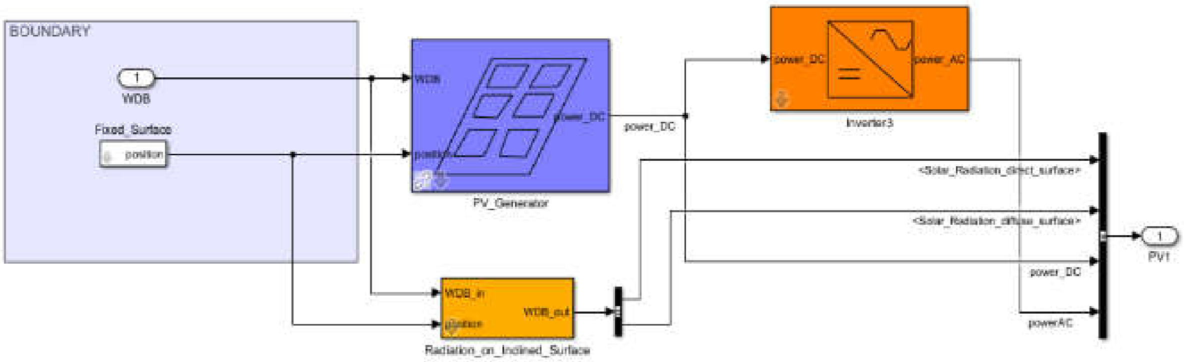

Figure 4.2: Simulink model of the PV system

The same model is implemented for surfaces in a different direction.

### 4.5.2 Model for the electric case

In order to implement the electric heating system only a constant block with the sum of all the heaters' power is introduced, since the electric and thermal power are the same.

The DHW system, on the other hand, is composed by several different blocks:

- Repeating_profile
- Flow_Mixer_Thermostatic
- Flow_Diverter
- Storage
- Transfer_fucntion

In the electric case, five DHW system are implemented in Simulink, one for each tap profile. Figure 4.3 illustrates the model for one DHW system.

The Repeating_profile blocks simulates the trends of the required DHW, based on the mass flow and periods.

Flow_Mixer_Thermostatic and Flow_Diverter are two communicating blocks. They are connected though the thermo-hydraulic vectors, called Thermo-Hydraulics Bus (THB) in Simulink. These two blocks allow the evaluation of the hot and cold mass flows, that later on are mixed, in order to obtain the mass flow required and its temperature. The Flow_Diverer is actually the block the operate the subdivision. This block is controlled by the Flow_Mixer_Thermostatic. Indeed, the latter, thanks to the THBs, is able to evaluate pressure drop and so communicate to the Flow_Diverter how to subdivide the mass flows in order to equal them. Thereby, these are iterative calculations.

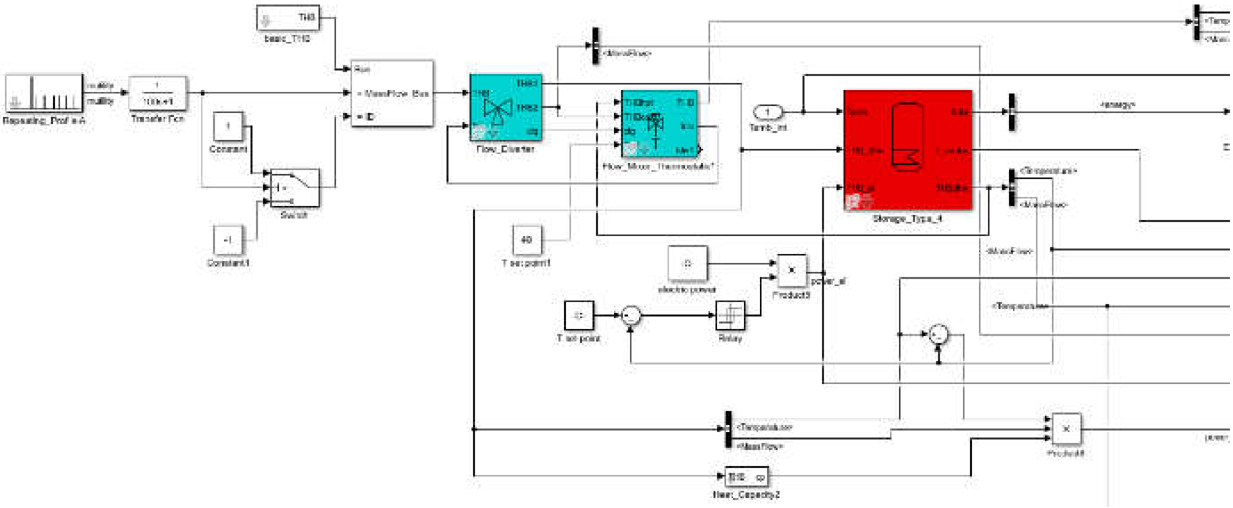

*Figure 4.3: Simulink model for the electric DHW system*

Moreover, Storage block represent the dynamic behaviour of a boiler. The volume of the cylindrical storage is divided in nodes of horizontal slices. For each node the energy balance equation is solved. As inputs, it requires the ambient temperature (in order to evaluate the thermal losses) and THBs of the vectors that exchange heat. In particular, the electric case is a special case because the electric THB is only a power provided to the pipe. Figure 4.4 shows the Simulink models inside the Storage block. The Electric_Heating block represent the electrical resistance in the E-boiler, while the pipe block simulates the changes in the water vector thanks to the heat received in the boiler. For sake of simplicity, the simultaneity factor is not implemented.

Finally, several Transfer_function blocks are added to different signals in order to add some capacitance in the system. These allow to have a more realistic behaviour of the system, since in the reality all changes do not happen immediately.

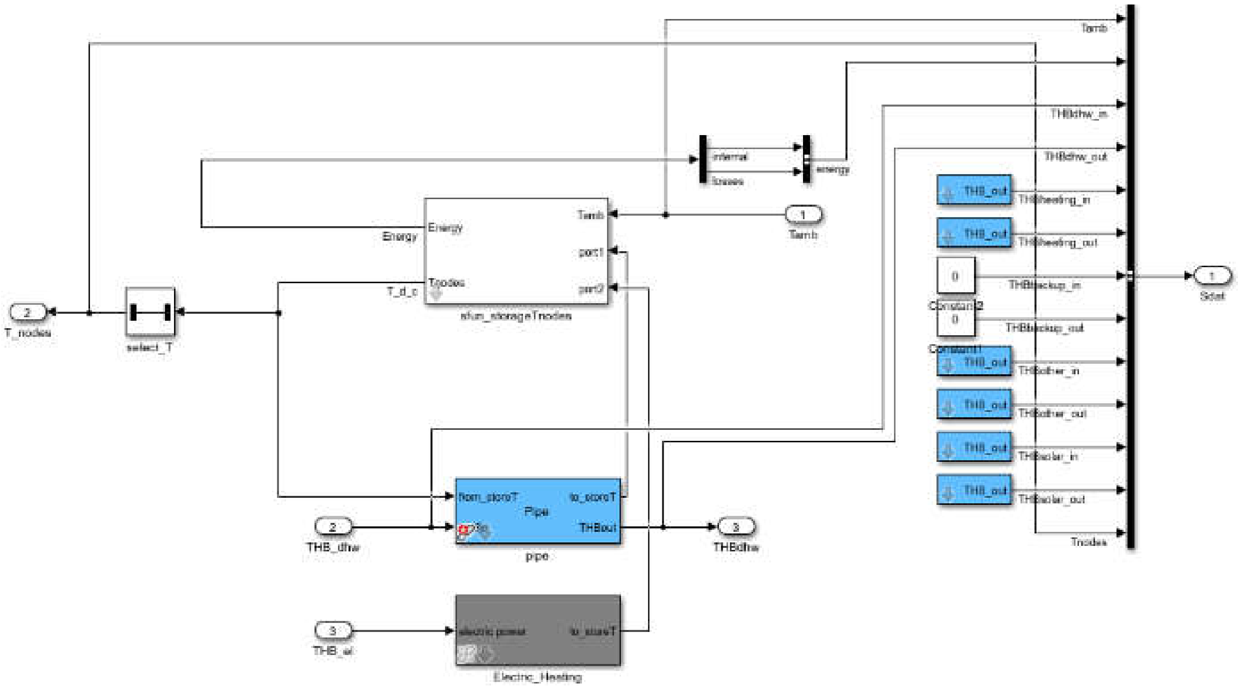

Figure 4.4: Simulink model for the electric storage

### 4.5.3 Model for the Heat Pump

In order to simulate the behaviour of the air/water heat pump, Lookup tables and a controller system are introduced in Simulink model. Moreover, the following blocks are modified (or added) compared to the electric system:

- Storage for DHW system
- Storage for heating system
- Radiator

Lookup Tables 3D are implemented in Simulink in order to read and interpolate data of the HP (see section 3.3.1 and Figure 3.3 - 3.4). Lookup tables are 3D because the inputs data are air temperature, water temperature and HP frequency. Four Lookup table are implemented, one for each necessary quantity: heating power, electric power, mass flow and evaporator temperature.

The control of the HP is based on several switches, that allows the transmission of a precise signal, based on a set criterion. The control includes both the defrost mode and the priority of the DHW, implemented as described in section 3.3.1. Moreover, the control is set based on the temperature by the use of a Proportional-Integrator (PI) controller and a blockset implemented by Bologna University (Università di Bologna). Figure 4.5 illustrates the implemented model of the heat pump.

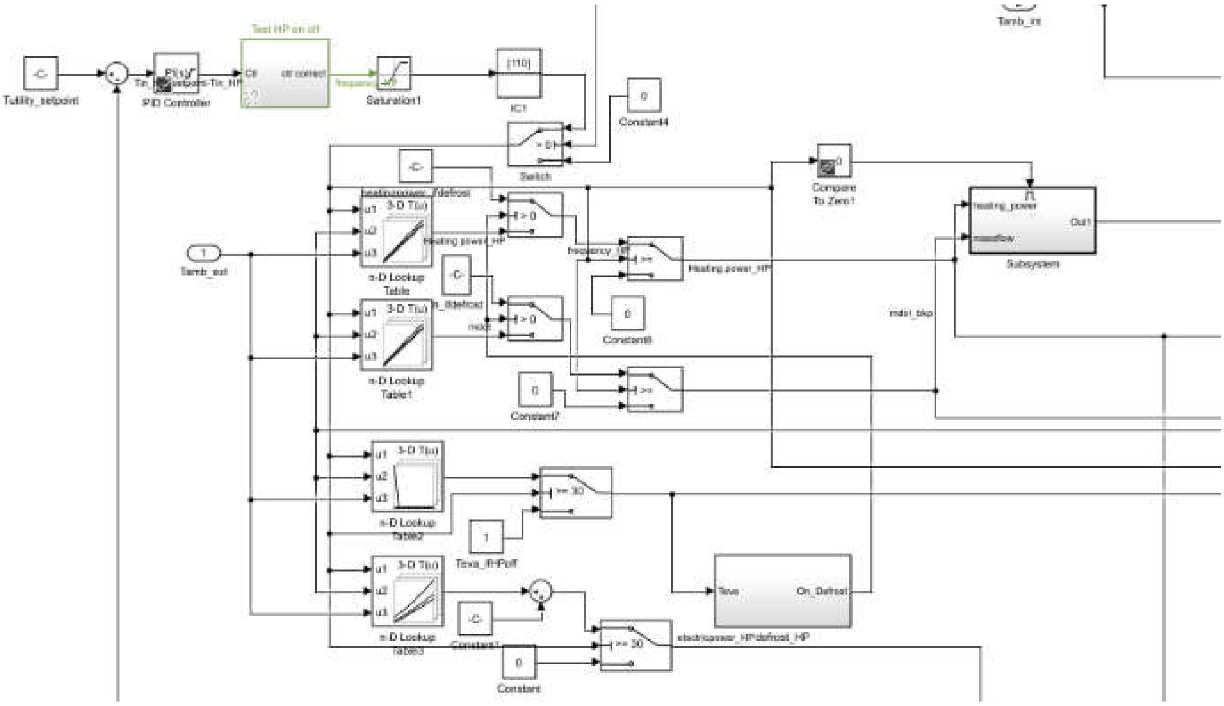

Figure 4.5: Simulink model for the controller and the look up tables of the heat pump

The storage for the DHW is different from the one in the electric case because the heat exchange is between two water mass flow (instead of a water mass flow and an electric resistance). Repeating profile is the sum of all the profile because a unique boiler is provided in case of HP. Flow_Mixer_Thermostatic and Flow_Diverter are implemented as in the electric case. Figure 4.6 shows the Simulink model in the Storage block for the HP case. There is a pipe block (as in the electric case), but this time it communicates with a Heat Exchanger (HX) block.

Moreover, a Storage block for the heating is added. This is similar to the DHW Storage block, but obviously it has the characteristics of the heating boiler illustrated in section 3.3.3.

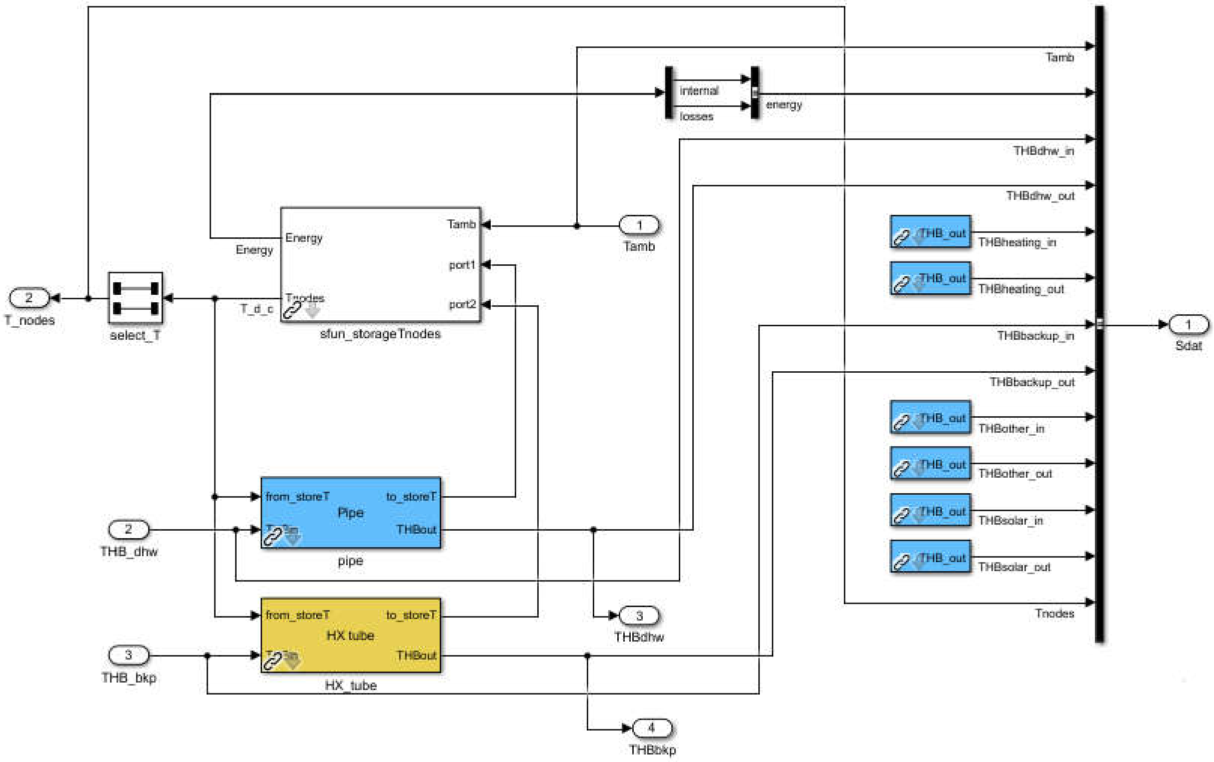

*Figure 4.6: Simulink model of the boiler for the DHW served by the HP*

Finally, the Radiator block is added. As inputs, it requires the room temperature and THB of the water that enters in the radiator. This block provides as output the thermal heating power given to ambient and the THB of the outgoing water (Figure 4.7).

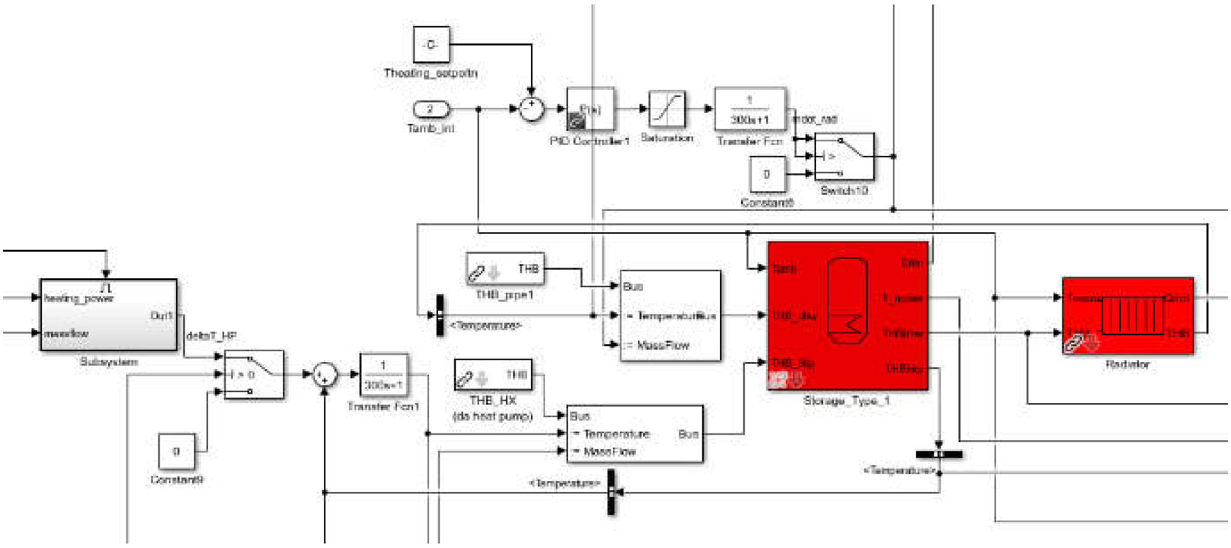

*Figure 4.7: Simulink model of the heating system served by the HP*

# 5 RESULTS

## 5.1 COMPARISON BETWEEN UA AND RC MODELS

Starting from the models descripted in the Chapter 2.2, simulations are performed for the office case.

Due to the different assumption, UA model and RC model show different trends of temperatures for the same case study. In particular, UA model show trends more softened. Moreover, peaks are late compared to the RC model, otherwise the late can accumulate so much that they seem in advance.

The following plots (Figure 5.1, 5.2 and 5.3) show the temperatures' trend in two considered models. The following symbols are adopted:

- $\theta_s$ is the sensitive temperature
- $\theta_c$ is the convective temperature
- $\theta_r$ is the radiative temperature

In particular, Figure 5.2 referrers to the period from the 1st to the 3rd of January, while Figure 5.3 referrers to the period from the 1st to the 3rd of July. For sake of simplicity, these periods are called three winter days and three summer days.

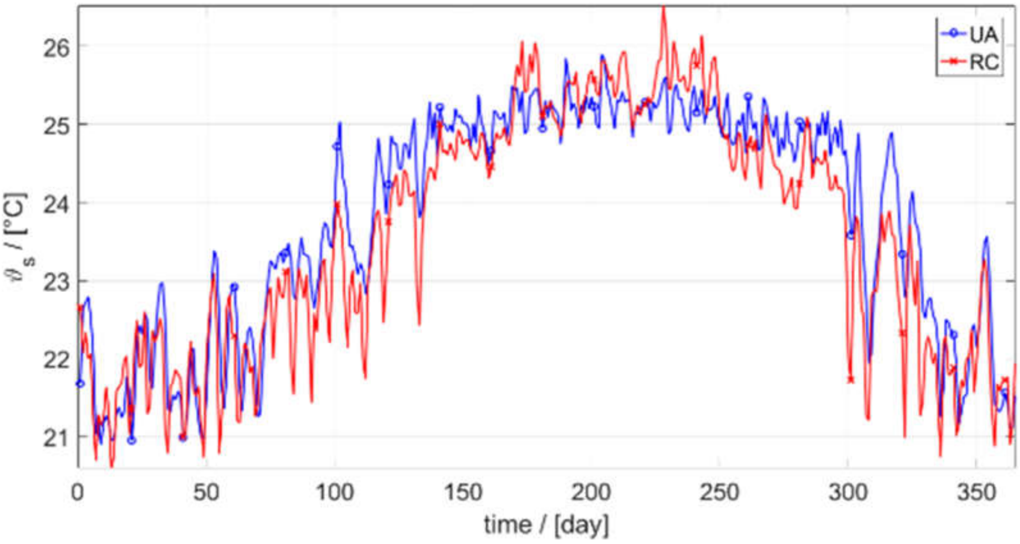

*Figure 5.1: Comparison of the sensible temperature in the UA model and RC model throughout a year*

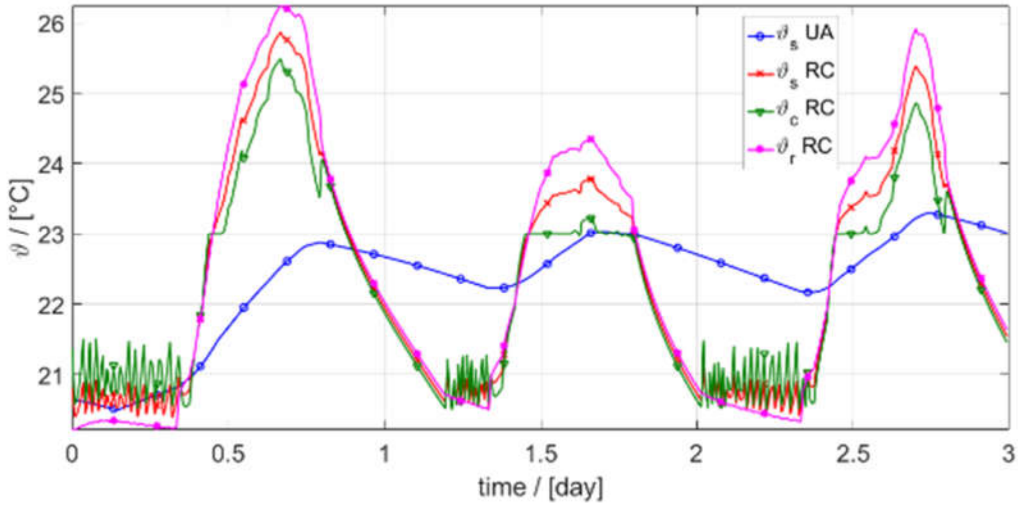

*Figure 5.2: Comparison of the sensible temperature in the UA and RC model throughout three winter days. Moreover, convective temperature and the radiative temperature are shown*

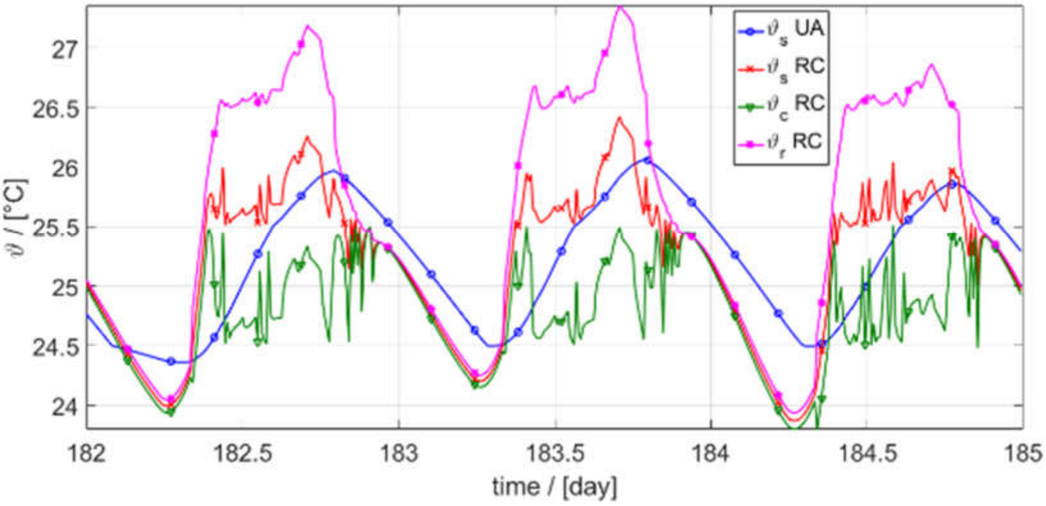

*Figure 5.3: Comparison of the sensible temperature in the UA model and RC model throughout three summer days. Moreover, convective temperature and the radiative temperature are shown*

Since the gain and the power are referred to the temperature, differences between the models are also about these quantities. This is explained by the fact that the external temperature is always the same for both models, but the internal reference temperature changes. Obviously, the deviations between the two models (i.e. UA and RC) should be acceptable.

Concept differences between the two models, influence the behaviour of the heating system too. As it is shown in Figure 5.4 and 5.5, the heating requested in the winter season in the RC model has continuous on-off cycles and with a major power. This happens because the balance is referred to the air node, which has a little capacitance and therefore the temperature varies very fast. On the other hand, in the UA model, having a unique bigger capacitance, the node needs more time to get heated and therefore the heating system operates continuously. In the same way, it needs more time to get cold too, so the power is off for longer time. Moreover, solar irradiation brings its contribute and so the heating system does not switch on for longer. The same behaviour is shown in summer days.

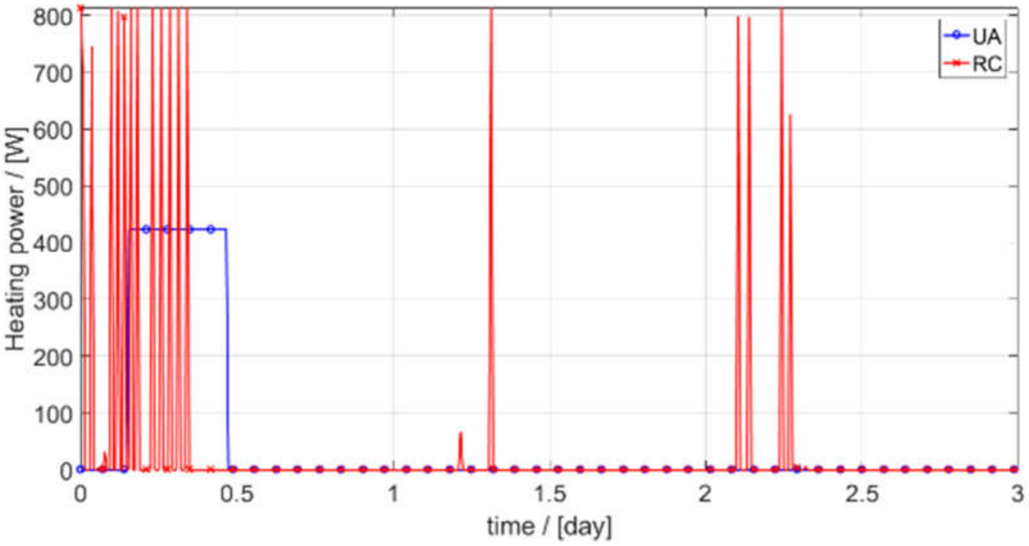

*Figure 5.4: Comparison of the heating power in the UA model and in the RC model throughout three winter days*

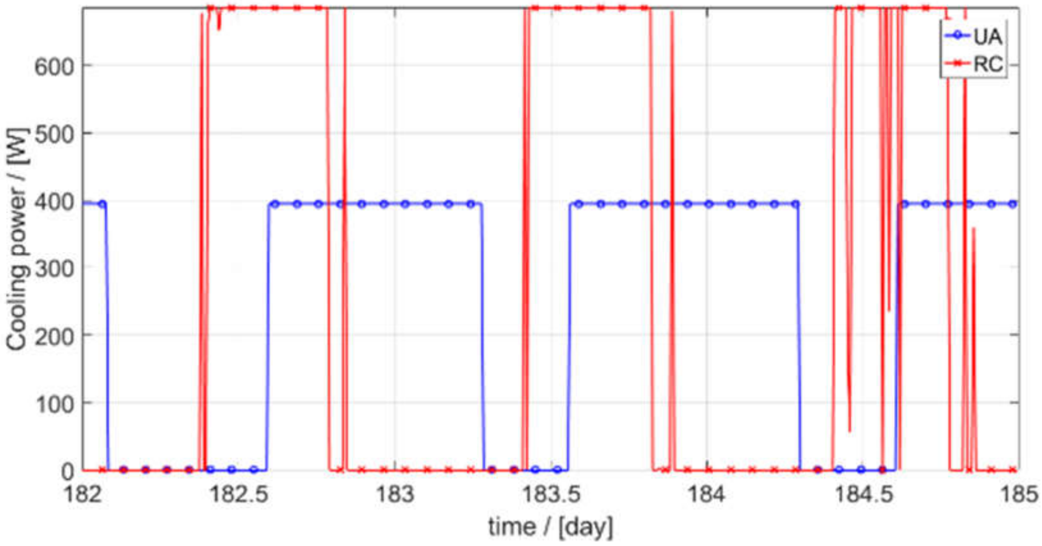

*Figure 5.5: Comparison of the cooling power in the UA model and in the RC model throughout summer days*

## 5.2 EFFECTS OF THE THERMAL MASS

As illustrated in Chapter 4.4.2, UA models with different capacities are compared with the RC model in order to study which value of capacitance leads to more accurate results.

### 5.2.1 The office case

UA models with different percentage of capacitance (see section 4.4.2) are simulated and then compared to the RC model, which is taken as the reference case. It should be stressed that the range between 20 % and 50 % of the original UA capacitance is the densest because results suggested the minimum error. To understand which case is the best, results are plotted and the root mean square is calculated between each case and the RC values. This procedure is applied for several quantities (sensitive temperature, transmission losses, ventilation losses, heating energy demand and cooling energy demand) and for different periods of the year (the whole year, ten days in winter and ten days in summer). As an example, sensitive temperature for the three winter days are shown in Figure 5.6, showing that the best matches with the RC trend is got for UA model with 10 % or 25 % of $C_{spec}$.

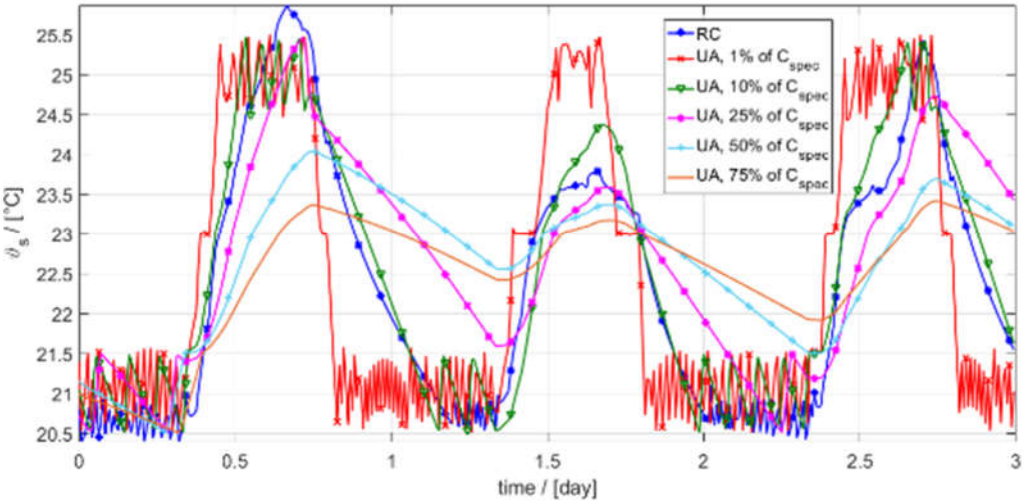

*Figure 5.2: Comparison of the sensitive temperature in the RC model and various UA models with different thermal mass throughout three winter days*

Table 5.1 shows the main thermal quantities, according to the UA model with different thermal masses. In particular, the following quantities are illustrated: sensitive temperature ($\theta_s$), thermal power through walls and windows ($Q_{trans}$), thermal power due to ventilation ($Q_{vent}$), thermal energy through the heating system ($Q_{energy\_heat)}$ and thermal energy through the cooling system ($Q_{energy\_cool}$). Highlighted values are those that correspond to the minimum difference from the RC model. Table 5.2 shown the same quantities referred to the summer values.

*Table 5.1: Root mean square error for winter values*

| **Quantity**<br>**Thermal mass** | **$\theta_s$ [°C]** | **$Q_{trans}$ [kW]** | **$Q_{vent}$ [kW]** | **$Q_{energy\_heat}$ [kWh]** | **$Q_{energy\_cool}$ [kWh]** |
|---|---|---|---|---|---|
| **UA, $C_{spec}$ 1 %** | 0,95 | 25,82 | 100,50 | 55,94 | 28,52 |
| **UA, $C_{spec}$ 10 %** | 0,46 | 19,85 | 68,31 | 28,10 | 12,45 |
| **UA, $C_{spec}$ 20 %** | 0,71 | 19,37 | 53,13 | 4,41 | 3,14 |
| **UA, $C_{spec}$ *25 %*** | *0,75* | *20,01* | *53,37* | *1,77* | *1,81* |
| **UA, $C_{spec}$ 35 %** | 0,89 | 22,52 | 64,12 | 13,09 | 1,06 |
| **UA, $C_{spec}$ 50 %** | 0,99 | 25,08 | 74,97 | 26,51 | 2,30 |
| **UA, $C_{spec}$ 75 %** | 1,04 | 24,40 | 81,56 | 32,49 | 2,30 |
| **UA, $C_{spec}$ 100 %** | 1,10 | 25,17 | 92,07 | 38,69 | 2,30 |

*Table 5.2: Root mean square error for summer values*

| **Quantity**<br>**Thermal mass** | **$\theta_s$ [°C]** | **$Q_{trans}$ [kW]** | **$Q_{vent}$ [kW]** | **$Q_{energy\_heat}$ [kWh]** | **$Q_{energy\_cool}$ [kWh]** |
|---|---|---|---|---|---|
| **UA, $C_{spec}$ 1 %** | 1,12 | 83,34 | 15,06 | 271,89 | 244,87 |
| **UA, $C_{spec}$ 10 %** | 0,39 | 82,41 | 14,50 | 113,06 | 121,93 |
| **UA, $C_{spec}$ 20 %** | 0,40 | 83,12 | 14,98 | 4,23 | 47,79 |
| **UA, $C_{spec}$ *25 %*** | 0,37 | *84,24* | *15,09* | *22,07* | *31,73* |
| **UA, $C_{spec}$ 35 %** | 0,36 | 84,35 | 15,62 | 59,04 | 0,78 |
| **UA, $C_{spec}$ 50 %** | 0,39 | 83,11 | 15,18 | 91,00 | 9,29 |
| **UA, $C_{spec}$ 75 %** | 0,52 | 82,77 | 15,09 | 115,09 | 17,54 |
| **UA, $C_{spec}$ 100 %** | 0,58 | 82,67 | 15,99 | 144,23 | 37,12 |

In particular, the reference RC model has the values shown in Table 5.3:

*Table 5.3: Values in the reference RC model*

| | **$\theta_s$** **[°C]** | **$Q_{trans}$** **[kW]** | **$Q_{vent}$** **[kW]** | **$Q_{energy\_heat}$** **[kWh]** | **$Q_{energy\_cool}$** **[kWh]** |
|---|---|---|---|---|---|
| **Min value** | 20,50 | -799,74 | -512,03 | | |
| **Average value** | 21,80 | -204,46 | -88,44 | | |
| **Max value** | 25,45 | -89,64 | 0,00 | | |
| **Final value** | | | | 71,59 | 2,30 |

Moreover, the relative error is evaluated, in order to understand the weight of each difference (see Table 5.4). In this case the following quantities are taken into account: sensitive temperature ($\theta_s$), thermal energy through walls and windows ($Q_{energy\_trans}$), thermal energy due to ventilation ($Q_{energy\_vent}$), thermal energy through the heating system ($Q_{energy\_heat}$) and thermal energy through the cooling system ($Q_{energy\_cool}$).

*Table 5.4: Relative error for winter values of the office case*

| **Quantity** / **Thermal mass** | $\theta_s$ [°C] | **$Q_{energy\_trans}$** **[kWh]** | **$Q_{energy\_vent}$** **[kWh]** | **$Q_{energy\_heat}$** **[kWh]** | **$Q_{energy\_cool}$** **[kWh]** |
|---|---|---|---|---|---|
| **UA, $C_{spec}$ 1 %** | 0,032 | 0,009 | 0,425 | 0,782 | 12,408 |
| **UA, $C_{spec}$ 10 %** | 0,017 | 0,006 | 0,282 | 0,392 | 5,418 |
| **UA, $C_{spec}$ 20 %** | 0,025 | 0,005 | 0,100 | 0,062 | 1,366 |
| ***UA, $C_{spec}$ 25 %*** | *0,027* | *0,006* | *0,031* | *-0,025* | *0,786* |
| **UA, $C_{spec}$ 35 %** | 0,032 | 0,005 | -0,080 | -0,183 | -0,462 |
| **UA, $C_{spec}$ 50 %** | 0,036 | 0,001 | -0,214 | -0,370 | -1,000 |
| **UA, $C_{spec}$ 75 %** | 0,039 | 0,003 | -0,310 | -0,454 | -1,000 |
| **UA, $C_{spec}$ 100 %** | 0,040 | -0,008 | -0,387 | -0,540 | -1,000 |

As shown above, there is not a unique best case. But, averagely, the 25% of the capacitance can be considered the best. This means that some models are near the RC model, but no one of them can have a perfect match of the results. In particular, different results are obtained for winter and summer days. Averagely, in the summer days a major accordance between UA model and RC model is obtained for lower values of the specific capacity. Obviously, results of the whole year are an average value between the two seasons.

Finally, a comparison between the original RC simulation (that is the one with the HVAC governed by the convective temperature) and the UA simulation with the 25% of the total capacitance is performed.

As an example, the results for the winter days are shown in Figure 5.7.

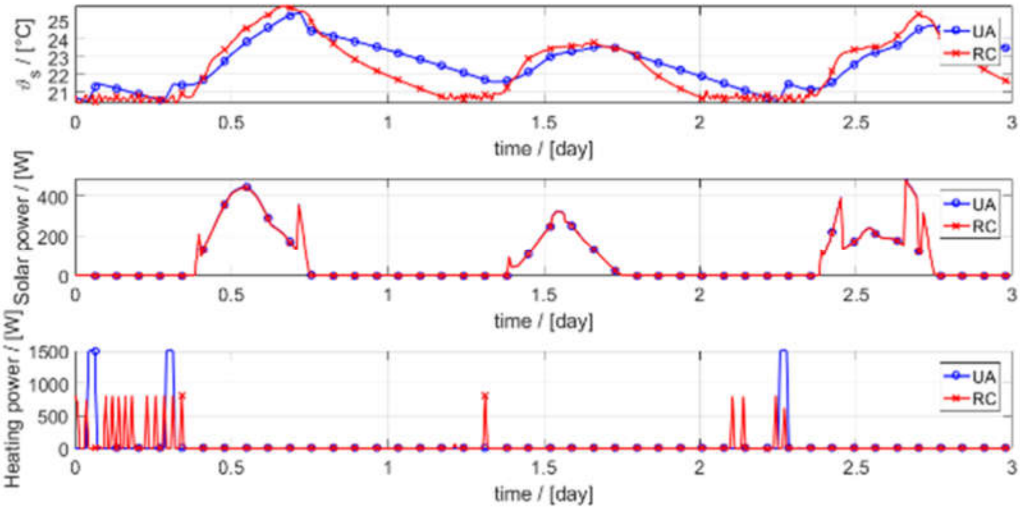

*Figure 5.3: Comparison of sensitive temperature, solar power and heating power between RC model and UA model with 25% of thermal mass throughout three winter days*

It has to be noticed that the initial value of the capacity is a simplified value, according to the PHPP and equal to 132 $\frac{Wh}{m^2\ K}$ (mixed building). From the obtained results, it can be deduced that a right capacity should be taken as less than the light value.

Another factor to be taken into account is the simulation time. Indeed, different models with different levels of complexity need different simulation time. Simulation with the same condition of the software are carried out for a comparison. As shown in Table 5.5, the RC model is the one that needs more time, this is justified by the major complexity of the model. Immediately after, there is the UA model with 1% of the capacity, while all the other models have approximately the same simulation time. The original UA model has a slightly higher simulation time.

*Table 5.5: Comparison of simulation time for different models*

| | **seconds** | **minutes** |
|---|---|---|
| ***RC*** | *504,026* | *8,400* |
| **UA, $C_{spec}$ 1 %** | 486,987 | 8,116 |
| **UA, $C_{spec}$ 10 %** | 98,198 | 1,637 |
| **UA, $C_{spec}$ 20 %** | 77,468 | 1,291 |
| ***UA, $C_{spec}$ 25 %*** | *77,819* | *1,297* |
| **UA, $C_{spec}$ 35 %** | 71,184 | 1,186 |
| **UA, $C_{spec}$ 50 %** | 74,564 | 1,243 |
| **UA, $C_{spec}$ 75 %** | 75,338 | 1,256 |
| **UA, $C_{spec}$ 100 %** | 99,075 | 1,651 |

As a consequence of the illustrated results, it has been made the choice to simulate the building subject of this study with a Resistance Capacitance (RC) model, that it is a two-nodes model. The choice is due to the major precision of the first model, even if this results to higher complexity of the whole model and therefore a higher computational effort.

### 5.2.2 The An-der-Lan building case

In this case, different results are obtained. Even though the original capacitance was bigger than in the office case ($204 \frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$ versus $132 \frac{\mathrm{Wh}}{\mathrm{m^2\,K}}$), the optimum UA model is not one with reduced capacity, but the one with increased capacity.

As in the case of the office, there is not a unique best case, but it depends on the considered quantity. Indeed, for example, regarding the temperature in winter, the minimum difference with the RC model is obtained with a capacity 1.75 times bigger than the initial one. On the other hand, regarding the power, it varies from the initial capacity and 8 times that (see Table 5.6).

Moreover, for the summer days lower values of capacitance lead to minimum difference with the RC model, similar to the office study.

The root mean square between RC model and UA models for different quantities for ten winter days is shown in Table 5.6. The analysed quantities are: sensitive temperature ($\theta_s$), thermal power through walls and windows ($Q_{trans}$), thermal power through infiltration ($Q_{inf}$), heating power ($Q_{heat}$), mechanical ventilation power ($Q_{ventmech}$) and heating energy ($Q_{energy\_heat}$).
The highlighted values are those that correspond to the minimum difference from the RC model.

*Table 5.6:Root mean square for winter values of the An-der-Lan building*

| **Quantity**<br>**Thermal mass** | $\theta_s$ [°C] | $Q_{trans}$ [kW] | $Q_{inf}$ [kW] | $Q_{heat}$ [kW] | $Q_{ventmech}$ [kW] | $Q_{energy\_heat}$ [kWh] |
|---|---|---|---|---|---|---|
| **UA, $C_{spec}$ 25 %** | 0,421 | 54982 | 19 | 2553 | 59 | 392 |
| **UA, $C_{spec}$ 50 %** | 0,202 | 54987 | 12 | 2442 | 36 | 333 |
| **UA, $C_{spec}$ 75 %** | 0,129 | 54988 | 9 | 2356 | 28 | 307 |
| **UA, $C_{spec}$ 100 %** | 0,098 | 54988 | 8 | 2325 | 24 | 292 |
| **UA, $C_{spec}$ 125 %** | 0,086 | 54988 | 7 | 2344 | 22 | 282 |
| **UA, $C_{spec}$ 150 %** | 0,081 | 54988 | 7 | 2359 | 20 | 277 |
| **UA, $C_{spec}$ 175 %** | 0,081 | 54988 | 6 | 2386 | 19 | 275 |
| **UA, $C_{spec}$ 200 %** | 0,081 | 54989 | 6 | 2423 | 19 | 273 |
| **UA, $C_{spec}$ 400 %** | 0,088 | 54990 | 6 | 2452 | 18 | 263 |
| **UA, $C_{spec}$ 600 %** | 0,090 | 54991 | 6 | 2316 | 17 | 284 |
| **UA, $C_{spec}$ 800 %** | 0,093 | 54991 | 6 | 2216 | 17 | 288 |
| **UA, $C_{spec}$ 1000 %** | 0,095 | 54991 | 6 | 2219 | 17 | 287 |

In conclusion, even if the initial value of the specific thermal mass in the PHPP is already the highest (204 $\frac{Wh}{m^2\,K}$), it should be increased again.

Figure 5.8 shows the $\theta_s$ development for the different models. In particular, in the UA cases, the percentages are referred to the $C_{spec}$ indicated in PHPP. The figure presents the first three days of the year. The UA trend with 175% of the PHPP capacitance and the RC trend are highlighted, because these are the models with the more.

It is noted that if the thermal mass is small, the sensitive temperature varies very fast because it is heavily influenced by the presence of the sun. The same applies for the heating power.

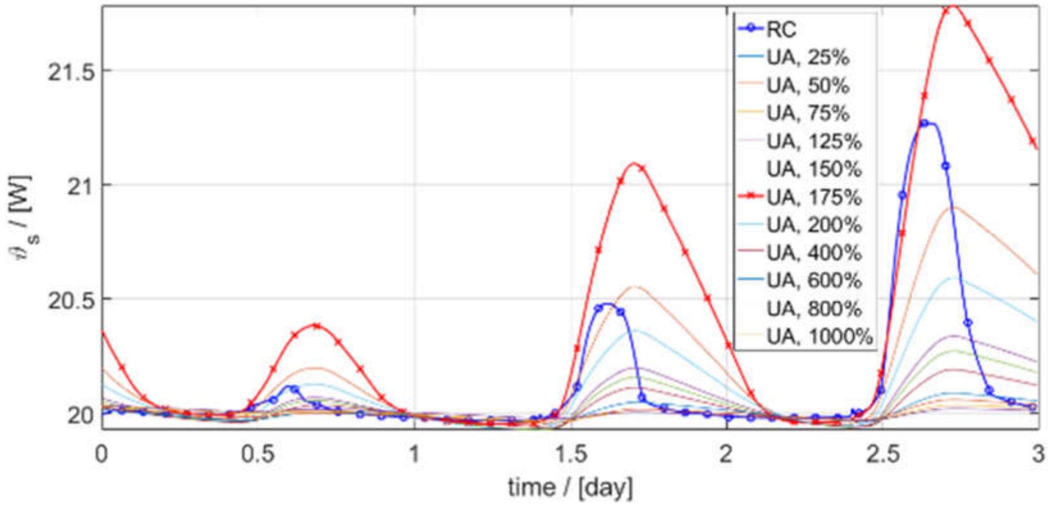

*Figure 5.4: Comparison of the sensitive temperature in three winter days. RC model and the UA model with minimum error are highlighted.*

The ventilation and the infiltration power show approximately the same trend in the RC and UA model. As an example, the mechanical ventilation power for different cases is shown in Figure 5.9.

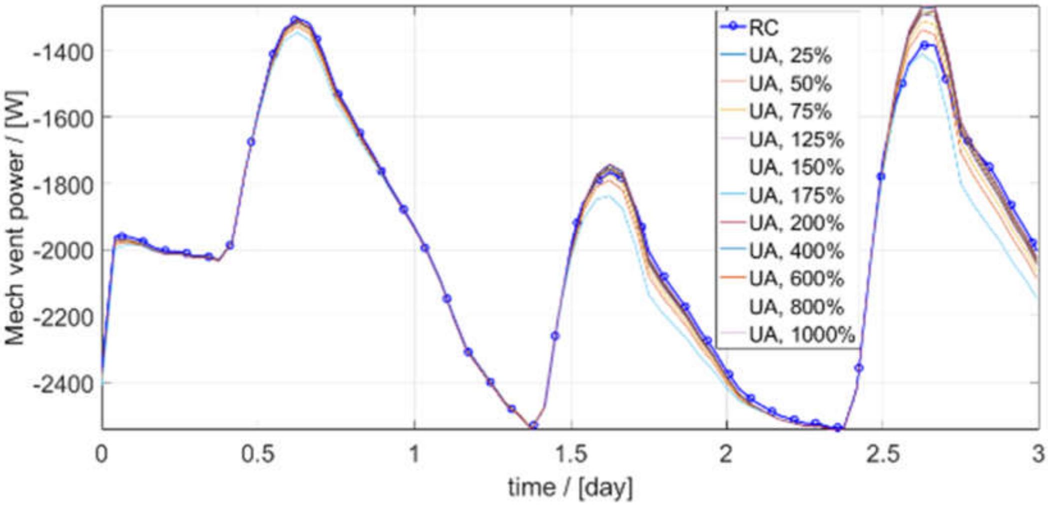

*Figure 5.5: Comparison of the mechanical ventilation power in three winter days*

On the opposite, the transmission power (due to walls and windows) has completely different trend in UA models and in the RC model, as it is illustrated in Figure 5.10. In particular, all the UA models have the same trend, while the RC has a completely different behaviour. This is explained by the fact that in RC model there are two balances: one on the inside part of the wall and the other on the outside part. Each of these two capacitances can accumulate and then release energy in a different moment. In this case, the outside part of the wall has a great importance and it is the one which is heavily influenced by the presence of the sun. Indeed, this part is affected by the solar gain due to the absorbed solar power, which is a part of the incidence solar irradiation. This term is positive in the balance. At the same time, this part is also affected by the negative transmission term, due to the fact that in winter the outside temperature is lower than the inside one. In conclusion, the external side of the wall shows these fast oscillations, but they do not occur in the inner part. Obviously, the two balances integrated in the year must have the same value.

This behaviour does not occur in the UA model because there is only one balance.

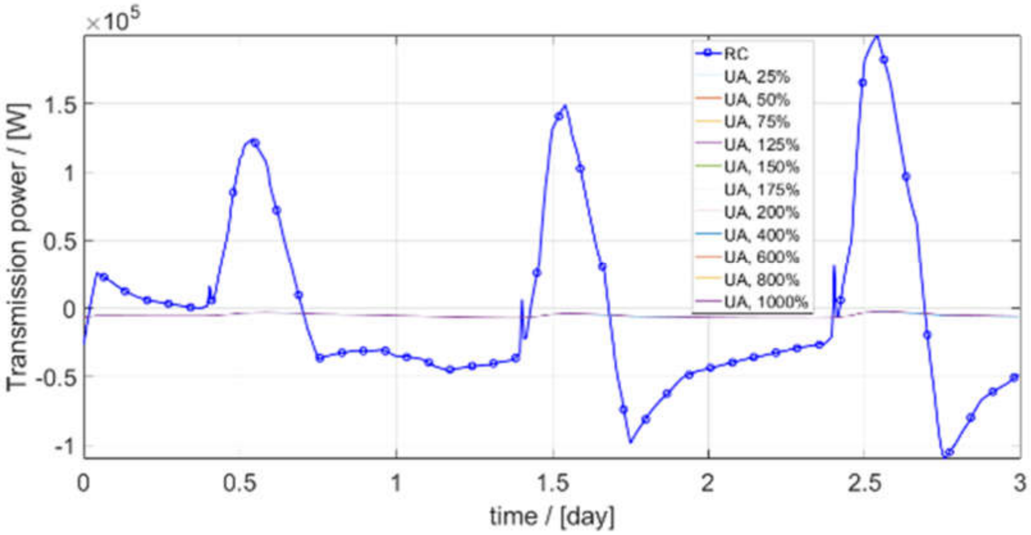

*Figure 5.6: Comparison of the transmission power in three winter days*

## 5.3 SIMULATION RESULTS OF DIFFERENT HEATING SYSTEM AND PV AREAS

### 5.3.1 Case1: Electric heating and electric DHW

In this section results about the reference case are shown and discussed. Figure 5.11 shows the percentage of time that each value of the sensitive temperature has in a year.

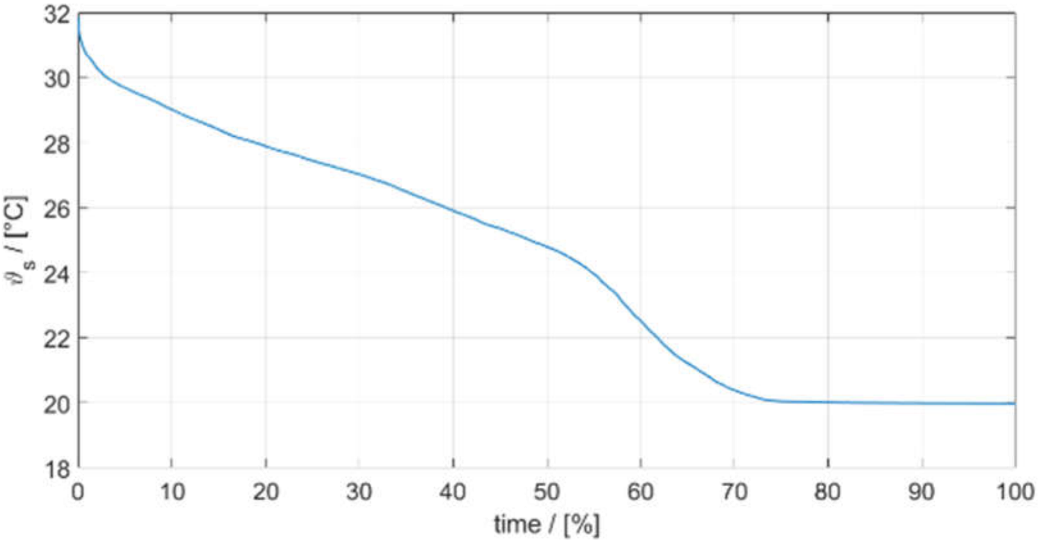

*Figure 5.7: Percentage of comfort for the sensitive temperature for Case1*

The plot shows that the required temperature inside the building (20 °C) is always reached by electric heaters. Indeed, no values under 20 °C are presented. In particular, for approximatively 25% of the year is 20 °C, for the rest of the time the temperature is higher. This trend is due to the absence of the cooling system. Indeed, as Figure 5.12 illustrates, the $\theta_s$ increases simultaneously with the ambient temperature ($\theta_{amb}$).

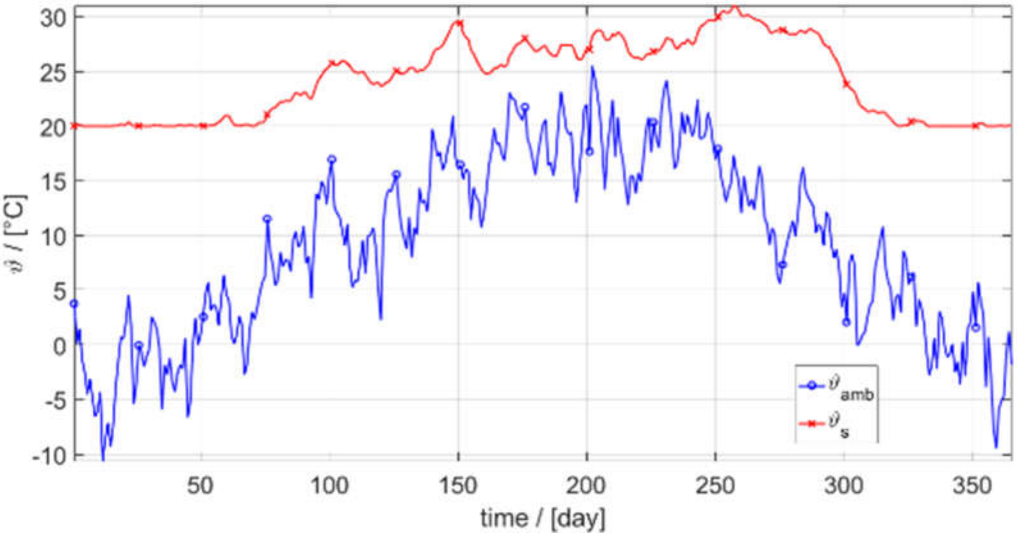

*Figure 5.8: Ambient temperature and sensitive temperature trend in a year for Case1*

Monthly average values of the sensitive, convective and radiative temperatures are shown in Table 5.7.

*Table 5.7: Monthly average temperature outside and inside the building for Case1*

| | $\theta_{amb}$ [°C] | $\theta_s$ [°C] | $\theta_c$ [°C] | $\theta_r$ [°C] |
|---|---|---|---|---|
| **January** | - 2,50 | 20,03 | 19,89 | 20,19 |
| **February** | 0,16 | 20,10 | 19,92 | 20,28 |
| **March** | 5,23 | 21,22 | 21,02 | 21,43 |
| **April** | 9,74 | 24,62 | 24,42 | 24,82 |
| **May** | 14,38 | 26,14 | 26,04 | 26,25 |
| **June** | 17,33 | 26,47 | 25,95 | 27,00 |
| **July** | 19,27 | 27,41 | 26,95 | 27,87 |
| **August** | 18,54 | 27,21 | 26,71 | 27,71 |
| **September** | 14,99 | 29,81 | 29,62 | 29,99 |
| **October** | 9,55 | 27,24 | 26,97 | 27,50 |
| **November** | 4,01 | 20,77 | 20,55 | 20,98 |
| **December** | -0,85 | 20,03 | 19,92 | 20,13 |

Table 5.8 shows the monthly energy values for thermal losses and thermal gains for the An-der-Lan building. The following quantities are taken into account: thermal losses through wall ($Q_{Twalls}$), through windows ($Q_{Twind}$), through the ground ($Q_{Tground}$), through mechanical ventilation ($Q_{ventmech}$), through infiltration ($Q_{inf}$) and finally thermal gains ($Q_{intgains}$).

*Table 5.8: Thermal losses and thermal gains for each month*

| | $Q_{Twalls}$ [kWh] | $Q_{Twind}$ [kWh] | $Q_{Tground}$ [kWh] | $Q_{ventmech}$ [kWh] | $Q_{inf}$ [[kWh]] | $Q_{intgains}$ [kWh] |
|---|---|---|---|---|---|---|
| **January** | -2164 | -2502 | -715 | -1812 | -716 | 2403 |
| **February** | -1680 | -2014 | -652 | -1444 | -565 | 2170 |
| **March** | -1312 | -1707 | -734 | -1274 | -491 | 2403 |
| **April** | -1608 | -1528 | -776 | -1133 | -435 | 2325 |
| **May** | -369 | -1222 | -768 | -924 | -350 | 2403 |
| **June** | -470 | -886 | -750 | -3144 | -248 | 2325 |
| **July** | -122 | -774 | -765 | -2889 | -226 | 2403 |
| **August** | -571 | -871 | -771 | -3072 | -241 | 2403 |
| **September** | -1729 | -1501 | -989 | -1109 | -423 | 2325 |
| **October** | -1828 | -1915 | -1043 | -1376 | -531 | 2403 |
| **November** | -2011 | -1799 | -693 | -1292 | -499 | 2325 |
| **December** | -2370 | -2347 | -669 | -1681 | -660 | 2403 |

Since the building is always the same in all cases, these values are valid for the next cases too.

Regarding the domestic hot water, the sorted supplied temperatures for each profile are presented in Figure 5.13.

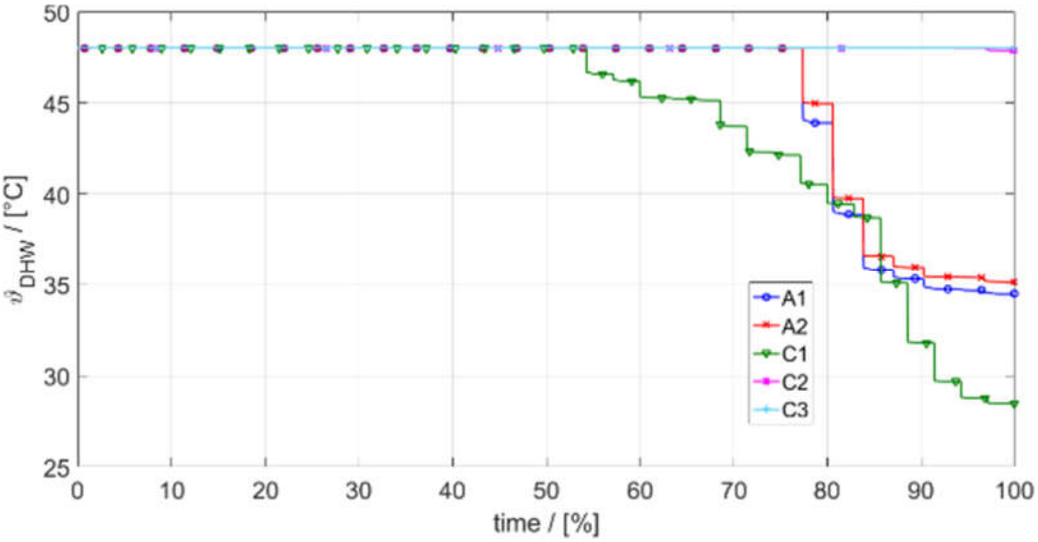

*Figure 5.9: Percentage of comfort for different DHW boiler for Case1*

It is clear that the comfort is not fulfilled for boiler A1, A2 and C1. Indeed, for DHW profiles A1 and A2 for approximately 25% of the time the temperature is lower than the set point (that is 48 °C), reaching the minimum temperature of 35 °C. C1 trend is even worse because only for 55% of the time fulfils the required temperature. This occurs since the DHW demand is higher and thus the design volume of the storage is not sufficient. In order to have the comfort for each boiler, a post heating is established, to supply the required 48 °C.

The monthly electricity values distinguished in heating, DHW production and appliances are shown in Figure 5.14. Moreover, the monthly energy produced by the photovoltaic system is also shown with the continuous line.

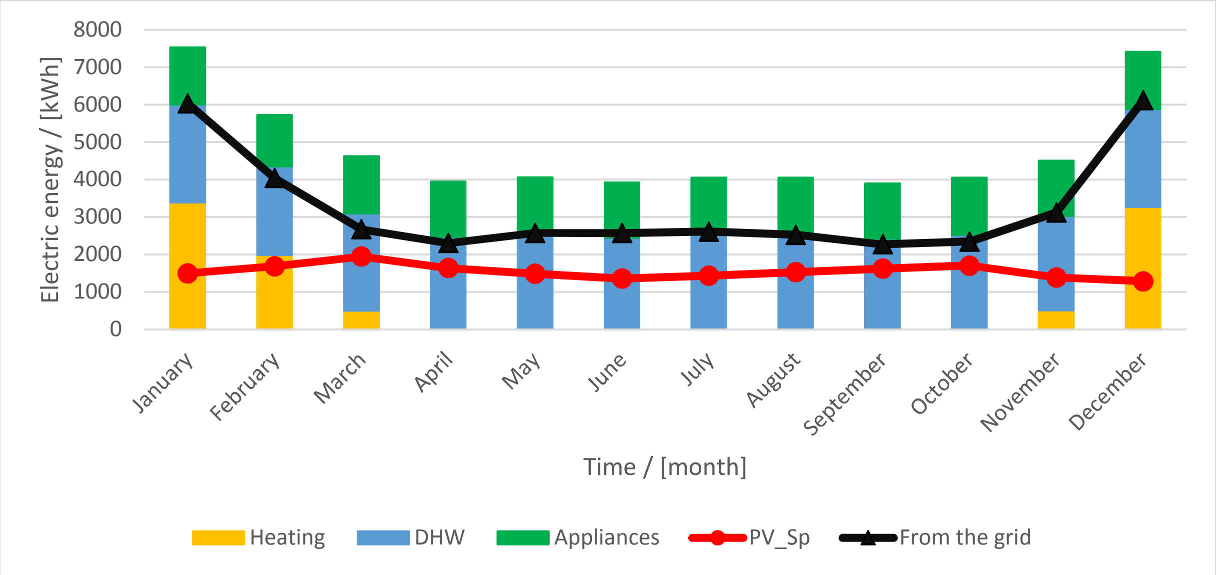

*Figure 5.10:Monthly electric energy required and provided for Case*

From this graph it is clear that, in every month, the energy produced by the PV system is not enough to cover all the energy requests of the building. Indeed, this is not possible not even in summer (when the heating system is off) because the PV production is not at its maximum point and, moreover, appliances and DHW requests are still too high.

Daily analysis show that in few days of the year, it is actually possible to avoid the request of energy from the grid. Moreover, it is possible to supply energy to the grid, as shown in Figure 5.15.

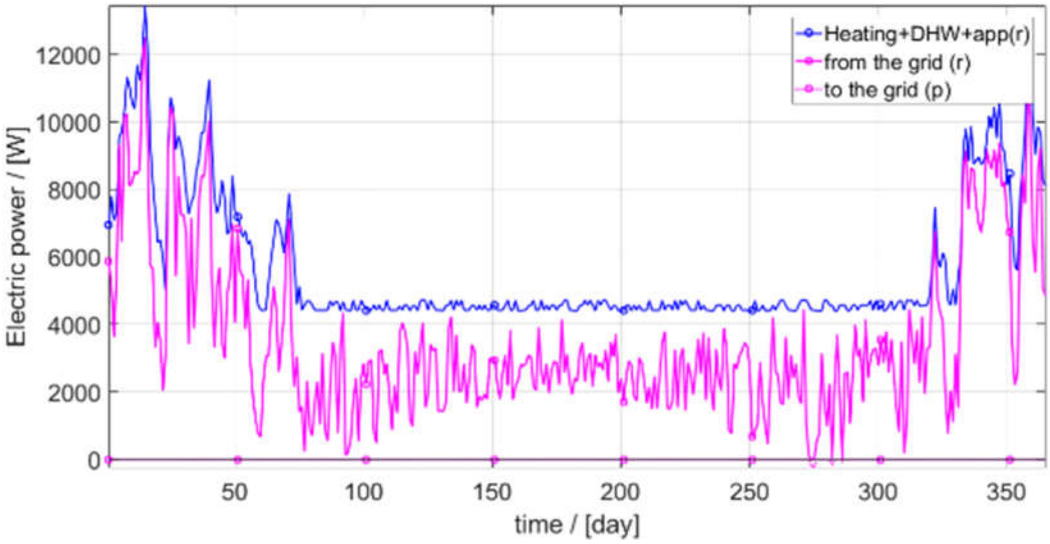

*Figure 5.11: Daily average electric power for Case1*

For a couple of days in Autumn (at the begin of October), the balance between energy required and energy produced is negative. This behaviour is represented by the magenta dot line.

This trend is also presented in Figure 5.16, in which only one day is shown. In this plot only requests of DHW and appliances are represented, since they are assumed the same every day. Consequently, they are independent from the considered day of the year. Moreover, the PV production is shown for two different days of the year.

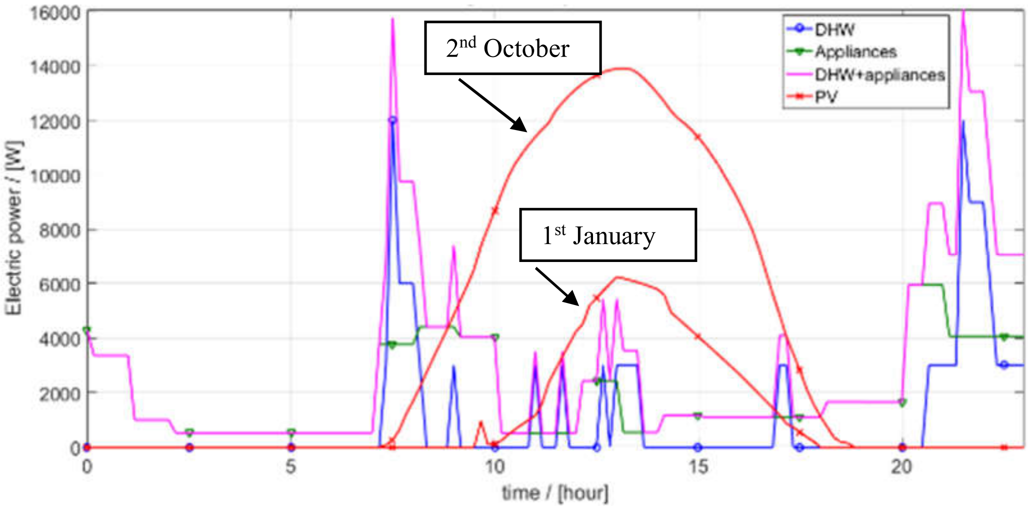

*Figure 5.12: Daily electric power required and provided*

With the solar irradiation, and the PV production, in October it is possible to cover much more energy required. In addition, in October the heating is system is never switched on due to the good thermal insulation of the building. Therefore, in the first days of October there is the combination that allows an energy production to the grid.

For the comparison of the boilers volume, firstly, the comfort is analysed. As already said, in the base case the comfort is not fulfilled, so it is predicted that with a reduction of the volume the situation is going to be worse. Figure 5.17 illustrates these trends.

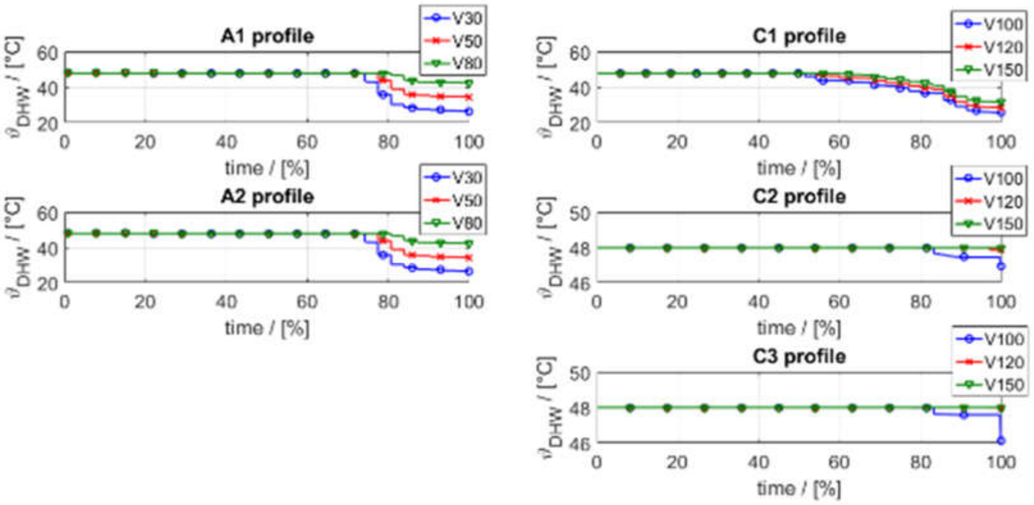

*Figure 5.13: Comparison of DHW boiler volume: comfort achieved*

The reduction of volume leads to a reduction of comfort. The opposite trend is obtained for an increase of the volume. This occurs for A1 and A2 profile. About C1 profile, it can be seen that comfort is not reached with any of the considered volumes. On the other hand, the change of boiler for C2 and C3 profile doesn’t affect the comfort, since in all three cases it is fulfilled. Indeed, the only slightly different trend is the one with the 30 litres boiler, but also in this case the comfort can be assumed reached because for only 1 % of time the DHW is sent at 46 °C (instead of 48 °C) to the utility. Consequently, for C2 and C3 the minimum boiler can be suggested.

Secondly, the electric energy required to heat the different boiler is analysed. The trend is the same for every boiler, so as an example only the A1 boiler trend is shown in Figure 5.18. The plot illustrates that the bigger the volume is, the more energy is required to keep the water at the desired temperature (60 °C).

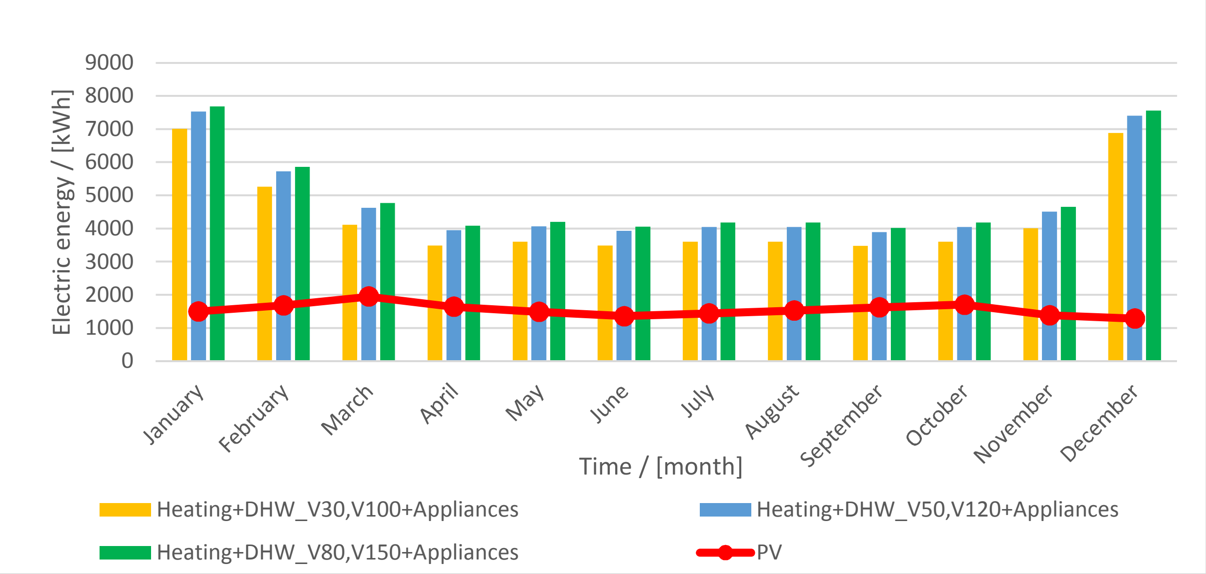

*Figure 5.14: Comparison volume: electric energy required and produced*

The second comparison is about different surfaces of PV considered. Obviously, the higher the number of installed panels is, the more electric energy is produced (and consequently the less has to be required from the grid). Actually Figure 5.19 illustrates that even with enormous PV surfaces, the balances between energy required and produced is really difficult to be reached.

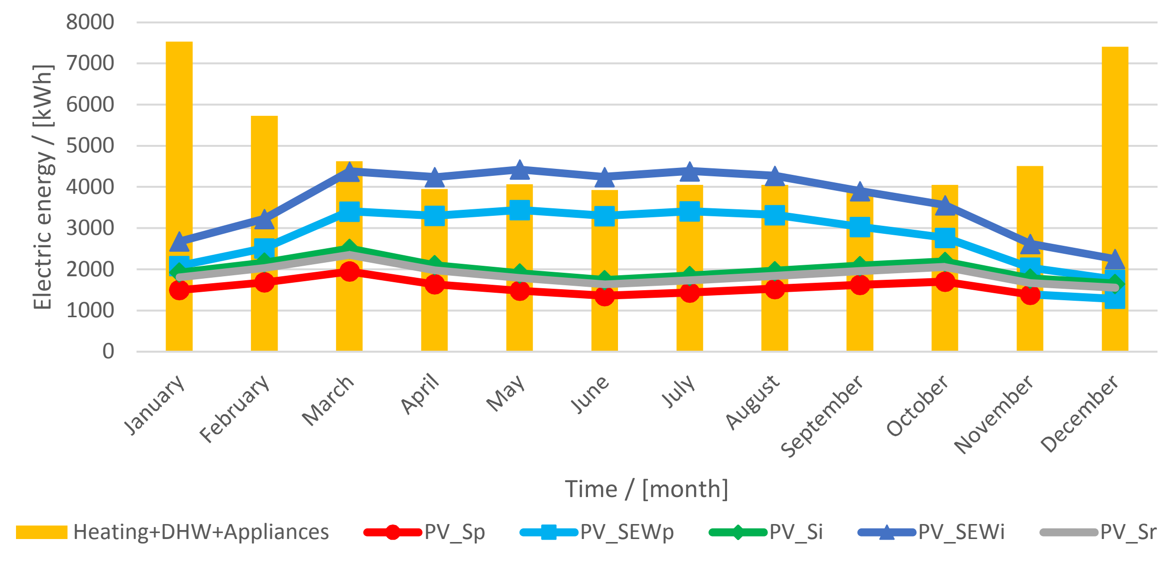

*Figure 5.15: Comparison PV: monthly energy required and produced*

Indeed, only in the variant with ideal surface of panels in the South, East and West facades the energy produced by the PV system is higher than the needed energy (see Figure 5.20). More precisely, the monthly electric energy required from the grid for each variant is shown in Figure

5.20 (evaluated with monthly balance). The dot line, that corresponds to negative values, represents moments when actually the energy is given to the grid.

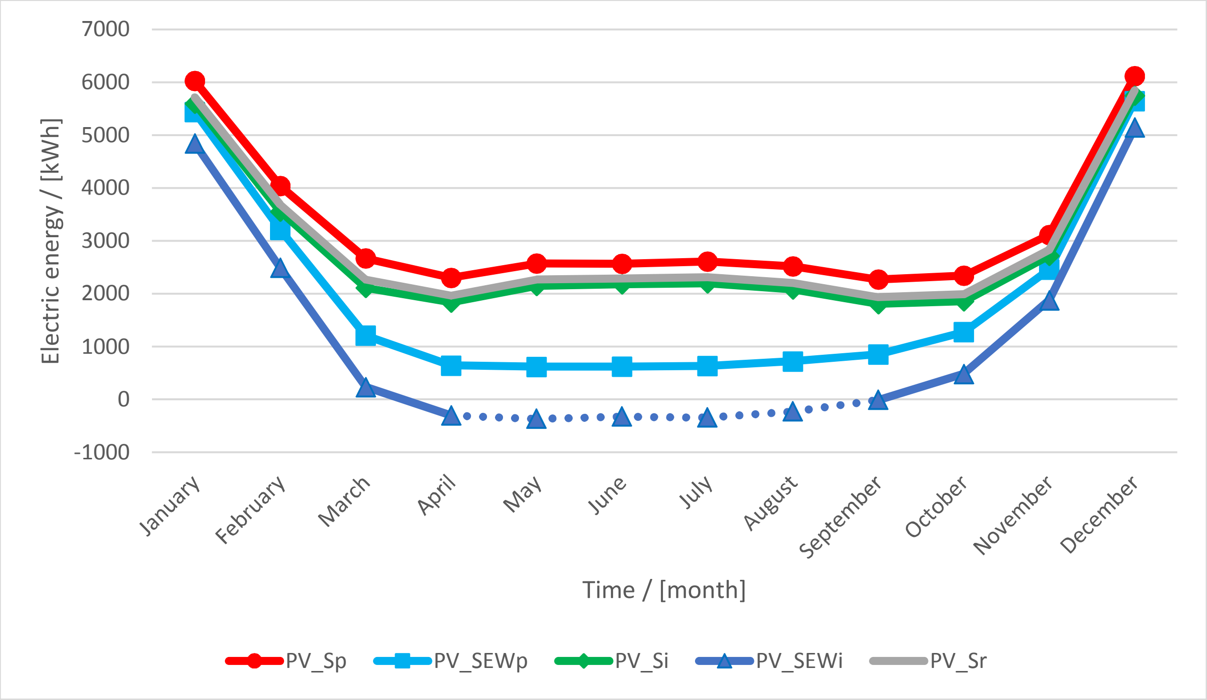

*Figure 5.16: Comparison PV variants: monthly energy required from the grid (evaluated with monthly balance)*

### 5.3.2 Case2: Heat pump for heating and domestic hot water

In this section results from the Case2 simulation are illustrated. Figure 5.21 shows the comfort inside the building regarding the sensitive temperature.

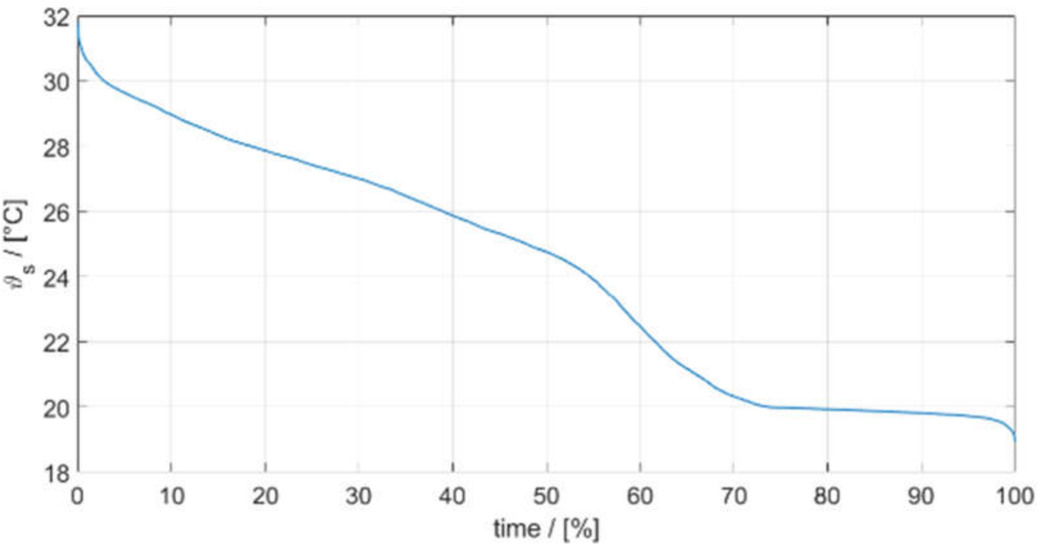

*Figure 5.17: Percentage of comfort for the sensitive temperature for Case2*

It shows that for some percentage points of the time the sensitive temperature is below the set point of 20 °C, but the comfort can be considered fulfilled in any case. This behaviour is due to the heat pump, since it has more inertia than the electric heaters. Figure 5.22 shows the trend of the sensitive temperature with the heating system powered by the heat pump along with the external temperature.

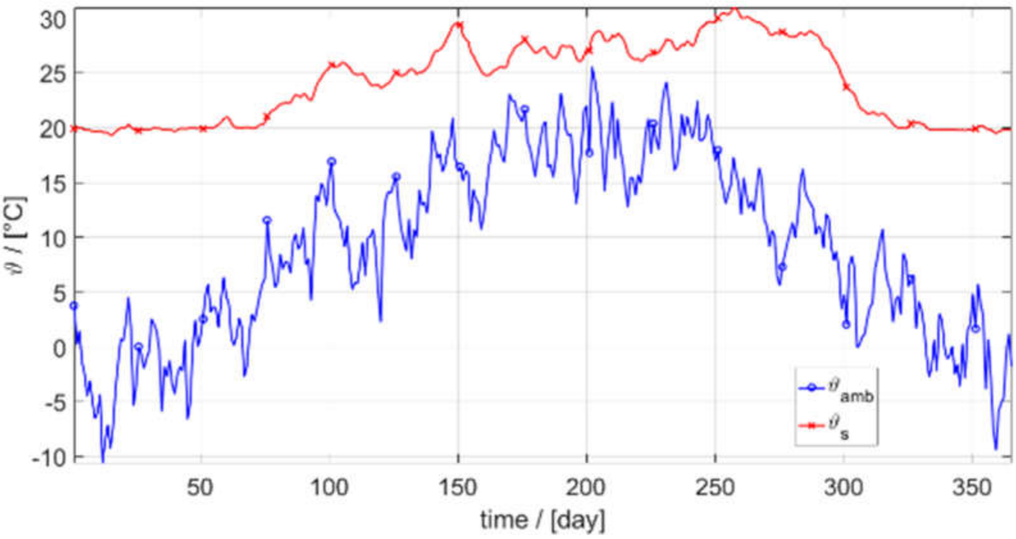

*Figure 5.18: Ambient temperature and sensitive temperature trend in a year for Case2*

Indeed, comfort is also confirmed by the observation that monthly thermal energy delivered in Case1 and Case 2 are very similar. Table 5.9 shows monthly thermal values supplied in the electric and heat pump case.

*Table 5.9: Thermal monthly energy for heating*

| | **Thermal energy Case1 [kWh]** | **Thermal energy Case2 [kWh]** | **Losses thermal energy Case2 [kWh]** |
|---|---|---|---|
| **January** | 3389 | 3292 | 610 |
| **February** | 1986 | 1958 | 546 |
| **March** | 497 | 484 | 259 |
| **April** | 0 | 0 | 2 |
| **May** | 0 | 1 | 15 |
| **June** | 0 | 0 | 6 |
| **July** | 0 | 0 | 4 |
| **August** | 0 | 0 | 0 |
| **September** | 0 | 0 | 1 |
| **October** | 0 | 1 | 15 |
| **November** | 506 | 479 | 23 |
| **December** | 3263 | 3171 | 611 |

It has to be emphasized that an ideal control system would control the temperature of the radiator on the basis of the internal temperature. This means that the radiator temperature would decrease when the difference between the set point temperature and the sensitive temperature decrease. For sake of simplicity, this behaviour is not considered. As a consequence, the heat pump efficiency is underestimated, since the decrease of the requested water temperature would allow the heat pump to a higher COP.

Differently from the electric case, the comfort regarding the DHW is always reached with the adoption of the heat pump. To have a "fairly" comparison between the electric case and the heat pump for the DHW production, a post heating is added at the Case1. The additional thermal power (that in the case if electric production is equal to the electric power) is evaluated as the difference between the thermal power for Case2 and the thermal power for case 1, as shown in Table 5.10.

*Table 5.10: Thermal energy for DHW for Case1 and Case2 and post heating for Case1*

| | **Thermal energy for DHW Case1 [kWh]** | **Thermal energy for DHW Case2 [kWh]** | **Post heating energy Case1 [kWh]** |
|---|---|---|---|
| **January** | 1958 | 2131 | 173 |
| **February** | 1768 | 1925 | 157 |
| **March** | 1956 | 2131 | 174 |
| **April** | 1887 | 2062 | 176 |
| **May** | 1950 | 2032 | 181 |
| **June** | 1888 | 2063 | 175 |
| **July** | 1951 | 2131 | 180 |
| **August** | 1951 | 2131 | 180 |
| **September** | 1890 | 2063 | 173 |
| **October** | 1951 | 2131 | 180 |
| **November** | 1895 | 2063 | 168 |
| **December** | 1958 | 2131 | 173 |

Monthly values of electric energy required in order to accomplish the heating system, the DHW production and appliances are shown in Figure 5.23. PV production is shown too, and the difference between the energy required and produced is the energy required from the grid. As in the Case1, it is clear that in every month energy is needed from the grid, since the PV production is never higher than the requested energy.

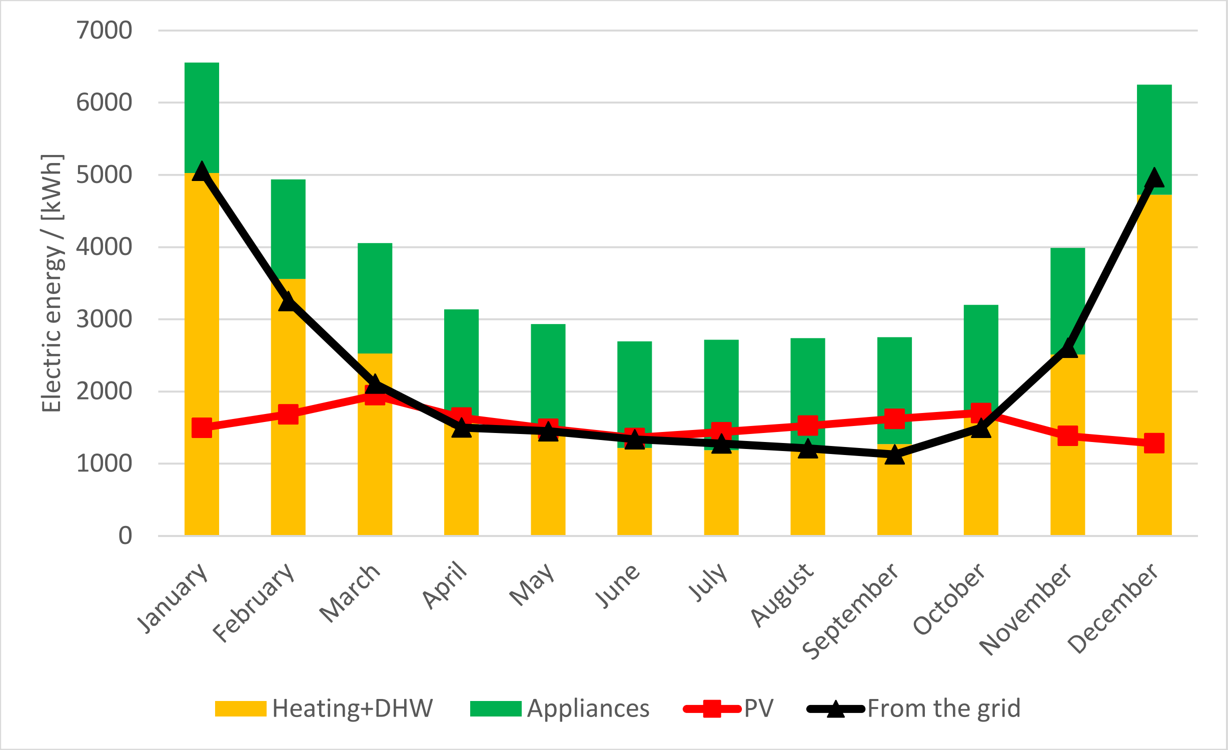

*Figure 5.19: Monthly electric energy required and produced*

In particular, it has to be emphasized that the electric energy is sensibly lower than the electric case. This is possible due to the principle of the heat pump. Indeed, as the Figure 5.24 shows, the thermal energy delivered by the heat pump is higher than the electric energy required by the heat pump. In particular, the plot shows the electric energy used for the normal mode and electric energy required only for the defrost mode.

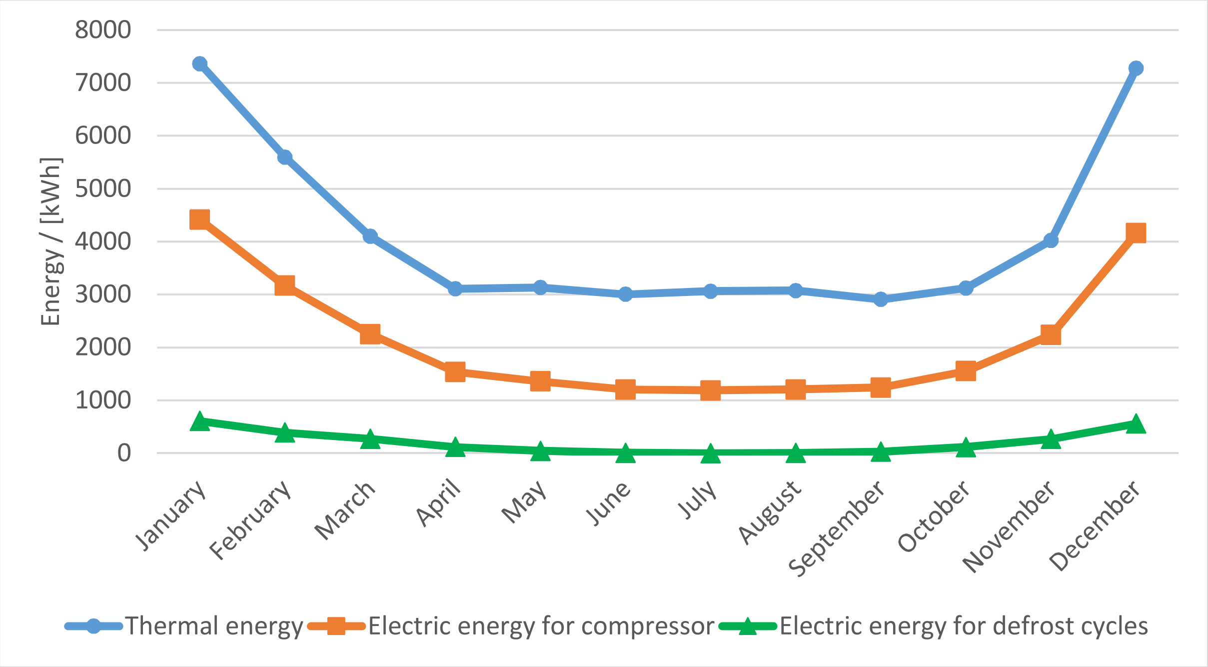

*Figure 5.20: Monthly energy (thermal and electric) involved in the heat pump*

Daily analysis is shown in Figure 5.25. For some days is actually possible to have a PV production higher than the required energy.

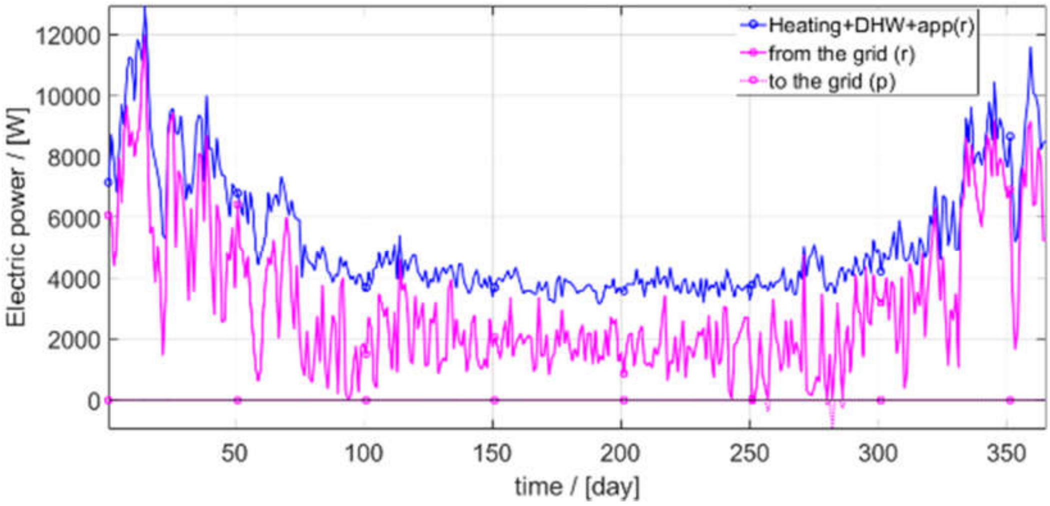

*Figure 5.21: Daily average electric power for Case2*

Furthermore, it has to be emphasized that the production of DHW was at 60 °C. However, if a lower temperature is set, the heat pump works with higher performance. Indeed, in the reality, it is possible to produce water at 50 °C and only once per week make a cycle (heating the water at 60 °C in order to kill the Legionella bacteria). This control would increase significantly the performance of the heat pump.

With the variant in the boiler volume different results are obtained compared to the Case1. Indeed, as Figure 5.26 shows, comfort is guarantee with all the volumes. In particular, only for the minimum volume a slightly different line is presented. But the difference is only for less than 1% at 46 °C (instead of 48 °C), so the comfort can be considered fulfilled.

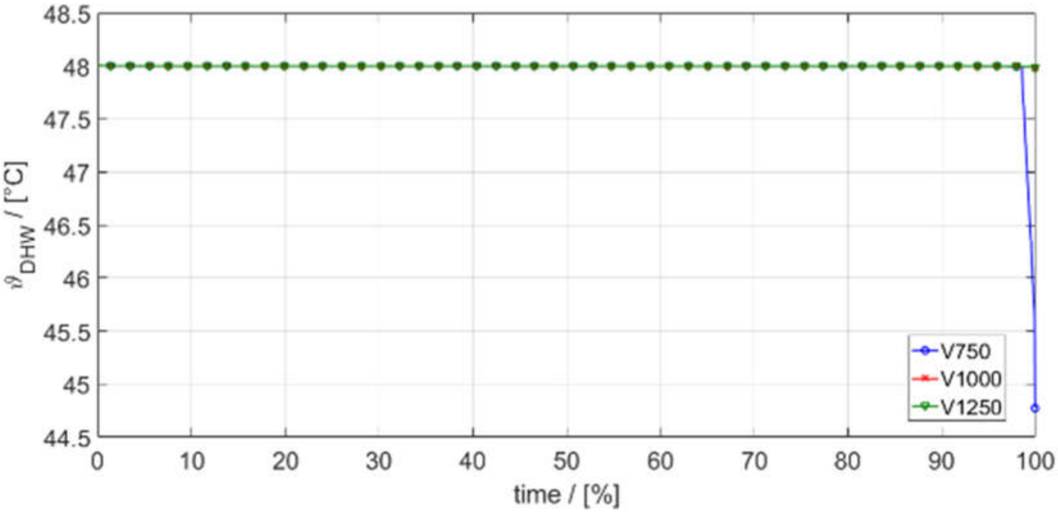

*Figure 5.22: Comparison of boiler volumes, percentage of comfort for the DHW temperature*

As a consequence, in this case the choice for the most convenient boiler is made only on the basis of the electric energy required. As Figure 5.27 illustrates, the minimum boiler is the one with the more electric energy convenience.

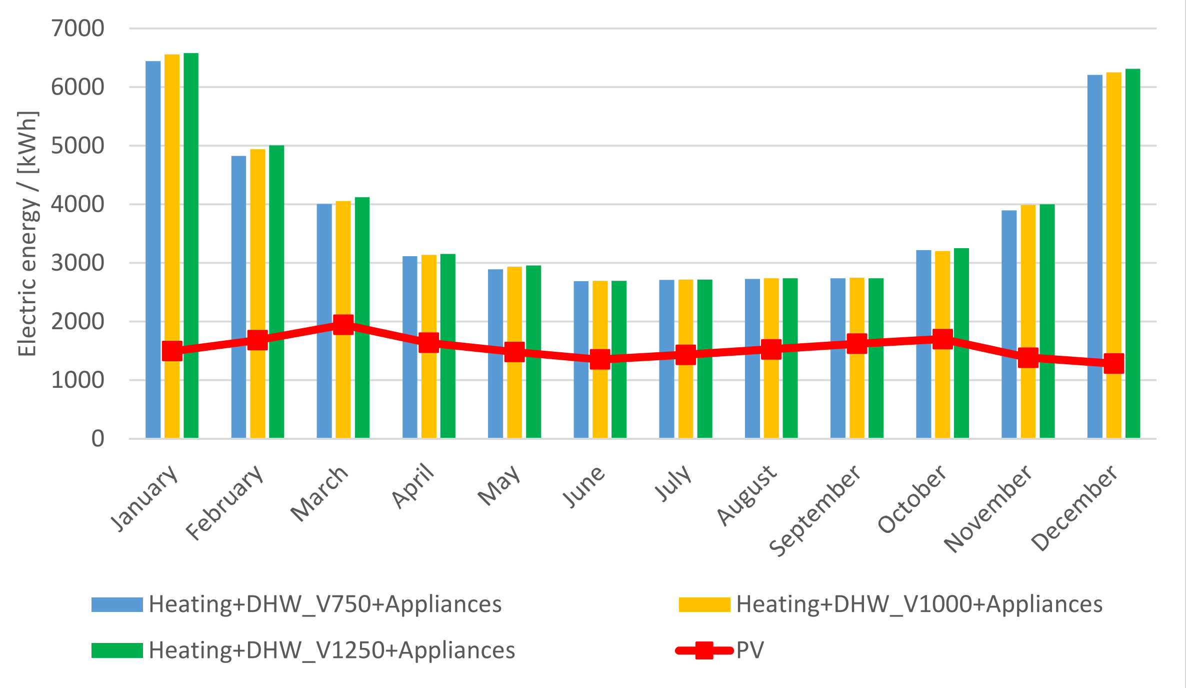

*Figure 5.23: Comparison volume. electric energy required and produced*

For the PV variants, different results are obtained for the heat pump case. Indeed, also the case with normal panels installed on the south, east and west façades show a major production of electricity than the request for several months of the year. Figure 5.28 and 5.29 present the PV energy produced compared to the energy required from the heat pump and therefore the monthly energy required from the grid (evaluated with monthly balance).

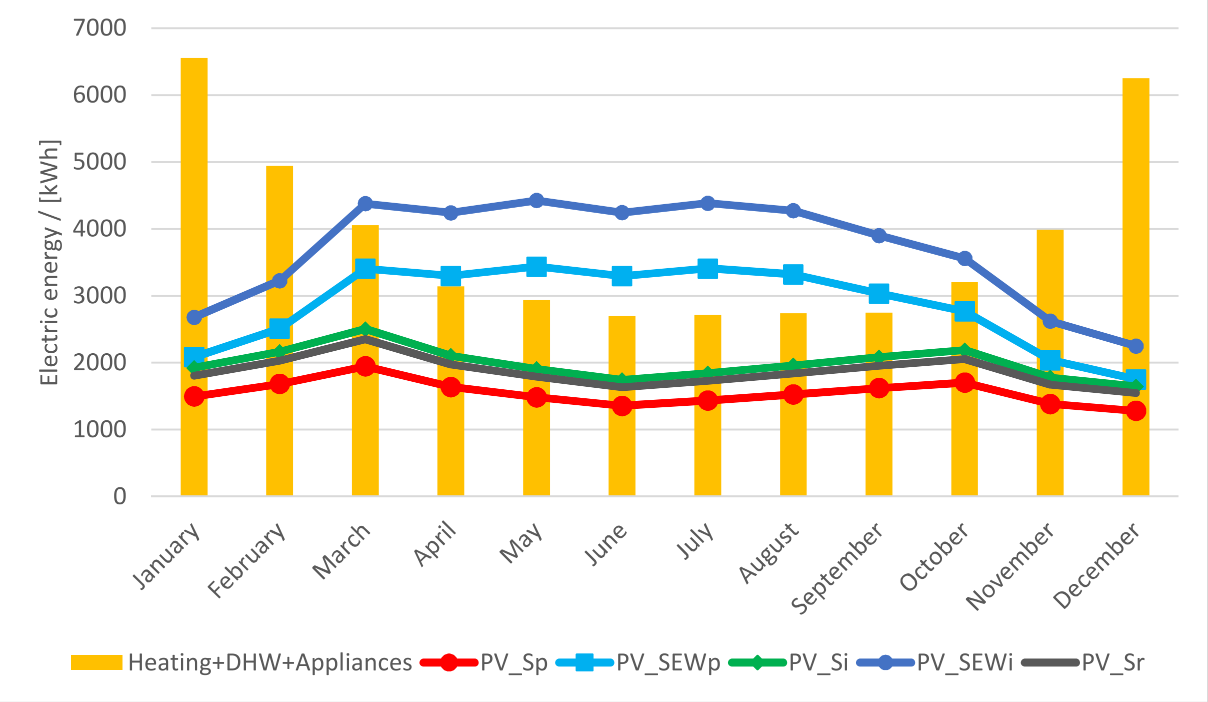

*Figure 5.24: Comparison PV, electric energy required and produced*

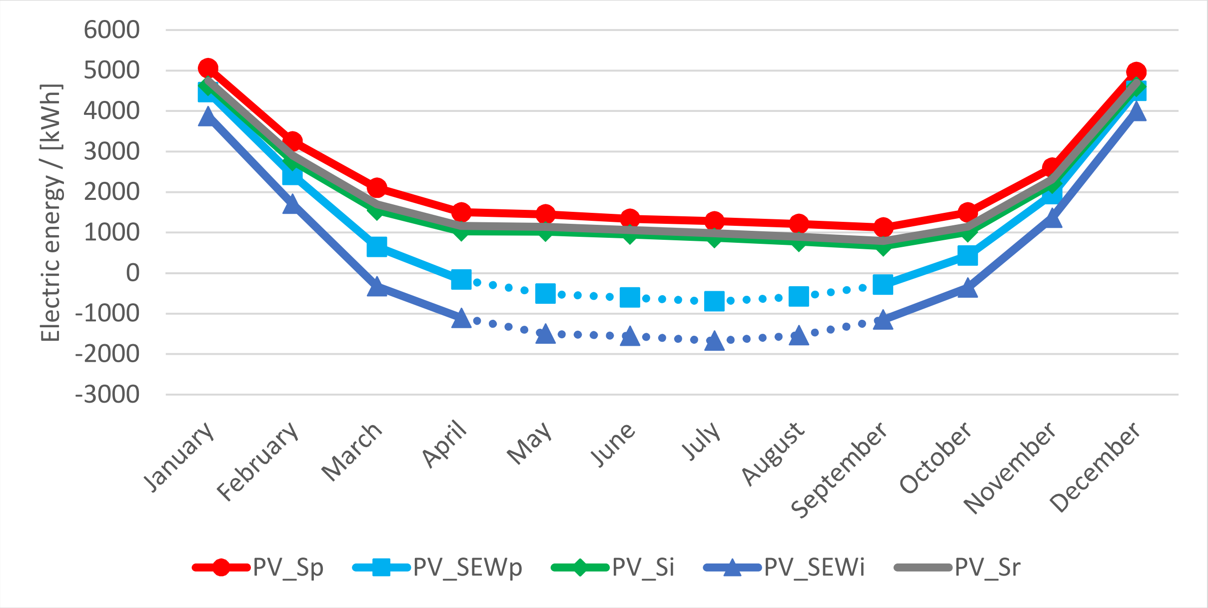

*Figure 5.25: Comparison PV, electric energy required from the grid (evaluated with monthly balance)*

### 5.3.3 Comparison of all cases

Case3 and Case4, as described in section 3.6, are simulated too. In order to have a more global vision of all the cases, monthly comparison of the electric energy is made and shown in Figure 5.30.

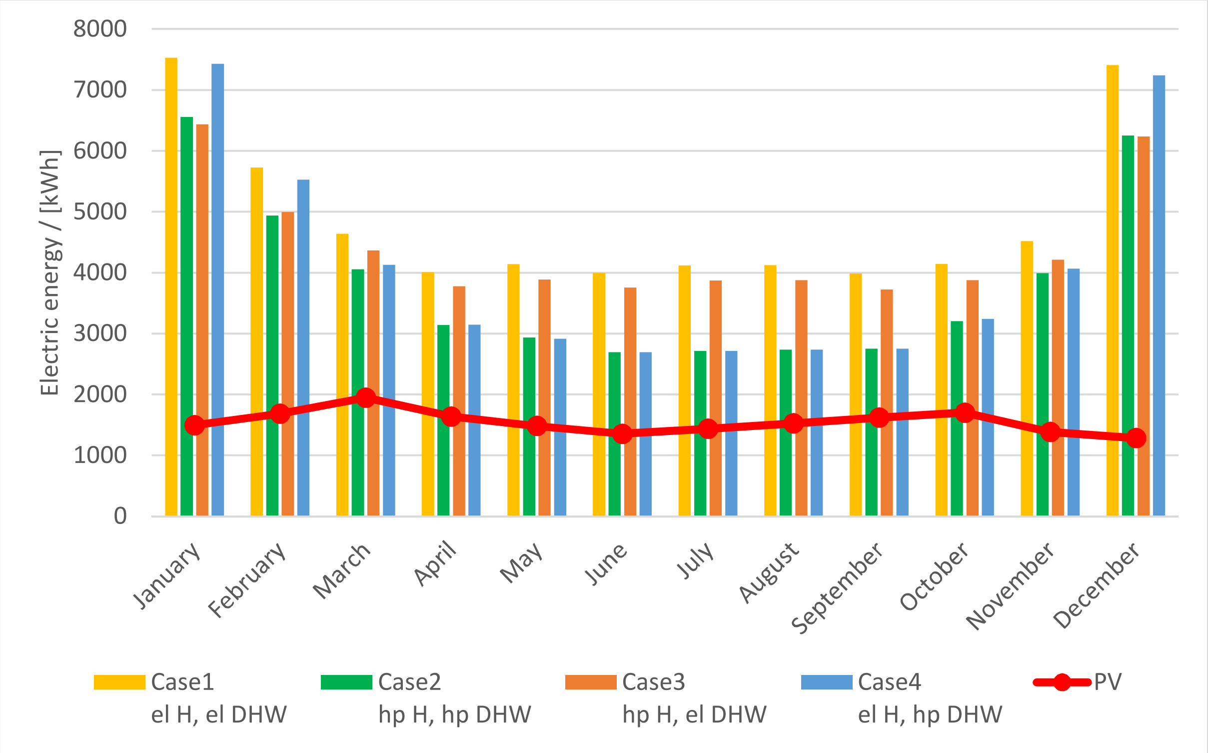

*Figure 5.26: Comparison of cases, electric energy required and provided*

Firstly, it is clear that for none of the cases, the PV system installed is enough to cover the energy required. Moreover, the case with the heat pump is always the one which requires the less energy. Particular results are only in December, where the electric energy for Case2 is the same as the Case3 (so heating from the heat pump and electric DHW), and in January where the trend is the opposite. This behaviour is explained by the distribution losses, since the only difference between the two systems is the DHW production. Moreover, it is justifiable by the trend of performances of the HP depending on the outside temperature. In particular, Figure 5.31-5.34 show the useful monthly energy and thermal losses for each case. It is clear how the losses play an important role in the heat pump trends.

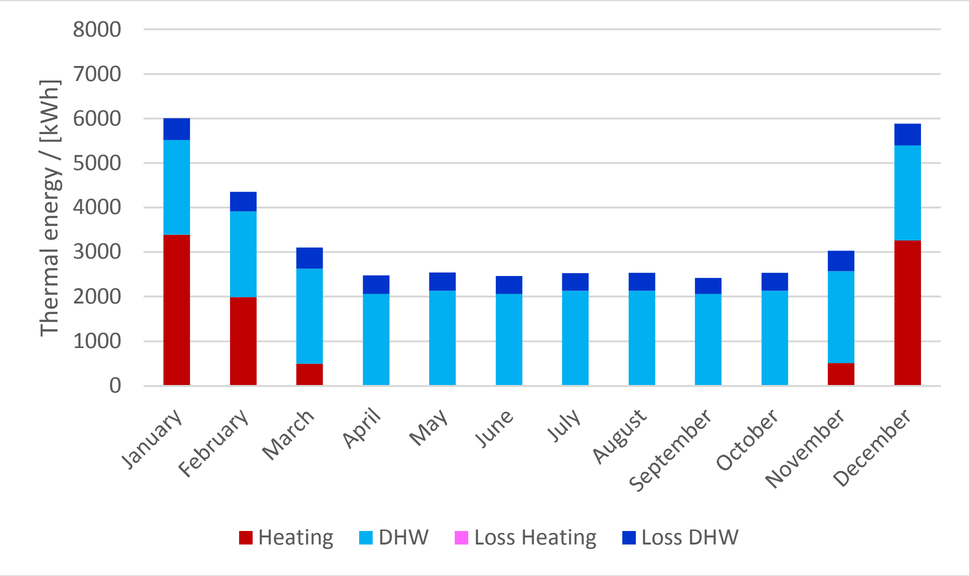

*Figure 5.27: Monthly values of useful energy and thermal losses for Case1 (el H, el DHW)*

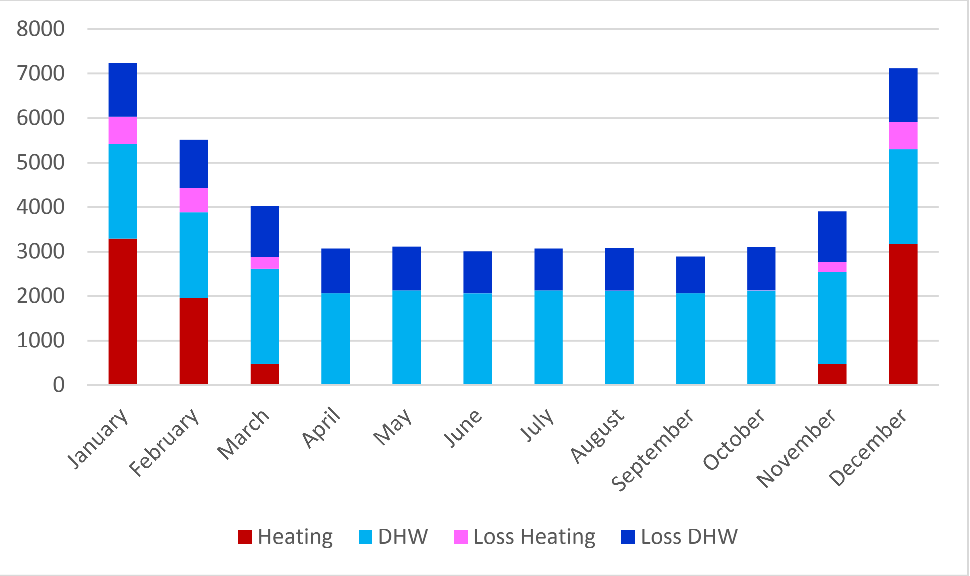

*Figure 5.28: Monthly values of useful energy and thermal losses for Case2 (hp H, hp DHW)*

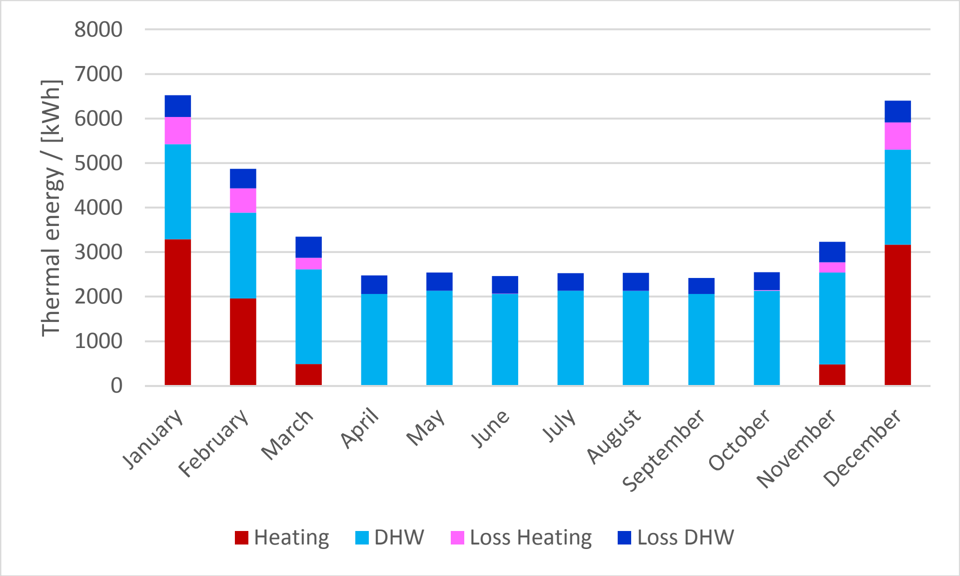

*Figure 5.33: Monthly values of useful energy and thermal losses for Case3 (hp H, el DHW)*

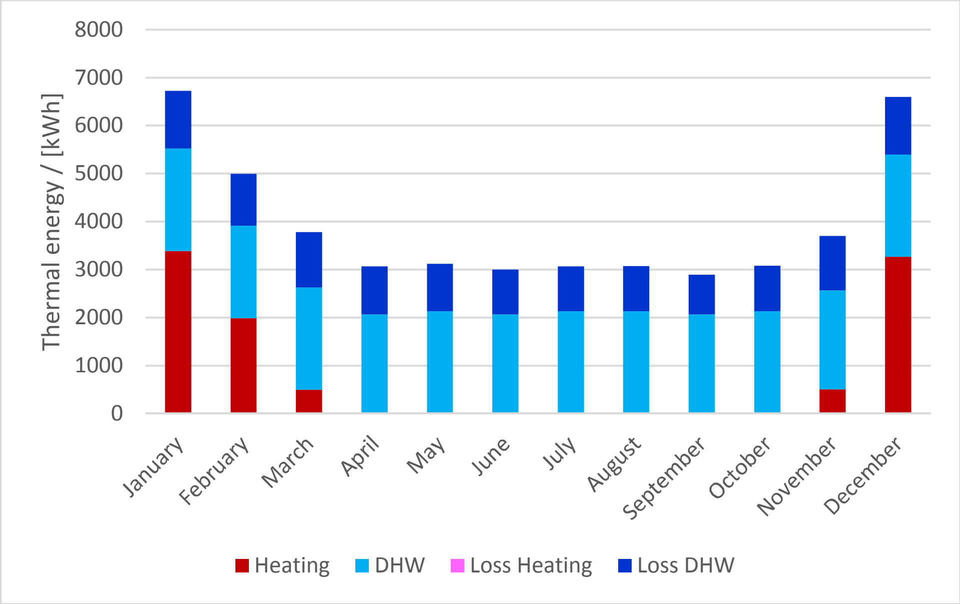

*Figure 5.294: Monthly values of useful energy and thermal losses for Case4 (el H, hp DHW)*

Furthermore, Figure 5.35 recap annual values of electric energy for the four considered cases.

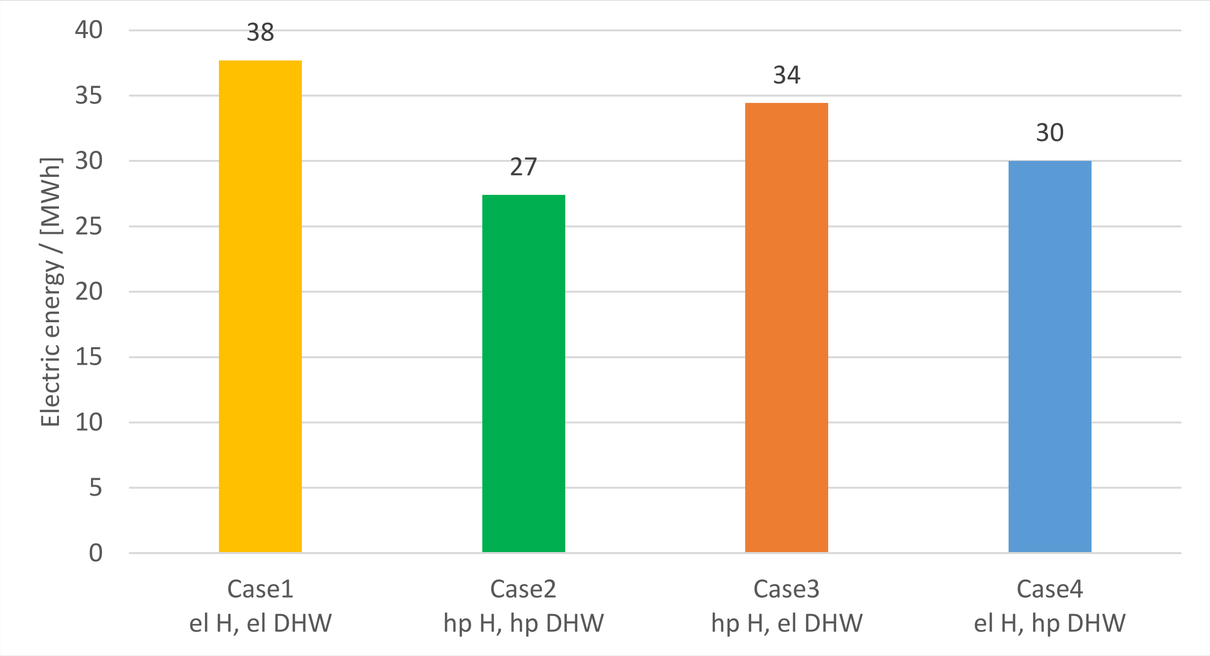

*Figure 5.30: Annual electric energy required from the grid (evaluated with monthly balance)*

Figure 5.35 shows that Case2 is the less energy demanding, therefore the heat pump convenience is verified. On the opposite, Case 1 is the worst so the operational costs for electric heating don’t make this system affordable, even though the absence of thermal losses. Comparing the two mixed case, results shows the energy convenience of a heat pump for DHW preparation rather than space heating.

### 5.3.4 Comparison of different periods balances

Furthermore, a comparison between PHPP and simulation results is carried out. Case1 with first and third PV variant are taken into account. Figure 5.36 shows the electric energy required from the grid in the two cases. With the first PV variant, PHPP and simulation results are quite similar. Some differences are presented in Spring and Autumn. While considering the third variant, the plot shows that PHPP overestimates the electric energy given to the grid. Indeed, the needed energy could be required in period without PV production and therefore it has to be required from the grid. Monthly balances cannot take this behaviour into account and therefore lead to misleading results.

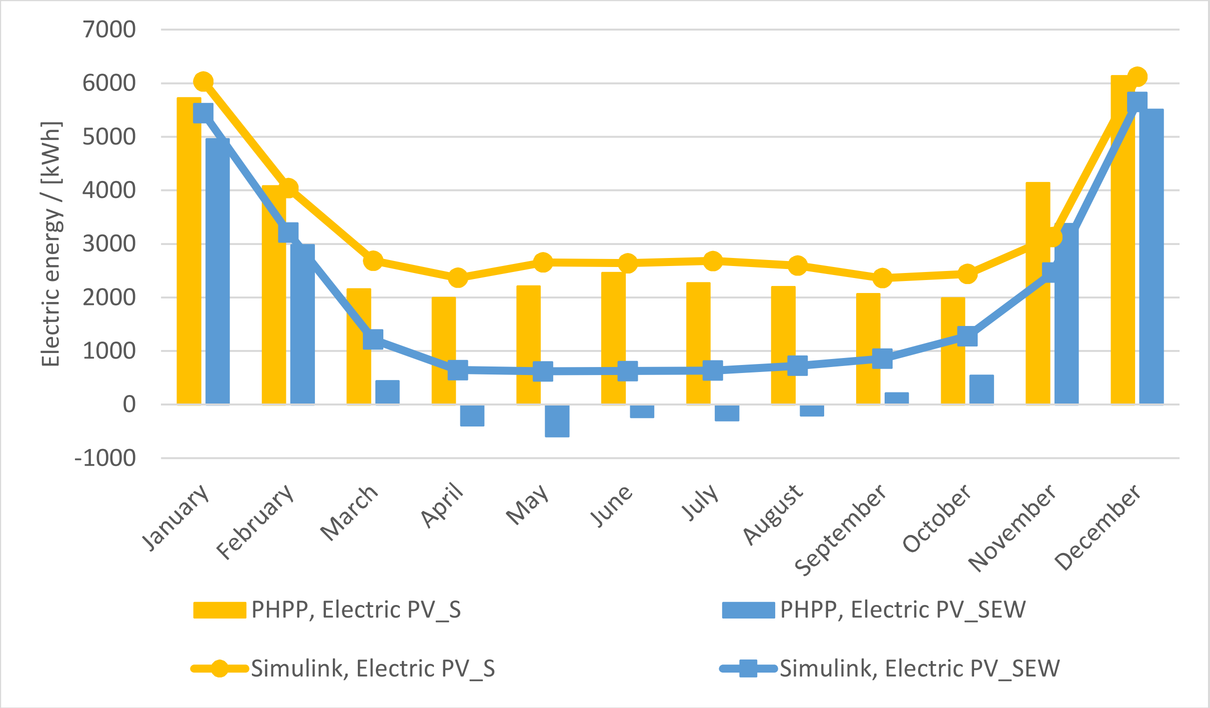

*Figure 5.31: Comparison results from PHPP and simulation: monthly values of electric energy required from the grid (evaluated with monthly balance)*

Finally, a comparison among different time step balances is made. For this purpose, peak power and electric energy required from the grid are considered. Yearly results are different according to different time step balances because of the approach, explained in Equation (5.1).

$$E_{grid,annual} = \sum_{i=1}^{n} E_{building,i} - E_{PV,i} \tag{5.1}$$

Where:

- $E_{grid,annual}$ is the yearly electric energy required from the grid
- $E_{building,i}$ is the electric energy required from the building (for space heating, DHW preparation and appliances)
- $E_{PV,i}$ is the electric energy produced by PV system
- $n$ changes according to the considered time step balance, in particular:
  - $n$ = 52560 with 10 minutes balance
  - $n$ = 8760 with hourly balance
  - $n$ = 365 with daily balance
  - $n$ = 12 with monthly balance

Peak values of needed power, produced power from PV and required power from the grid are evaluated for different time steps. This is due to the fact of considering mainly the contemporaneity of the needed and produced power. Indeed, for example, with daily balances for some days the outcome could be that all the power required is actually produced from the PV system. This can be a misleading result. With a smaller time step, it can be simulated a trend more similar to the real one because balances take actually into account when the power is needed and if in that moment is truly available power from the renewable source. If this is not verified, that power has to be taken from the grid. This is reason why with different time steps, different results are obtained. In particular, a more realistic (and less optimistic) view is offered with smaller time step. Table 5.11 show a comparison among five considered time steps for the all four cases.

*Table 5.11: Results comparison of peak power for different quantities and different time step of simulation*

| | | **Time step** | | | | |
|---|---|---|---|---|---|---|
| | | **10 minutes** | **1 hour** | **1 day** | **1 month** | **1 year** |
| **Case1**<br>**el H, el DHW** | **Required [kW]** | 61 | 35 | 12 | 8 | 4 |
| | **PV [kW ]** | 18 | 18 | 5 | 3 | 2 |
| | **From the grid [kW]** | 61 | 35 | 11 | 6 | 2 |
| **Case2**<br>**hp H, hp DHW** | **Required [kW]** | 31 | 28 | 13 | 9 | 5 |
| | **PV [kW ]** | 18 | 18 | 5 | 3 | 2 |
| | **From the grid [kW]** | 31 | 28 | 12 | 7 | 3 |
| **Case3**<br>**hp H, el DHW** | **Required [kW]** | 63 | 37 | 11 | 8 | 4 |
| | **PV [kW ]** | 18 | 18 | 5 | 3 | 2 |
| | **From the grid [kW]** | 63 | 37 | 10 | 6 | 2 |
| **Case4**<br>**el H, hp DHW** | **Required [kW]** | 29 | 28 | 14 | 10 | 6 |
| | **PV [kW ]** | 18 | 18 | 5 | 3 | 2 |
| | **From the grid [kW]** | 29 | 28 | 14 | 8 | 3 |

Furthermore, the electric energy required from the grid evaluated with different time balances is presented. Figure 5.37 shows how the value of electric energy required from the grid changes if balances with different time steps are considered. For all cases, the trend is the same.

Daily and monthly balances are quite the same (difference is only in range of kWh). This means that with daily storages, the PV production is self-consumed almost all. This means that no bigger storages (like seasonal storages) are needed. On the other side, appreciable differences are shown with hourly or 10 minutes' balances. The smaller the time step is, the higher is the required energy from the grid.

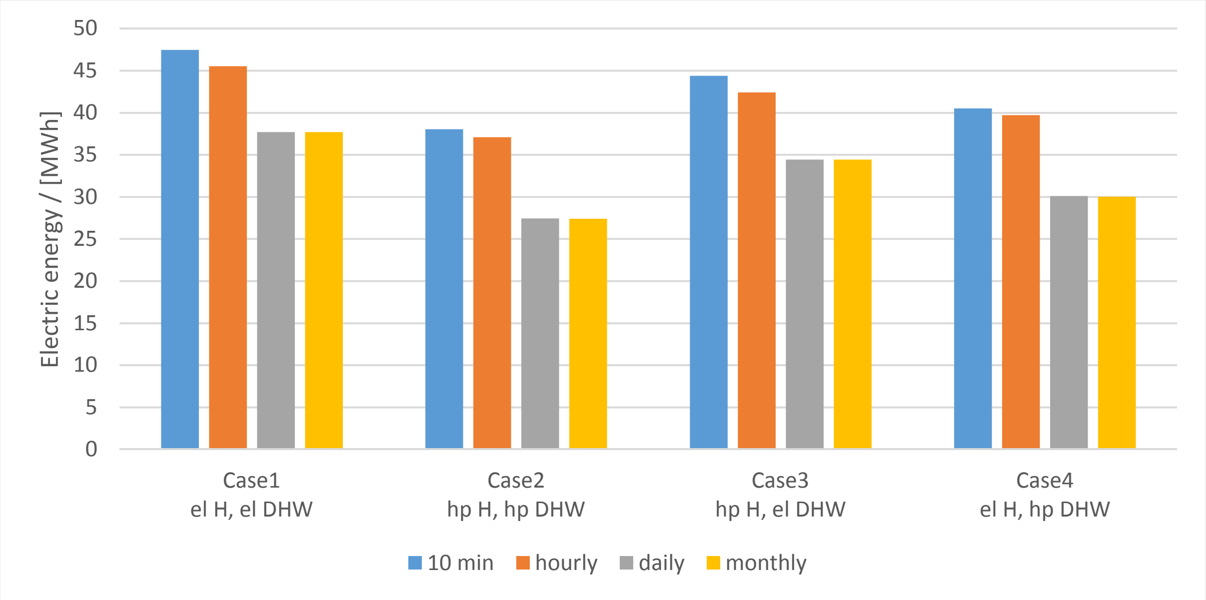

*Figure 5.32: Required energy from the grid according to different time balances*

More precisely, Table 5.12 illustrates values of the electric energy required from the grid according to different time balances.

*Table 5.12: Comparison of electric energy required from the grid according to different time balances*

| | | **Time step of balance** | | | |
|---|---|---|---|---|---|
| | | **10 minutes** | **Hourly** | **Daily** | **Monthly** |
| **Qgrid,annual,i [MWh]** | **Case1** | 47 | 46 | 38 | 38 |
| | **Case2** | 38 | 37 | 27 | 27 |
| | **Case3** | 44 | 42 | 34 | 34 |
| | **Case4** | 41 | 40 | 30 | 30 |
| $\frac{\mathbf{Qgrid, annual, i}}{\mathbf{Qgrid, annual, 10min}}$ | **Case1** | 100% | 96% | 79% | 79% |
| | **Case2** | 100% | 98% | 72% | 72% |
| | **Case3** | 100% | 96% | 78% | 78% |
| | **Case4** | 100% | 98% | 74% | 74% |

Table 5.12 shows that an hourly storage is more convenient with the electric case. An electric battery or a thermal storage may be reasonable solutions as storages. On the opposite, a daily storage would allow to reduce the request from the grid of the 28% in case of heat pump. This value would be only 21% in case of electric system. This means that in the electric case, more energy is required from the building when the PV system is not able to supplies it.

## 5.4 PHPP RESULTS

An additional study uses the PHPP as tool to compare alternative solutions. The PHPP is used to calculate the useful, final and primary energy (Dermentzis et al., 2018).

A parametric study is performed aiming to compare the investigated system (direct electricity for heating and DHW in combination with PV- case A) including improvements (case B and C) to a centralized heat pump system (case D and E). Table 5.13 presents the different variants.

*Table 5.13: Five different investigated systems*

| Case | System description | PV |
|---|---|---|
| **A** | Direct electric system with PV in the South façade | 27.3 kWp – South facade |
| **B** | System of case A plus shower drain-water heat recovery | 27.3 kWp – South facade |
| **C** | System of case A plus PV in the East and West façade | 57.9 kWp – South, East & West facade |
| **D** | Reference centralized air-source heat pump (4-pipe distribution system) | - |
| **E** | Reference centralized groundwater-source heat pump (4-pipe distribution system) | - |

In the cases D and E, a centralized heat pump was used with a 4-pipe distribution system (2 pipes connected to floor heating and 2 pipes for DHW supply assuming fresh water station in each flat). The sink temperature of the heat pump is 35 °C for space heating and 50 °C for DHW supply. In cases A, B and C, the set point in the electric boilers is 50 °C.

Figure 5.38 demonstrates the monthly specific electricity consumption and production for the case A (as constructed), case C (with the largest PV system) and case E (with the lowest electricity demand). In case A, with PV installed only in the south facade, the electricity from PV is not enough to cover the whole electricity demand not even in the summer months. Thus, additionally electricity from the grid is required anyway. In case C, there is overproduction of electricity by PV in summer months, but underproduction in winter months, when the electricity demand increases significantly (compared to summer months). The monthly consumption in case E decreases, compared to case A and C, more significantly in winter months (in which the renewable energy production is low) than in summer months.

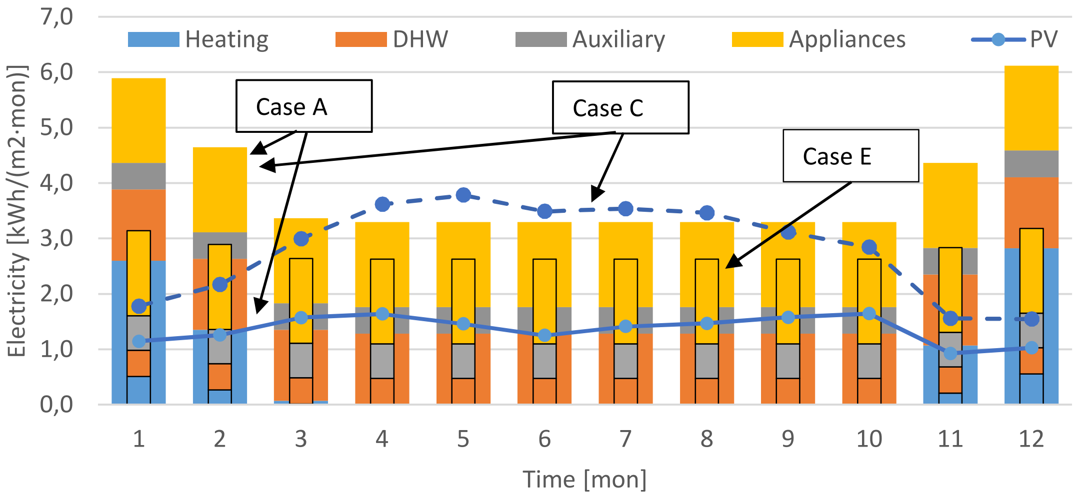

*Figure 5.33: Monthly share of electricity consumption and PV electricity production for the cases A, C and E (Dermentzis et al., 2018)*

Figure 5.39 is similar to Figure 5.38, but it shows the annual specific electricity for all cases. The lowest electricity demand is in case E. Comparing case B and A, the shower drain water heat recovery decreases the electricity consumption by 6%, while the reduction to the electricity for DHW is 18%. In case E, the electricity consumption for heating, DHW and auxiliaries, which is 14.7 $\frac{kWh}{m^2\,a}$, can be balanced annually, if a PV system in the south façade same as in case A or B (with a PV yield of 16.4 $\frac{kWh}{m^2\,a}$) is installed, leading to an NZEB (excluding electricity for appliances).

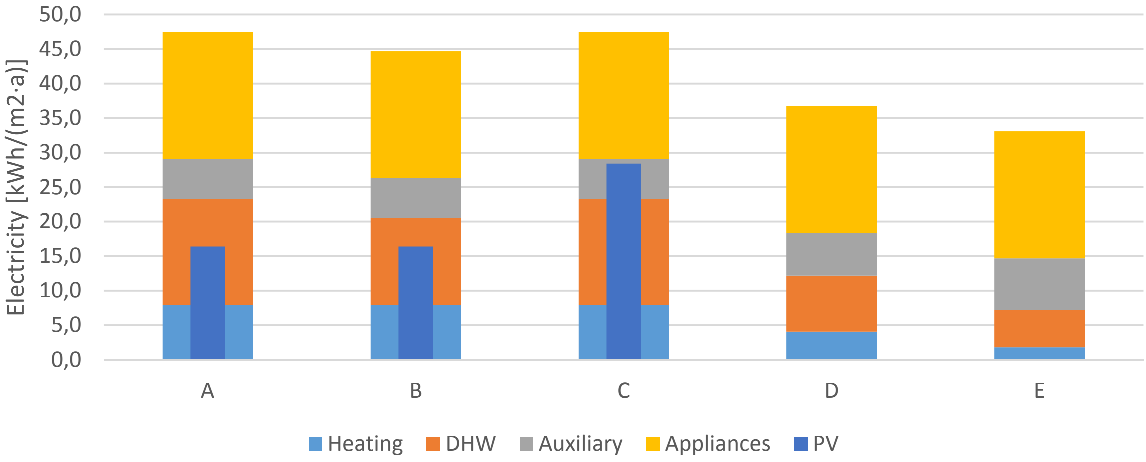

*Figure 5.34: Share of electricity consumption and PV electricity production for the five cases (Dermentzis et al., 2018)*

# 6 CONCLUSIONS AND OUTLOOK

In this master thesis, dynamic building and HVAC simulations were performed with the aim to compare different heating concept for nZEBs. A real project, the so-called An-der-Lan building in Innsbruck was taken as a case study. With this project, a multi-storey building in Passive House standard investigations on a PV powered electric heating and DHW preparation system are conducted by means of monitoring and simulation and its performance is compared to conventional heating systems. The building represents a concept for cost effective housing by combining PH standard, with low-cost heating system by means of using direct electricity in radiators and boilers. The basic idea is to compensate the poor efficiency of electric heating by avoiding distribution losses on the one hand and generating on-site electricity with a large façade integrated PV system in combination with battery storage on the other side.

Firstly, UA and RC building models were compared with respect to simulation speed and accuracy of the heating demand and heating load as well as cooling demand and cooling load. RC simulations require significantly more simulation time, but depict the thermal mass with better accuracy. In average, a RC model simulation requires a computational time six times higher than an UA model. An investigation on the effective thermal capacitance in the UA model is conducted in order to investigate if the UA model can be calibrated to the RC model. However, results proved there is not a unique UA model representing best the RC model. Indeed, based on the considered quantity (i.e. sensitive temperature, heating demand or cooling demand), UA model with a different thermal mass is more similar at the RC model, taken as the reference. For example, a higher percentage of the thermal mass is required in order to match the cooling demand between the two models, while a lower thermal mass is required for the heating demand. Particularly, the type of building has a great influence on the thermal mass representing the RC model best. Hence, generally, it is not possible to select a UA model, which can represent the RC model, but it has to be calibrated for each case.

Secondly, different heating system for space heating and DHW preparation are simulated and compared. Results show the energy convenience of an air/water heat pump serving both system. The disadvantage of the central heat pump is the distribution losses, but the heat pump is characterized by better efficiency. For this reason, the system based on the heat pump requires less electric energy compared to direct electric heating. Particularly, the electric energy required in case of heat pump is 27% less than adopting an electric system. The same PV system is adopted for the electric system and the heat pump system. In both systems, the PV is not enough to cover the energy request. Indeed, only for few days in a year, it would be possible to give energy to the grid instead of take it. Further investigations proof that if PV panels are installed in the east and west facades too, electric energy is not needed from the grid for several months. Systems served by the combination of electric heating and heat pump system are analysed too. The case with heat pump serving the DHW is more energy convenient than the case with space heating supplied by heat pump. This is explained by the higher performance of the heat pump during summer (when only the DHW is required) compared to the electric system. In addition, COP of the heat pump increases when the ambient temperature increases, making this system the more appropriate for DHW preparation.

An important factor to take into account is the time period of balancing required and produced energy in the post-processing process, if on-site energy storage is not included in the simulation. Balances with annual, monthly, daily, hourly and 10 minutes basis are considered and compared in this master thesis. Without storage, balances with smaller time step predict more realistic results. With larger time steps for the energy balances the effect of daily (battery) or long term storage can be (qualitatively) considered. Indeed, they consider that the produced energy can be not used immediately, but in a daily or monthly period. For example, a daily battery could allow to reduce the energy required from the grid of 21 % (in the electric case) or of 28 % (in case of heat pump adoption). Particularly, it is noted that with a daily storage, the energy produced by the PV system is self-consumed almost all. This means that it is not reasonable to adopt bigger storage (like seasonal storages).

Further studies can investigate by means of a sensitivity study the influence of different variations in the proposed and the reference system such as higher set point temperature of DHW storage when the PV system produces more energy than required. Moreover, in case of the heat pump, a floor heating instead of the radiators and ground or ground water as heat source could be considered. The lower sink and higher source temperature results in higher performance of the heat pump and thus, lower consumption in particular in winter, when PV generation is low. Better performance of the air/water heat pump can be achieved with lower set point temperature of the DHW storage. For this purpose, the temperature could be set at 50 °C (instead of 60 °C). and in order to kill the Legionella bacteria, the temperature can be set at 60 °C once per week.

A further important step would be to simulate the building and heating system with different climatic conditions. Finally, an economic analysis should be conducted.

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