TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ALEJANDRO FANEGAS MARTIN

AN APPROACH TO OPTIMAL NEARLY ZERO-ENERGY BUILDINGS UNDER FINNISH AND SPANISH CONDITIONS

Master of Science thesis

Examiner: Hannu Ahlstedt
Examiner and topic approved by the Faculty council of the Faculty of Engineering Sciences
on 4th February 2015

ABSTRACT

ALEJANDRO FANEGAS MARTÍN: An approach to optimal nearly zero-energy buildings under Finnish and Spanish conditions
Tampere University of Technology
Master of Science thesis, 119 pages, 15 appended pages
May 2015
Examiner: Hannu Ahlstedt

Keywords: Nearly zero-energy buildings (nZEB), EPBD recast, Cost-optimal analysis, Energy efficiency measures, Photovoltaic (PV) generation

Europe has stablished the path towards nearly zero-energy buildings (nZEB), soon required in every new construction and large renovation in existing buildings. Regarding to this, the European energy performance of buildings directive (EPBD) proposes to search for cost-optimal building designs.

The current study explores a great number of single-family house configurations, consisting on different energy-saving measures and energy-supply systems. In order to do this, a multi-stage methodology is used to reduce the number of needed simulations, performed by the Dynamic Building Energy Simulation model (DBES). The studied cases consist on single-family houses in Finland and Spain. Starting from reference buildings in these countries, different envelope parameters, heat recovery units, heating/cooling systems and renewable energy sources were considered.

Results reveal cost-optimal solutions with primary energy consumption close to 125 kWh/m^{2}a in Finland and 122 kWh/m^{2}a in Spain. In order to achieve nZEB level, i.e., to reduce that consumption to 50 kWh/m^{2}a, 20 m^2 of PV-panels are needed in Spain to generate electricity. However, this value rises to 50 m^2 in Finland. Global annual costs remain similar, or lower in the case of Spain, to those of the reference buildings.

It has been proved that improving the insulation of the thermal envelope beyond current regulation requirements is not cost-efficient. Low installation-cost heating systems (e.g. air-to-air heat pumps) are the base of cost-optimal solutions, under the financial parameters considered in this study. Although, more efficient systems (e.g. ground source heat pumps) could soon reach the cost-optimal solutions if their costs keep decreasing.

PREFACE

This study was carried out during 2014 and 2015 in the department of Mechanical Engineering and Industrial Systems at Tampere University of Technology, Finland.

I am very grateful to Prof. Timo Kalema for offering me this research subject and for his continuous support and guidance. Next, I would like to thank Prof. Hannu Ahlstedt for accepting and supervising this master's thesis. Finally, I wish to thank Joni Hilpinen and Maxime Viot for developing DBES, the starting point of my work. Their altruistic and tireless help all along my long fight against Matlab was essential for me.

I would like to pay my deepest gratitude to my family. Their support and encourage have carried me until here. Standing me during my studies was neither an easy nor a well-paid job. It was not either for Alba, who I thank for walking this long path beside me and for inspiring me all these years.

Last, but not least, my special gratitude to my friends from Tampere, high school, university and my village, I know they hate me calling them this way. Thank you for fighting with me this battle against and for engineering or just for being my link to the reality outside it.

Tampere, May 2015

Alejandro Fanegas Martín

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

AAHP	*Air-to-air heat pump*
AHU	*Air handling unit*
ASHRAE	*American society of heating, refrigerating and air-conditioning engineers*
BAWT	*Building augmented wind turbine*
BIPV	*Building-integrated photovoltaics*
CHP	*Combined heat and power*
COP	*Coefficient of performance*
DBES	*Dynamic building energy simulation*
DCV	*Demand controlled ventilation*
DH	*District heating*
DHW	*Domestic hot water*
DOE	*US Department of energy*
DX	*Direct expansion*
EPBD	*Energy performance of buildings directive*
GSHP	*Ground source heat pump*
HAWT	*Horizontal axis wind turbine*
HRV	*Heat recovery ventilation*
HVAC	*Heating, ventilation and air-conditioning*
ICS	*Integrated solar collector*
IDEA	*Institute of energy diversification and saving*
IEA	*International energy agency*
IEQ	*Indoor environmental quality*
IWEC	*International weather for energy calculations*
NOCT	*Nominal operating cell temperature*
NREL	*National renewable energy laboratory*
nZEB	*Nearly zero-energy building*
PCM	*Phase-change materials*
POA	*Plane-of-array*
PV	*Photovoltaic*
SAM	*System advisor model*
SDK	*Software development kit*
SHGF	*Solar heat gain factor*
SSC	*SAM simulation core*
STC	*Standard test conditions*
TBC	*Technical building code*
TUT	*Tampere university of technology*
VAT	*Value-added tax*
VAV	*Variable air volume*
VAWT	*Vertical axis wind turbine*
VRV	*Variable refrigerant volume*

Floor-m^2 or m^2	*Floor area of the building*
g	*Energy generation (kWh)*
G	*Weighted energy generation (kWh)*
G_b	*Direct beam irradiance (kWh/m2)*
$G_{d,ground}$	*Diffuse irradiance reflected from the ground (kWh/m2)*
$G_{d,sky}$	*Diffuse irradiance from the sky (kWh/m2)*
G_H	*Global radiation on the horizontal plane of the Earth's surface (kWh/m2)*
G_{ref}	*Reference direct irradiance (kWh/m2)*
l	*Buildings energy load (kWh)*
L	*Buildings weighted energy load (kWh)*
P_{ac}	*Final alternating current power from a photovoltaic array (kW)*
P_{dc}	*Direct current power from a photovoltaic array (kW)*
P_{dc0}	*Photovoltaic array nameplate DC rating (kW)*
P'_{dc0}	*DC power from a photovoltaic array after taking into account the system losses (kW)*
w_d	*Weighting factor for delivered energy*
w_e	*Weighting factor for exported energy*
ε_{sys}	*Photovoltaic system efficiency*
γ	*Photovoltaic module temperature coefficient*

1. INTRODUCTION

The building sector is the main final energy consumer in Europe, reaching a 40 % share last years [1]. Furthermore, buildings are responsible for 36 % of greenhouse gas emissions on the planet. Specifically, residential buildings account for the biggest consumption, as it can be noted in Spain and Finland with 18 % and 22 %, respectively, of the total final energy consumption [2]. Not only energy consumption and emission shares are especially important. A wide range of possible energy saving points building sector as the main target of many energy regulations.

Within this framework, the European Commission introduced legislation to reduce energy consumption in buildings. This legislation is included inside “The 2020 climate and energy package”, which sets several goals. Known as the “20-20-20” targets, these goals aim at reducing greenhouse gas emissions, raising renewable energy production and improving energy efficiency. For example, as part of this legislation, the Energy Performance of Buildings Directive (EPBD) [3] settles that from 2020 every new building must be a nearly zero-energy building (nZEB). As well, the directive proposes the application of a cost-optimally methodology for setting requirements over the envelope and technical systems of these new buildings. These requirements are expected to be different for each European country.

A nearly zero-energy building could be defined, in a simplified manner, as a very low-energy demand building where renewable sources supply most of the energy consumed. However, several details must be stablished to provide an exact definition. This definition for nZEBs will vary among the different European members and most of them have not presented it yet. There is also an open discussion about the best approach to this characterization, regarding to how to specify energy boundaries and to which metric must be used. [4]

This study aims to analyze nearly zero-energy buildings, searching for an optimal path to fulfill their definition, regarding to the thermal envelope and technical systems properties. In addition, the study will apply a multi-stage methodology to find the cost-optimal approach for these buildings. The studied buildings will be single-family houses located under Finnish and Spanish conditions.

In order to do this, some theoretical background will be provided, introducing the concept of nearly zero-energy building and its current situation. An analysis of the different nZEB definitions will be carried, introducing the discussion around them. Below, it will be reported the actual implementation of the EPBD, as well as the specific status of nZEBs in the studied countries. Moreover, different examples of this kind of building, which are currently being tested in Europe, will be analyzed.

The chosen case of study will be defined next, along with the considered design variables, related to envelope parameters, heating/cooling systems and energy-supply options. Finally, the multistage approach to cost-optimal calculations will be introduced. This includes the explanation of the simulation program applied and its adjustment for this study, so finally, the results and conclusions can be discussed.

2. THEORETICAL BACKGROUND

2.1. Energy in buildings and EPBD directive

The concept of net zero-energy building appears as reaction to the large increase in world energy consumption. This rise in the consumption is caused by several processes, such as the economic and technological development, an improvement in quality life, the growth in developing countries and, chiefly, an increase in the world population. Projections are not favorable for next decades, as it is reported in [5], therefore it is necessary to adopt certain measures. Otherwise, actual problems resulting from this situation will aggravate, including global warming, climate change and the exhaustion of energy resources.

Energy consumption in buildings is studied in [6], concluding that this sector represents 40 % of total energy use in EU and USA. As a consequence, it is an error to underestimate its importance over other sectors such as transport and industry. This considerable energy consumption in buildings will continue raising if more constructions are made, unless buildings start to supply as much energy as they require. Moreover, as explained in [7], the possible cost-effective energy savings reach the 20 % in the building sector.

Most of the energy consumption in a building is due to defend itself from the outside, as it must maintain its hydrothermal and lighting comfort. Lowering this consumption starts by reducing the demand applying improved building envelopes and passive strategies, combined with high-efficiency mechanical systems. Moreover, it is noteworthy that one third of the building consumption is related to lighting. Its saving potential reaches the 50 %, according to [7], by installing energy-saving electric bulbs.

These reasons are enough to consider a new approach to the use of energy in buildings. First step would be creating low-energy buildings based on the ideas of energy saving and energy efficiency. Secondly, focusing in reducing the impact of buildings on the environment, renewable technologies would come into the concept, mitigating CO_2 emissions. In this context, through the EPBD, European Union has stablished a future requirement that new buildings will have to be nearly zero-energy buildings. The US has also established a similar requirement through the Building Technologies Program of the US Department of Energy (DOE) [8]. As explained before, a nearly zero-energy building is a high energy performance building which low-energy balance is covered mostly by renewable sources. Its exact definition is more complicated and there is a big discussion around it, as it will be explained later.

The first Energy Performance of Buildings Directive introduced, in 2002, the compulsory use of renewable energy sources in buildings [9]. In addition, it implemented the energy performance certificate beside its efficiency improve recommendations. The EPBD recast (Directive 2010/31/EU) came into force on the 9th of July 2010 introducing, as has been shown before, the concept of zero-energy buildings. Alonside the nZEBs, the EPBD proposes, among others [3]:

- The use of common methodologies for the calculation of buildings energy consumption.
- The adoption of new performance requirements on buildings.
- A new regulation about inspections of heating and air conditioner systems.
- New guidelines about energy performance certificates.

The EPBD do not settle minimum performance requirements that buildings must comply to be considered as nZEBs. Instead, Member States are responsible for setting those requisites, following a common methodology. These requisites must chase the cost-optimal between investment in the building and energy savings. In addition to this, the different European countries must implement their own national plans for increasing the number of nZEBs. In order that by the 31st of December 2020 all new buildings must be nearly zero-energy buildings. As the public sector should lead the way with more ambitious targets, all new public buildings should be nZEBs by the 31st of December 2018.

Concluding, energy consumption in buildings means a considerable big share in global consumption. EPBD represents the biggest effort of European Union to decrease this consumption, both with economic and environmental benefits. In order to do this, nearly zero-energy buildings are introduced as a possible solution, which applies energy saving measures and renewable energy supply options.

2.2. Nearly net zero-energy buildings

As introduced before, a nZEB building could be defined as high-efficient building which is almost energetically neutral over the year. This means that it requires as much energy from the grid or from non-renewable fuels as it supplies to the grid through renewable energy sources. The concept seems to be definite enough, however, for applying it over a real construction more details must be established.

Lowering emissions, applying any regulation about on-site energy generation or accomplishing a national energy meter requirement are some of possible concerns of the designer or owner of a building. These concerns determine the preferred definition. Therefore, they influence in which way the designer combines different efficiency measures and renewable supply options to achieve the specific nZEB goals.

A construction could be considered as a net zero-energy building under one definition but not under another, if the requirements or the approaching method are changed. As a result, they are needed some common basis among the definitions in the different countries. Although, the details will, of course, depend on the exact weather and energy situation.

As the EPBD requires, some countries have already started to publish regulations preparing the implementation of nZEBs. As a consequence, it is already necessary to stablish the common basis commented above, that is the goal of the project Task 40: “Towards Net Zero Energy Buildings”. This collaborative project, supervised by the International Energy Agency (IEA), is investigating several methodologies for approaching nZEB calculations. It is aiming to provide a common framework the European policy makers. In addition, many researchers in the field are contributing to this framework [10] [11], approaching a realistic definition. This practical definition would avoid the existence of inefficient nZEBs, which, for example, used oversized PV systems without applying any energy saving measures.

In order to propose an appropriate framework, the main elements of the path towards zero-energy buildings must be entirely analyzed. This path includes energy efficiency measures and renewable energy sources, in addition to some other criteria that will define the calculation methodology.

2.2.1 Nearly net zero-energy building definition

According to the EPBD, the definition of a nearly zero-energy building is:

“Nearly zero-energy building means a building that has a very high energy performance […]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [3]

This definition introduces the importance of the energy efficiency measures and the necessity of balancing a very low-energy demand with energy from renewable sources. Nonetheless, this description is not exact enough for applying it in a realistic way.

A certain load and some generated energy usually characterize a net zero-energy building. Part of this generation is consumed directly inside the building, hence, in case of excess of energy production, the net difference with the load is exported to the grid. Conversely, if the generation is not enough to cover the building load, then that net difference will be taken from the grid, named as “delivered energy” in Figure 2.1. The energy carriers exchanged with the grid are generally electricity, heat or fuels. Figure 2.1 summarizes the interaction between the building and the grid, introducing some new concepts as the weighting system that will be explained later.

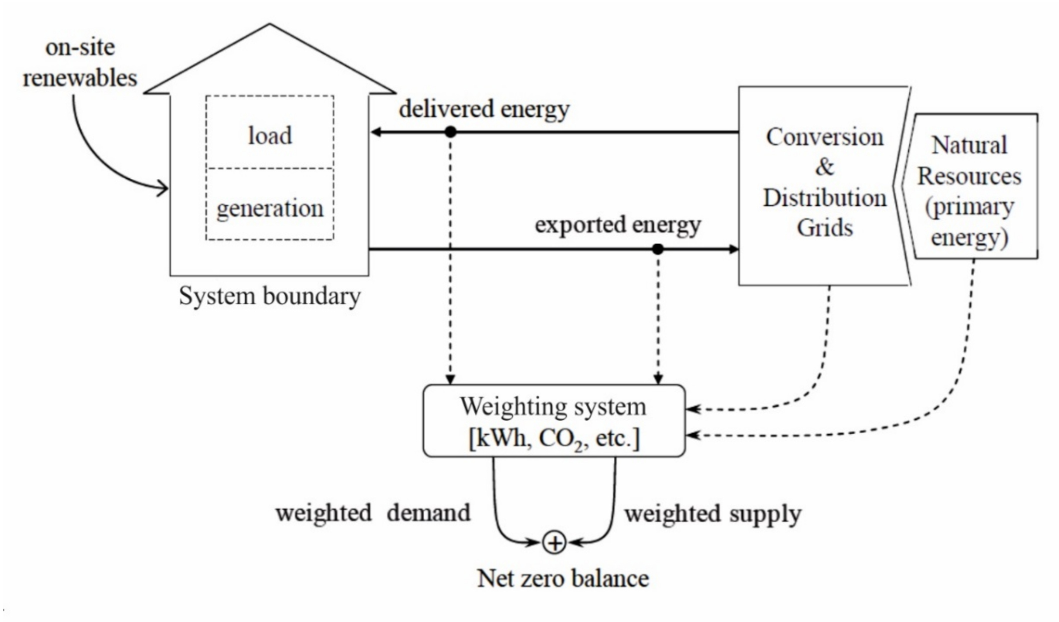

Figure 2.1. *Sketch of the interaction between the building and the grids. (Adapted from* ***[11]****)*

Meeting the load when the on-site renewable sources are not enough justifies the **connection to the grid** of net zero-energy buildings. In addition, this leaves open the possibility of supplying to the grid the excess energy, offsetting future imports. Grids are based on different carriers such as electricity, district heating and/or cooling, natural gas, biomass or other fuels. The electrical grid operates in both directions, importing and supplying energy. This could also be the case of the district heating network. It is assumed that the grid always accepts the excess energy of the building, at least for the electrical grid, although this depends in the specific regulation in each country.

Autonomous buildings, not connected to the grid, rely on oversizing their energy sources and have a big dependency on storage systems not mature yet. This kind of buildings can also achieve the nZEB concept but probably not in a cost-optimal way. Therefore, in this study the grid connection will be assumed, talking about net zero-energy buildings from now on [10]. This “net” term refers both to the connection to the grid and to the net balance of exchanged energy with it.

In the strict sense of the term, a net zero-energy building generates from renewable sources as much energy, or more, as it consumes. This could not be strictly necessary, consequently, it is frequently used the term “nearly”, referring to a possible slightly negative balance. The performance level required for the nearly zero-energy building is a national decision that will depend on cost-optimal studies and other factors. These factors include percentage of renewable coverage requirements and the ambition of the nZEB definition itself. Finally, the acronym used in this study for the nearly zero-energy buildings is “nZEB”, as the net concept is assumed. However, some authors adopt the acronym “nnZEB”, meaning nearly net zero-energy building. [12]

Saving energy is easier and cheaper than producing it from renewable sources. As a result, the majority of researchers agree that the **energy efficiency** is the priority on the path towards nZEB. Among the possible efficiency measures are the use of new highly efficient HVAC systems, high-level insulation, natural ventilation, passive solar heating, evaporative cooling, daylighting and high airtightness. Several of these measures are not widely developed or spread in the field yet, so they will not be taken into account in this study.

Different countries and organizations propose several minimum efficiency requirements. The EPBD introduces the use of cost-optimal studies for calculating a required performance level. The European commission also considers to set a specific efficiency label (A+, A, B…) for the building. Alternatively, other countries propose the fulfillment of commercial standards such as Passive House, Energy Star and Minergie. Which of these requirements is the best choice depends on the climate, among other factors, as it is discussed in [13].

How to introduce these last requirements into the technical building code of each country is also discussed. The first option would be setting minimum values for the HVAC systems performance, specific fan power, airtightness or U-values. The second option is to settle a minimum total performance of the building. This performance is quantified as an energy need or weighted energy demand per square meter. Finally, a combination of both points of view is also possible. [14]

The next important pillar of nZEBs is **renewable energy sources,** since they must offset the energy balance in the building. Among the suitable renewable technologies for a building, the most common are the photovoltaic and solar water heating systems. These technologies make a big difference in terms of emissions compared with the conventional sources such as coal and natural gas. Other possibilities include wind and hydroelectric systems or the use of biofuels.

Stablishing a hierarchy among the supply options is a widely discussed topic [14] [15]. Some of the factors affecting this decision are the emissions, efficiency and availability of the sources. In addition to minimize the environmental impact, it is important to consider the cost and lifetime of the system as well as its current development and growth.

P. Torcellini et al. [10] propose a specific hierarchy classifying the different energy sources depending on their location, as shown in Table 2.1. The EPBD definition talks about energy production on-site or nearby. Although the term “nearby” should be specified, most of the authors agree on prioritizing on-site generation. Producing energy on-site, and specially on the footprint of the building, seems to be more faithful to the nZEB concept as the energy balance is offset in the building itself. As introduced before, solar hot water, photovoltaic, hydro and wind systems are some of the most common examples for on-site production. There are other options, such as combine heat and power systems (CHP) using gas as a fuel. This system would not be classified as renewable. However, its high efficiency makes it suitable for locations where the grid does not have an important renewable share. Consequently, it could be necessary to settle a minimum renewable share on the building supply. It is worth to mention that solar thermal energy is consumed completely inside the building, so usually this energy is not exported to the network. This is why some researchers consider this system as an energy saving or demand reduction method [16].

Table 2.1. *ZEB renewable energy-supply options hierarchy.* ***[10]***

Option number	ZEB supply-side option	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation and cooling, evaporative cooling, etc.
	On-site supply options	
1	Use renewable energy sources available within the building's footprint	PV, solar hot water and wind located on the building.
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro and wind located on-site, but not on the building.
	Off-site supply options	
3	Use renewable energy sources available off site to generate energy on site	Biomass, wood pellets, ethanol or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits or other "green" purchasing options. Hydroelectric is sometimes considered.

This approach is opposite to the sometimes called "off-site ZEB". This last kind of ZEB relies on the combination of two strategies. The first is the use of sources outside the building boundary, e.g. by directly purchasing green energy. The second consists on generating energy on-site but from energy sources imported from the outside, such as biomass, biofuels or waste. Figure 2.2 shows a simpler view of the on-site and off-site source classification.

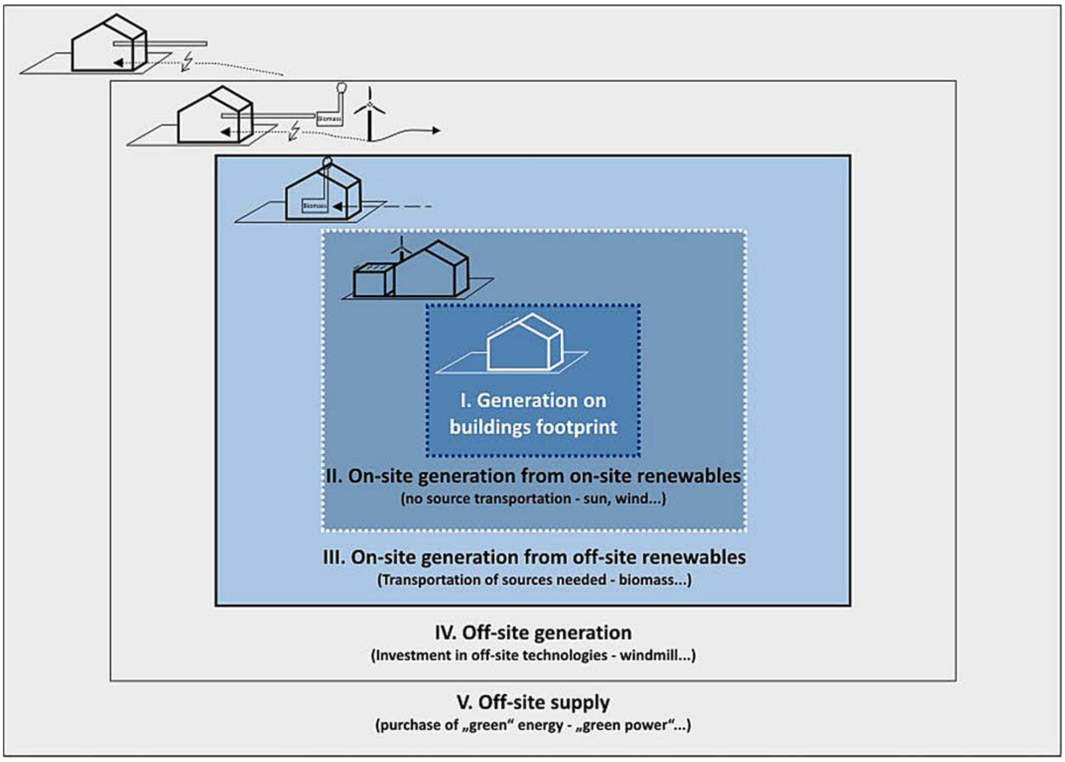

Figure 2.2. *Source classification according to the location.* ***[17]***

Buying green energy from the outside does not encourage to design a building focused on the energy saving and efficiency. Therefore, it could be considered that these off-site ZEBs are not completely fulfilling net zero-energy buildings goals. However, some countries, such as the United Kingdom, contemplate the investment on off-site zero emissions projects by the building budget. Even some methodologies mention the possibility of buying carbon credits in the carbon market [4]. This leads to a new discussion about how to introduce that kind of source in the energy balances, as shown in [14].

In this subchapter, the main base of the nZEB definition has been presented. However, for completing this definition some specific criteria must be set. Those criteria, such as the balance, the metric, the weighting factors and the boundaries, define the methodology for studying the nZEB concept, as will be shown below.

2.2.2 Study methodology of nZEBs

The main core on nZEB studies is, based on its importance in their definition, the energy balance previously introduced. However, it is necessary to present a framework that includes the definition of building boundaries and metrics that will be used in that balance. Afterwards, it will be possible to deeply analyze the net balance and different ways of approaching it.

The first criterion introduced is the **boundary** of the balance. Basically, this boundary represents which energy uses are considered inside the balance and which are excluded.

The conditions of this boundary include several items. Firstly, it is necessary to specify the number of buildings included in the study. Although studies usually contemplate just one building, studying several buildings as a whole is also possible. Hence, occasionally, a cluster of buildings could fulfill the nZEB requirements while the individual buildings do not do it by their own. Finally, the study must define each one of the grids interacting in the balance. These grids could be two-way grids, such as electricity and sometimes district heat.

Finally, in order to completely define the boundary of the study, some functional characteristics must be specified. These include the type of building and the number of occupants. There is a big difference, for example, between the approach of a residential building and other types such as offices, schools or hospitals. The climate will also be relevant, as well as the comfort conditions decided by the designer or users.

As explained in [14], the boundary is the result of combining the physical boundary and the balance boundary. The first specifies which renewable sources are considered as on-site and off-site, while the second decides which energy uses are included. These uses could be heating, cooling, ventilation, lighting, domestic hot water, appliances… According to the EPBD, it is not mandatory to consider appliances in the balance, which include the electricity for households and outlets [12]. However, most of the studies include them. According to this boundary combination concept, energy flows crossing both boundaries will be incorporated into the balance. Figure 2.3 shows an example of a nZEB boundary. It shows the different elements inside the boundary, such as the net energy need and the delivered/exported energy compounded of different energy flows. The figure also introduces two different approaches to the balance that will be explained later, represented by two dashed rectangles.

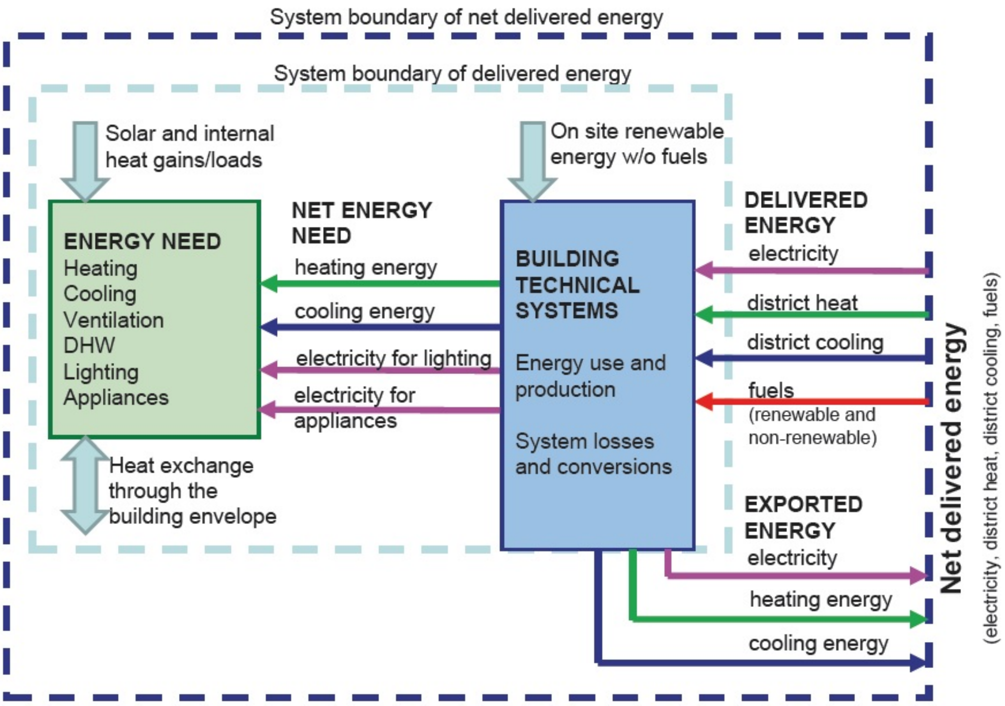

Figure 2.3. *Example of an energy boundary for a nearly zero-energy building.* ***[12]***

A well-defined boundary allows to compare the performance of several buildings under similar climate and functional conditions. Moreover, it is critical for designing the measurement system monitoring the building. For example, if the boundary does not include the appliances, it will be necessary to measure their specific consumption. Therefore, it can, finally, be removed from the final electricity consumption. In addition, specifying the boundary conditions is crucial to study the deviation of the measured performance. These deviations from the expected results could be due to different use conditions or other reasons.

Another important criterion is the **meter** used in the balance. Although there are others, the balance is usually studied under one of the following meters: primary energy, final energy, cost or CO_2 emissions. Which meter is selected will determine the kind of balance used. Each kind has its own advantages and disadvantages, as it will be explained later. As shown in Figure 2.1, nZEB studies use a **weighting system**, also called the credit system. This system transforms the different physical units to a selected uniform meter, showing a more realistic evaluation in the net balance. This provides a weighted supply and a weighted demand that are finally incorporated into the net balance. Thanks to the weighting system, the different energy sources can be taken into account, as well as their particular properties. These properties include source availability and conversion or distribution processes.

Establishing the value of the weighting factors is not an easy task, it depends on many aspects. Some of these aspects are not objective, so there is not something as a completely correctly evaluated factor. The mix of energy sources on a region and its variation on time influence the weighting factors. The political preferences are also critical. For example, the promotion of a certain new technology or the penalization of another, such as limiting the use of biomass as the land must be also used for food production. Weighting factors are usually estimated as the average on time of a specific region, so the value of the factor is fixed on time. It is also possible to use dynamic weighting factors. Lots of data are needed to establish reliable dynamic factors and the calculations become more complicated, while the benefits are not so big. Hence, dynamic weighting factors are rarely used, except for some authors applying them on cost balances.

Usually, weighting factors are symmetric, which indicates that the same factor is applied to exported and imported energy. This can be understood as follows: the amount of energy produced on-site will not have to be produced in other place. Nevertheless, this approach does not consider that, occasionally, the exported and imported energy do not have the same value. Asymmetric weighting factors consider different costs and losses during transport and storage related to an energy source. They can also take into account the promoting feed-in tariff for young technologies. This is the case of PV systems in Spain over the past years. On the other hand, these factors could contemplate the considerable embodied energy in the PV-panel, so the value of its exported energy would be lower. Therefore, the asymmetry makes that the same energy carrier, for example electricity, could have a different weighting factor depending on its source, as discussed in [14]. Other scenario is the use of asymmetry factors to promote on-site generation. For example, in Germany (2012) one kWh of delivered electricity was equivalent to 2,4 kWh of primary energy while the relation was 1 to 2,8 for exported electricity [16].

The choice of weighting factors will determine which the optimal technology for a nZEB is. For example, lowering electricity factors will promote the use of heat pumps in a highly renewable grid, as in the case of Denmark and Norway [16]. They will also influence on the amount of photovoltaic panels a building needs to be a nZEB.

Once the basic framework around the **net ZEB balance** is presented, more details about its different types and methodologies can be introduced. As Figure 2.1 shows, a building is characterized by its load and generation. Depending on the self-consumption of energy in the building, this load and generation determine the delivered and exported energy, setting the interaction with the grid. Consequently, two kind of balance can be defined: *load/generation* balance and *exported/supplied* balance. In these balances, all values are weighted according to the selected credit system. The second type of balance is more used when a building is being monitored while the first one is typically used during the design phase, as it does not need self-consumption calculations. The self-consumption of energy in a building depends on uncertain factors such as the exact climate and user's behavior. As a result, its calculations can be really complicated. Since the equations used for both balances are quite similar, this study will focus on the *load/generation* balance. Most of Building Technical Codes use this balance, shown in Equation (1), where both values are weighted by the correspondent weighting factor:

$$\sum_{i} g_i \cdot w_e - \sum_{i} l_i \cdot w_d = G - L \geq 0 \qquad (1)$$

In the equation, i stands for each energy carrier considered, g and l are the generation and load correspondingly. Terms w_e and w_d refer to the weighting factors of exported and delivered energy, respectively. Obviously, in case of using symmetric weighting factors, both values would be the same. Finally, G and L stand for weighted generation and load. The *load/generation* balance, since no self-consumption is calculated, could be understood as if the building imports all its load from the grid and exports all its generation. This does not pose a problem regarding the calculations to be made. [14]

Net balance in Equation (1) refers to a net zero-energy building, i.e., the balance must be zero or above zero. This means that the building does not consume energy on a net basis during the chosen period. From this point of view, Figure 2.4 visually represents the net ZEB concept and also shows the nearly net ZEB, where the balance is slightly negative.

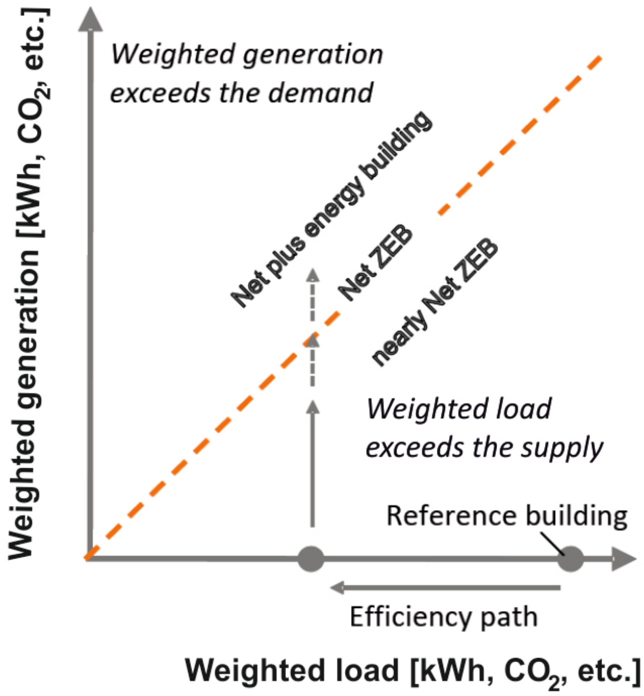

Figure 2.4. *Graphic representing the net zero balance and the path towards nZEB. (Adapted from **[16]**)*

As it can be interpreted from Figure 2.4, the reference building is the starting point in the design of a nZEB. The reference building fulfills current minimum requirements in the specific National Building Code. Over it, the designer applies efficiency measures that lower the demand, moving the studied case along the x-axis. These efficiency measures, as previously mentioned, are the most important part of the path towards nZEBs, since their generation capacity is usually limited. Last step would be generating enough energy, or weighted credits, so the balance value is zero or nearly zero.

The time period during which the balance is applied is another important fact. The most common, and convenient, is calculating on an annual basis because one year covers all operational and weather conditions. A second option is to use the whole life cycle of the building, this way all the energy invested during the construction, operation and demolition of the building is considered as well. However, the annual balance can also consider an annualized embodied energy. Finally, last options consist on carrying out the balance in a monthly or seasonal basis. Using these methods, results and optimal solutions are different for each month or season, which is not favorable from the designing point of view. [11]

The German Building Code proposes a third approach to the net balance, called *monthly virtual balance*. This method performs one *load/generation* balance every month for each of the considered energy carriers. Finally, the monthly residuals are handled in an annual balance so they can be interpreted as some kind of virtual monthly self-consumptions. This method provides information about the matching between building and grid. As a consequence, it is useful for analyzing the seasonal performance without needing a complete self-consumption calculation. This kind of balance is widely discussed in [14] [16].

The graphic on Figure 2.5 represents the relation between the results of applying each of the mentioned balances. It also shows how the boundary for *load/generation* balance is settled inside the building, studying the different loads and on-site energy sources. On the other hand, *exported/supplied* balance is applied over the connections to grids.

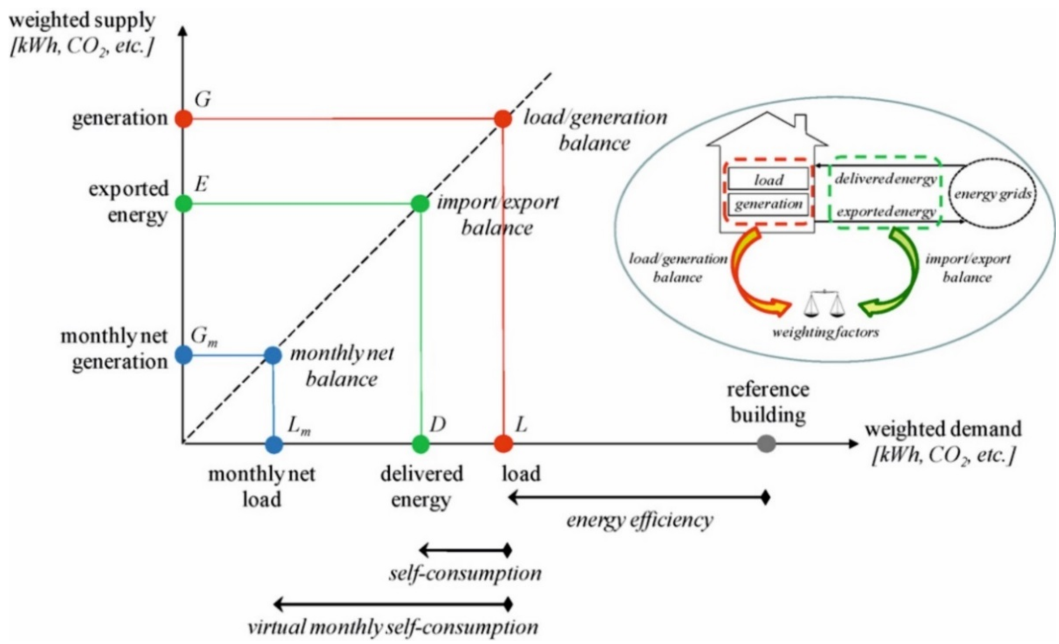

Figure 2.5. *Graphic showing the three types of net balances used on nZEB studies.* ***[14]***

The next open discussion around the net balance relates to what to include inside it. As described before, most of the methodologies include energy involved in heating and cooling systems, ventilation systems and others more related to user's behavior. The last ones include domestic hot water, appliances, lighting and plug loads. It is noteworthy that how to estimate these user related loads will be different for each country and methodology. In addition to the items previously proposed, some researchers consider to incorporate into the balance energy related to other complete different systems. Such systems, e.g. charging the batteries of an electric car or dealing with the treatment of rainwater, could help to regulate or optimize the interaction between building and grid. Furthermore, the balance can also take into account the embodied energy in the building. This energy could be important as an intensive consumption is made during the manufacturing of building materials. This increased consumption is due to some of the new materials used for recent efficient building envelopes or technical systems such as photovoltaic panels. How including the embodied energy affects the results of the calculations in low energy houses is analyzed in [18].

Which exact metric is selected for the study, and how it is treated, also influences the net balance. As previously mentioned, this metric is usually energy, cost or emissions. However, how to consider the energy will be critical in the calculation process. Two cases are possible, naming the metric as site energy, referring it to the final energy, or as source energy, referring it to the primary energy [11]. When the balance uses final energy, no weighting factors are taken into account, therefore all energy units are equivalent. One kWh produced by gas is equivalent to one obtained by biomass, so this method does not promote renewable energy. This conservative approach stimulates the use of electric heating systems, such as heat pumps with high coefficients of performance (COP), instead of the use of gas systems with lower efficiencies [10]. One advantage of using final energy is that the balance does not depend on external factors such as the costs of energy and political preferences. At the same time, the method is very simple, making nZEB concept easier to understand and apply. It is worth to mention that in the case of a net ZEB, the building will produce exactly as much energy as it will consume, as not weighting factors are considered.

Alternatively, the use of the primary energy as metric does integrate the weighting factors. As previously explained, the specific energy source will affect the quantity of energy counted. Therefore, this methodology could stimulate the use of gas boilers as the common ratio of weighting factors between consumed gas and electricity produced is 1:3 [10]. Less photovoltaic panels would be necessary to offset the used gas, making nZEBs easier to achieve, on the contrary to the final energy metric case. The disadvantage of this source metric is related to the unreliability of the weighting factors. As explained before, these factors depend on the size of the chosen region and they are time-dependent, hence it is needed a continuous improvement of the credit system.

If the authors of a study choose costs as a metric for the net balance, there will be also a dependency with the specific energy sources as each of them have a different price. From the point of view of this kind of study, the owner of the building is paid as much money for the exported energy as he expends on importing energy. Consequently, results are easily verifiable in the bills. The optimal solution appearing in the results will vary depending on the availability of each energy source in that exact location. The main problem of this metric is that, as the weighting factors did, the energy prices tend to highly vary over time. As a result, controlling the energy demand becomes critical. Even the wide implantation of nZEBs could affect energy prices. It must be taken into account that in some countries, e.g. currently in Spain, electricity companies do not pay the owners for the excess of production in their buildings that is transferred to the grid.

Finally, the last of the most common metrics is emissions. A building the balance of which is based on emissions must produce at least the same amount of emissions-free energy as it imports as emissions-producing energy. It would be possible to achieve this kind of nZEB by importing all the energy from offsite emission-free sources. In countries such as Finland and Spain, with an important share of renewable energy sources in their grid, this approach would be possible thanks to hydropower and wind power sources. Consequently, it is very important, and at the same time difficult, to determine which kind of energy source is producing the electricity used. [10]

Other important topic in nZEB studies methodology, apart from the net balance and its framework, is related to the **temporal energy match**. A nZEB should not only fulfill a balance in an annual basis but try not to be an extra stress for the grids it is interacting with. Moreover, buildings could be a slight help for the grid, if energy exchanges are optimized. Some authors have developed different indicators to analyze the temporal energy match inside the building and between the building and grids. These indicators are highly time-dependent and need a big amount of data to be calculated, including prizes, pick hours and emissions. However, they will be critical factors when smart grids are wider spread and developed. The first of these indicators is the load matching, which analyses the temporal match between the load and the generation in a building. It is common that a building generates most of its energy during summer, due to the use of photovoltaic panels. Graphics like the one on Figure 2.6 help to study this and other phenomenon.

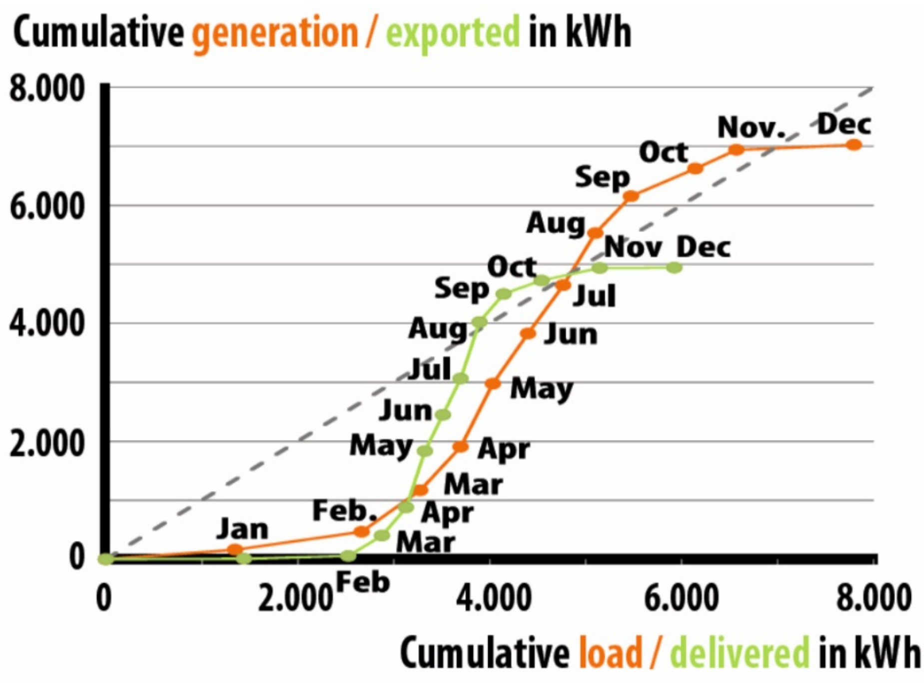

Figure 2.6. *Five minutes resolution monitoring results for a small nZEB in Germany.* ***[16]***

A high load matching is not always recommended. Occasionally, the weighted value of exported energy could compensate the losses on the storage systems needed to rise the matching.

The second important indicator is called “grid interaction”. This indicator analyses the temporal match between the imported/exported energy and the necessities of the grid. Definitely, it is necessary to do self-consumption calculations in order to obtain that imported/exported energy, unless the study is carried out during the monitoring phase. Both, load match and grid interaction, are widely discussed in [14] and [16], while some mathematical expressions are proposed in [19].

Finally, the explanation of the study methodology for nZEBs can be end introducing the **monitoring procedure**. The study of a nZEB cannot stop after its definition, design and calculation phases. It is necessary to check the final performance of the building and compare it with expected results and regulations. If results differ from the expected, some changes should be made, hence it is necessary to set some tolerances. This monitoring procedure must evaluate three parameters: load, generation and comfort. The measuring of the first two parameters will allow to evaluate the net balance. At the same time, it provides data for an *exported/supplied* balance and some characteristics of the temporal match previously explained. As mentioned before, excluding certain items from the balance, for example the plug loads, implies more sensors and measurements. The last parameter, comfort, is the first priority during the operation of the building, and must be always guaranteed. Comfort is usually related to the indoor environmental quality (IEQ) that studies the health and wellbeing of the occupants. For studying the comfort not only air temperature must be measured but also other factors such as the enough use of daylight and air quality. As a result, the monitoring process involves installing a considerable amount of sensors. [11] [14]

2.3. Actual situation in Europe

European Union member states have proved to be conscious about the important role of buildings on achieving 2020 goals and even longer term objectives fighting the climate change. EPBD directive settled that the different countries should report their progresses to the European Commission. For that purpose, this commission has created a common reporting methodology through several templates. Thus, it is easier to compare the progress of each member and finally evaluate them and provide some guidance. [20]

According to the European Commission, every national plan, which have been already submitted in most of the cases [21], should include some basic elements, such as:

- Application of the nZEB definition in practice. More than half of the members already settled an exact definition. Most of them include a numerical indicator for primary energy, aiming to 45-50 kWh/floor-m^{2}a for residential buildings. Although, not so many countries have set a minimal share on renewable sources, but they propose a qualitative requirement. In Figure 2.7, it is presented the reported data until October 2014, where only two countries, Greece and Spain, did not inform of their progress.

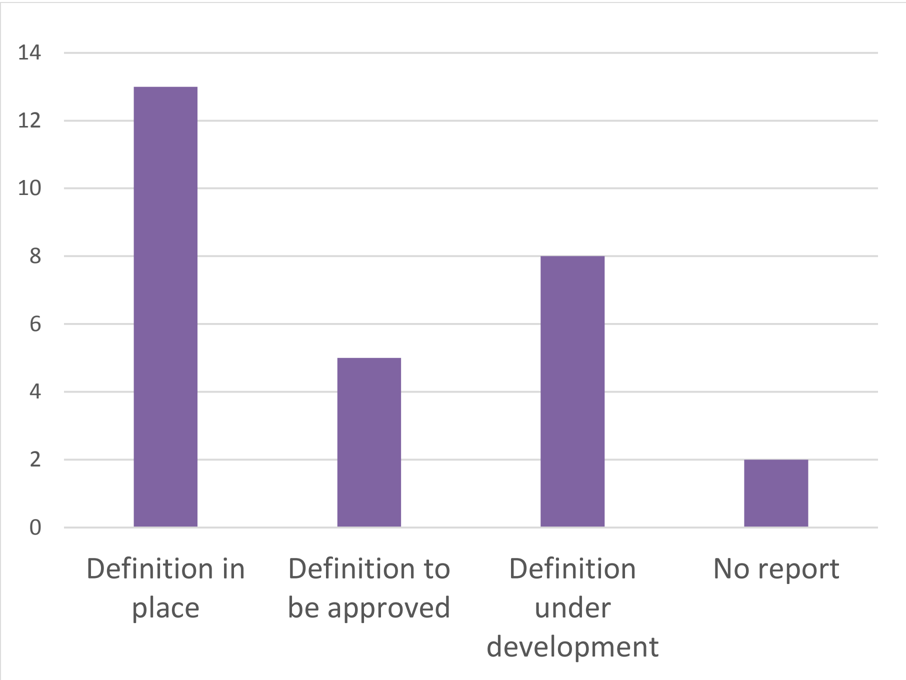

Figure 2.7. *Development status of NZEB definition in European Union member states. (Adapted from* ***[21]****)*

- Intermediate targets for improving the energy performance of new buildings by 2015. The majority of the states has established these intermediate targets through minimum energy performance requirements (e.g. 50 kWh/m^{2}a by 2015) or a specific energy performance certificate rating (e.g. level B by 2015). It has been also settled an exemplary role for the public sector in several countries.
- Policies and measures for the promotion of nZEBs. More than two thirds of the member states have already reinforced their building regulations, offer financial incentives to nearly zero-energy constructions or propose other measures for making people aware of the importance of energy efficiency in buildings.

Following, the specific situation in Spain and Finland will be analyzed as part of the comparison considered in this study.

2.3.1 EPBD implementation status in Spain

Since the publication of the European regulation introducing the future requirement of nZEB, Spain has followed an implementation route consisting on several Royal Decrees. These decrees settle different requirements and regulations such as periodic inspections to thermal installations, temperature limits for indoor air depending on the season, maximum thermal transmittance values for thermal envelopes, minimal efficiency on lighting and compulsory integration of renewable energy sources in new buildings.

Having the energy performance certificate of a dwelling is compulsory for selling or renting it since June 2013. This certificate rates the building in an A to G scale according to different parameters such as annual energy consumption and carbon dioxide emission per square meter. The Institute for Energy Diversification and Saving (IDAE) suggested to expand this scale, adding A+ and A++ ratings, facing the future existence of nearly zero-energy buildings [22].

Last step towards creating a legal framework for nZEBs was taken through the Technical Building Code (TBC) modification in 2013 [23]. This modification includes a substantial reduction on the allowed energy demands in buildings and the consequent increase in energy efficiency requirements. An example of the changes introduced in the thermal transmittances (U-values) is shown in Table 2.2 for the specific case of the weather zone D, where Madrid is located. Furthermore, these values could have to be lower under specific circumstances to fulfill the maximum energy demand requirement, which is 55.33 kWh/m^{2}a for a 150 m^2 house.

Table 2.2. *Maximum thermal transmittance required by the Technical Building Code in 2006 and 2013, for Madrid (weather zone D).* ***[23] [24]***

Parameters	TBC 2006	TBC 2013
Thermal transmittance of external walls (W/m^{2}K)	0.86	0.6
Thermal transmittance of roofs (W/m^{2}K)	0.49	0.4
Thermal transmittance of windows and doors	3.5	2.7

Next step in the route towards nZEBs framework will be taken in the period 2016-2017 when the government will publish a new modification of the technical building code. This new TBC will include the regulative nZEB definition and will set mandatory requirements for 2019, in the case of the new public buildings, and 2021 in the rest of the cases. For calculating these minimal requirements, it is necessary to accomplish several cost-optimal studies that are being executed nowadays. [25]

Spain is one of the slowest countries in the European Union preparing itself for the introduction of nZEBs, according to the reports of the Energy European Commission [20] [21]. The commission mentions that Spain is one of the two countries that have not presented yet, in October 2014, its report indicating the existence of a national plan. This report is required by the Article 9 of the EPBD. Additionally, Spain has neither reported to the European Commission any consolidated information including intermediate targets, policies or measures for promoting nearly zero-energy buildings.

2.3.2 EPBD implementation status in Finland

Finnish authorities are really progressing on their way to implement regulations for nearly zero-energy buildings and they are fulfilling every checkpoint settled by European Commission. As a result, Finland has already submitted a national plan and the consolidated information on nZEBs.

National Building Codes on energy performance in Finland have existed since 1976. Their requirements have been updated over the years, last modification was in 2012, after the publication of the EPBD. In Table 2.3, it is shown how the U-value requirements have evolved until last code’s values, resulting on a 55 % reduction of heat losses since 1976 [26]. This new code introduces lower minimal U-values but also changes the point of view in the search for more energy efficient buildings. As a result, Part D3 of National Building Code settles maximum values for the total consumption of energy depending on the type of building. This consumption is affected by weighting factors resulting on the denominated E-value. Additionally, the code defines boundaries for delivered energy and on-site produced energy that will be helpful when defining the nZEBs.

Table 2.3. *Development of minimum requirements for new buildings according to Finnish National Building Code.* ***[27]***

U-values for building components W/m².K	1976	1978	1985	2003	2007	2010	2012
Walls	0.4	0.29	0.28	0.25	0.24	0.17 0.40 logwall	0.17 0.40 logwall
Roof	0.35	0.23	0.22	0.16	0.15	0.09	0.09
Floor	0.40	0.40	0.36	0.25	0.24	0.09/0.16/0.17[1]	0.09/0.16/0.17[2]
Windows	2.1	2.1	2.1	1.4	1.4	1.0	1.0
Doors	0.7	0.7	0.7	1.4	1.4	1.0	1.0
Other base values							
n_{50}-value	6	6	6	4	4	2	q_{50}[3]=4
Annual efficiency for heat recovery systems	0	0	0	30%	30%	45%	45%
Maximum values for energy consumption kWh/m².year							Based on building type[4]

1, 2 Base floor bordering on outside air = 0.09 W/m².K, building component against the ground = 0.16 W/m².K, base floor bordering on crawl space = 0.17 W/m².K.
3 q_{50} is the air leakage value of the building envelope.

Within its national plan to increase the number of nearly zero-energy buildings [28], Finland presents several policies and measures for promoting this kind of building, including:

- Every renovated public buildings must be rated at least with a class C energy efficiency since 2010.
- In the period 2012-2015, several kind of loans are offered for the renovation of dwelling units targeting class C energy efficiency and also for the new constructions rated with A class.
- The government develops a successful campaign promoting nZEB construction. As a result, it is expected to achieve the 15 % share of nearly zero-energy buildings among the one-family houses by 2015.

The final definition of the nZEB has been delayed until 2015, when technical recommendations will be provided. The main reason for this delay is the inclusion of updated parameters in the cost-optimal studies, taking into account future prices and developments in construction technologies and energy systems. A big collaborative effort among companies, research organizations and government is being made with the intention of supplying a building regulation for nZEB in 2017. Although a technical definition on nZEB is not ready yet, Finland has supplied some consolidated information to the European Commission settling several parameters including the physical and system boundaries.

2.4. Existing net zero-energy buildings

Buildings with a highly reduced energy consumption, i.e., Passive Houses, are a well-developed topic, many times put into practice. Hence, there were many passive houses already built around the world. Nonetheless, the concept of net zero-energy building is slightly newer, thus there are less buildings that can be taken as an example. However, during last years, first test buildings have been built.

According to [29], there are over 40,000 certified Passive Houses in the world, half of them located in Germany. In the case of nZEBs, they are mostly located in Europe. Figure 2.8 shows how the majority of European nZEBs where located in Germany at the end of 2013. The figure shows in red the new buildings, most of them, and in other colors the renovated ones.

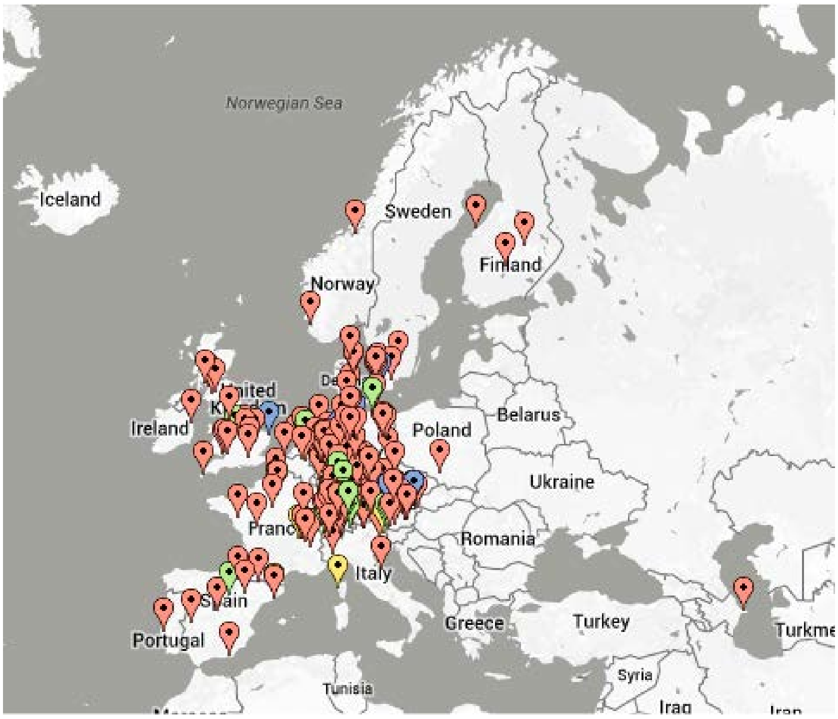

Figure 2.8. *Nearly net zero-energy buildings in Europe.* ***[30]***

In this subchapter, several existing buildings will be briefly analyzed. The adopted technologies, which will be explained in following subchapters, will be mentioned as well as the different primary energy consumptions. The chosen examples are mainly in Finland and Spain, locations in the scope of this study, but also in other European countries.

The first building analyzed, Kuopas nZEB, is located in Kuopio, Finland, where the annual average temperature is around 3 degrees. The Finnish building is shown in Figure 2.9.

Figure 2.9. *Kuopas nZEB, located in Kuopio, Finland.* ***[31]***

This building contains apartments for students and has an approximate energy balance of -2300 kWh/a, which means that it buys that small energy from external sources. Due to the size of the building, that negative balance is very close to 0 kWh/m^{2}a. The renewable energy sources on-site are PV and solar thermal panels and a geothermal heat pump; used for heating and cooling. The building is also relied on the electric grid and a district heating network, based on biomass, for covering the annual demand. On Figure 2.10, it can be seen how the sold energy during spring and summer offsets the energy purchased during the rest of the year.

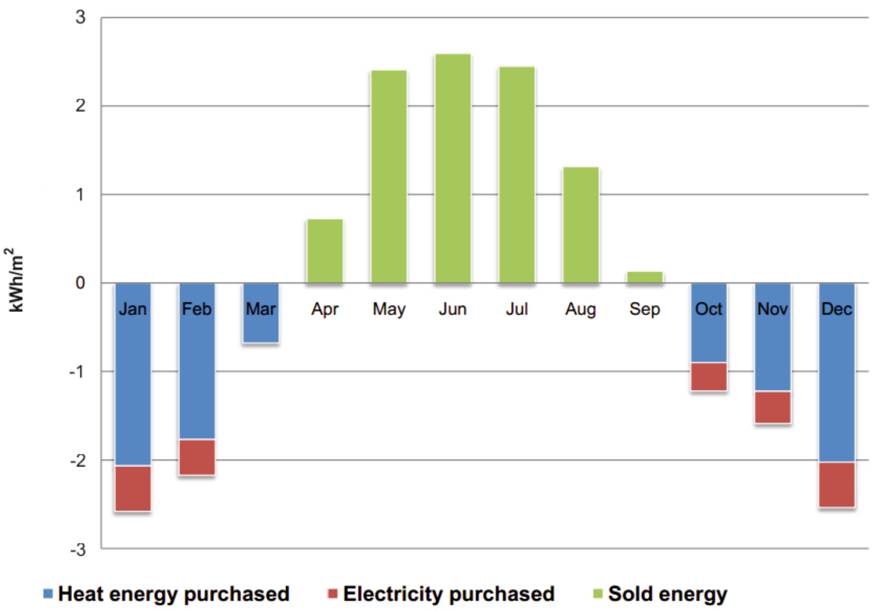

Figure 2.10. *Monthly purchased and sold energy in Kuopas nZEB. (Adapted from* ***[32]****)*

More information about this building, included its online live monitoring, can be found in the website of the project [32].

The next building analyzed is also located in Finland. Lantti zero-energy house is a single-family house built for the Housing Fair 2012 held in Tampere. As usually, the philosophy of this zero-energy building starts by reducing the demand through efficiency measures. As a result, the construction was very delicate. The designers took special care on thermal bridges and the use of natural light. The envelope was carefully isolated and best quality windows were applied.

Building systems were also high technology solutions. Lantti house has a ventilation unit with 80 % efficiency on heat recovering. In addition, it applies home automation technics such as a high automatized room temperature control for lowering the building consume when the house is not occupied. Some of the systems installed in the building can be seen in Figure 2.11.

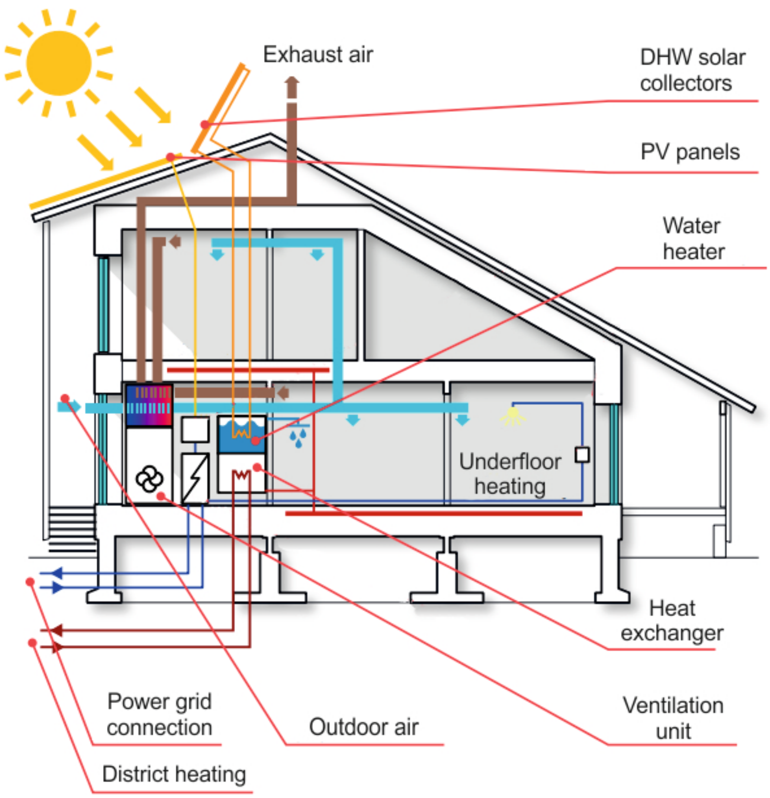

Figure 2.11. *Lantti zero-energy house systems diagram. (Adapted from* ***[33]****)*

The main energy systems applied were district heating, 8 m^2 of solar collectors and 60 m^2 of PV-panels. These last two components produced, respectively, half of the annually consumed DHW and electricity equivalent to more than half of building's annual demand. In Figure 2.12, it is shown how, finally, the yearly balance is offset thanks to these two renewable systems, obtaining a final E-rating equal to minus one. [33]

Figure 2.12. *Lantti zero-energy house energy balance. (Adapted from **[33]**)*

The low-energy building prototype called "Building 70 CIEMAT" was constructed in Madrid, Spain, as part of ARFRISOL project [34]. This construction is an example of an excellent combination of active and passive systems for lowering and supplying the demand of a building.

Employed passive techniques rely on an optimal use of solar radiation. As seen in Figure 2.13, by installing parasols on the windows and a big pergola over the roof, designers make the most of solar gains during winter and avoid them in summer. In addition, these devices incorporate PV-panels for electricity production. Moreover, each façade has a different design depending on its orientation and they also apply thermal inertia procedures.

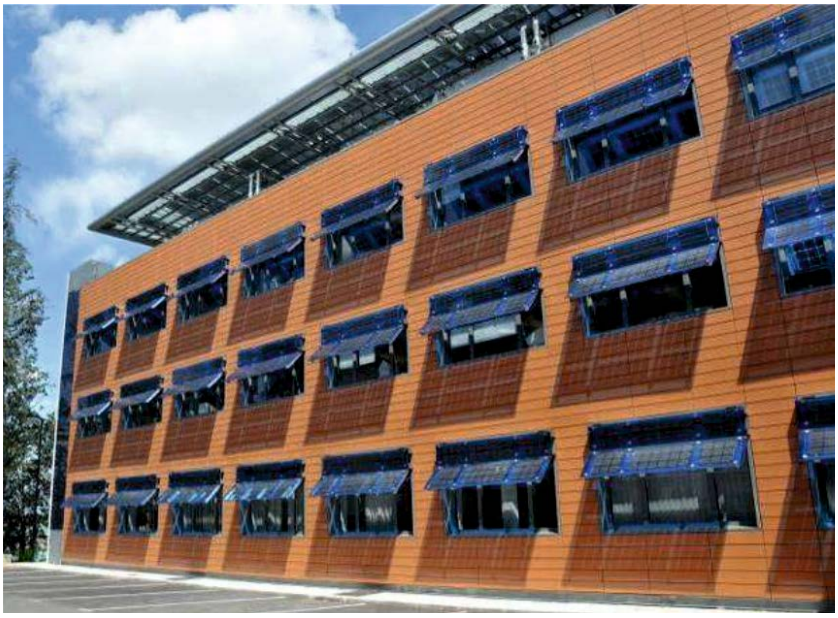

Figure 2.13. *South façade of Building 70 CIEMAT, in Madrid.* ***[35]***

The main active systems included in the building are based on solar resources. Solar collectors and PV-panels are integrated on the building for heating and cooling purposes, as the installation includes solar absorption cooling systems. In addition to this, there is a condensing boiler powered by natural gas working as a backup. [36]

The headquarters of ACCIONA Solar in Navarra, Spain, are the first zero-emissions building in Spain. According to the company, this building has a 52 % lower energy consumption than a conventional building and supplies all its demand by renewable sources.

The building has innovative architectonic elements such as its double-skin façade. This greenhouse façade, oriented to the south, preheats the air supplied to the heating systems in winter. Previously, this air is circulated through underground tubes. The geothermal energy is exploited during all the year, also precooling the air in summer. In Figure 2.14, the mentioned façade is shown as well as the PV-panels and thermal collectors.

Figure 2.14. *South façade and roof views of the ACCIONA headquarters in Navarra.* ***[37]***

In order to provide the necessary energy, the building includes solar systems and a backup biodiesel boiler, which only supplies 11 % of the annual demand. The PV-panels, with an installed capacity of 50 kW, are located on the roof and the south façade. Finally, 156 m^2 of solar collectors are installed on the roof. These collectors cover the heating demand but also the cooling needs, thanks to two solar absorption machines. Figure 2.15 presents a comparison of this building with a conventional one. Furthermore, it is shown how half of demand is saved thanks to efficiency measures. [37] [38]

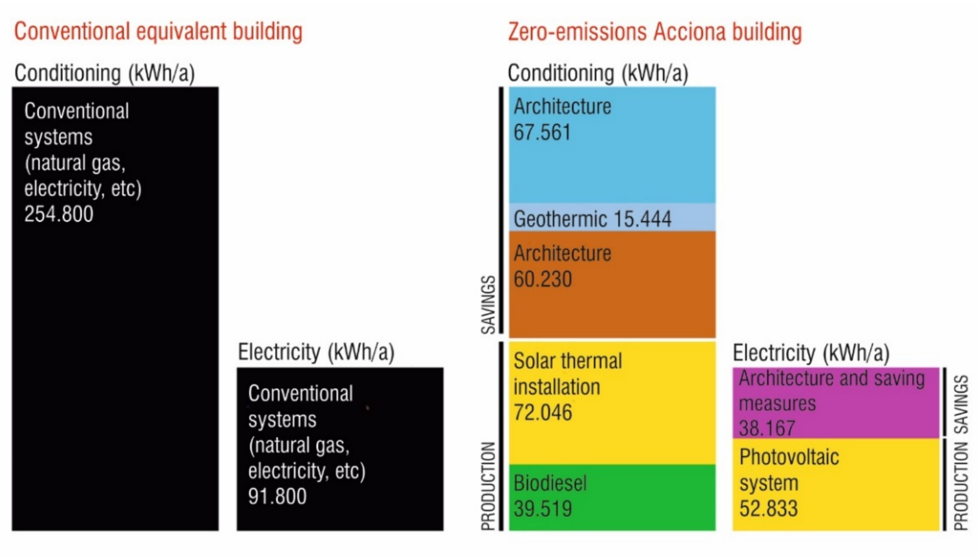

Figure 2.15. *Energy comparison between a conventional building and zero-emissions Acciona building. (Adapted from* ***[38]****)*

Other European nearly zero-energy building is Elithis Tower, located in Dijon, France. This tower is a clear example of the importance of the monitoring process in nZEBs. Thank for this process, the performance of the building has been improved, after some years optimizing its operation, reaching a primary energy use close 50 kWh/m^{2}a.

As other buildings mentioned before, Elithis Tower applies solar passive shading techniques and mechanical ventilation with a high-efficiency heat exchanger. In addition, it implements free cooling through high ventilation during summer nights. Active heating systems are composed by a solar thermal installation combined with a wood boiler, which works as backup. On the other hand, the cooling system consists of two stages. The first is based on evaporative cooling and the second, used in case of extreme outside temperatures, is a high-efficiency heat pump. [39]

Other building that worth to be mentioned is the Woods Hole Research Center, located in Falmouth, the United States. This building operated with a ground heat pump, solar collectors and photovoltaic panels. Finally, after a few years, a 100 kW on-site wind turbine was installed inside the building's footprint. This turbine is currently providing close to the 50 % of the building's energy needs. [40]

Comparing all the solutions introduced, it can be concluded that every building is focused on reducing its demand as a first goal. Finally, the systems applied will differ depending on the climate, availability and designers' preferences, although renewable sources will be always present.

2.5. Passive systems design in nZEBs

Along this subchapter, it will be carried a brief review on the most basic passive techniques applied to reduce heating and cooling consumption of a building. Although the amount of techniques is huge and keeps increasing, some commonly applied concepts are the foundations of passive techniques.

First step on the design process is how to orientate the building and define its shape. The geometry of a house determines the size of the surfaces exchanging heat with the outside. Additionally, the orientation of the façades sets which parts receive more or less direct solar radiation and wind.

According to this, south façades and roofs are the best zones for collecting sun during winter, although this could be a problem in summertime. In addition, rectangular building shapes with the long side in the west-east orientation are the best choice, as they make the most of that extra energy over the south façade.

Building designers use different ratios in their optimization processes. One of these ratios is the relation between building's width (north-south oriented length) and length. Other example is the ratio between envelope's area and building's volume. The lower this last ratio is the slower a building heats up.

Next design step is construction materials and, hence, thermal mass effects. These effects define how much and how fast the building storages heat coming from internal gains and solar radiation. Heat storage in building's materials allows to reduce inside temperatures in summer, especially combined with night ventilation. Furthermore, thermal mass effects can be used in winter to avoid overheating during the day while keeping warm temperatures when there is no more sunlight.

A careful design of façades and glazing, especially those oriented to the south, is crucial for making the most of thermal mass effects. For example, as it is done in Trombe Walls. This kind of façade is covered by a glass and an air gap, creating a greenhouse effect. As a result, heat coming from solar radiation is stored during the day and slowly released to the building at night. Moreover, some variations include openings in the wall to vent it during summer. In Figure 2.16, it is shown the schematic working of Trombe Walls provided with overhangs: during winter, heat is stored and transferred to the building but in summer the heat gain is avoided.

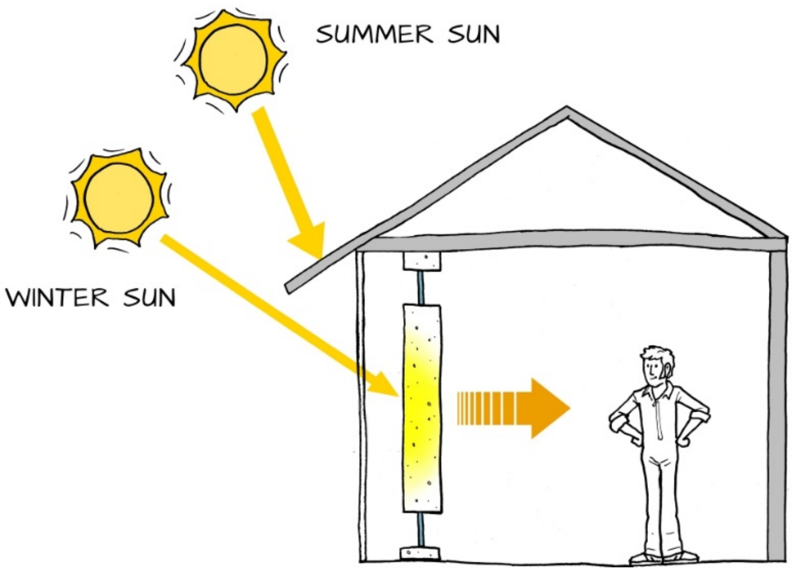

Figure 2.16. *Scheme of a Trombe Wall with overhang.* ***[41]***

Other example is the use of phase-change materials (PCM) in order to soften daily temperature swings. These compounds can be designed to absorb heat, by changing their phase, above required room temperature and releasing this heat when room temperature drops.

Along with construction materials, envelope design and its insulation are another important issue in lowering buildings' demand. As mentioned in other chapters, the thermal transmittance (U-value) characterizes insulation properties. The insulation for walls and roofs usually consist on mineral wool or newer materials such as vacuum insulation or polystyrene. There is an open discussion, commented in [42], about installing insulations in the interior or exterior of roofs and walls. However, a common agreement exists about implementing thermal bridge breaking in double or triple glazed windows with aluminum frames. In addition to the insulation, it is also important a high airtightness in the building to prevent unwanted filtrations.

Solar radiation is one of the main heat gains along the year. Therefore, allowing this gain or avoiding it through shading is another important passive procedure. Several devices or parts of the landscape are used for providing shade:

- Overhangs on south façades protect from direct radiation of summer high sun. Conversely, they allow this heat gain in winter, when the sun is lower, as can be seen in Figure 2.16. These devices are not so useful in west and east façades due to the lower height of the sun when it points to these orientations.
- Trellis and trees are a better choice in this last case. Trees' leafs fall in autumn allowing the sun to heat the building. Moreover, they are a good protection against cold winds in winter.

- External rollups made from clothes of different grades are another good option. They allow in more or less radiation depending on their properties and can be retracted during winter.

Other devices directly block radiation, such as sun blocking screens, curtains or venetian blinds. In addition, these tools also allow to control the sun lighting of the rooms. Finally, new technologies as electrochromic and thermochromic windows can regulate their transmittance depending on the heating needs. It is also noteworthy the use of sunspaces. These glass rooms are attached to the building in south orientations. Their goal is to storage and transfer heat obtained from solar radiation. [42] [43]

Concluding, the application of passive techniques on a building is mainly focused on isolating the envelope as much as possible and making the most of solar radiation. For this last purpose, the south façade is the most important element as it receives the majority of the solar energy.

2.6. Active systems design in nZEBs

Once the passive systems applicable in buildings are introduced, this study will focus on active technologies. These technologies require to be provided with some kind of energy, such as electricity or any fuel, to perform their duty. Most of the necessary systems on a building will be presented, including those covering space heating and cooling, ventilation and domestic water heating. Finally, those configurations that rely on renewable energy sources to provide these services will be explained.

2.6.1 Heating, ventilating and air conditioning systems

In this subchapter, it will be shown a general idea about air conditioning of buildings and systems related to it. Finally, the best choices for energy-efficient homes will be discussed along with the most suitable configurations for nZEBs.

Air conditioning systems are not anymore in charge only of cooling air. On the contrary, this concept involves dealing with air quality and temperature, as well. Therefore, these systems care for the comfort and health of building users.

These installations handle many issues, such as temperature and humidity control, and air renovation and cleaning. Thus, several processes must be managed: heating, cooling, humidifying, dehumidifying, ventilating, air moving and particle filtering. Heating, ventilation and air conditioning systems, also called HVAC systems, handle all these processes. The main goals of HVAC systems aim to provide comfort and fresh clean air. In order to do that, their approach should be energy efficient, economically viable and environmentally clean.

HVAC systems must control how users exchange heat with the environment as this determine their perception of comfort. Thermal comfort is influenced by many factors which can be divided into three categories, as can be seen in Figure 2.17. These categories are related to specific conditions of the environment, individual characteristics and personal conditions.

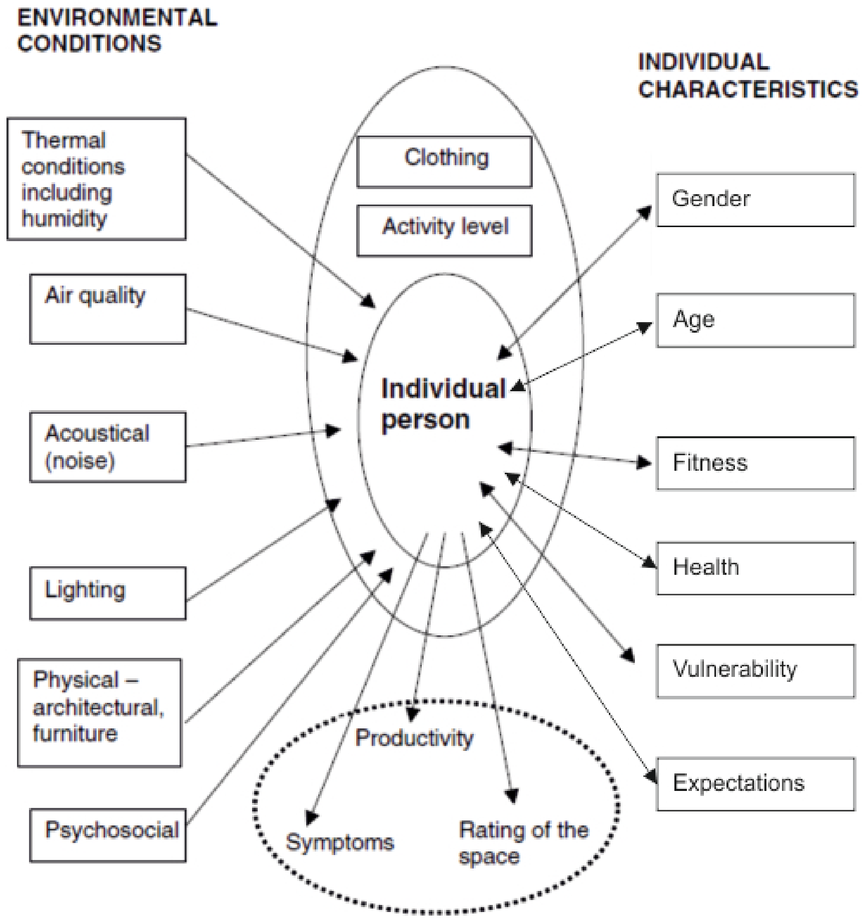

Figure 2.17. *Factors influencing thermal comfort. (Adapted from* ***[44]****)*

Controlling air temperature means to deal with a heating or cooling loads. In order to calculate these loads, several external and internal inputs are taken into account. External loads are those related to heat conduction through the envelope, heat gains through glazing and ventilation and infiltration losses. Finally, internal loads comprise heat gains related to the occupants, lighting and appliances.

The components of HVAC systems can be divided into four categories: energy source, heat distribution, heat delivering and control. Among the cooling source equipment the next three cases are the most common:

- Vapor-compression refrigeration: divided into direct expansion (DX) systems and water chillers, depending on if they cool air or water, respectively. This is the most common cooling source.

- Absorption refrigeration: based on the absorption cycle. Its efficiency and costs are more adverse than the first option. However, it is an attractive choice when there is an available free heat source such as the solar radiation or district heating in summer, e.g. in the case of Finland.
- Evaporative cooling, which is the same process used in cooling towers. The most common procedure consists on spraying water over a wetted membrane. The air is circulated through this membrane, provoking the evaporation and corresponding cooling. One possible use of this technique is the evaporative cooling of exhaust air for the subsequent cooling of supply air.

On the other hand, heating source equipment includes boilers, furnaces, electric resistance heating and electric heat pumps. The last ones use a vapor-compression cycle to supply heat, relying on an air, water or ground heat source. Moreover, there is one last heating source called district heating. This system delivers heat produced in a centralize location usually by combined heat and power with fossil fuels or biomass.

Distribution components include fans, pumps, ducts and pipes. The delivery components are diffusers, fan-coils, radiators and induction units. And finally, the control system is composed by thermostats, valves and different actuators. The configuration of delivery and distribution components define what type of system is applied. According to this, many authors classify HVAC systems as all-air, air-and-water or all-water.

They are called all-air systems because air is the only fluid distributed to the terminal units located in the different rooms of the building. The main element of these systems is the air-handling unit (AHU), usually rooftop units, consisting on a mixing chamber, filters, heating and cooling coils, a humidifier and a fan. The sequence can be seen in Figure 2.18. In the mixing chamber, the intake air is mixed with outside air for ventilation and energy saving purposes. The heating and cooling coils are connected to their respective energy sources, for example chillers or boilers, as explained before.

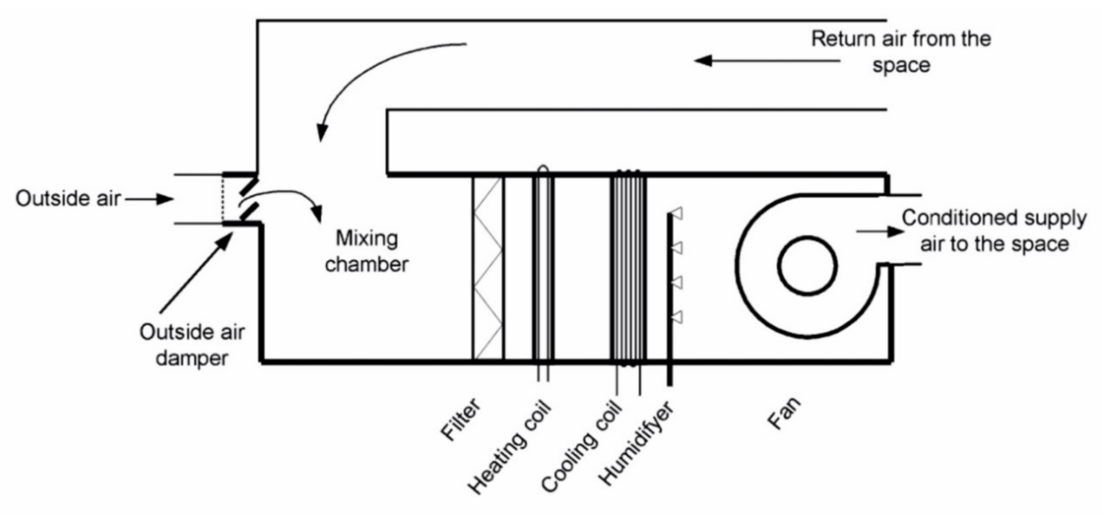

Figure 2.18. *Air-handling unit scheme.* ***[44]***

The control of these systems can be made by regulating air temperature or air volume. According to this, there are three main different possibilities. The first are the reheat systems, which heat the cooled air back to the necessary temperature. The second ones are the variable air volume (VAV) systems, which adjust air volume using dampers or bypass boxes. The last possibility is dual duct systems, where the air delivered to the rooms is a mix of hot and cold air circulating through different ducts.

There are alternatives to the rooftop units, such as split systems and air-air or air-ground heat pumps. The split systems are characterized by separation of the compressor and condenser from the evaporator. Hence, the noisy elements are outside the building and thinner pipes can be used, as they carry refrigerant instead of air.

The second big category of HVAC configuration is all-water systems. As their name suggests, these systems only distribute water to terminal units. Therefore, ventilation needs must be covered by the users, manually opening windows, or by a separate ventilation system. The advantage of all-water systems is that they occupy less space, as the piping is thinner, and that they can work with low temperatures, such as the ones provided by solar energy.

The following terminal units are the most used in all-water HVAC configurations:

- Natural convection and low temperature radiation heating units, more known as radiators. Working temperature of the water does not usually exceed 70 ºC. There are several types and configurations, with different control systems: varying the water flow or its temperature.
- Panel heating and cooling, which includes radiant floor and ceiling radiant panels. These systems work with lower temperatures, always limited by the comfort of the users.
- Fan-coils and induction units, where an air flow is forced through the water coil.
- Water source heat pumps. These kind of heat pumps are used for exchanging heat with the ground or transferring it around big buildings, combined with a boiler and a cooling tower.

Finally, the last possible configuration, air-and-water HVAC systems, distributes both fluids to terminal units in the rooms. In these systems, the air is used for ventilation and partially for heating and cooling, not using it when the building is unoccupied.

HVAC systems usually take care of ventilation processes, but, as mention before, not all of them do it. Traditionally, there are three kind of ventilation techniques: mechanical, natural and hybrid. Mechanical ventilation relies on the use of fans while natural, or passive, ventilation does it either on the wind or in the difference of pressures along the building, known as buoyancy ventilation. Finally, hybrid systems make the most of both techniques in order to reduce energy consumption and noise levels. [45]

In old buildings having low airtightness envelopes, natural ventilation through infiltrations was considerably big. This was combined with the use of operable windows, where users were in charge of the ventilation and air-quality maintenance. However, new buildings have really small infiltration rates and manual ventilation is not energy efficient. Therefore, mechanical ventilation is recommended for new low-energy buildings.

New technologies are also applied in ventilation processes in order to reduce their energy consumption. For example, new control strategies based on CO_2 sensors adapt ventilation to occupancy levels. These systems are called “demand controlled ventilation” (DCV). In addition to this, heat recovery ventilation (HRV) was long ago implemented. In HRV systems, an exchanger recovers the excess of energy in exhaust air with efficiencies from 50 % to 80 %. Finally, other interesting technique is night ventilation. During summer days, buildings act like heat sinks absorbing solar radiation and internal heat gains. This technique applies active and passive ventilation processes to flush warm air out and to cool the thermal mass for the next day. [46]

As mentioned before, only a general idea about HVAC systems and their configuration has been shown, as more detailed explanations are out of the scope of this study. More information and examples can be found in [44] and [47].

2.6.2 Domestic hot water and integrated HVAC-DHW systems

Along with space heating and cooling, installations in a building must cover the domestic hot water demand. This potable water is usually heated until a temperature varying from 40 to 60 ºC, minimum temperatures of 60 ºC are usually required to prevent risks due to legionella bacteria. Energy demand related to DHW is becoming relatively more important as the space heating and cooling demands decrease in low-energy buildings. In addition, reducing water consumption is complicated as it depends on the fixtures, appliances and user habits. Consequently, the implementation of renewable energy sources becomes really important, against the use of conventional systems.

These conventional systems included direct electric heating, air to water heat pumps, district heating and condensed gas boilers. As alternatives, there are new green technologies like ground heat pumps and solar water heating. Finally, the most attractive option for zero-energy buildings is the integrated HVAC and DHW multi-energy systems. These installations combine different energy sources, some of them renewable, to cover all three demands: DHW, space heating and space cooling.

Enrico Fabrizio et al. performed a long review [48] analyzing several integrated HVAC and DHW systems that suit zero-energy buildings. These systems include the combination of a highly efficient gas boiler with a solar thermal circuit, usually incorporating waters storages. As an alternative, solid biomass boilers, which will be explained later, are also attractive. Moreover, they are very popular among low-energy homes heating systems based on solar assisted air-to-water heat pumps, as the one shown in Figure 2.19.

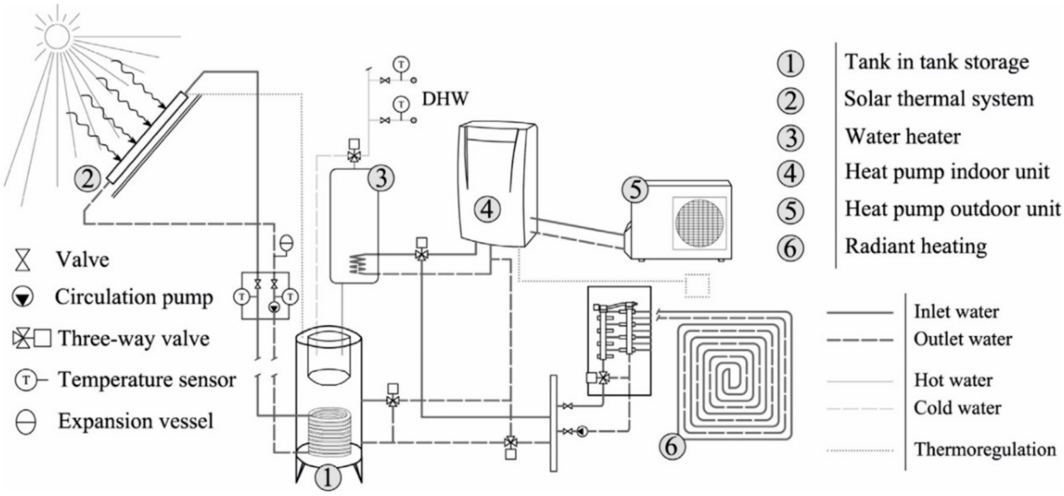

Figure 2.19. *Schematic of a solar assisted heat pump system for space heating and DHW.* ***[48]***

In this case, most adopted solution to provide cooling is the use of reversible heat pumps. It is worth to mention that DHW heating must be covered also when there is a space cooling demand. In order to solve this, single stage or double stage heat pumps are used. Double stage heat pumps are able to supply heating and DHW or cooling and DHW at the same time. Another possible solution is the variable refrigerant volume systems (VRV).

Finally, multi-source installation is frequently proposed by authors in the field. For example, the combination of a gas boiler and a solar assisted heat pump. In this system, the gas boiler is used when low temperatures outside decrease the COP of the heat pump or when the pump cannot cover all the demand by its own. Details about the systems mentioned above and more kinds of installations, such as those based on gas absorption heat pumps, can be found in Fabrizio's article [48].

2.6.3 Renewable energy systems

An energy source is considered renewable when its resources are theoretically inexhaustible. This means that resources are replaced at the same or faster rate than they are being consumed. Some of these renewable energy sources, such as solar radiation, wind and geothermal heat, are applicable to provide energy for a building, as it will be explained below.

Photovoltaic energy production

Among the energy sources available in the building framework, photovoltaic production of electricity is one of the most extended. This source relays on the direct transformation of solar radiation to electricity thanks to photoelectric effect on a semiconductor diode. Hence, it is inexhaustible, unlike others such as petroleum, natural gas and coal.

Since the first solar cell was developed in 1945, there has been a continuous expansion of this field. Nevertheless, one of the firstly discovered kind of solar cell, the silicon-based one, still dominates the market due to the abundant supply of silicon and its lower ecological impact [49] [50]. The photovoltaics sector keeps evolving and growing, in 2013 there was at least 38.4 GW of new installed generation capacity in the world. This means at least 138.9 GW installed globally. In addition, in Europe, 66 % of the market consists in roof mounted panels, i.e., the building sector [51].

Solar cells, consisting on a pn-junction, are connected in series and packed into a solar module, moreover these modules are grouped together into a photovoltaic array. This system presents a low maintenance and long life expectancy: more than 25 years [52]. On the other hand, for many applications, the fluctuation of the isolation and electricity demand creates the necessity of accumulators. This is not the case of the nZEBs which are usually connected to the grid, using it as a kind of accumulator. Another disadvantage could be the high cost of this technology, but the continuous development keeps these costs decreasing over the time. Furthermore, the integration of photovoltaics in buildings (BIPV) is supposed to decrease the costs, as the systems form a part of the building and fulfil a secondary function, such as shading [51].

Once the background and actual situation of photovoltaic technologies were briefly explained, below it is proposed some basic technical explanation and key terms for understanding the energy production estimation. Solar heating uses both components of solar radiation, direct and diffuse, but its performance is not good when only the last one is present. On the contrary, solar photovoltaic panels convert radiation into electricity even if it is only composed by diffuse radiation, e.g. on cloudy days. This has especial importance in northern countries, like Finland, where the proportion of diffuse radiation is big.

The power received from the sun is one of the first issues to take into account when calculating a photovoltaic system. Global radiation on the horizontal plane of the Earth's surface, G_H, represents this last concept. Global horizontal radiation measures the power per area unit in a horizontal plane. Its maximum value varies around 1 kW/m^2 depending on time and location. More important is to know the power received exactly into the solar module, which will be tilted with respect to the horizontal plane. There are different methods to calculate the radiation on inclined surfaces [50]. Basically, all of them take into account the sum three components: direct radiation from the sun, diffuse radiation from the sky and reflected radiation from the ground, as follows:

$$G_{poa} = G_b + G_{d,sky} + G_{d,ground} \tag{2}$$

Once measured or estimated the power received over the module, it is interesting to know the produced electricity. Consequently, the different losses and efficiencies need to be taken into account. How these losses and efficiencies are implemented mathematically into the estimation will be discussed in future chapters.

Firstly, the efficiency of the modules shows how much of the received energy, in form of solar radiation over the tilted array, will be transformed to electricity by the solar cells. Therefore, these parameters fix the size of the array when an output power is previously set. The exact efficiency value depends on the quality of the module, among other factors, varying around 15 %. The temperature of the cell is the most important of those affecting factors. Basically, cell's efficiency and its temperature share a linear relation where the efficiency decreases when the temperature is higher, at a rate close to -0.5 % / ºC. More information about this dependence, along with some calculation models, can be found at [53].

Secondly, different performance losses take part into the estimation of electricity production. The photovoltaic system not only consists in the solar array. As shown in Figure 2.20, the system contains several electricity meters, cables connecting different elements and the inverter. This last device converts direct current from the array into alternating current.

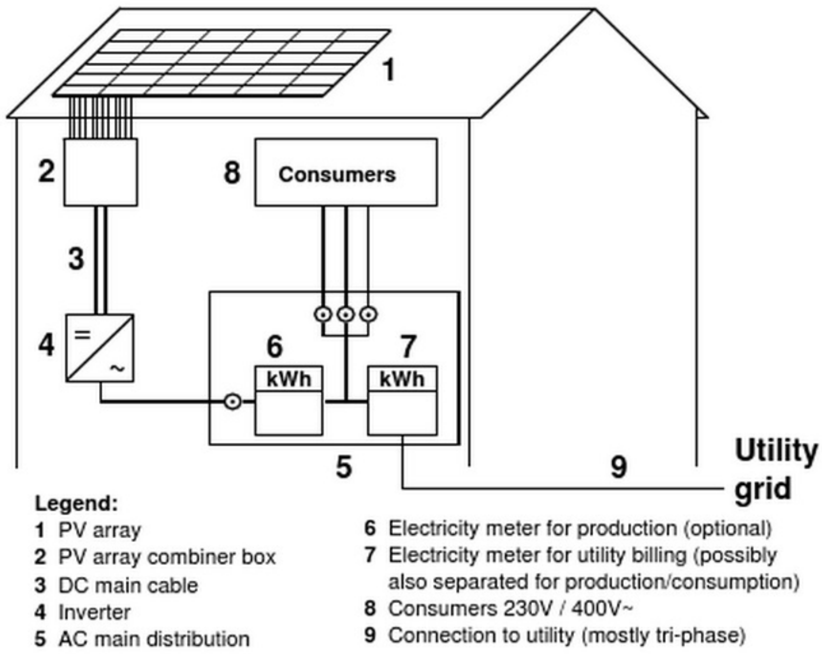

Figure 2.20. *Layout of a typical PV system mounted on a building. [4]*

Finally, it is necessary to introduce some losses into the model, some of them representing these elements, including [54]:

- Inverter's DC to AC conversion efficiency.
- Soiling: dirt or snow over the modules that could reduce solar radiation on solar cells.
- Shading: reducing the solar radiation over the array.
- Wiring and connections: several resistive losses in different parts of the system.
- Mismatch and nameplate rating: due to imperfections in the manufacturing process of the modules.
- Availability of the system: reduction in the output energy caused by shutdowns.

It is worth mentioning that the effect of the temperature over the module efficiency can also be understood as another kind of loose in the system, in this case within the module.

Photovoltaic production is one of the most direct and cleanest ways of obtaining green electricity in buildings. As a result, it is the common link among almost every zero-energy building approach. However, this system is not the only method to employ sunlight as an energy source, as it will be presented below.

Solar water heating systems

It has been already shown the potential of the sun for energy purposes. Systems studied in this occasion employ solar radiation for producing heat instead of electricity. This extracted heat is later used with two possible purposes: domestic water heating or space heating and cooling. The system used will be different depending on its goal, so both types of systems must be studied separately.

Solar water heating systems are one of the most popular applications of solar technologies, due to their simplicity and reliability. Therefore, this technology, classified as a low-temperature technology with a temperature range between 45 ºC and 60 ºC, is widely spread in the building sector. According to [55] and [56], during 2010 the solar hot water heating existing capacity in the world was 149 GW, accounting for 80 % of the solar thermal market.

In these kind of solar systems, the solar radiation is absorbed in a collector that heats a working fluid circulating through it. This heat transfer fluid can be water, air or more commonly water-ethylene glycol, which prevents the fluid from freezing. Finally, the obtained heat is directly used or stored in a tank, most of the times using a heat exchanger. The existence of a storage tank allows the system to work properly even if radiation conditions are not favorable at that moment. The amount of heated water produced by this technology depends, obviously, on the size of the system and the radiation values in the location where it is installed.

There are several possible classifications of this water heating systems, depending on the followed criteria. According to the heat transfer method used between the working fluid and the consumption point, systems can be divided in:

- Direct or open loop systems: the collector directly heats the domestic water.
- Indirect or closed loop systems: the collector heats a working fluid that transfers its energy to the domestic water in a heat exchanger. This exchanger can be inside or outside the storage tank.

It should be noted that, in areas with very low exterior temperature, indirect systems are more commonly used for avoiding the fluid freezing. However, recirculating warm water from the storage tank or draining the collector allows to prevent freezing in direct systems, if there are no system failures.

Other possible classification uses as criteria the way the fluid is circulated, i.e., if the system relies on mechanical devices or on natural circulation:

- Passive or natural systems: the fluid is moved without pumps thanks to the action of natural circulation. These thermosyphon systems are more reliable and have a longer live. However, their design is more complicated and unaesthetic as the storage tank must be in the most elevated point of the system.
- Active or forced circulation: the working fluid is pumped through the collectors and the rest elements of the system. They are usually more expensive and less efficient, as they need extra controllers since the flow rate is not in phase with the radiation levels, like in the passive configuration.

The main elements of water heating systems are, like introduced before, collectors, storage tank and heat exchanger, in case of close loop circuits. There are different kind of collectors such as flat plane, evacuated tubes, compound parabolic or integrated collector systems (ICS), where a part of the tank works as collector. Moreover, other elements are needed in these systems, including pipes, valves, several sensors, auxiliary sources and; expansion tanks and pumps, for active configurations. The auxiliary sources are used when the demand is not completely covered with the available radiation level or stored water. More details about each component of solar water heating systems, their different configurations and calculation methodology can be found in [42].

Solar space heating systems

Solar systems used for space heating have a very similar operation to water heating ones. The same basic process performs, solar collectors heat a working fluid that is later stored in a tank. From this storage tank, the fluid is circulated to the place of use, in this case for space heating. System elements are analogous to the ones explained before in the solar water heating configuration.

In this case, it is not viable to cover all the heating demand of a common building, as the system size and costs would be too high. In addition, there is no big enough storage capacity for winter. For these reasons, these systems are supported by an auxiliary heating source. It is noteworthy solar space heating systems have better results combined with solar air cooling systems, as the total efficiency becomes higher. Furthermore, their combination with solar domestic water heating systems is also popular and commonly called “combisystem”.

This kind of technology has innumerable possible configurations. The configuration depends, among other factors, on the fluid used for delivering heat to the building rooms and the fluid used to extract heat from the collector. For the heat delivering fluid, the choice varies between water, for radiant floor systems, and air, when air handling units are used. The heat transfer fluid, which circulates through the collectors, can be water, sometimes mixed with glycol, or air. Water’s heat capacity is considerably bigger as well as its convective heat transfer coefficient. As a result, water systems are cheaper, occupy less space; due to lower volume flow rates, and their collector heat-removal factor is higher. The only advantage of air systems is that they do not have freezing or corrosion problems.

Another possible combination of solar systems for space heating consists on the denominated solar assisted heat pump systems. This configuration can combine a heat pump with a solar system for space heating as well as for domestic hot water heating. Heat pumps are a good alternative as an auxiliary heating system, as their efficiency is considerably higher to gas boilers or electric heaters. In addition to this, the evaporator of the heat pump can be supplied with energy from the solar system, whose temperature is higher than the ambient, so the COP is increased. The diagram explaining how this last configuration works appears in Figure 2.21.

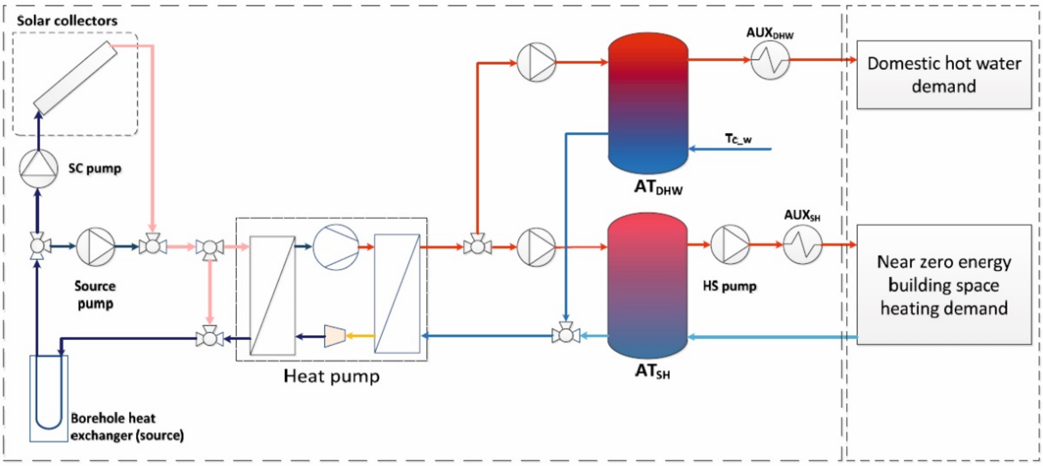

Figure 2.21. *Working diagram of a serial solar assisted ground source heat pump system.* ***[57]***

An alternative to this disposition is the parallel configuration, shown in Figure 2.22. In this case, heat pump only work when the energy obtained by the solar collectors is not enough to cover the building demand. Finally, it is also worth to mention that heat pumps can work on cooling mode in the summertime. [42] [57]

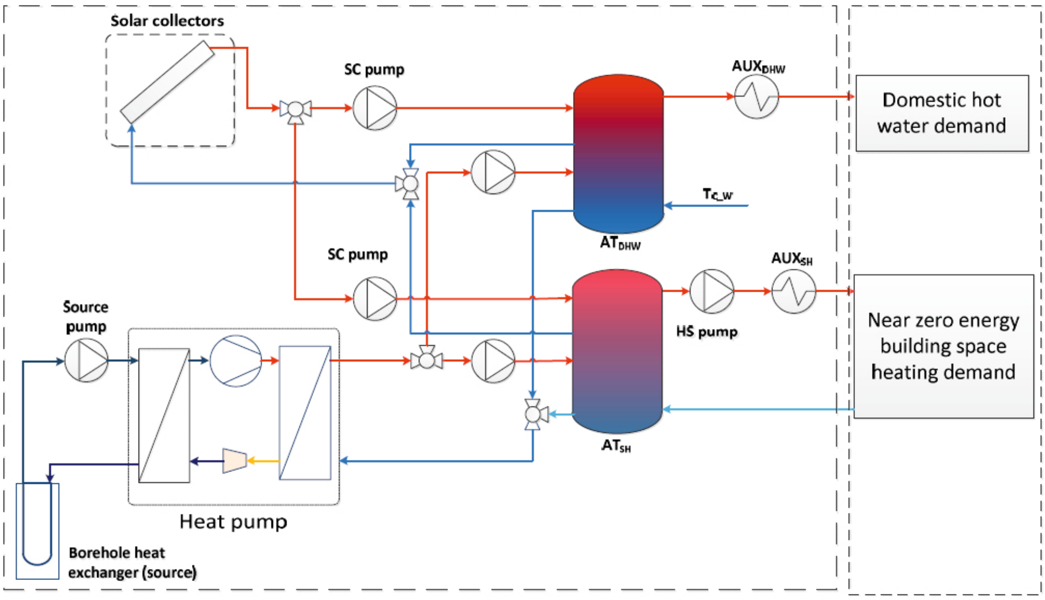

Figure 2.22. *Working diagram of a parallel solar assisted ground source heat pump system. [38]*

So far, the explained uses of solar radiation point towards heating a fluid or producing electricity in a photovoltaic panel. However, sunlight is also useful for providing space cooling employing different cycles that will be explained right after.

Solar space cooling systems

The use of solar energy as an alternative to vapor-compression cooling systems has been a deeply studied option during last decade. Main advantage of these solar systems is that the cooling load is usually in phase with the higher radiations levels over the year. Even though, this alternative has not widely spread yet due to its high costs and low efficiency. Hence, there is not a vast experience in these systems. They are mostly used in public buildings with big loads, such as shopping centers. In these places, this configuration can be viable due to their big cooling loads and thanks to its combination with solar heating systems.

Four different types of systems are most commonly used for solar space cooling, based on mechanical or sorption processes:

- Solar mechanical processes: based on the usual vapor-compression refrigeration cycle. Its main peculiarity is that the compressor is powered by electricity generated in PV-panels. This system is not very attractive because of the low efficiency and high cost of the photovoltaic panels.

- Solar absorption systems: through sorption processes, these systems avoid the compression work of mechanical process. As shown in Figure 2.23, the sun is the heat source used in these cases for reactivating the sorbent. Absorption is the most promising technology although it is still expensive as its use in small scale is still recent. Typically, there are two kind of units: ammonia – water based, where the ammonia is the refrigerant, and lithium bromide (LiBr) – water based, using water as refrigerant.

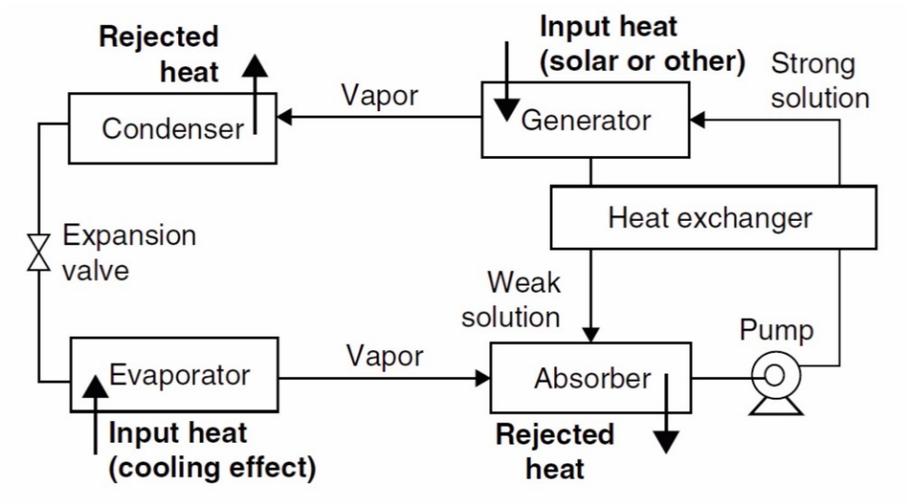

Figure 2.23. *Basic principle of absorption cooling systems.* ***[42]***

- Solar adsorption systems: in this process, it is a solid substance the one working as sorbent instead of a liquid as in the absorption systems. Most common sorption refrigeration pair is water – ammonia, however the highest efficiency is found on the activated carbon – methanol pair.
- Desiccant cooling systems: another sorption process where also an air dehumidification is carried. Several desiccant agents are used, both solid and liquid.

More information about these processes, and other options such as the use of Stirling engines or hybrid systems, can be found in this paper [58].

Geothermal heat exchangers

Geothermal energy is a renewable energy source which employs heat produced and stored deep in the ground. Part of this heat is produced by the molten core, consisting on high temperatures at high and medium depths. In addition to it, near to the surface, where temperatures are lower, it is stored heat coming from the solar radiation, easier to exploit.

One of the techniques for exploiting this resource is through geothermal heat exchangers, usually attached to heat pumps. This combined system, that enhances the efficiency of the heat pump, is usually denominated “ground source heat pump” (GSHP) or “ground heat pump” (GHP). Other possible techniques include the use of these exchangers for preheating or precooling air before common air conditioning units.

Ground heat pumps are a high-efficiency technology that uses the ground as energy source, or sink, for space heating and cooling or even for heating domestic water. As explained in [59], these heat pumps do not create heat, as conventional heating systems, but transfer it from or to the ground for conditioning a building. Moreover, this heat is multiplied thanks to the work invested through the compressor of the system.

As showed in Figure 2.24, after descending approximately 10 meters into the ground, temperature remains considerably constant over the year. This temperature is higher than the ambient during winter and lower during summer. Consequently, GHP systems can extract the stored heat during winter and give it back in summertime. Although the exact value can vary among different locations, GHPs usually work between ground temperatures of 5 ºC and 30 ºC, consisting on a viable technology in every country. [60]

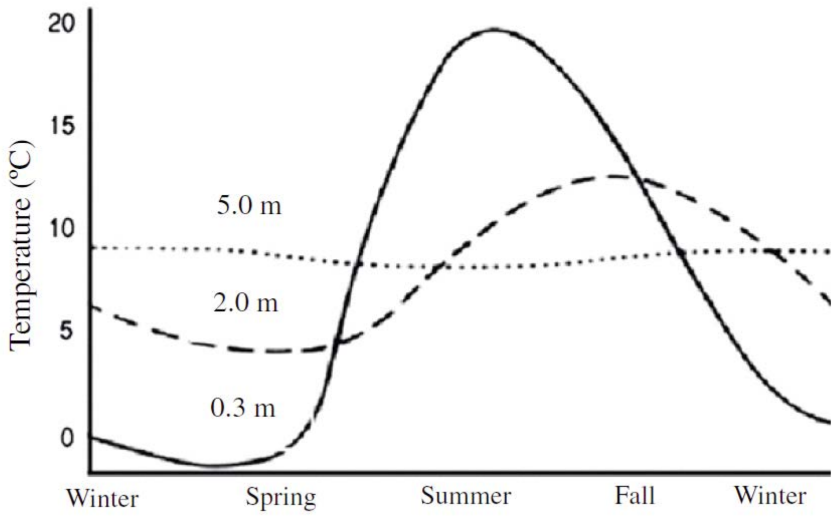

Figure 2.24. *Example of the undisturbed ground temperature along the year for different depths in Ottawa, Canada.* ***[61]***

Frequently, a mix of water and antifreeze circulates through a set of pipes in the ground in order to exploit its heat capacity. This loop extracts heat from the ground, returning the water to the exchanger of the heat pump, where, finally, it transfers thermal energy to the refrigerant of the vapor-compression cycle. The process would be reverse in the case of cooling purposes. [62] [63]

Main elements of ground source heat pump systems, which are presented in Figure 2.25, include:

- The ground loop: consisting on a horizontal piping or, more commonly, a vertical borehole. For residential buildings, vertical holes are bored between 45 and 100 meters into the ground and they usually have a diameter of 10 cm. The space between the different holes is around 5 meters in order to avoid interferences among them. [61]

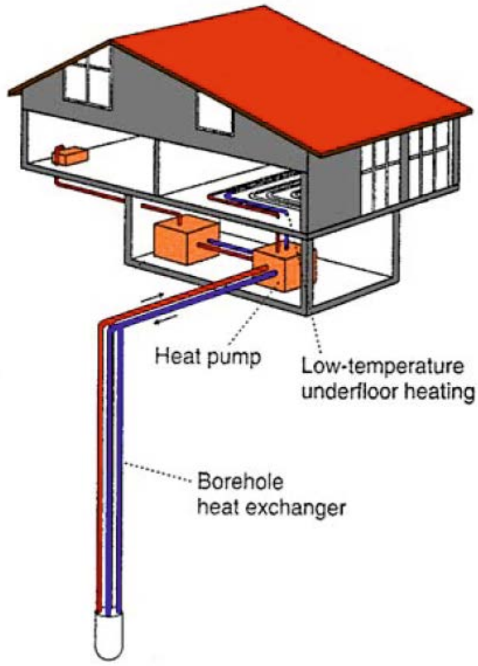

Figure 2.25. *Main elements of a typical GHP system in a residence building.* ***[60]***

- The heat pump: that operates using a basic vapor-compression refrigeration cycle. Basically, it is composed of two heat exchangers; evaporator and condenser, a compressor, an expansion valve and the refrigerant. The two exchangers can swap their function for switching between heating and cooling mode. A complete description of the thermodynamic process applied in ground heat pumps can be found in [64].
- A heat distribution system: which distributes the heat obtained along the rooms of the building. The performance of GHPs is better on low temperatures so floor heating is the best option, although radiators are also considered. According to the heat distribution system, GHPs can be classified in water-to-water or water-to-air heat pumps. Water-to-water heat pumps, which work on lower temperatures, can also supply heat to air-handling units. Their control is easier and they offer a direct output of domestic hot water. On the other hand, water-to-air heat pumps are a better choice when each zone of the building requires a separate control. However, their maintenance is more complicated and they need an extra heat exchanger. This extra exchanger, called “desuperheater”, provides domestic hot water, as shown in Figure 2.26.

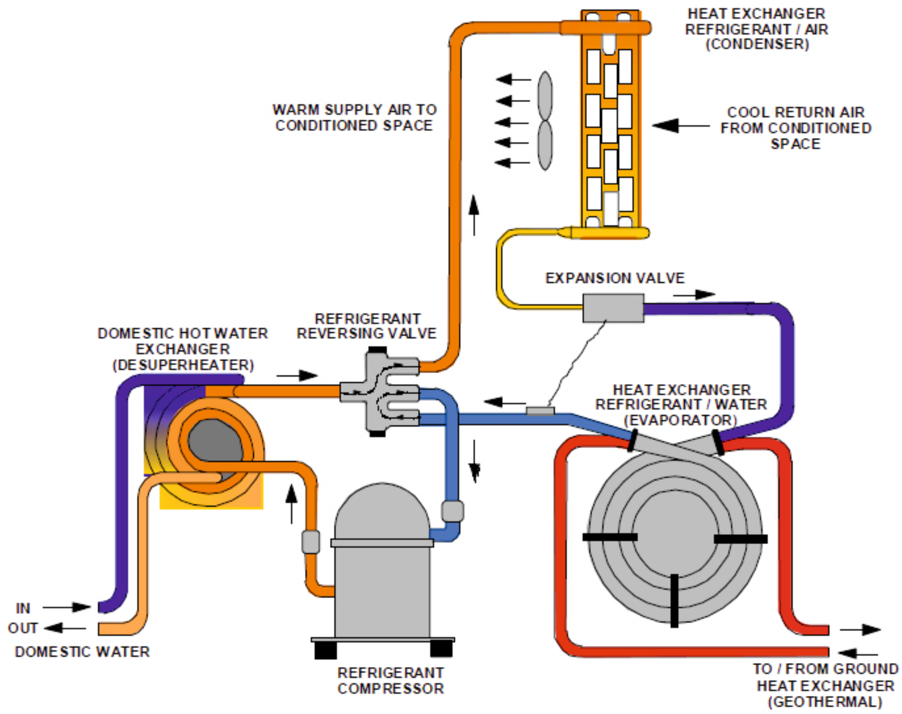

Figure 2.26. *Layout of a water-to-air GHP on heating mode.* ***[60]***

In order to calculate the efficiency of these systems, different factors must be taken into account. These factors include characteristics of the system, such as the bore depth, and characteristics of the ground, such as its temperature and its variability. The efficiency of these heat pumps is considerably high in comparison with conventional heating systems. Electricity is only used for powering the pumps and compressor, obtaining between three and six times more thermal energy than the electrical energy inverted. For example, a GHP could use 100 kWh of electricity to transform 200 kWh of freely available heat in the ground into 300 kWh of heat suitable for space heating. The main difference with common air-to-air heat pumps is that they use the ambient air, colder in winter and hotter in summer, as a heat source or sink. As a result, these air-to-air heat pumps have lower efficiency. However, the installation costs are higher in the case of GHPs. [61]

Ground heat pumps are a widely spread technology and it has been proved to be a reliable choice for approaching zero-energy buildings. This kind of heat pumps means around 71 % of the world-wide installed thermal power, which was approximately 70 GW at the end of 2014 [65].

Micro-wind turbines

Wind turbines are considered as micro-wind turbines when their swept area is less than 25 m^2 and their power capacity lower than 25 kW. This technology is applied as turbines mounted on buildings or integrated into them. Micro-wind turbines on buildings propose many new challenges comparing with stand-alone turbines or wind farms.

Those challenges include the mounting method, how vibrations affect the integrity of the building, how shadows and noise affect people's comfort, esthetic issues and bird strikes. In addition, the studies necessary to check the viability of the installation are too expensive and time-consuming for small projects. Moreover, there is a considerable difficulty in estimating the yield of this technology on a reliable way, as current methods are not robust on urban zones. As a result, this technology is not widely spread, having a noncompetitive cost per unit of produced electricity compared to wind farms or other renewable sources. [66] [67]

Nowadays micro turbines can be classified into two categories, depending on the position of their shaft:

- Horizontal Axis Wind Turbines (HAWTs), whose blades' position is radial to the shaft, like in traditional windmills. This type is still the most widespread even if it is maybe not the optimal one.
- Vertical Axis Wind Turbines (VAWTs), which is less used currently. This kind of turbine could be a better solution as their performance is higher than HAWTs under the turbulent flows found in buildings. There are several configurations including Darrieus and Savonius types. The first kind is a lift-driven turbine consisting of two or more airfoil-shaped blades. The second one, with a simpler design, consists of two semicircular blades, as can be seen on Figure 2.27. Savonius turbine has lower efficiency, however it can produce energy from lower wind speeds and its design is cheaper.

Figure 2.27. *Horizontal axis wind turbine (left), vertical axis Darrieus wind turbine (center) and vertical axis Savonius turbine (right).* ***[68]***

The topography and the shape of the buildings heavily influence wind velocity and turbulence intensity. Therefore, disturbed flows around buildings could provoke higher speeds at some points. One last micro-turbine category, Building Augmented Wind Turbines (BAWTs), make the most of this concentration phenomenon. These turbines are placed on those extra-speed points or even buildings are designed in a way that the wind is concentrated at their position. [68] [69]

There are several issues to solve or to improve until wind turbines become an attractive solution in zero-energy buildings. Therefore, once dealt with noise and vibration complications and longer developed vertical turbines, wind energy could increase its share in building energy generation.

Micro-hydro power

Hydropower is one of the most extended renewable energy sources, generating around 20 % of the electricity consumed in the world. Its application to nZEBs is reduced to the denominated pico-hydro generation, which has proved to provide good results in hybrid systems. However micro-hydro generation could be also considered for a big group of buildings. The general classification sets that pico-hydro systems cover power capacities until 5 kW while micro-hydro has capacities lower than 100 kW. Furthermore, pico-hydro applications are more suitable in this context as low-head sites are more common. These run-of-river installations have a negligible environmental effect because they do not require big dams.

Pico-hydro generation is the most cost-effective renewable source when applied in off-grid systems. Therefore, it is a popular solution for least developed countries where a grid connection is usually expensive. In addition to this, other factors make it especially suitable for these countries. These factors include easy on-site manufacture of the equipment and that maintenance can be performed by the costumer.

Water turbines transform the pressure in water into mechanical energy, which can be finally converted to electricity in an induction generator. The quantity of energy generated by these systems depends on the amount of available water and the variability of its flow. Turbines applied in this framework are characterized by their working principle, the necessary civil work and power capacity. The most commonly used turbines are Pelton, Turgo, crossflow turbines and pumps used as turbines, more information about them and different possible configurations are found in [70].

If hydropower systems continue their development, they will be an attractive option for supplying building loads. Meanwhile, the main goals are to improve their affordability and lower their maintenance needs through low-cost durable turbines. [71] [72]

Biomass and biofuels

Biomass is an abundant renewable energy source presented in many forms. Several of them are currently being used in the world, included wood, agricultural crops and residues such municipal solid waste and animal waste. Their main purposes are electricity generation, space heating and biofuel production.

The products considered inside the biofuel category are biodiesel and bioalcohol, this one includes bioethanol and biobutanol. The first, biodiesel, is produced by chemical conversion while the second ones are the result of biological processes. However, biofuels are more used in the transport sector. Solid biomass is the one having an important role in space heating and domestic hot water in the building sector. [73]

Biomass is considered environmental friendly as its net emissions are lower than those of fossil fuels such as coal, oil or gas, even having into account all their manufacture process. In addition to this, biomass is considered as carbon neutral. This means that it closes the carbon cycle initiated by plants, as schematically presented in Figure 2.28. Moreover, it is considered a kind of energy valorization as, in many of its origins, it means a transformation of waste that was going to be disposed. Nevertheless, the use of biomass is socially controversial as, occasionally, there is a competition between producing energy or food in some parts of the planet.

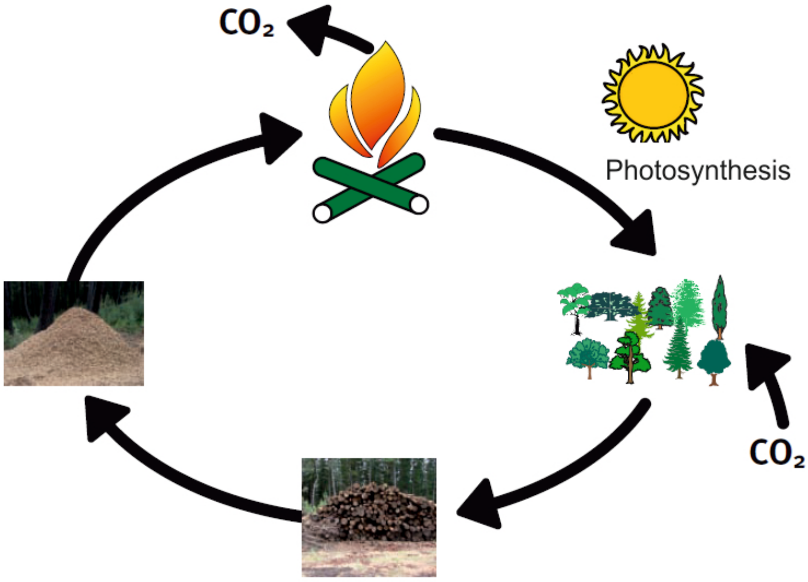

Figure 2.28. *Carbon neutral cycle of biomass. (Adapted from* ***[74]****)*

Among solid biomass, pellets are replacing conventional firewood. Furthermore, they have proved to be a better choice compared with willow chips, peach stones, industrial wood waste and others. The use of pellets made biomass a competitive renewable resource. Their main advantages are lower fuel consumption, easier storage and operation and no need to dry the fuel [48]. In addition, they are a good choice in terms of emissions compared with oil and gas, as presented in Figure 2.29. Finally, they also have a good performance in hybrid systems with solar thermal technologies, reducing emissions and the amount of fuel needed, as shown in [75].

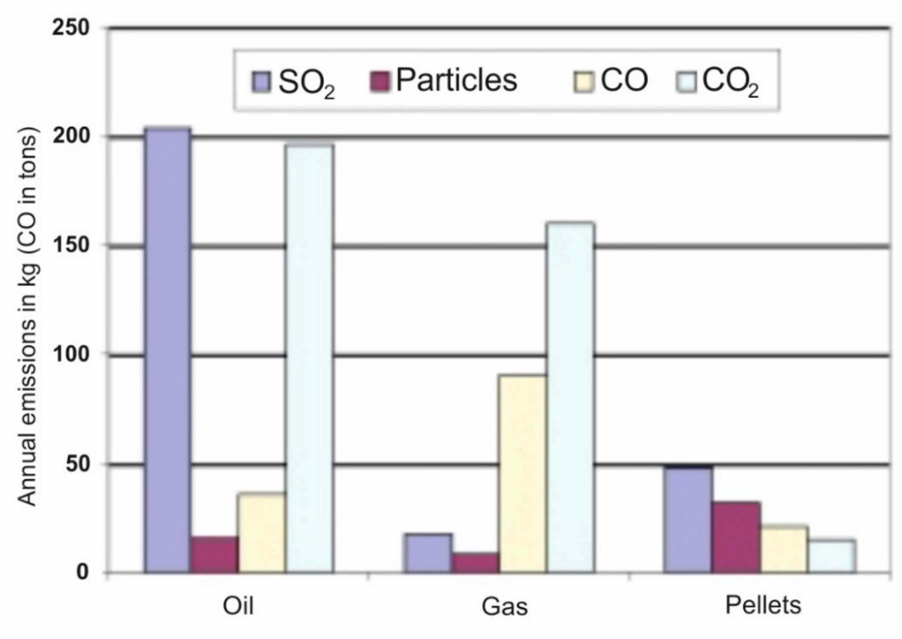

Figure 2.29. *Life-cycle emissions comparison of different fuels. (Adapted from* ***[76]****)*

The application of biomass in building heating relies on the combustion process. Conventional fireplaces are not efficient anymore, and their emissions are too high. As a result, new automatic boilers have been developed during the last twenty years. These new technologies make of biomass heating systems a clean and durable technology really easy to operate. However, these systems have a high capital cost that makes necessary some kind of financial incentives most of the times. [77]

3. CASE OF STUDY

3.1. Building location

The present study places the analysed building in two different locations: Finland and Spain. Selected cities are the capitals of each country. Helsinki (60º N, 25º E) and Madrid (40º N, 4º W) are located in the south and centre of the respective countries as showed in Figure 3.1.

Figure 3.1. *The two selected locations pointed on the map of Europe.* ***[78]***

From an energy point of view, both locations are highly differenced by their climate as well as by their building regulations. The main goal of this study is to analyze nearly zero-energy buildings. As commented in other chapters, regulations will adapt to the concept of nZEBs. Therefore, throughout the study, building regulations are not strictly considered. However, some useful data from the codes will be contemplated such as typical domestic water consumption or reference light and appliances electricity consumption.

Air temperatures and solar radiation over the building are very influencing in the results of energy simulations. Therefore, the climate is a critical parameter when simulating the behavior of a building. Helsinki climate is classified as humid continental. It is characterized by short days in winter and long days, up to 19 hours of light, during summer.

Average monthly temperatures vary during the year from -6 ºC in winter to 16 ºC in summertime. On the other hand, Madrid is considered to have a Mediterranean climate, with some continental influence. Average daily sunshine is 12.7 hours, considerably higher than the 8.7 hours in Helsinki. In this case, average temperatures are also higher, with a minimum of 5.4 ºC in January and a maximum of 25 ºC in July [79]. In Figure 3.2, average daily air temperature is compared in both location as well as monthly global solar radiation.

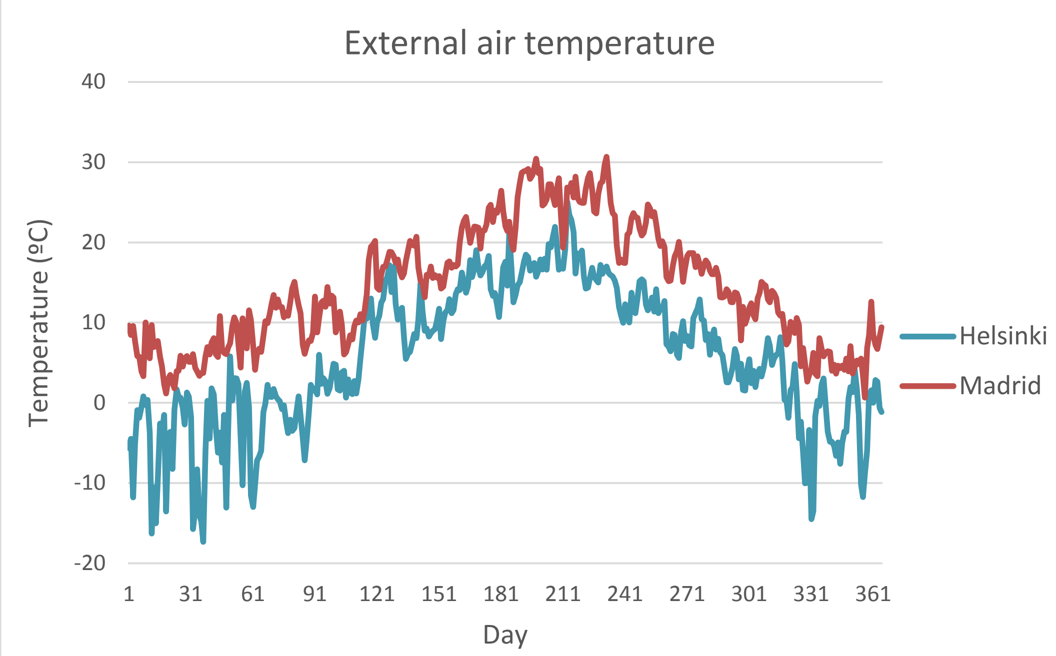

Figure 3.2. *External air temperature during the year in both studied locations.*

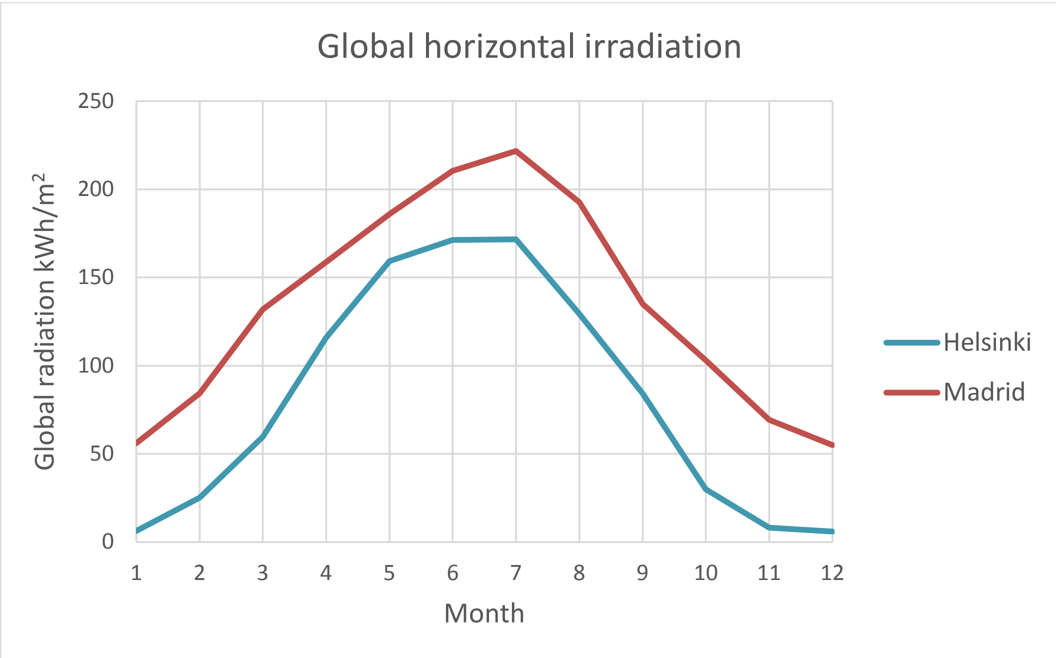

Figure 3.3*. Global horizontal radiation during the year over both studied locations.*

The data used to elaborate the charts above belongs to the same weather files used in the simulations of this study. In the case of Helsinki, this file contains reference weather data for Vantaa in 2012. In the case of Spain, the file is the ASHRAE International Weather for Energy Calculations (IWEC) data for Madrid.

3.2. Building definition

The studied building is a single-family house. This kind of building is very representative among dwellings in Finland, and not so rare in Spain. According to [80], almost 70 % of the Finnish population live in single-family houses. As well, the choice is conditioned by the ease of its definition, which allows to focus on the nZEB balance concept. A brief summary of the house properties can be found in Table 3.1.

Table 3.1. *Reference building main properties.*

Locations	Helsinki and Madrid
Floor area	150 m^2
Total window area	22.2 m^2 (15 % of the floor area)
Azimuth of the southern façade	0 º
Internal height of the rooms	2.6 m

The house consists of one only floor with an area of 150 m^2 oriented to the south, with several similarities to that studied in [81]. As shown in Figure 3.4, the dwelling is divided into two only rooms. In this simplified approach, one of the rooms represents the living areas, facing the south, while the other represents the bedrooms. Each one of the rooms will be affected by different use profiles. As can be obtained from Figure 3.4, the glazing area represents the 15 % of the floor area. Finally, the internal height of the rooms is 2.6 m.

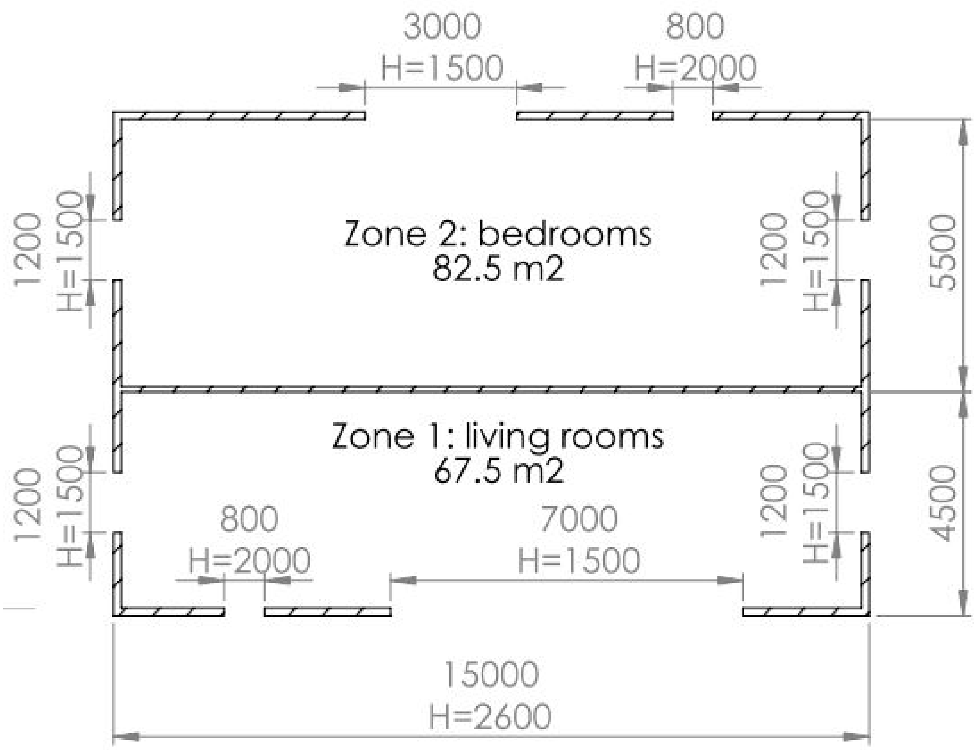

Figure 3.4**. Top view of the studied single-family house.* ***[81]

Internal gains due to people, light and appliances have been set according to the National Building Codes of each of the locations. As a consequence, in Madrid, the average internal gain is 4.25 W/m^2 for bedrooms and 5.3 W/m^2 for living rooms, while for Helsinki these values are 4.5 and 5.6 W/m^2 respectively. Furthermore, the DHW consumption has been calculated using equations provided by both building codes. As a result, the daily DHW consumption is settled as 140 liters in Spain and 246 liters in Finland. For these calculations, it has been assumed 5 people living in the house, according to the usual 0.033 people/m^2, and a storage temperature of the water of 60 ºC in Spain or 58 ºC in Finland.

3.2.1 Building thermal envelope

The optimization method applied for studying nZEBs starts improving the performance of a basic building, as it will be explained later. This building is called the reference building and implements recommendations related to the envelope appearing in the National Building Codes of Spain and Finland. According to this, the main properties of the thermal envelope are shown in Table 3.2 for both locations.

Table 3.2. *Thermal performance of reference buildings studied in Spain and Finland.*

	Spain, Código técnico de la edificación. DB HE 2013.	**Finland, Rakennusten energiatehokkuus, Määräykset ja ohjeet. D3 2012**
	U-value (W/m^2K)	
Walls	0.27	0.17
Roof	0.22	0.09
Floor	0.34	0.16
Windows and exterior doors	1.7	1.0
	Other values	
Infiltration q50 (m^3/hm^2)	2	2

In the Table 3.2, it can be observed the higher requirements of the Finnish envelope, obviously due to weather conditions. It is worth to mention that U-values in reference buildings are around 48 % better to those found in residential buildings constructed between 2000 and 2008, as shown in Table 3.3.

Table 3.3. *Comparison between U-values of the reference building and buildings constructed during the period 2000-2008. Data obtained from* ***[82]****.*

	Spain		**Finland**	
	Construction between 2000-2008	**Reference building**	**Construction between 2000-2008**	**Reference building**
	U-value (W/m^2K)			
Walls	0.8	0.27 (-66 %)	0.26	0.17 (-35 %)
Roof	0.54	0.22 (-59 %)	0.18	0.09 (-50 %)
Floor	0.7	0.34 (-51 %)	0.28	0.16 (-43 %)
Windows	3.1	1.7 (-45 %)	1.5	1 (-33 %)

Table 3.3 proves how requirements have improved over the years and its importance towards the implantation of nZEBs. Yearly simulations have been run for these refer-

ence buildings with standard systems using DBES model, which will be deeply explained in future chapters. The results are shown in Figure 3.5.

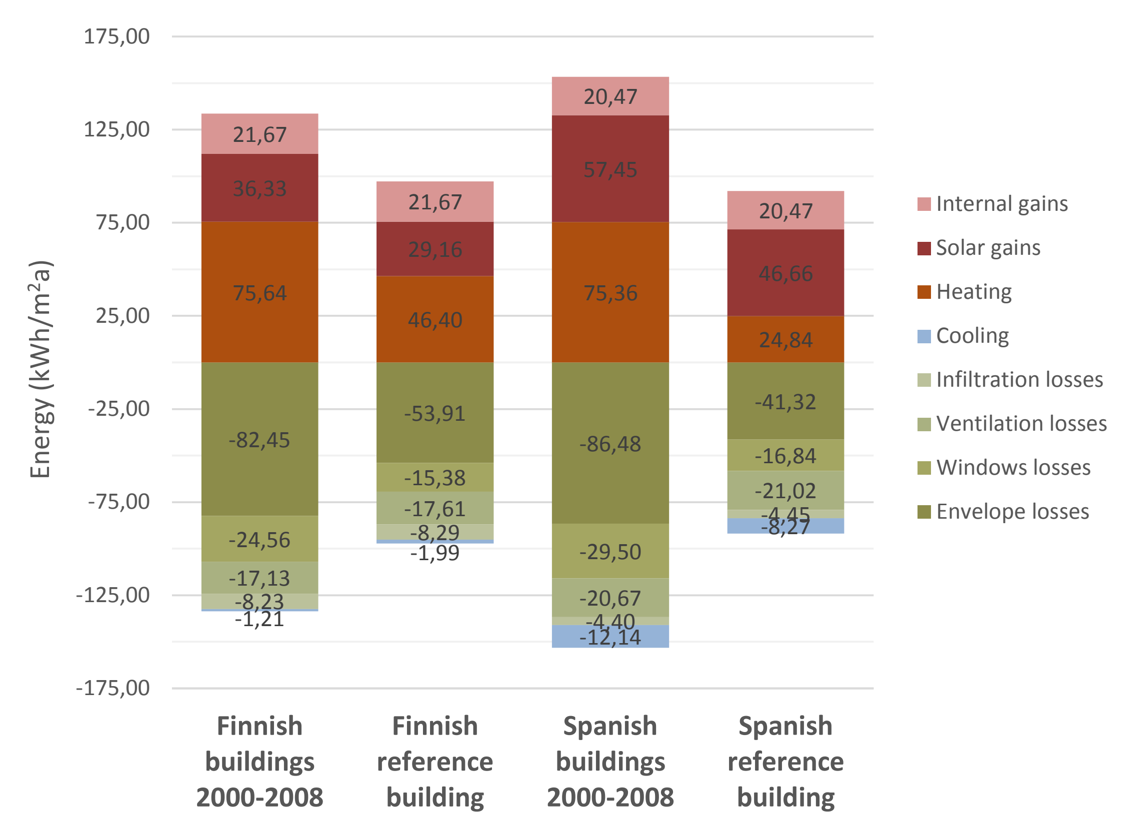

Figure 3.5. *Yearly balance of reference buildings and buildings constructed during the period 2000-2008 in Finland and Spain.*

These results show how the improvement in envelope requirements decreases heating and cooling demands.

3.2.2 Building technical systems

Above, it was explained the layout and envelope properties of the reference building. For completely defining a reference building, it is necessary to describe the systems it includes. These systems are related to space heating and cooling, domestic water heating, lighting and appliances.

Lighting and appliances consumptions have been taken into account according to the Finnish National Building Code. Therefore, the consumption is about 1050 kWh/a for lighting and 2370 kWh/a for appliances. A brief study of the consumption of different high-efficiency appliances was carried using data from Spanish suppliers. The results pointed to a very similar yearly consumption to that settled by the Finnish code.

There are several options for space and water heating and all of them will be studied separately. These options include air to air heat pump or district heating, both coupled with solar collectors for DHW, and ground source heat pump hybrid systems. Comfort inside the building is defined in base for the operative temperature, therefore the set points for heating and cooling are 21 ºC and 27 ºC respectively. In the paragraphs below, a brief definition of each of the heating systems applied is proposed.

District heating system

As showed in Figure 3.6, this system consists of two district heat exchangers, one for DHW and other for space heating. In addition, hot water storage connected to the solar collectors supports both DHW pre-heating and space heating.

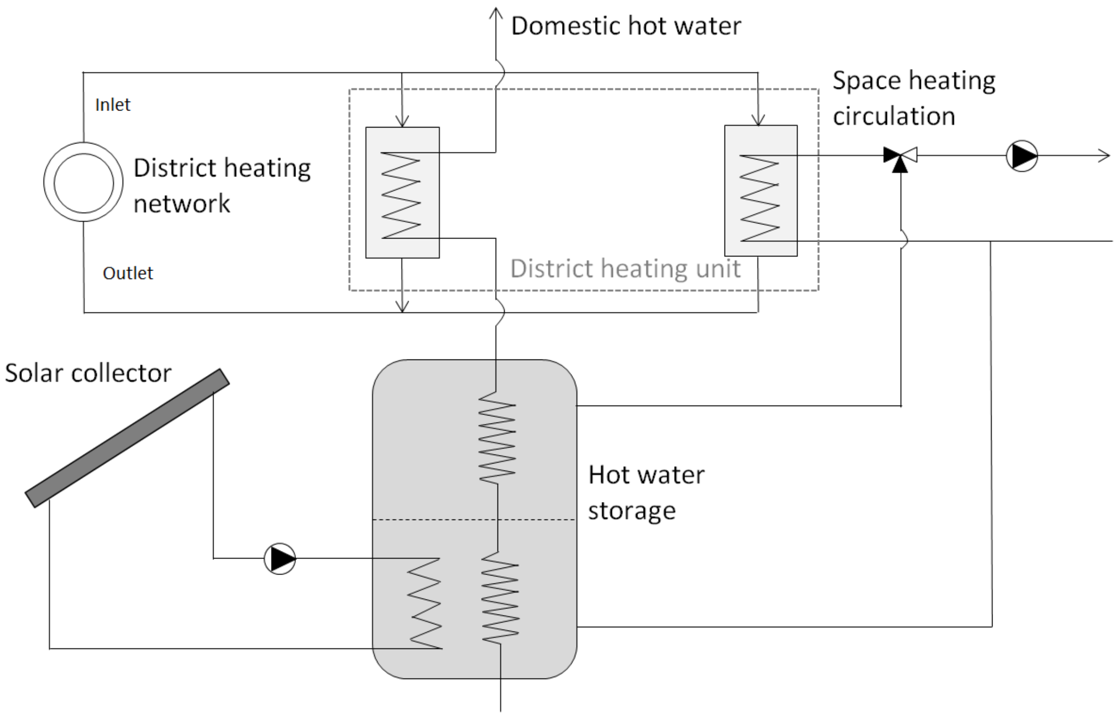

Figure 3.6. *District heating system coupled to solar collectors.* ***[81]***

The cooling load is provided by a standard air to air heat pump connected to the air handling unit.

Ground heat pump with domestic hot water storage

Performance of ground source heat pumps has already been explained in previous chapters. In this case, the heat pump provides service to both DHW and space heating. However, it cannot do it simultaneously. Heating domestic water is prioritized, therefore a small buffer storage for space heating is included, as can be seen in Figure 3.7.

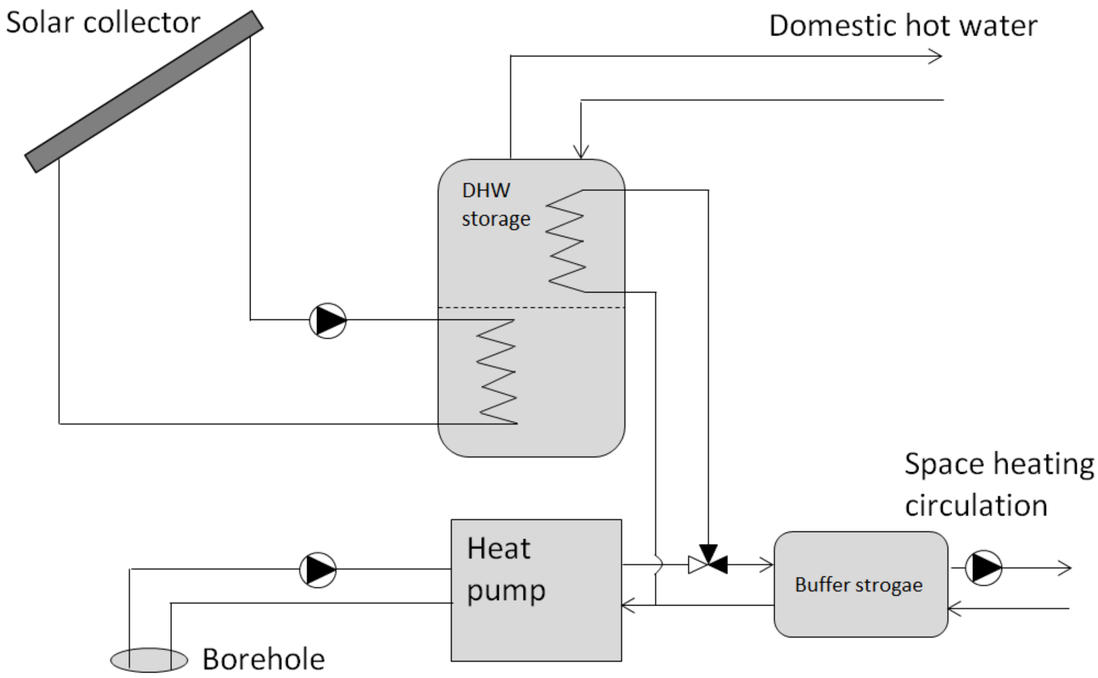

Figure 3.7. *Ground heat pump with DHW storage coupled to solar collectors.* ***[81]***

In this case, the cooling load is provided using free-cooling. This means that, during summer, water coming from the ground exchanger is pumped to the air handling unit, bypassing the heat pump.

Air-to-air heat pump system

This system consists of two separated installations. The air heat pump heats or cools air and sends it to the rooms. Separately, an electrical heating coil provides service to small DHW storage, also supported by solar collectors. It is worth to mention that as air is used to provide heating, the heating efficiency is lower than when using circulated water. Therefore, it is frequently needed to use electrical radiators, which cover around 25 % of the heating load. A diagram of the installation is shown in Figure 3.8.

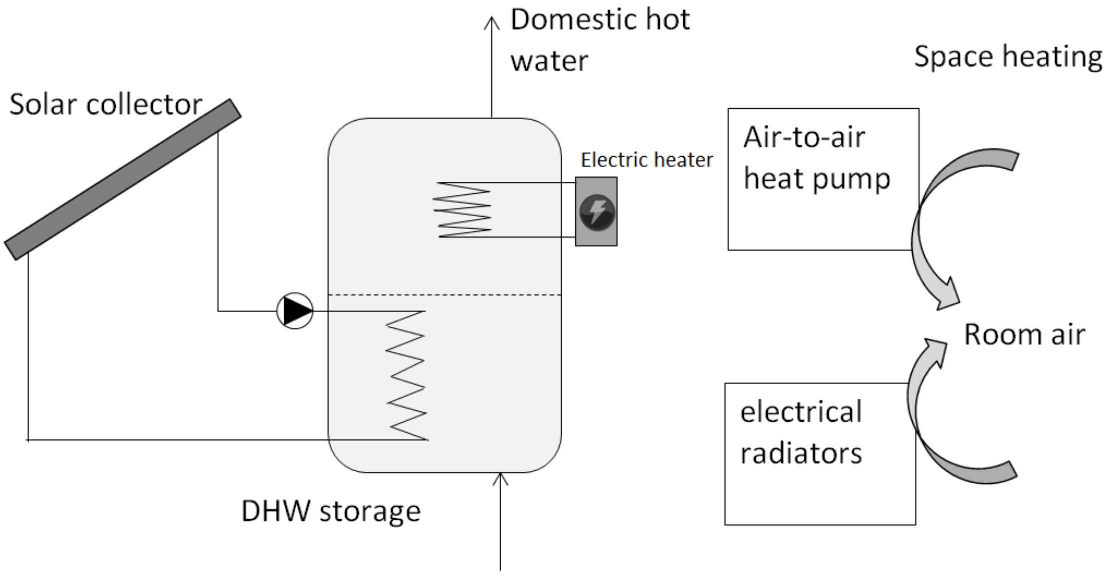

Figure 3.8. *Air to air heat pump system couple to solar collectors.* ***[81]***

In addition to HVAC systems, another system has been included in the study related to renewable on-site energy production. **Photovoltaic panels** will be considered in buildings analyzed. These panels are supposed to have a standard efficiency of 15 %. This is equivalent to approximately 6.6 m^2 of panels to achieve 1 kW of installed capacity. The efficiency of the PV system is considered 82.5 %, already including a 96 % efficiency inverter. This efficiency values are the standard ones according to [83]. Panels are oriented to the south with a tilt angle that depends on the locations. This angle is the one with optimal results, 40º in Spain and 60º in Finland.

4. RESEARCH APPROACH AND METHODS

4.1. Building energy simulation

As introduced before, the results of this study come from several simulations of the performance of buildings with different parameters. These simulations are accomplished by computer software. This kind of software, called building energy simulation programs, predicts heating, cooling, ventilation, lighting and water use in a building. Moreover, it allows to optimize the characteristics of a building in order to find optimal energy or cost solutions.

The inputs of a building model are abundant in order to provide a precise prediction. One of these inputs is the location of the construction, this will settle the use of specific weather data. As well, it is important a proper definition of the building: floor plan, orientation, construction materials and envelope properties. Other concepts like internal gains and airtightness are also important. These inputs allow the program to calculate the thermal loads, in order to maintain comfort inside the building. Finally, it is necessary an exact definition of the systems implemented in the building. These systems are related to space heating and cooling, ventilation, domestic water, lighting and appliances. Thus, a prediction of final energy consumption can be done from the previously calculated energy demand. Other outputs can be expected, such as cost calculation and optimization results, depending on the chosen software. More details about how these models work will be explained in the next subchapter, while describing the used software.

A long list of commercial building simulation programs can be found in [84], some of the most used in research are Energy Plus, DOE-2 and TRNSYS. However, this study does not employ any of those commercial program. The selected software is called Dynamic Building Energy Simulation (DBES) model. The election of this model is conditioned by the ease that Matlab provides in the optimization process design. Moreover, this study tries to prove the usability and precision of DBES model itself.

4.1.1 Dynamic Building Energy Simulation model (DBES)

Dynamic Building Energy Simulation (DBES) model is a Matlab based program developed in Tampere University of Technology (TUT). The program runs hourly simulations in order to predict the behavior of a building. These simulations are heat balance-based and depend on provided inputs defining the building, systems, weather and comfort requirements. DBES performance is validated according to two different European Standards: EN15255 and EN15265.

A complete description of DBES model can be found in [81]. However, it will be provided a brief description of the program structure, its inputs and outputs and the theory lying behind it: transient model and heating systems model.

First step on a year simulation in DBES is to load all the inputs of the building and weather data. Subsequently, the program calculates the hourly radiation over each surface of the building. Finally, an hour by hour simulation is performed. Each simulation starts by calculating the building heat balance and air handling unit balance. In order to do that, it is necessary to fetch the external conditions for that step. The result is the space and AHU heating and cooling demand. This demand is the input to the heating system heat balance. If this demand is too high for the heating system, it will perform at its maximum power and the heat balances will be recalculated from the beginning. At the end of the step, the results are stored. After running the whole simulation, yearly results are calculated. The structure of the program is shown as a flow chart in Figure 4.1.

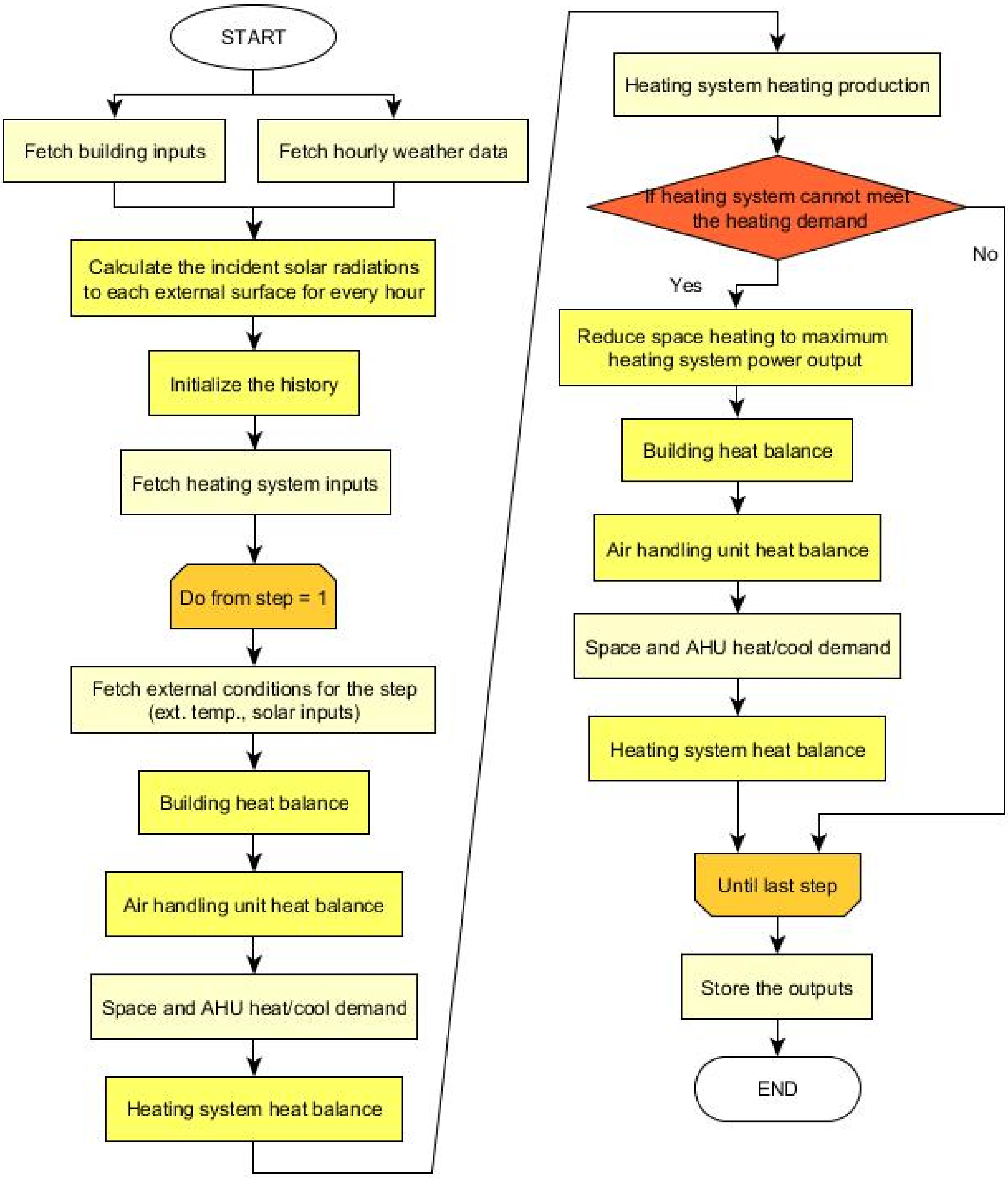

Figure 4.1. *Flow chart of the main process for DBES program.* ***[81]***

As listed in [81], the inputs and outputs of DBES program are the following.

- Building inputs:
  - Geographic location and orientation.
  - Properties of external and internal surfaces (convective heat transfer coefficient, emissivity, absorptance and reflectance).
  - Size of every room and connections among them.
  - Size and position of windows and doors
  - Properties and schedule of solar shadings (external or integrated to windows)

  - Thermal properties of all the structure elements
  - Time distribution and level of the internal heat gains (convective and radiative)
  - Infiltration rate
  - Ventilation type, schedule and airflow rate
  - Scheduled air or operative temperature control
  - DHW and space heating and cooling system type and properties.
- Building outputs for every hour:
  - Average air and operative temperatures in (°C)
  - Space heating and cooling power demand in (W)
  - Internal heat gain power in (W)
  - Solar heat gain in (W)
  - Windows loss in (W)
  - Infiltration loss in (W)
  - Ventilation loss in (W)
  - Facades' losses (walls, windows and doors separately) in (W)
  - Ventilation's supply air pre-heating and pre-cooling demand in (W)
  - Ventilation's heat and cold recovered in (W)

The theory where DBES model relies is based on a transient heat transfer model. Transient heat balances are performed for every hour and every room, including the air and all the surfaces. These balances are calculated using the response factors method developed by Mitalas and Arseneault [85]. Moreover, these factors are calculated by TASE program, developed in TUT [86] [87] [88] [89].

In order to perform all the transient heat balance calculations, DBES must also calculate other elements. For example, the boundary conditions of the building, influenced by the weather and solar heat gain through glazing. Furthermore, the view factors must be calculated as well as the ventilation and heat recovery processes.

Finally, DBES includes three heating system models. These models supply space heating and cooling and heat for domestic water. These three systems, with the option of coupling them with solar collectors, are district heating, ground heat pump; which includes three different configurations, and air to air heat pump. More details about the heating system models can be found in [81].

4.1.2 Implementation of photovoltaic system simulation

In previous chapters, it was described the importance of photovoltaic energy production for achieving the nZEB concept. It was also discussed the most important factors influencing the performance of solar arrays. Consequently, it is necessary to implement a photovoltaic production model into the global building simulation, in this case, into DBES model.

For this study, the solar model PVWatts has been selected among different solar models that were accessible. This model is provided by the National Renewable Energy Laboratory (NREL), part of the U.S. Department of Energy.

The implementation in DBES model, which as explained before runs under Matlab, relies on the SAM Simulation Core (SSC), whose software development kit (SDK) provides one wrapper for Matlab language. Therefore, it is possible to call PVWatts model from DBES model, using SCC. This SAM Simulation Core is the main library of the program System Advisor Model (SAM), also provided by NREL, which makes electricity generation predictions for grid-connected power projects. [90] [91]

PVWatts estimates the hourly electricity production of a photovoltaic system from an irradiance input and some parameters defining the system. To do so, it uses several interrelated sub-models which calculate sun position, total irradiance on the plane-of-array (POA), cell temperature and the global efficiency of the system.

The photovoltaic model assumes some typical module and inverter characteristics, however it still needs to be feed with some inputs, including [92]:

- System DC size or nameplate DC rating (P_{dc0}): total nameplate capacity of the array, usually specified by the manufacturer as the power in kilowatts at standard test conditions (STC). This value will be set in the Excel Input sheet of DBES model.
- Location: it is needed to load the specific weather data and calculate the movement of the sun. Obviously, this location variable will have the same value that the one provided for DBES model calculations.
- Total irradiance on the plane-of-array: although PVWatts can calculate this data by itself, from the weather data and location, in this implementation the hourly irradiance will be directly provided to the model. This irradiance on the array is calculated by DBES model, so same exact data will be used for calculations in both models.
- System efficiency (ε_{sys}): it represents the overall system performance, taking into account all system losses explained previously. This factor will take a value between 0 and 1, usually 0.825, and it is set in the code of the Matlab function

running PVWatts. The system efficiency value is obtained from a combination of typical values for the different system losses, as explained in [83].

- Module parameters: as said before, some module properties are assumed by PVWatts but the following ones must be manually set. All of them are specified in the Matlab code:
  - Module temperature coefficient (γ): representing the loss of efficiency in the module due to increase of the cell temperature comparing to the reference one. It usually will take values near to -5 %/ºC.
  - Tilt of the array: exact tilt from the horizontal of the array, this value is optimized for the location selected for running the model.
  - Azimuth: this angle shows the orientation of the array and it is the angle clockwise from the north. Most of the times, it will set to 180º, i.e., facing to the south.
  - Nominal operating cell temperature (NOCT) of the module: temperature of the module under certain operational and weather conditions that will be fixed at 45 ºC, normally. [50]
  - Reference cell temperature (T_{ref}) and reference irradiance (G_{ref}): it is respectively set at 25 ºC and 1 kW/m^2 for STC conditions.

The PVWatts model includes other variables and functions that have not been used in this implementation, such us the inclusion of tracking systems. The main function developed and implemented into DBES model can be found in Appendix A.

According to what has been explained before, it is understandable how the model computes the output DC power of the array (P_{dc}):

$$P_{dc} = \frac{G_{poa}}{G_{ref}} P_{dc0} \left(1 + \gamma \left(T_{cell} - T_{ref}\right)\right) \tag{3}$$

where it is observable how the array efficiency decreases at a linear rate as a function of the cell temperature.

As mentioned before, after this calculation it is necessary to take into account the system losses using system efficiency as follows:

$$P'_{dc} = P_{dc} \cdot \varepsilon_{\text{sys}} \tag{4}$$

where P'_{dc} represents the DC power after taking into account the system losses. Finally, PVWatts applies the inverter efficiency, obtaining the final AC power output (P_{ac}).

In addition, the implementation developed for this study includes the efficiency of the modules, which as explained in previous chapters is near the 15 %. This way, the total area of the array is visible in the DBES Excel input sheet as a result of the set nameplate DC rating.

Running the model for year in a basic system, 1 kW system DC size and basic properties, provides an idea of the global performance of the photovoltaic systems (Table 4.1). The selected places for these simulations are Helsinki and Madrid, the tilt angles are 60º and 40º respectively and the orientation of the arrays is south in both cases.

Table 4.1. *Performance results of a photovoltaic system in Helsinki and Madrid, simulated with PVWatts implementation in DBES model.*

	Helsinki	**Madrid**
Annual Yield (kWh/kWp)	876.3	1355.2
Produced annual energy per square meter (kWh/m^2)	131	203.3

The higher performance values for Spain demonstrate the importance of solar irradiation and weather data in the simulated location. These results are very close to those obtained using System Advisor Model and other models, such as PVGIS or PVSyst [93] [94] [95].

4.1.3 Other modifications in DBES model

During this subchapter, the modifications implemented inside the code of DBES model will be introduced. These modifications are not related to that additional code that was necessary to perform the specific calculations about nZEBs, which will be explained in the next subchapter.

These modifications are associated to the addition of a new location to DBES. Performing simulations in Madrid meant a considerable amount of changes in DBES code. The basic changes are related to the addition of Madrid coordinates in the calculations and the inclusion of IWEC Madrid weather data files. These data are the result of ASHRAE Research Project 1015 in several locations of Europe, as explained in [96]. In addition, it was necessary to change the input files of DBES so they offered the new location as an option.

Placing a building in a complete different location also means to adapt the simulation approach to the conditions there. There is no sense in applying an envelope previously design to face Finnish winter on a house in Madrid. For this reason, new response factors were created using TASE program. These response factors belong to windows and structures, such as façades, ceilings and floors. In order to create these new factors, a brief study about the typical Spanish structures and windows used in Spain was made. As a result, new structures and windows meeting Spanish Technical Code requirements were added to DBES, as well as several other structures for cost-optimal calculations. One example of the composition of a typical façade under Spanish requirements and which parameters are necessary for its definition in TASE are shown in Table 4.2. In addition, the inputs to creat new windows in DBES can be found in Table 4.3. Along DBES code and during the calculations for this study, the structures and windows meeting the requirements or recommendations of a Technical Building Code are tagged as “recommended”.

Table 4.2. *Inputs for TASE program. Layer composition and properties of a "recommended" wall in Spain.*

Structure code name: recommWall270					
	d (m)	λ (W/mK)	ρ (kg/m^3)	c_p (J/kgK)	R (m^2K/W)
Surface resistance of exterior side	0	0	0	0	0.07
Perforated brick	0.115	0.76	1600	1000	0
Air Gap	0.03	-	-	-	0.1
Mineral Wool	0.107	0.035	50	1030	0
Double hollow brick	0.07	0.49	1200	920	0
Plaster	0.015	0.3	800	920	0
Structure total U-value	0.27 W/mK				

Table 4.3. *Inputs for DBES model. Properties of a "recommended" window in Spain.*

Window code name: recommWindow17	
Type of glazing	Double
Solar heat gain	0.57
Transmission (τ)	0.52
Fraction of frame	25 %
Glass U-value	1.8 W/Km
Frame U-value	1.3 W/Km
Window total U-value	1.7 W/Km

In Table 4.2, it is shown how some parameters are not needed by TASE program, mainly, the exact properties of the air inside the air gap. It is also worth to notice, that there are other layers included in the structure of façades but they are not relevant from the energy point of view. For that reason, they are omitted, facilitating TASE calculations.

Finally, another important modification in DBES code is related to the cooling loads. DBES model calculated the cooling load necessary to maintain comfort inside the building. In the case of Finland, this load is very low, even negligible. For that reason, in the majority of single-family houses in the country, there are no air-conditioning installations. According to this, the heating system code in DBES model did not calculate final energy consumption for covering these loads. However, in Spanish conditions these loads are considerably higher. Deeply modeling the performance in the cooling mode of the different systems included in DBES is outside the scope of this study. Therefore, it was done a research about common efficiencies among cooling installations in both countries. The cooling systems studied are highly efficient as they will belong to low energy buildings. These efficiencies, shown in Table 4.4, where implemented in DBES code so it finally provides an approximated energy consumption for covering cooling loads.

Table 4.4. *Coefficient of performance of the cooling systems for studied locations.*

	Madrid	**Helsinki**
Air to air heat pump (3 kW)	5.8	6.9
Geothermal free cooling	7	7

In previous chapters it was mentioned how new values representing Spanish users' behavior was added to the model. These values refer to DHW and lighting electricity consumption. Regarding to this, DBES model did not take into account the electricity consumption of appliances in the building. This consumption is important when studying nZEBs so it was added to the model, as well. In addition, internal heat gains were settled according to Spanish Building Code recommendations.

Heating system parameters were optimized for working in a Finnish location when developing DBES. Therefore, some of them were modified to operate closer to Spanish values, improving system efficiencies. For example, the water storage temperature was raised to 60 ºC and the cold inlet water was set at 12 ºC, typical conditions in Madrid.

Finally, few small bugs were found and solved along DBES code. These bugs did not provoke significant errors in the results for Finnish simulations. However, they became visible when simulating for Spanish buildings. For example, the definition of an insufficient water flow for space heating when floor heating was used. However, most of the times bugs were related to mistyped variables.

4.2. Approaching to nearly net zero-energy buildings

Along this study, nZEB buildings were defined and also different techniques that can be applied to achieve a low-energy building. Finally, the main goal of this thesis is to analyze nZEBs using a simulation environment. This analysis consists on evaluating how several parameters of the building affect its behavior. These parameters include location, characteristics of the envelope, used heating systems and implemented renewable energy sources.

The analysis will always focus on optimizing the energy behavior of the building. However, it is also important to have into account the costs of this process. These costs include investment in energy saving techniques or high-efficiency systems and, obviously, the cost of the energy consumed.

Therefore, two final parameters will define a low-energy building: annual consumed energy, which is the chosen meter as will be discussed later, and annual costs. The next step is to optimize the building characteristics in order to find the ones minimizing energy consumption and costs. These are the cost-optimal calculations proposed by the EPBD in order to settle new building regulations. The expected results should look similar to those showed in Figure 4.2.

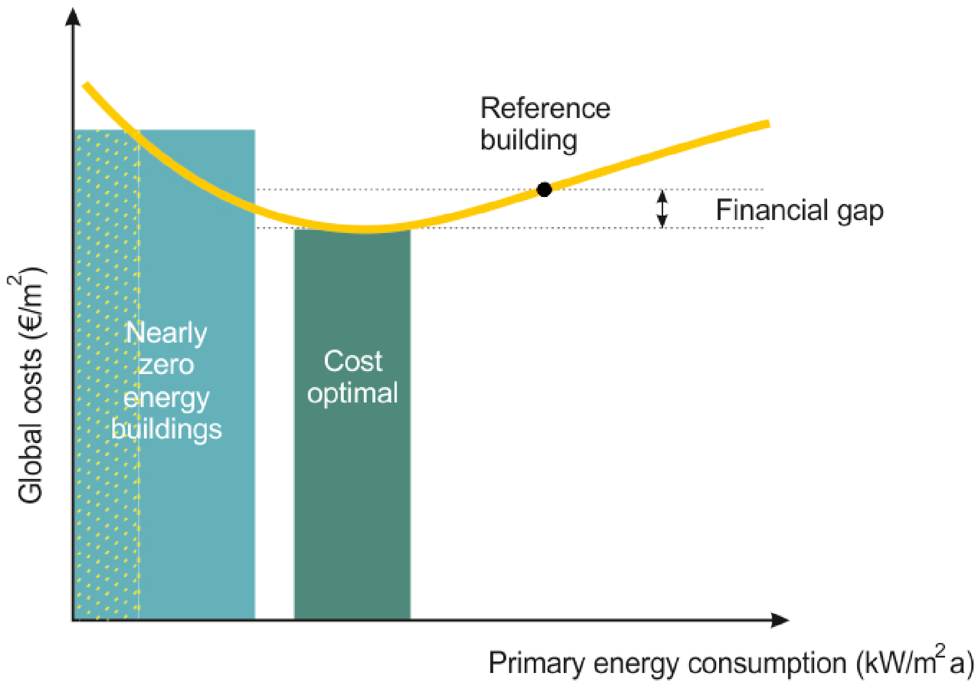

Figure 4.2. *Cost-optimal solutions and nearly zero-energy buildings depending on global costs and primary energy consumption.*

This graphic shows how there is a financial gap where investing in reducing the energy consumption means a reduction in global costs on an annual basis. Once made that investment, the building is in its cost-optimal situation. If the investment continues towards a nearly zero-energy building situation, the costs will increase. The area shown in Figure 4.2 around the cost-optimal solution represents where the new minimum performance requirements should be placed. The width of this area, and the one representing nearly zero-energy buildings, should be settle depending on how strict the regulation is about the nZEB concept. Most likely, the investment needed to reach nZEB situation will be always beyond the cost-optimal. As explained in previous chapters, that extra investment should be funded by the state.

In following subchapters, it will be discussed the exact nZEB definition used in this study as well as the process applied to make the cost-optimal calculations. Some additional studies will be introduced. These studies are considered necessary defining the basic nZEB or to be helpful for interpreting the final results.

4.3. Applied nZEB definition

The main decisions to take in order to settle a nZEB definition are related to the boundary, the meter and the period of study. These terms were deeply explained at the beginning of this thesis. The definition was chosen trying to be the most convenient and also similar to those found in the research community in order to compare final results.

Regarding to the boundary, studied nZEBs will consist on only one residential building occupied by 5 people and located in Helsinki or Madrid. Its interaction with the grids will be limited to electricity, two ways interaction, and heat, in the case of district heating systems being used. Comfort conditions are defined through set points with operative temperatures of 21 and 27 ºC. Finally, the balance boundary takes into account all heating, cooling, ventilation, lighting and heating domestic water processes. In addition, appliances are included in order to avoid extra measurements in a theoretical future monitoring procedure. Also concerning the boundary, the only energy renewable sources considered are rooftop PV-panels and solar thermal collectors. These are the most extended technologies in the building sector for both of the studied locations. Therefore, the considered sources can be classified as on-site and available within the footprint of the building.

The chosen meter, as most of researchers suggest, is primary energy or source energy. Thus, the type of energy and its background is taken into account in the energy balance. The weighting factors are those proposed by Spanish and Finnish codes, presented in [97] and [98], which are shown in Table 4.5. As can be observed, the weighting factors are supposed to be symmetric and not time-dependent, in order to simplify the calculations.

Table 4.5. *Official primary energy weighting factors in Finland and Spain.*

	Finland	Spain
Electricity	1.7	2.423
District heating	0.7	0.7*

**No weighting factor is defined for district heating in Spain. However, values do not vary too much among different countries in Europe. For this reason, same weighting factors as in Finland has been applied.*

In order to use a *deliver/exported* energy balance, a reliable self-consumption model must be employed. This is not the case of DBES mode. Therefore, as in most of nZEB studies, *load/generation* balance was applied. The calculations were made in an annual period in order to take into account all operational and weather conditions. Although the prices used in the cost prediction will be explained later, it is worth to mention that not embodied energy was considered, in favor of simpler calculations.

4.4. Cost-optimal calculations

The used methodology follows a similar process to those found in the research [97] [99] [100]. The procedure used can be seen in Figure 4.3. The study starts from a reference building, which applies minimum requirements of the regulations in the studied location. Firstly, the design variables that will be involved in the optimization are selected. Combining several values of those variables, multiple different candidate buildings are created.

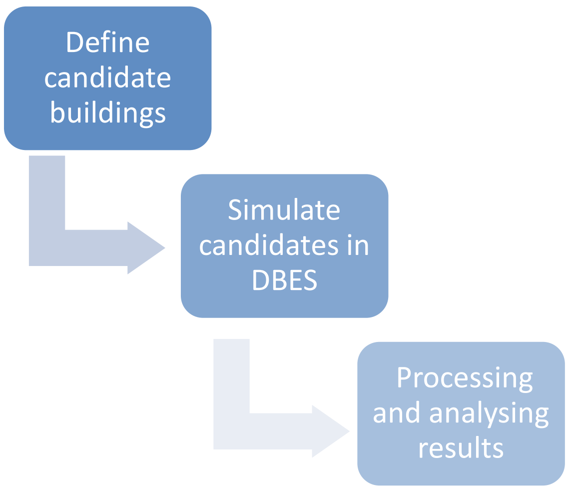

Figure 4.3. *Flow chart of the cost-optimal analysis.*

Secondly, the behavior of all those buildings is simulated using DBES program. Finally, the last step consists on extracting the necessary results and analyzing their meaning.

This process is performed in each step of the multistage methodology employed in the cost-optimal calculations. This methodology will be introduced below, just after explaining each action inside one stage.

4.4.1 Definition of candidate buildings

A candidate building is a theoretical construction with specific properties. The behavior of this building will be studied to examine the effect of varying those properties. After defining the basic candidate, the first step is to decide which ones are going to be those design variables.

The basic candidate building will be the reference building defined before. This building has been designed taking into account common advice for passive housing. As a result, it tries to maximize the solar gains during winter. Therefore, it has a rectangular shape with its longer façade facing south. Moreover, the south façade implements most of the house glazing. Finally, shading devices have been installed in these southern windows to prevent excessive gains during summer. Due to the limitations of DBES model, other passive techniques had to be neglected.

After this basic design, most decisive properties affecting the energy performance of a building are those related to its envelope and systems. Therefore, selected design variables are related to thermal transmittance of the envelope, airtightness, efficiency of the heat recovery system and, finally, the used heating and cooling system. These variables are also the chosen by several studies in the field.

In the case of the thermal transmittance, the optimization study performed using DBES model in [101] suggests that the quality of all envelope components should evolve in the same direction. For example, there is no sense in improving the insulation in the floor but not in the façades or ceilings. On the contrary, U-values in ceiling, floor, façades and windows must keep a similar level. For this reason, these variables have been grouped in one only design variable called “envelope package”. This strategy is also defended and adopted in [100] and [102]. As it is shown in Table 4.6 and Table 4.7, four packages are studied with rising U-values in their components.

Table 4.6. *Envelope packages for the U-values of the candidate buildings in Spanish location.*

Spain	Envelope package 1	Envelope package 2	Envelope package 3	Envelope package 4
Floor	0.27	0.2	0.15	0.1
Ceiling	0.22	0.15	0.1	0.07
Façade	0.34	0.2	0.15	0.1
Window	1.7	1	0.7	0.7

Table 4.7. Envelope packages for the U-values of the candidate buildings in Finnish location.

Finland	Envelope package 1	Envelope package 2	Envelope package 3	Envelope package 4
Floor	0.17	0.14	0.11	0.08
Ceiling	0.09	0.08	0.07	0.05
Façade	0.16	0.14	0.12	0.1
Window	1	0.7	0.7	0.6

It is worth to mention that, although windows are represented by their U-value, their solar factor and number of glazing were also modified when improving their quality. Finally, each one of the packages was created as a Matlab variable containing the set of elements.

The next two design variables are airtightness and heat recovery efficiency. In this case, the same values for both variables will be studied in Helsinki and Madrid, as shown in Table 4.8.

Table 4.8. *Airtightness and heat recovery efficiency values for candidate buildings in Helsinki and Madrid.*

Infiltration q50 (m^3/hm^2)	4 | 2 | 1 | 0.5
Heat recovery efficiency	45 % | 65 % | 75 %

The values of the design variables were selected with a starting point on those of the reference building. The infiltration rate is an exception. The value 4 m^3/hm^2 was added, after analyzing some results, to properly check the tendency of the airtightness effect over the cost and energy consumption.

One of the few variables left is the one related to heating, cooling and energy generation systems. As explained before, three different systems are considered. Moreover, each of those three systems will be studied with and without solar collectors. In the case of using solar thermal energy, two parameters of these systems have been optimized: water storage volume and solar collector area. The optimization was done through several DBES simulations aiming to maximize the obtained solar thermal energy. However, it must be cared not to produce more heat than necessary during summertime and not to have excessive temperatures in the storage during the year. As a result, storage volume is 300 liters and collector area 2 m^2 for buildings in Madrid. In Finnish buildings, optimal parameters depend on the heating system. For ground source heat pump systems and district heating, values are 400 liters and 5 m^2, while for air-to-air heat pump systems they are 400 liters and 4 m^2.

It is worth to mention that the power capacity of heat pumps has been set near to the maximum load of the building. As a result, the air to air heat pump for Spain has 3.5 kW capacity and for Finland 3.2 kW. Ground source heat pumps have in both cases 6 kW capacity due to the limitations of the market. In addition, GSHP also heat domestic water so their capacity must be slightly higher.

Finally, the design variable for photovoltaic systems is the area of the panels. This value has been considered in order to achieve a specific performance level on candidate buildings. It is worth to mention, that the photovoltaic simulation module in DBES model can be run separately from the rest of the building model. As a result, a considerable amount of time is saved. The function “**pvchanger**” is responsible for running this part of the model and apply the new PV results over already simulated buildings. In addition, this function was developed to find the exact PV-panel area needed to make zero the annual energy balance or to reach a certain level of performance. This script can be found in Appendix A.

The default method for providing DBES program with inputs is through an Excel file. This method can be convenient when analyzing only one building. However, in the case of analyzing more than one thousand buildings, it is unfeasible to modify one by one those Excel files. For this reason, a new input method has been developed for this study. This new method consist on a simple modification in the main script of DBES. After this modification, DBES loads inputs from a selected Matlab file instead of an Excel file.

For creating these input Matlab files, a new function was built. This function, called "**buildingcreator**", generates multiple input files according to a specific range of values of design variables. As a result, by just entering the design data appearing on the tables above in this function, input files for the entire population of candidate buildings will be created. The complete code of the building creator function can be found in Appendix A. Lastly, all this input files will be handled to another function in order to simulate each of the buildings, as it will be shown in the next subchapter.

4.4.2 Simulation process

Once the input files of the candidate buildings are available, it is time to simulate each of them. The DBES program is designed by default to simulate one only building. New measures have been taken so DBES can simulate a bunk of buildings without user's intervention. However, firstly cost and primary energy consumption calculations and their implantation in DBES will be explained.

The calculation of primary energy is very simple once known the weighting factors proposed by each country. Equation (5) was incorporated to a new "**PrimEC**" function, shown in Appendix A. This function is now implemented in the main module of DBES code.

$$PEC = C_{DH} \cdot w_{DH} + C_{el} \cdot w_{el.in} - G_{PV} \cdot w_{el.out} \tag{5}$$

In this equation, *PEC* stands for annual primary energy consumption and *C* for the annual energy consumption of each of the carriers, including electricity and district heat. G_{PV} stands for annual generation of photovoltaic electricity. Finally, the weighting factors are expressed by *w*, where the subscript represents the carrier: district heat or electricity, including consumed and generated. Each one of the elements of Equation (5) is obtained from DBES results in order to calculate the annual primary energy consumption. Once again, the function is presented in Appendix A.

Another function, available in Appendix A, has been implemented concerning the cost calculation. This function adds costs related to building investment, including in thermal envelope and systems, and energy consumption costs. In addition, it takes into account the earned money due to electricity generated by photovoltaic panels. "**CostCalc**" function uses the list of prices shown in Appendix B. Prices for Finland are similar to those proposed in [101], while the ones for Spain are the result of a market study. The current valued-added tax (VAT) in each country, 24 % in Finland and 21 % in Spain, has been applied during the calculations.

It is worth to mention that, in the elaboration of this cost table, many assumptions were done. For example, as the district heating market is not widely spread in Spain, it was not possible to obtain prices from manufacturers. In the case of district heat installation, the same prices as in Finland have been adopted in Spain. However, the energy price was set different. The price adopted was 100 €/MWh corresponding to small cities in Finland [103]. This price is higher than prices in big cities like Helsinki.

Investment costs were annualized over 30 years with and interest rate of 3 % for the calculation [97] [104]. The capital recovery factor, shown in Equation (6), has been applied on each of the items appearing in Appendix B, but energy prices.

$$Capital\ recovery\ factor = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{6}$$

In the equation above, n stands for the calculation period and r for the interest rate. The effect on the results of these two parameters will be studied.

It is also important to notice that the calculated costs only include those costs related to energy related measures. Therefore, the absolute value of the total costs is only useful for comparison purposes.

Once DBES is able to calculate costs and primary energy consumed, everything is settled in order to simulate the annual behavior of candidate buildings. As mention before, DBES is configured by default only to run one building. "**metaZEB**" function was created in order to simulate a defined group of candidate buildings. This function can be analyzed in Appendix A.

4.4.3 Data extraction for results analysis

The DBES program presents annual results separately for each building in an Excel file. For analyzing the results of the cost-optimal study, it would be convenient to extract the necessary data from those output files and gather them in a new sheet.

New designed function called "**zebdataextractor**" loads a group of building results files and extract from them specific data. This data includes annual heating and cooling loads, primary energy consumption and costs. In its last step, the function writes all this data in a new Excel file that gathers all the results for the candidate buildings.

Finally, all candidate buildings have been simulated and their results presented in one only file. Therefore, everything is prepared to analyze the results of the cost-optimal calculation.

4.4.4 Multistage methodology

There are six design variables, including the possibility of not installing solar collectors, with multiple values to be studied. This makes a total of more than 1100 candidate buildings for each location. Average runtime in DBES is about 3 minutes. Therefore, simulating every candidate building would take more than 4 days. That is unnecessary because many of those buildings are obviously far from being cost-optimal. For this reason, a multistage methodology has been developed, similar to that found in [97].

The multistage methodology consists, in this case, of three successive steps or stages. First stage focuses on the performance of the building itself, without considering the behavior of heating systems or photovoltaic panels. Therefore, candidates simulated vary only those design variable related to envelope package, airtightness and heat recovery efficiency. These simulations were configured with an air-to-air heat pump system as it is the one with the shortest runtime. It is worth to mention that the results of these candidate buildings include the cost of that heat pump. However, this is not a problem as only a comparison among costs is needed. Once simulated all 48 candidate buildings of this first stage, their results are analyzed. In this analysis, those buildings with lower costs all along the resulted primary energy range are selected to be studied in the second stage. Building creator function was design to be able to create new combinations only for those selected candidates.

The second stage of the methodology focuses on the performance of different heating and cooling systems. Each of the buildings selected in stage one is simulated three times, one for each of the studied heating systems. The same procedure is followed afterwards. The results are analyzed and those buildings with lower costs are selected to be studied in the final stage.

The third and last stage consist on implementing photovoltaic panels on cost-optimal solutions from the second stage. Thus, this local energy source allows buildings to achieve certain nZEB performance level. Running photovoltaic module, DBES manages to find the optimal PV-panel size for reaching the specific primary energy goal and study the effect on global costs.

It is worth to mention that other studies, such as checking the convenience of installing solar collectors, can be performed following a similar multistage procedure. Figure 4.4 is a chart presenting the flow along the cost-optimal methodology including main functions and their inputs and outputs.

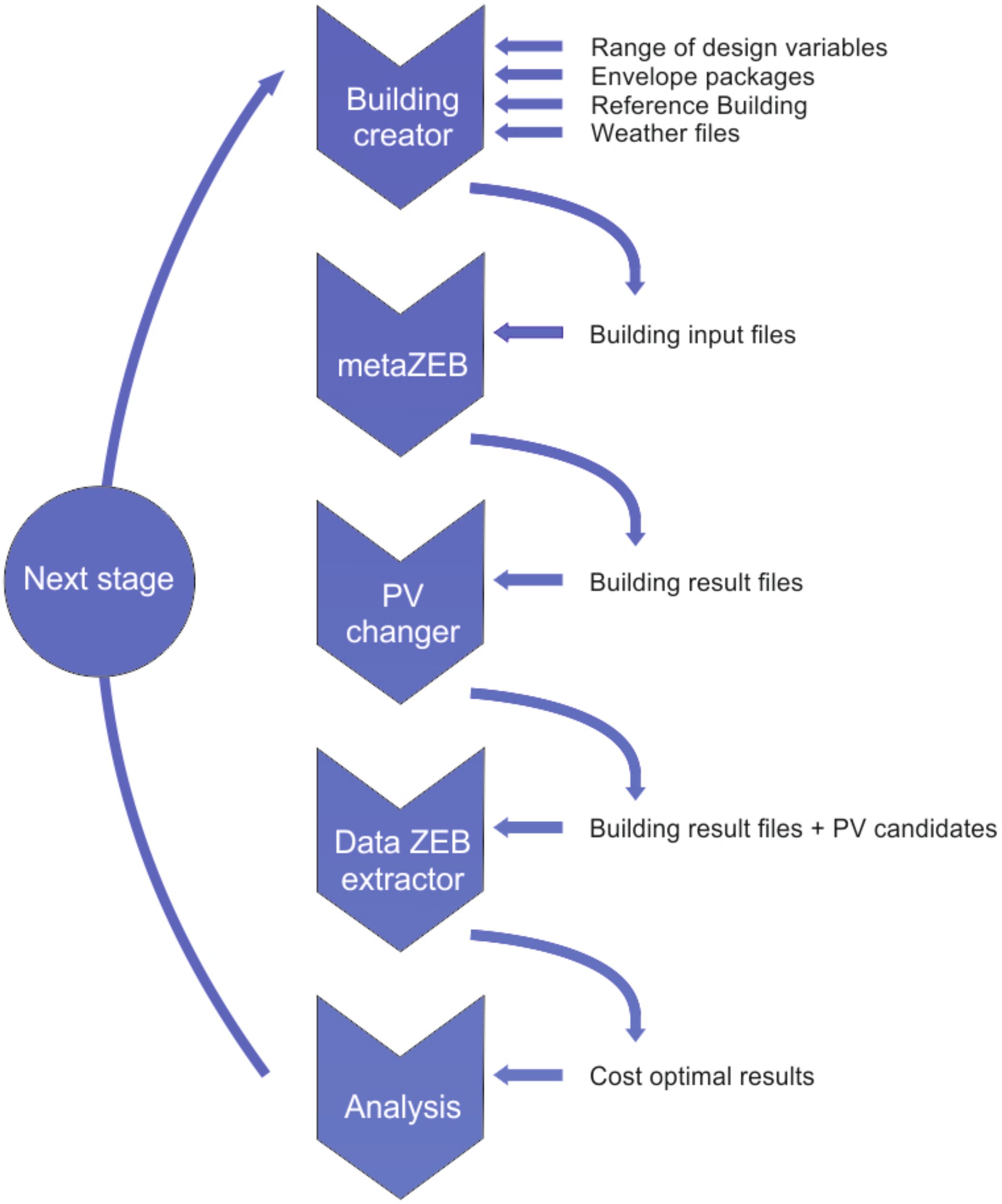

Figure 4.4. *Flow chart of the cost-optimal methodology in DBES.*

5. RESULTS AND DISCUSSION

The goal of this thesis is to find the specific configuration of building design, thermal envelope properties and HVAC systems, which results in a very low-energy building with reasonable costs. In order to do that, cost-optimal calculations have been performed seeking for results showing how improving the energy performance of a building affects its costs.

Results in this chapter are presented following a path towards this final goal. This path consists mainly in the three explained steps of the multistage methodology applied. However, several additional studies must be performed in order to understand and discuss results provided by the model. At the end, further analysis checks the sensitivity of the results to several parameters.

5.1. Stage 1: Optimal design of thermal envelope and heat recovery system

First stage of the cost-optimal methodology seeks cost-optimal candidate buildings disregarding the performance of their heating and energy-supply systems. Therefore, Stage 1 only takes into account combinations of different envelope packages, airtightness and heat recovery efficiency. The efficiency of the heat recovery system has been included because it affects directly heating and cooling loads of the buildings, a similar decision was taken in previous investigations [105].

For this first step of the methodology, forty-eight candidate buildings were simulated for each location. Before presenting the results of all those buildings, it is interesting to observe how each design variable affects the energy performance. For example, Figure 5.1 and Figure 5.2 show how the envelope package is related to different heat losses in the reference building.

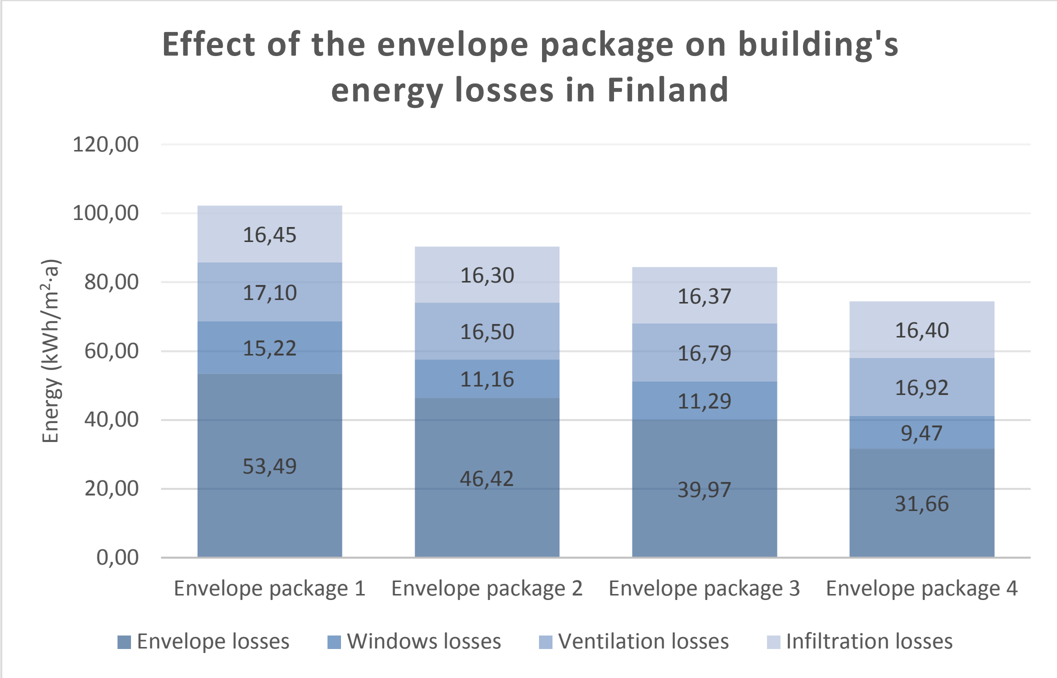

Figure 5.1. *Energy losses in Finnish reference building depending on the envelope package.*

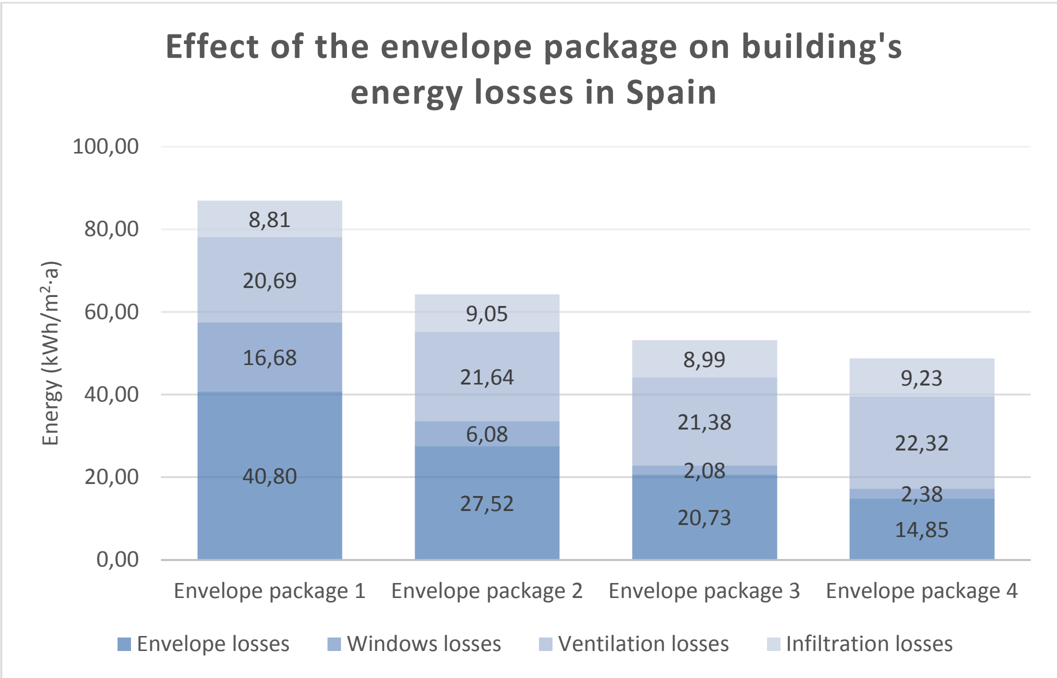

Figure 5.2. *Energy losses in Spanish reference building depending on the envelope package.*

In order to settle a framework for these graphs, reference buildings and envelope packages were described in Table 3.1, Table 4.6 and Table 4.7. In these graphs, we can see how energy losses decrease when improving envelope packages. As only the properties of the envelope are modified for this analysis, ventilation and infiltration losses maintain a similar level in all simulations. In addition, the relative improvement from one package to other depends largely on how packages were defined. Reducing heat losses along the year will affect heating and cooling loads, as can be seen in Figure 5.3 and Figure 5.4.

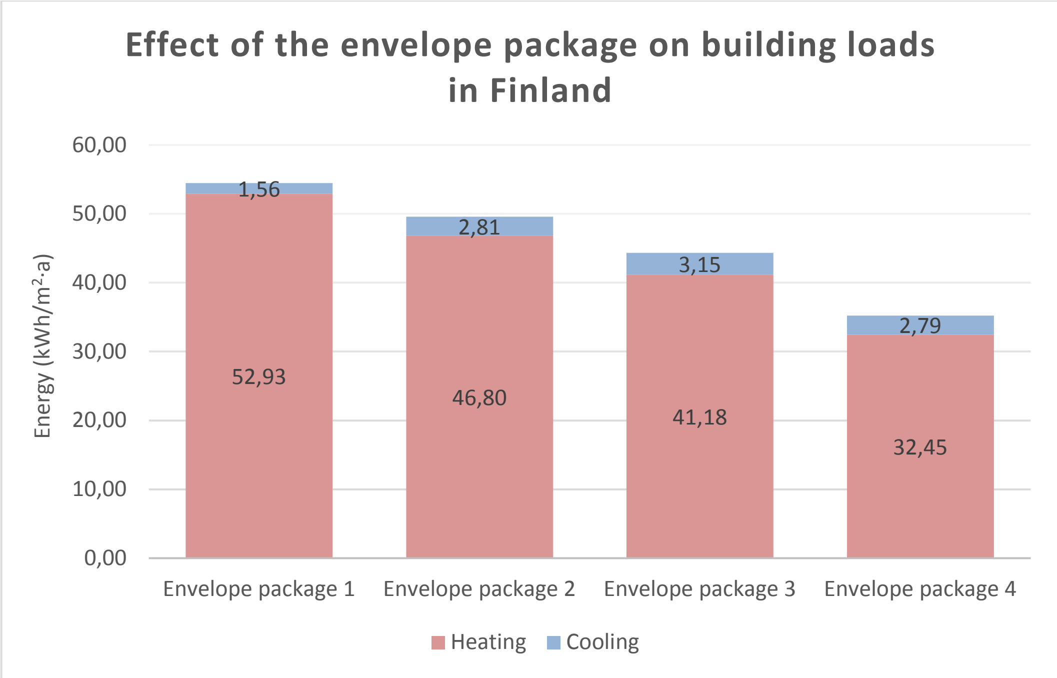

Figure 5.3. *Heating and cooling loads in Finnish reference building depending on the envelope package.*

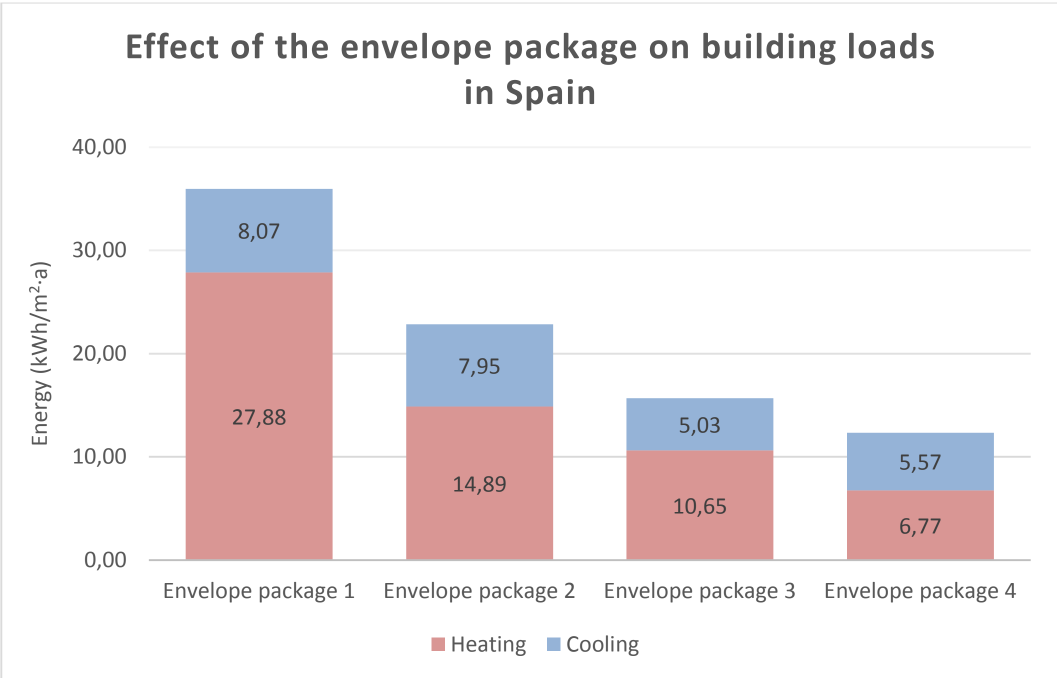

Figure 5.4. *Heating and cooling loads in Spanish reference building depending on the envelope package.*

As mentioned in [101], results reveal very low cooling loads in Finland, consequently these loads might be neglected. Nevertheless, it does not happen the same in Spain. In both cases, the total load decreases considerably when improving the envelope package.

Cooling loads depend on the thermal transmission of the envelope but also on solar heat gains. These gains occur mainly through glazing. For this reason, Spanish envelope packages were designed with windows of decreasing solar heat gain factor (SHGF) and improved thermal insulation. As a result, cooling loads were lower for each package. In Finland, solar gains are lower for each improved envelope package, as well. However, there is not a clear tendency in the cooling load due to the influence of other factors such as envelope and window losses.

It is necessary to check if the increase on energy performance justifies the higher costs of improved envelope packages. In order to do that, some results from Stage 1, shown in Figure 5.5, must be analyzed. As mentioned before, the investment costs on energy efficiency measures were annualized for a life-cycle of 30 years at 3 % interest rate. It is noteworthy that annual global costs consider energy expenses and the cost of all energy measures, not only those related to the envelope package. Thus, Figure 5.5 emphasizes the importance of the envelope over the global cost. These global costs do not contemplate the complete building construction costs, only those related to energy measures.

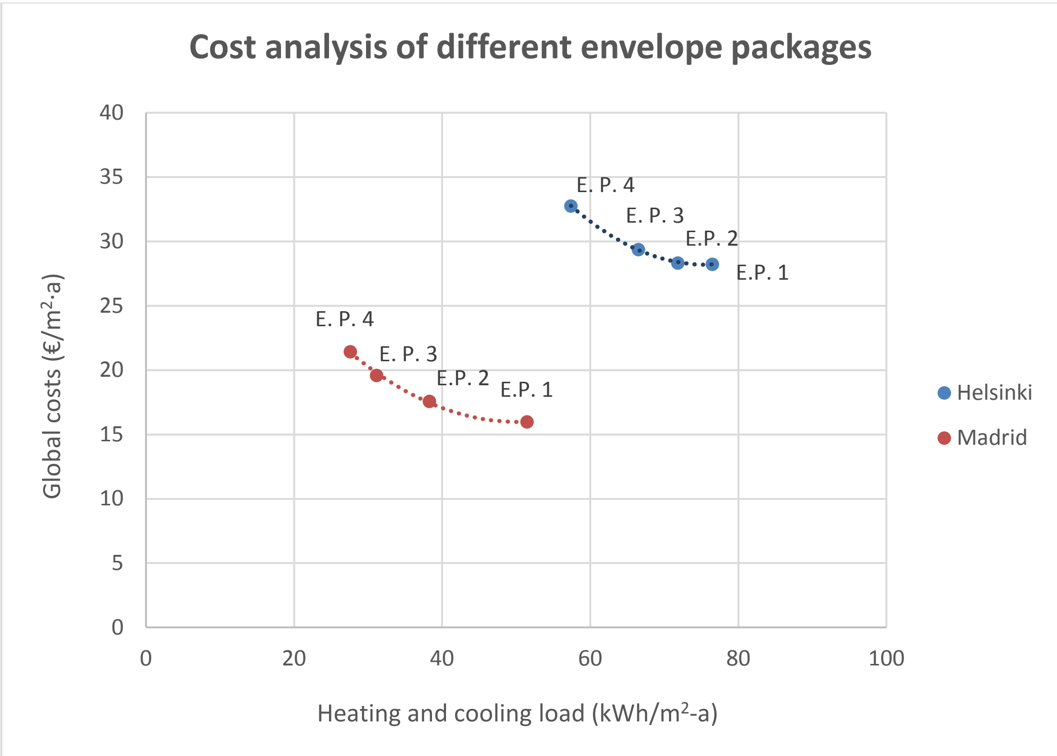

Figure 5.5. *Cost and energy performance of reference buildings depending on the envelope package.*

These simulations were run for an air-to-air heat pump, therefore annual global costs comprise the investment on that system. However, this is not a problem if results are analyzed with comparison purposes. Therefore, in Finnish conditions, only Envelope Package 2 is cost-efficient. For the other two packages, global costs increase compared with the reference building, although, of course, the energy consumption will decrease. The fact that investment in thick thermal envelopes is not economically attractive under Finnish conditions has already been suggested by other researchers [101] [106]. Financial savings due to lower energy consumptions are not enough to offset the additional investments. The explanation for this behavior is that the insulation requirements stablished by the Technical Building Codes are the result of previous cost-optimal calculations. In Spanish buildings, a similar tendency is found with no financial justification for any package. Moreover, in both locations the slope of the trend lines in Figure 5.5 suggests that decreasing energy consumption is more expensive the lower is this consumption.

A similar analysis process can be followed for the other two design variables included in the first stage of the calculations. In Figure 5.6 and Figure 5.7, it is shown the effect of airtightness on the energy losses of a reference building.

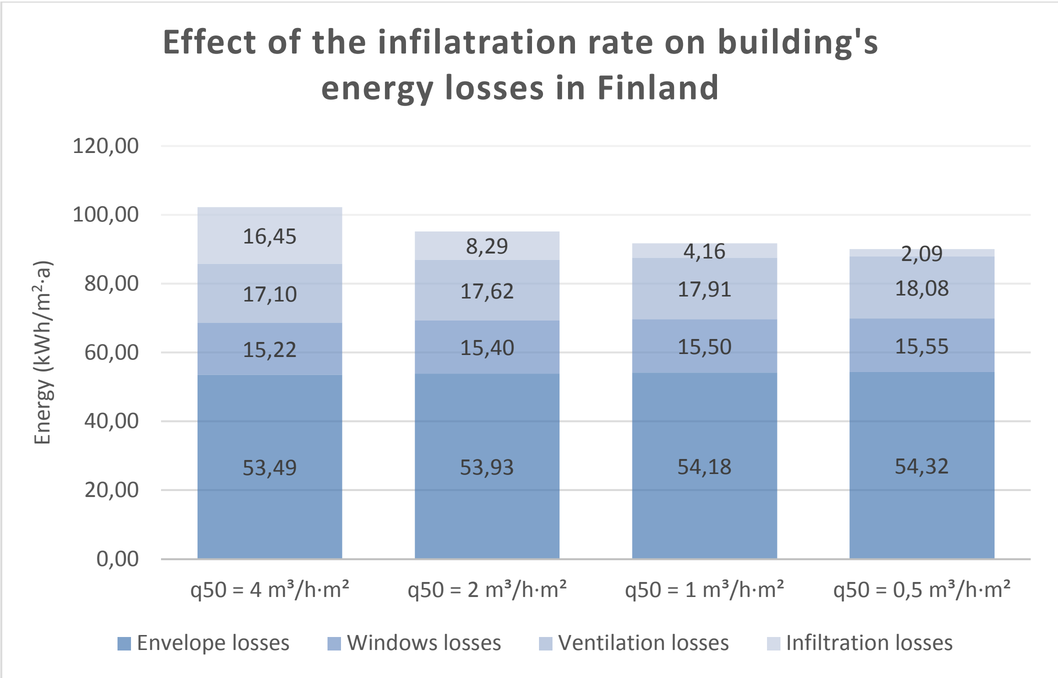

Figure 5.6. *Energy losses in a Finnish reference building depending on the infiltration rate.*

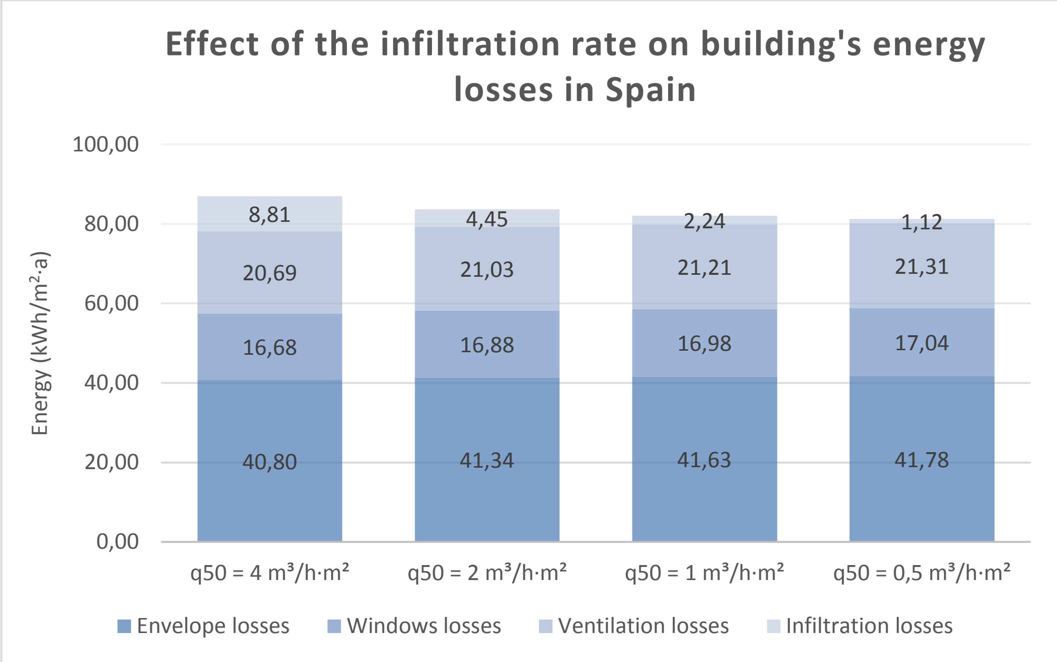

Figure 5.7. *Energy losses in a Spanish reference building depending on the infiltration rate.*

As expected, the only type of loss decreasing when decreasing the infiltration rate are infiltration losses. What is important to notice from these two figures is the relative importance of these losses compared with the whole energy loss. It is noticeable how considerable lower is the influence of this design variable compared with the envelope package. The same conclusion is obtained when analyzing the heating and cooling loads in Figure 5.8 and Figure 5.9.

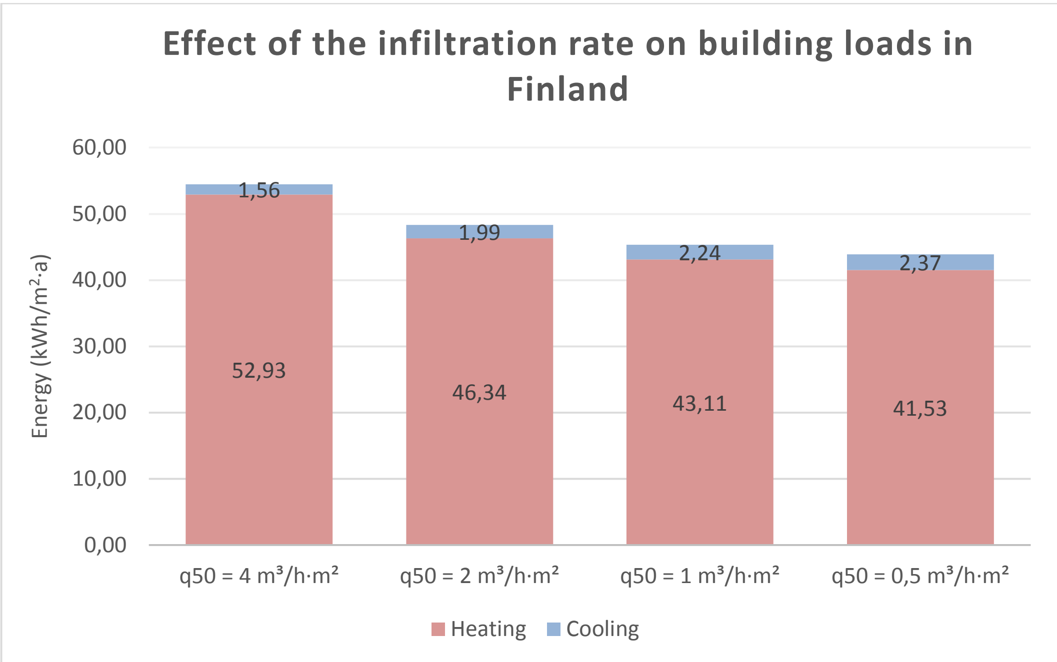

Figure 5.8. *Heating and cooling loads in a Finnish reference building depending on the infiltration rate.*

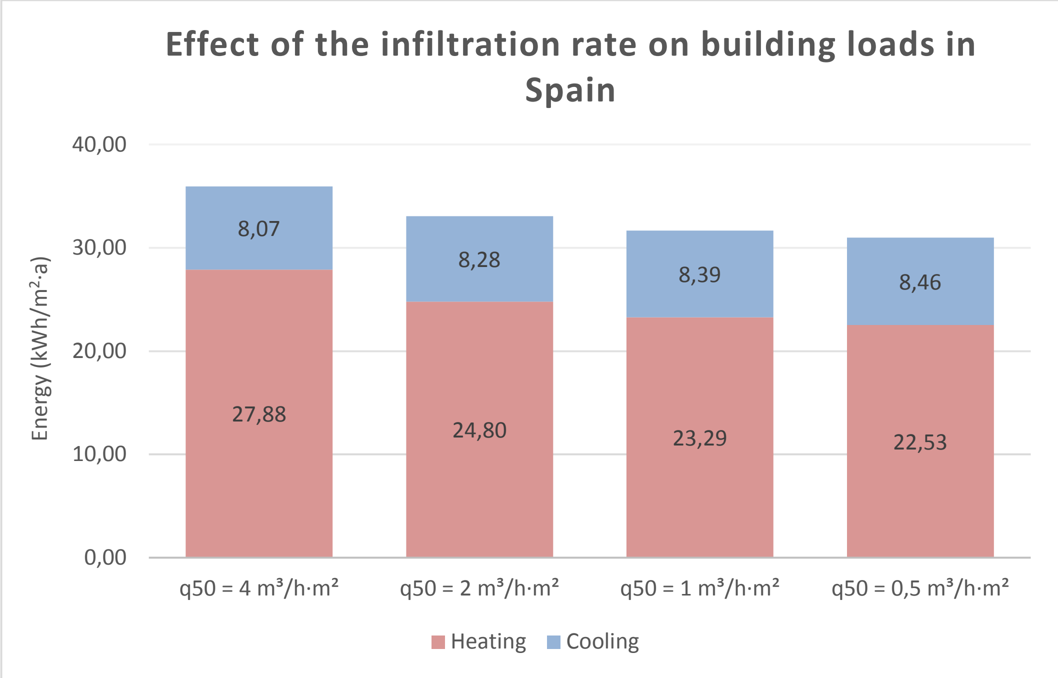

Figure 5.9. *Heating and cooling loads in a Spanish reference building depending on the infiltration rate.*

However, there is an important difference between the effect on annual global costs of this design variable and the envelope packages. Studying investment costs, it is found that the additional annual investment of the best envelope package in relation to the reference building package is around 4.5 €/floor-m^{2}a in Finland and 5.5 €/floor-m^{2}a in Spain. The same value in the case of airtightness investment is around 0.3 and 0.5 €/floor-m^{2}a in Finland and Spain, respectively. Therefore, investing in better airtightness is relatively cheap. For this reason, improving this design variable is cost-efficient, even though the effect on energy performance is limited.

Finally, last design variable involved in Stage 1 calculations is the heat recovery efficiency in ventilation units. In this case, this variable does not affect the heat losses of the building but ventilation heating/cooling needs. Figure 5.10 and Figure 5.11 evaluate the effect of increasing this efficiency on heating and cooling loads.

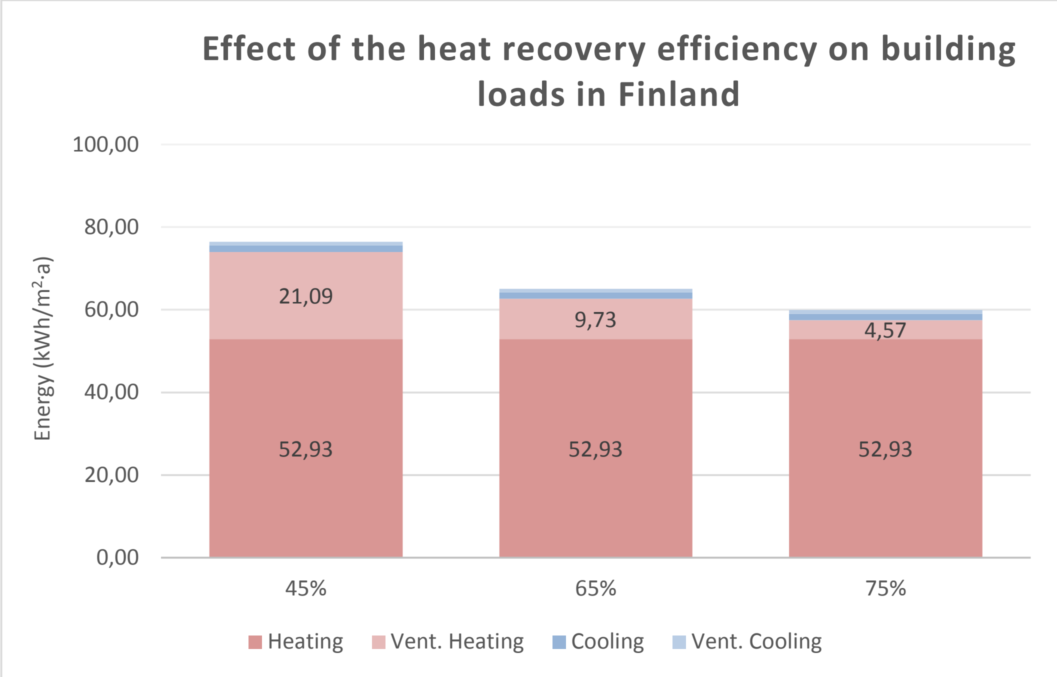

Figure 5.10. *Heating and cooling loads in a Finnish reference building depending on heat recovery efficiency.*

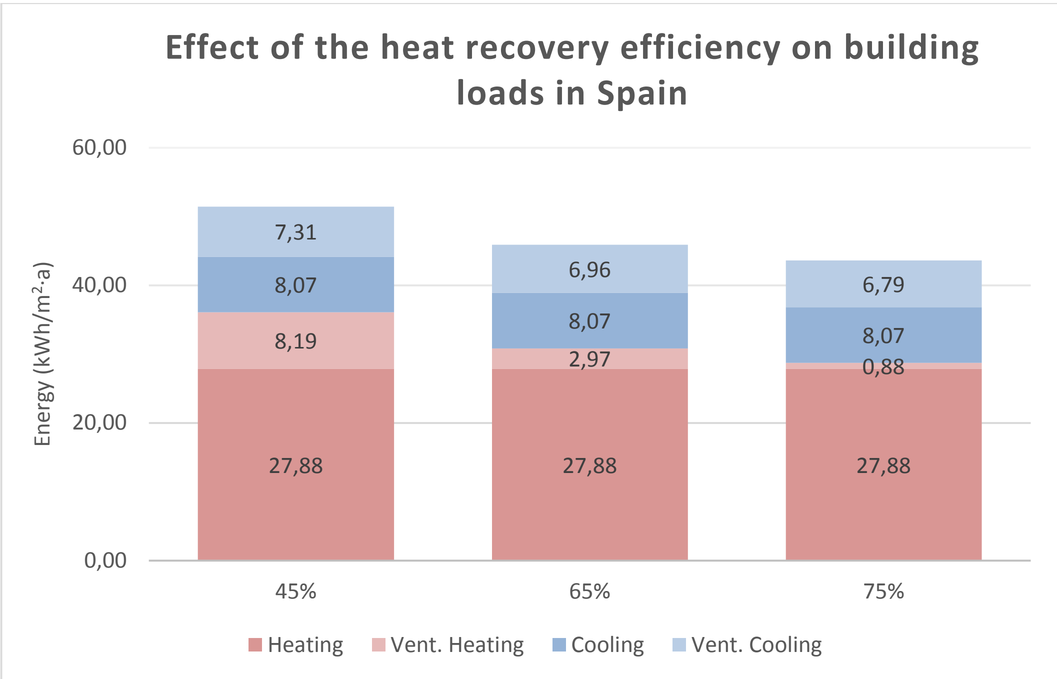

Figure 5.11. *Heating and cooling loads in a Spanish reference building depending on heat recovery efficiency.*

On this occasion, heating and cooling loads have been divided into those related to the ventilation and those which are not. Heat recovery units recover energy from outgoing ventilation air and employ it to reduce the demand in the intake flow. Results show how ventilation loads decrease significantly when increasing recovery efficiency, specially the heating needs as they are higher. In relation to the costs, as it is shown in Figure

5.12, investing in better heat recovery units is always cost-efficient. The reason is the considerable improvement on energy performance without very high investments.

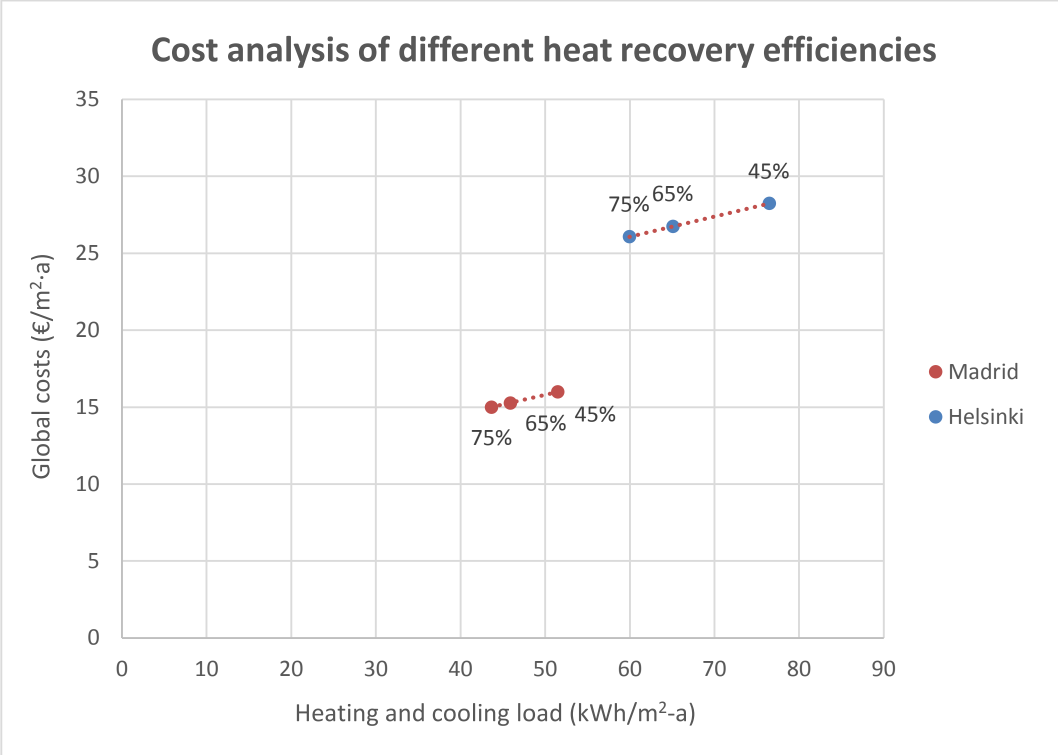

Figure 5.12. *Cost and energy performance of reference buildings depending on the heat recovery efficiency.*

Finally, it can be concluded that the only design variable far from being cost-optimal is related to the envelope package. On the contrary, investments on better heat recovery units and airtightness will always be justified.

Once known how the energy behavior and annual global costs are affected by the different design variables, complete results of Stage 1 can be analyzed. In Figure 5.13 and Figure 5.14, results for forty-eight candidate buildings are shown for each location.

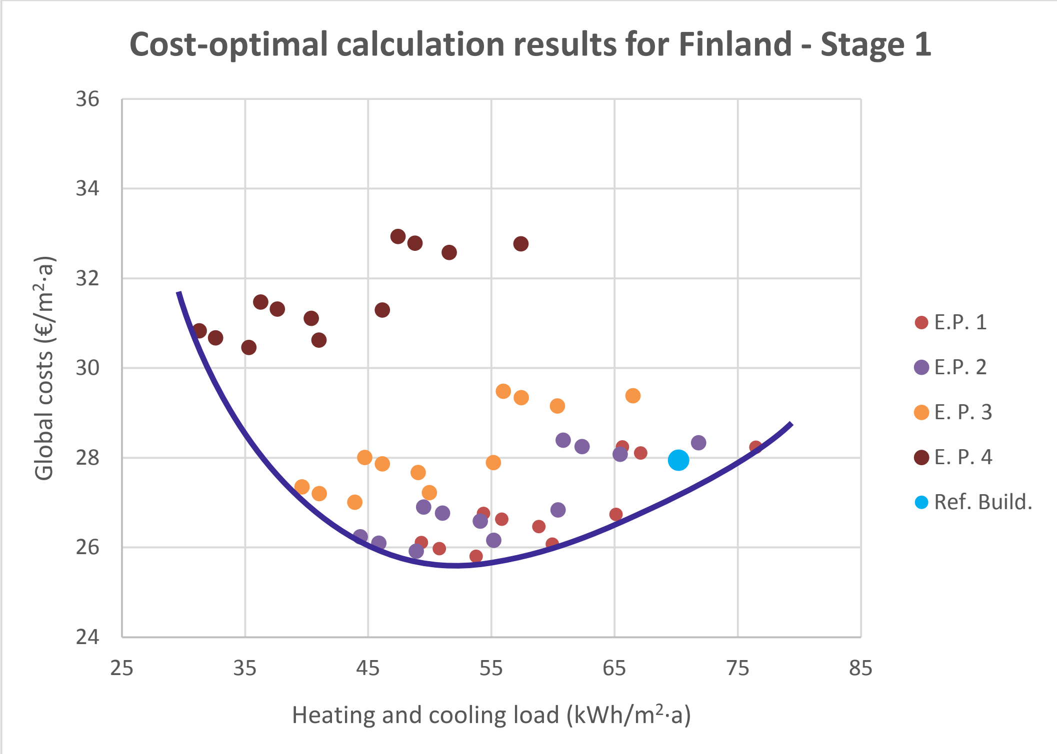

Figure 5.13. *Global costs and heating and cooling loads in Finnish candidate buildings of Stage 1.*

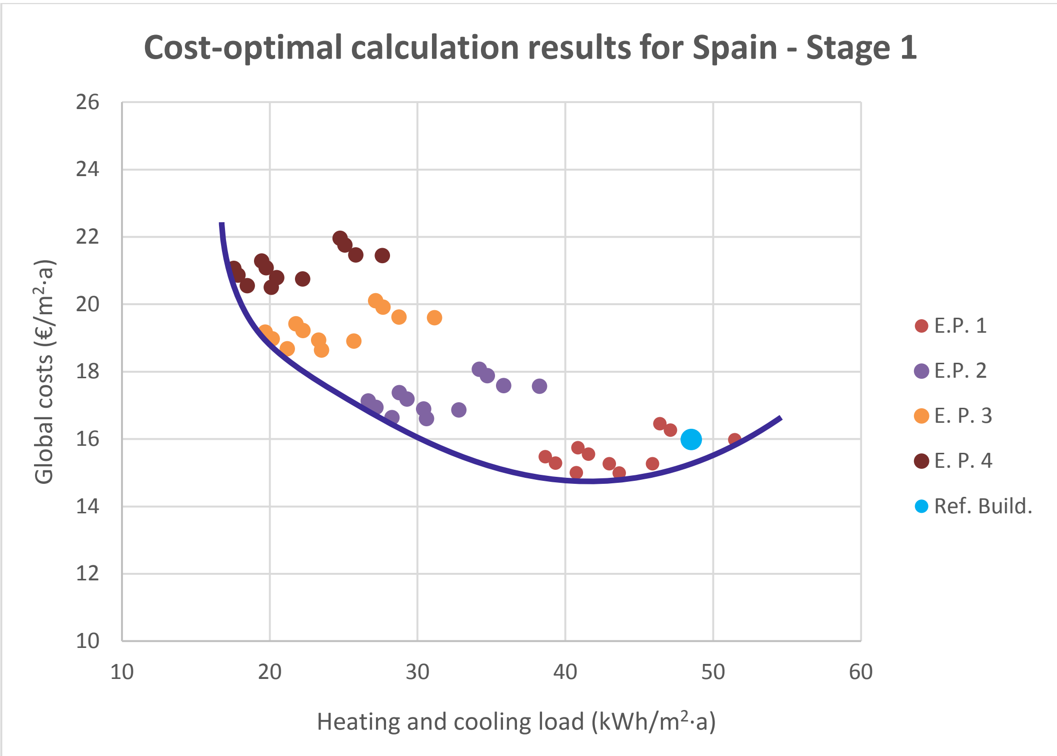

Figure 5.14. *Global costs and heating and cooling loads in Spanish candidate buildings of Stage 1.*

Envelope packages have been emphasized in different colors as this is the most influential design variable in Stage 1. The Pareto curve drawn in the figures is composed by several candidate buildings implementing each of those envelope packages. Those candidate buildings will be the ones studied in Stage 2.

It was mention before that investing on better envelope packages is not cost-efficient. For this reason, cost-optimal buildings implement the cheapest envelope packages, numbers 1 and 2 in Finland and only number 1 in Spain. The heating and cooling load for those cost-optimal buildings is around 50 kWh/m^{2}a in Finland and 42 kWh/m^{2}a in Spain.

It is worth to mention that annual global cost include the investment in the air-to-air heat pump system, therefore it is still soon to conclude any representative cost value. In addition, it can be judged that the design variables and their studied values were properly selected according to the amount of data near the cost-optimal.

5.2. Stage 2: Combination of optimal building designs and several HVAC systems

Second stage of cost-optimal methodology analyzes the performance of the best Stage 1 combinations when implementing different heating systems. As introduced before, systems included in the study are air-to-air heat pump (AAHP), ground source heat pump (GSHP) and district heating (DH). Some authors decide to analyze the systems without solar collectors installed and study their implementation afterwards. However, the performance of hybrid systems in this study is considerably influenced by these collectors. Therefore, they are included, with the optimal parameters, into each of the studied systems. Although, the viability of using thermal solar energy will be further analyzed.

Figure 5.15 and Figure 5.16 show Stage 2 results classified depending on the heating system implemented. In the case of Finland, 57 combinations were simulated while this value rises up to 99 for Spain. Pareto curve is composed mostly by air-to-air heat pump systems, especially at higher primary energy consumptions. The reason for this is both the lower cost and efficiency of this installation. However, at lower energy consumptions, district heating and ground source heat pumps are the only available technologies in the case of Finland.

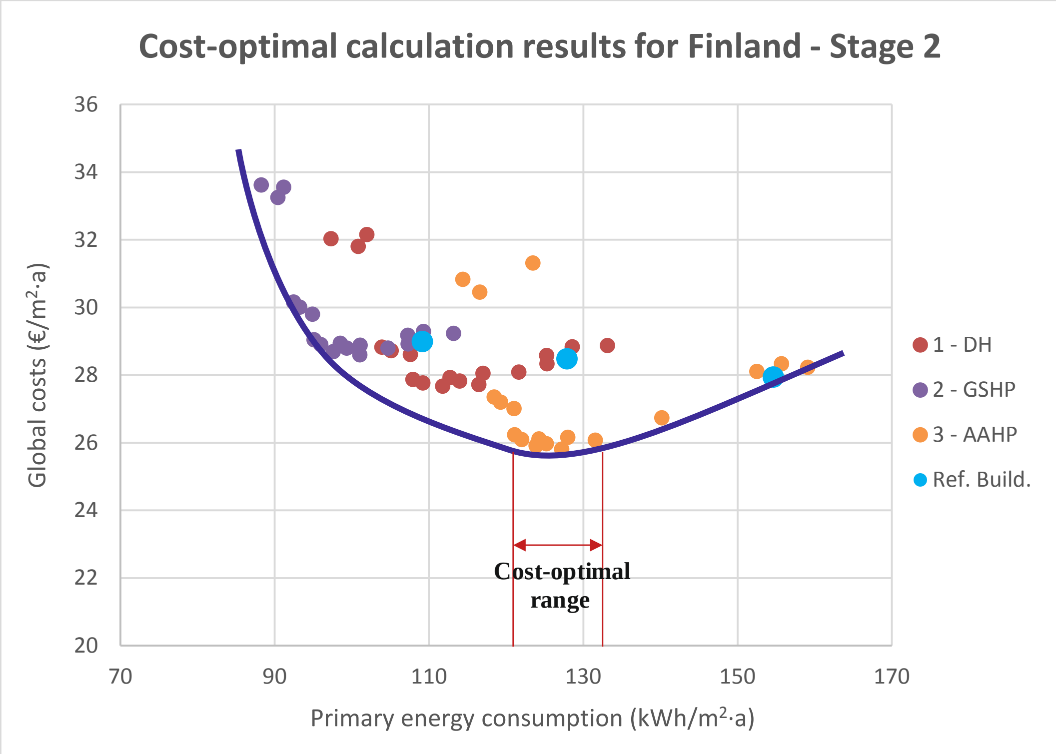

Figure 5.15. *Global costs and primary energy consumption of Finnish candidate buildings in Stage 2.*

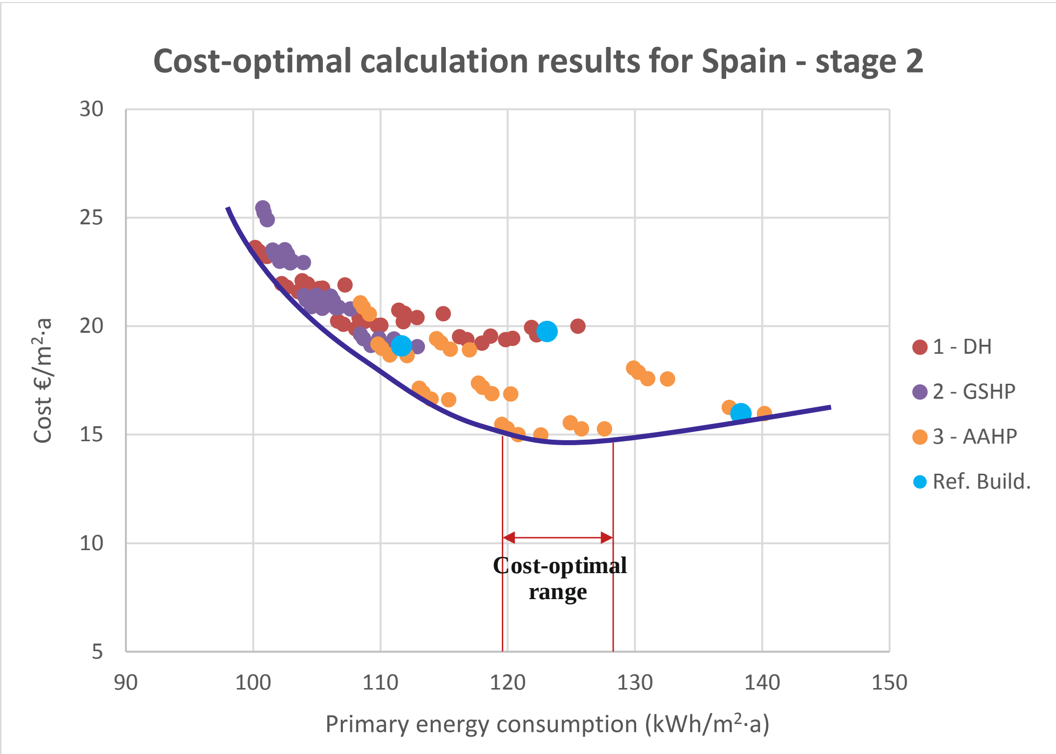

Figure 5.16. *Global costs and primary energy consumption of Spanish candidate buildings in Stage 2.*

Unlike in Stage 1, calculations in second stage provide final energy consumption results as it simulates heating system performance. Therefore, weighting factors in Table 4.5

have been applied to obtain primary energy consumption. Results are presented using source energy values, as a consequence the consumption is weighted depending on the energy carrier used. This primary energy consumption includes not only those related to heating and cooling but also consumption due to appliances, lighting and DHW.

Weighting factors have a significant influence in the results. For example, in Spanish results, Pareto curve has less representation of ground source heat pump systems than expected due to their high efficiency. The reason is the high electricity weighting factor compared with the one assumed for district heat.

Reference building results are pointed in Figure 5.15 and Figure 5.16 with bigger blue dots. For these buildings, results are presented in Table 5.1 and Table 5.2 implementing different heating systems, so later they can be compared with better design solutions.

Table 5.1. *Energy performance and costs of Finnish reference buildings.*

	Heating system	**Heating and cooling load (kWh/m²a)**	**Primary energy consumption (kWh/m²a)**	**Initial investment (€/m²)**	**Energy costs (€/m²a)**	**Annualized global costs (€/m²a)**
Reference building	DH	70.16	127.85	322.59	12.03	28.48
	GSHP	70.16	109.13	374.53	9.89	28.99
	AAHP	70.16	154.60	273.33	14.01	27.95

Table 5.2. *Energy performance and costs of Spanish reference buildings.*

	Heating system	**Heating and cooling load (kWh/m²a)**	**Primary energy consumption (kWh/m²a)**	**Initial investment (€/m²)**	**Energy costs (€/m²a)**	**Annualized global costs (€/m²a)**
Reference building	DH	48.51	123.08	180.40	10.57	19.77
	GSHP	48.53	111.65	229.95	7.37	19.10
	AAHP	48.52	138.32	134.24	9.13	15.98

Three reference buildings are considered, depending on the heating system implemented but employing all of them solar thermal collectors. It is worth to mention, the considerable difference between Finnish and Spanish investment costs. This difference is chiefly due to lower costs of envelope packages in Spain. As the weather is less extreme during winter in Spain, reference building requirements are softer, insulations thinner and, therefore, the costs lower.

As shown in Figure 5.15 and Figure 5.16, there is a group of candidate buildings with similar cost values in the cost-optimal zone. In this group, a really small increase in costs means a considerable reduction in energy consumption, especially in Finnish conditions. For this reason, it is not convenient to suggest just one cost-optimal solution but a cost-optimal range, as marked in the figures.

Cost-optimal range is located around 125 kWh/m^{2}a in Finland and 122 kWh/m^{2}a in Spain. Cost-optimal solutions implement air-to-air heat pumps and result in approximately 15 % energy saving and 7 % reduction of the costs compared with the reference building. This kind of heat pump, despite its slightly lower performance, proves to be a cost-optimal solution in several Finnish studies, such as [101] and [106], due to its wide implantation and low costs. Three candidate combinations inside cost-optimal range have been selected and presented in Table 5.3 to Table 5.6. Also, the candidate building with the best energy performance, disregarding costs, has been included in these tables.

Table 5.3. *Variable design values of Finnish representative combinations.*

Description	Id.	Envelope package	Infiltration rate (m^3/hm^2)	Heat recovery efficiency	Heating system
Cost-optimal solution	6	1	2	75 %	AAHP
In the cost-optimal range	21	2	1	75 %	AAHP
In the cost-optimal range	24	2	0.5	75 %	AAHP
Most efficient	48	4	0.5	75 %	GSHP

Table 5.4. *Variable design values of Spanish representative combinations.*

Description	Id.	Envelope package	Infiltration rate (m^3/hm^2)	Heat recovery efficiency	Heating system
Cost-optimal solution	6	1	2	75 %	AAHP
In the cost-optimal range	9	1	1	75 %	AAHP
In the cost-optimal range	12	1	0.5	75 %	AAHP
Most efficient	48	4	0.5	75 %	DH

Table 5.5. *Energy performance and costs of Finnish representative combinations.*

Description	Id.	Heating and cooling load (kWh/m^{2}a)	Primary energy consumption (kWh/m^{2}a)	Initial investment (€/m^2)	Energy costs (€/m^{2}a)	Annualized global costs (€/m^{2}a)
Cost-optimal solution	6	53.74	127.22	279.94	11.52	25.81
In the cost-optimal range	21	45.84	122.00	294.85	11.05	26.09
In the cost-optimal range	24	44.34	121.09	299.23	10.97	26.24
Most efficient	48	31.26	88.24	502.41	7.99	33.63

Table 5.6. *Energy performance and costs of Spanish representative combinations.*

Description	Id.	Heating and cooling load (kWh/m^{2}a)	Primary energy consumption (kWh/m^{2}a)	Initial investment (€/m^2)	Energy costs (€/m^{2}a)	Annualized global costs (€/m^{2}a)
Cost-optimal solution	6	40,74	120,82	137.70	7.98	15.00
In the cost-optimal range	9	39,33	119,97	144.39	7.92	15.29
In the cost-optimal range	12	38,63	119,55	148.67	7.89	15.48
Most efficient	48	17,55	100,15	318.86	7.36	23.62

Some expected results can be appreciated. All cost-optimal candidates have the best heat recovery efficiency possible, as the investment in this variable was always cost-efficient. The opposite occurred for the envelope package variable, therefore cost-optimal solutions have package one, in Spain, or one and two in Finland. As expected, the best infiltration rate is found on one of the cost-optimal candidates for both locations. However, this tendency was not strictly followed as other values were found as well.

The most efficient solutions include the best values for all design variables: envelope package, airtightness and heat recovery efficiency. Implemented heating system depends on the location. In this case, the solution is heavily influenced by primary energy weighting factors in each country, shown in Table 4.5. Finnish solution includes a ground source heat pump as this is the system with the best energy efficiency.

As mentioned before, selected weighting factors for Spain penalize electricity over district heat. In addition, when insulation is improved, domestic water heating loads become more important. Ground source heat pumps have lower COP for heating domestic water so their efficiency drops slightly in these cases, as explained in [101]. For these reasons, the Spanish best performance solution includes a district heating system instead of a ground heat pump.

It is also interesting to analyze the cost-optimal solution for each of the studied heating systems. The implemented system does not affect the heating and cooling demand of the building. Therefore, cost-optimal solutions for district heating or ground source heat pump present the same design variables as the one for air-to-air heat pump. A comparison among consumptions and costs of the three cost-optimal options is shown in Table 5.7 and Table 5.8.

Table 5.7. *Energy performance and costs of cost-optimal solutions for each heating system in Finland.*

Heating system	**Heating and cooling load (kWh/m^{2}a)**	**Primary energy consumption (kWh/m^{2}a)**	**Initial investment (€/m^2)**	**Energy costs (€/m^{2}a)**	**Annualized global costs (€/m^{2}a)**
DH	53.74	116.47	329.20	10.92	27.72
GSHP	53.74	101.03	381.14	9.15	28.60
AAHP	53.74	127.22	279.94	11.52	25.81

Table 5.8. *Energy performance and costs of cost-optimal solutions for each heating system in Spain.*

Heating system	**Heating and cooling load (kWh/m^{2}a)**	**Primary energy consumption (kWh/m^{2}a)**	**Initial investment (€/m^2)**	**Energy costs (€/m^{2}a)**	**Annualized global costs (€/m^{2}a)**
DH	40.74	117.98	183.85	9.83	19.21
GSHP	40.74	109.25	233.41	7.21	19.12
AAHP	40.74	120.82	137.70	7.98	15.00

Ground source heat pumps are the most efficient system. As a consequence, it has the lowest primary consumption of the three systems. However, its considerably higher investment costs make it the most expensive system in an annual basis in Finland. In Spain, the higher costs of district heat, compared with Finnish ones, provoke that the annual global costs of ground heat pump systems are slightly lower than district heating systems.

Concluding, cost-optimal solutions have been found for Spanish and Finnish conditions. These configurations include air-to-air heat pumps and reveal a considerable gap for energy saving and cost reduction. Next step consists on achieving the nZEB concept by installing renewable energy-supply systems on these low-energy solutions.

5.3. Stage 3: Achieving nearly ZEBs with photovoltaic power generation

In the third and last stage of the cost-optimal methodology, photovoltaic panels are considered as an on-site renewable energy source. The DBES program seeks the PV-panel size that allows buildings to achieve nearly zero-energy building qualification. This qualification has been considered as an annual net primary energy consumption equal to 50 kWh/m^{2}a. This value is settled in several European regulations, although it is not in Finnish or Spanish requirements yet. It is worth to mention, that 1 kW of installed capacity is approximately equivalent to 6.6 m^2 of photovoltaic panels due to an estimated panel efficiency of 15 %. Selected PV systems are located on the roof, so their area is limited. In Table 5.9 and Table 5.10, results for an optimal PV-panel size are presented for representative combinations studied in Stage 2. Last column shows the relative increase of global annual costs compared with cost-optimal solutions in Stage 2.

Table 5.9. *Photovoltaic capacity and costs of Finnish representative nZEB combinations, i.e., 50 kWh/m^{2}a annual net primary energy consumption.*

Description	Id.	Photovoltaic capacity for nZEB (kW)	Initial investment with PV-panels (€/m^2)	Energy costs with PV-panels (€/m^{2}a)	Annualized global costs with PV-panels (€/m^{2}a)
Cost-optimal solution	6	7.77	459.26	4.53	27.96 (8.35 %)
In the cost-optimal range	21	7.25	462.45	4.53	28.12 (7.77 %)
In the cost-optimal range	24	7.16	464.77	4.53	28.24 (7.75 %)
Most efficient	48	3.85	594.13	4.53	38.84 (3.62 %)

Table 5.10. *Photovoltaic capacity and costs of Spanish representative nZEB combinations, i.e., 50 kWh/m^{2}a annual primary energy consumption.*

Description	Id.	Photovoltaic capacity for nZEB (kW)	Initial investment with PV-panels (€/m^2)	Energy costs with PV-panels (€/m^{2}a)	Annualized global costs with PV-panels (€/m^{2}a)
Cost-optimal solution	6	3.24	156.55	3.30	12.97 (-15.71 %)
In the cost-optimal range	9	3.20	161.63	3.30	13.28 (-15.13 %)
In the cost-optimal range	12	3.18	164.94	3.30	13.48 (-14.80 %)
Most efficient	48	2.29	295.26	4.04	22.27 (-6.07 %)

Results show the optimal PV capacities of around 7 and 3 kW for cost-optimal nZEBs in Finland and Spain, respectively. This represents an approximate panel area of 50 and 20 m^2. Energy costs are lower as the building is generating, and selling, its own electricity instead of just buying it. However, initial investment costs are higher when installing a PV system. For this reason, in Finland, annual global costs are higher compared with those shown in Table 5.5. In Spain, photovoltaic technology is nowadays cost-efficient as the electricity production is better due to higher radiation levels. Therefore, less panels need to be installed to reach nZEB concept. As a consequence, annual global costs decrease approximately 16 % respect buildings without photovoltaic systems, as presented in brackets on Table 5.10.

As mentioned above, PV-panels are not cost-efficient in Finland yet. Nevertheless, nZEB solution has approximately the same annual global costs than the initial reference building due to the financial gap created by the energy measures implemented. Spanish nZEB solution shows an 18.8 % cost reduction, and it would be bigger if more panels were installed.

The situation in Spain is a perfect example of how a bad praxis is possible in nZEBs design. As photovoltaic technologies are cost-efficient, it would be possible to reduce annual costs and net energy consumption just by installing an oversized PV system. Therefore, energy saving measures could be left apart in the design process. The structure of the applied cost-optimal methodology avoids this bad praxis by considering PV-panels only after calculating the optimal combination of energy saving measures.

It is worth to mention that some assumptions were made for calculations at this third stage. Firstly, it is assumed that all generated electricity not consumed in the building itself is bought by the electrical company at the same selling price. In addition, results are sensitive to life-cycle lengths and installation costs, as it will be shown later in this thesis.

All the stages of the cost-optimal methodology have been completed so far. Therefore, cost-optimal nZEB solutions consist on high heat recovery efficiency and airtightness and standard envelope packages. They implement air-to-air heat pumps and photovoltaic panels which area depend on the location. In subchapters below, thermal collectors' feasibility and the sensitivity of the results will be analyzed.

5.4. Economic feasibility of solar thermal collector systems

During cost-optimal calculations, it was assumed that solar thermal collectors should be installed beside the heating systems so hybrid systems had a better performance. In order to prove this assumption, simulations over Stage 2 building candidates were run for systems without solar collector. As well, the efficiencies of solar collectors and costs per unit of energy generated were calculated.

The gross efficiency of solar collectors has been defined as the amount of heat produced by the collector divided by the radiation arriving to the array. Using DBES results, this efficiency is 50 % for collectors in Finland and approximately 57 % for collectors in Spain. On the other hand, the net efficiency was defined as the percentage reduction of purchased energy caused by the implementation of solar thermal collectors in a building. This efficiency is presented for different heating systems in Table 5.11.

Table 5.11. *Net efficiency and energy purchase reduction when implemented solar collectors for different heating systems.*

	Finland		Spain	
	Net efficiency	Energy purchase reduction (kWh/m^2)	Net efficiency	Energy purchase reduction (kWh/m^2)
AAHP	13 %	14	18 %	13
DH	12 %	18	14 %	14
GSHP	9 %	7	7 %	3

In Figure 5.17 and Figure 5.18, results for Stage 2 are shown and compared with those not implementing solar collectors. In this case, the presented value is primary energy, therefore, the results on Table 5.11 are affected by the weighting factors.

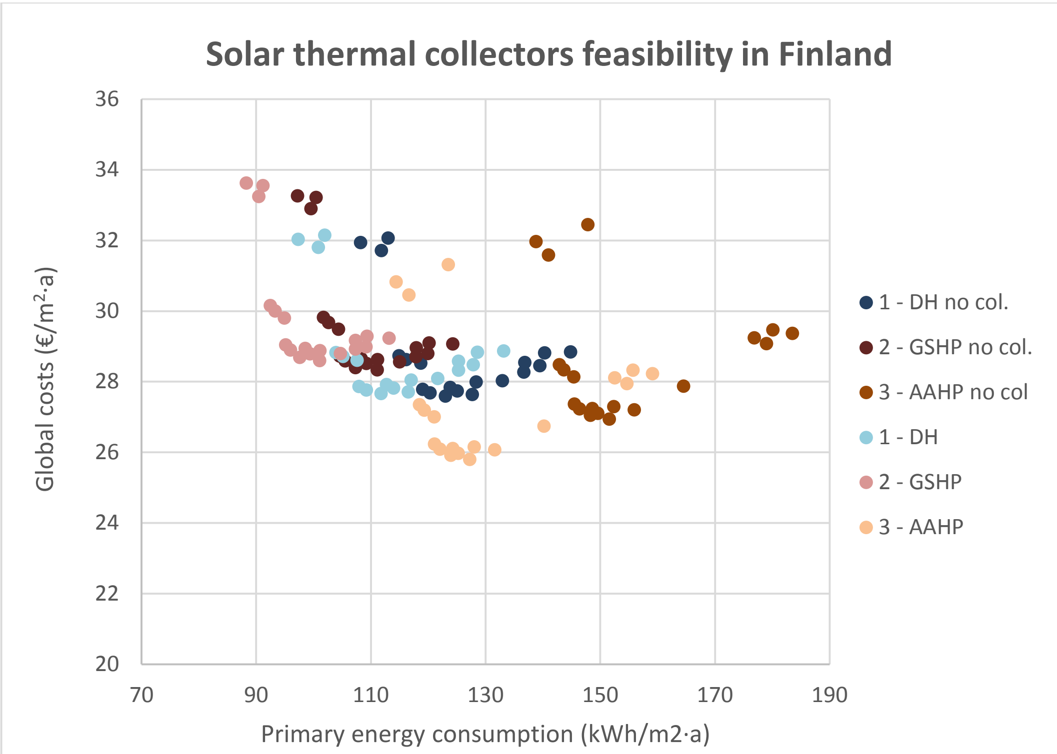

Figure 5.17. *Global costs and primary energy consumption of Finnish candidate buildings in Stage 2 with and without solar collectors.*

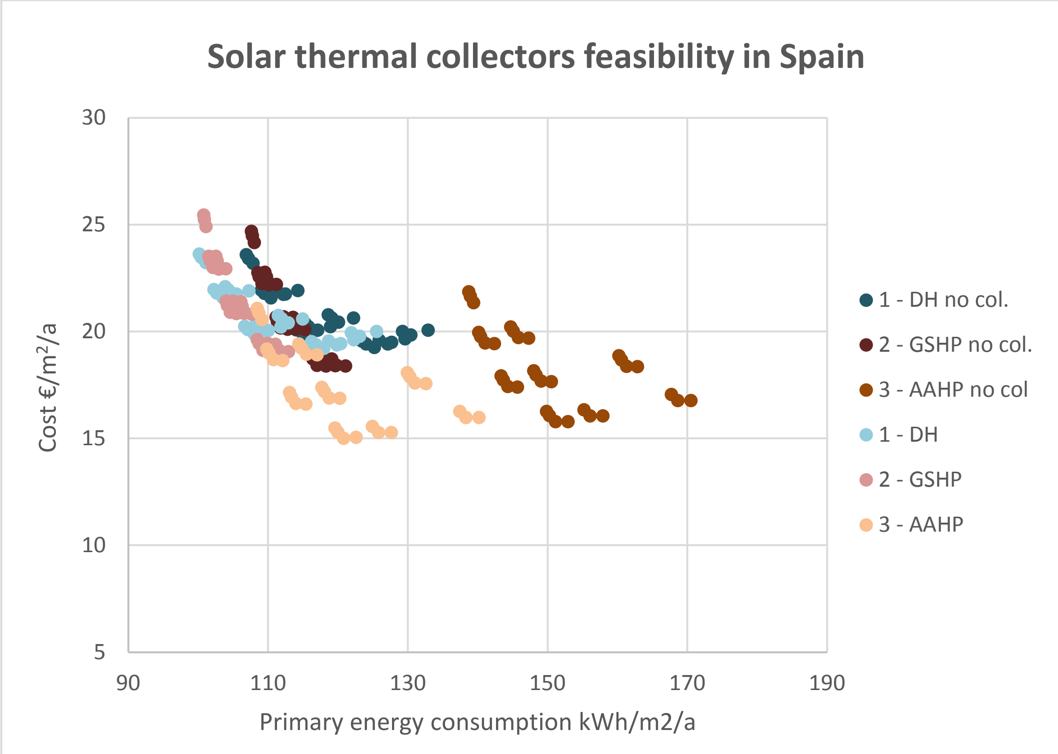

Figure 5.18. *Global costs and primary energy consumption of Spanish candidate buildings in Stage 2 with and without solar collectors.*

Results show how for AAHP systems, not implementing solar thermal collectors means considerably higher primary energy consumption and costs. Air to air heat pumps cannot heat water, therefore domestic water is heated with an inefficient electric coil. For this reason, this system shows the worst results when omitting solar collectors, as suggested in [101].

In the case of a GSHP, it can heat water so the energy not provided by the collectors is replaced by electricity, but affected by the COP of the heat pump. Finally, in the case of district heating systems that energy is replaced by relatively cheap heat from the grid, which applies a low weighting factor. For these last two options, solar collectors are not as cost-effective as in the case of AAHP systems, costs remain the same or slightly higher. However, while the DHW consumption remains at reasonable levels, solar collectors will be an economically attractive option, at least within the considered financial parameters.

Buildings implementing a GSHP without solar collectors results to have 2 % lower annual global costs compared with the ones with solar collectors. Regarding to this, it is noteworthy that DBES model is designed to simulate hybrid systems, so results without solar collectors are not so reliable and must be subjectively analyzed. When no solar collectors are considered, the COP of the heat pump is expected to be slightly lower than DBES suggests, so the electricity consumption and expenses would be a little higher. The annual cost reduction would be lower than 2 %, which worths the approximately 6.5 % of primary energy consumption saved when installing solar collectors. For these reasons, solar collectors are finally considered for the GSHP candidates in both locations.

Finally, it was calculated the cost of energy produced by solar collectors and compared with the cost of electricity produced in photovoltaic panels. In order to do that, installations costs and annual energy production were taken into account. Results, shown in Figure 5.19 for both locations, were similar to the prices provided in [107].

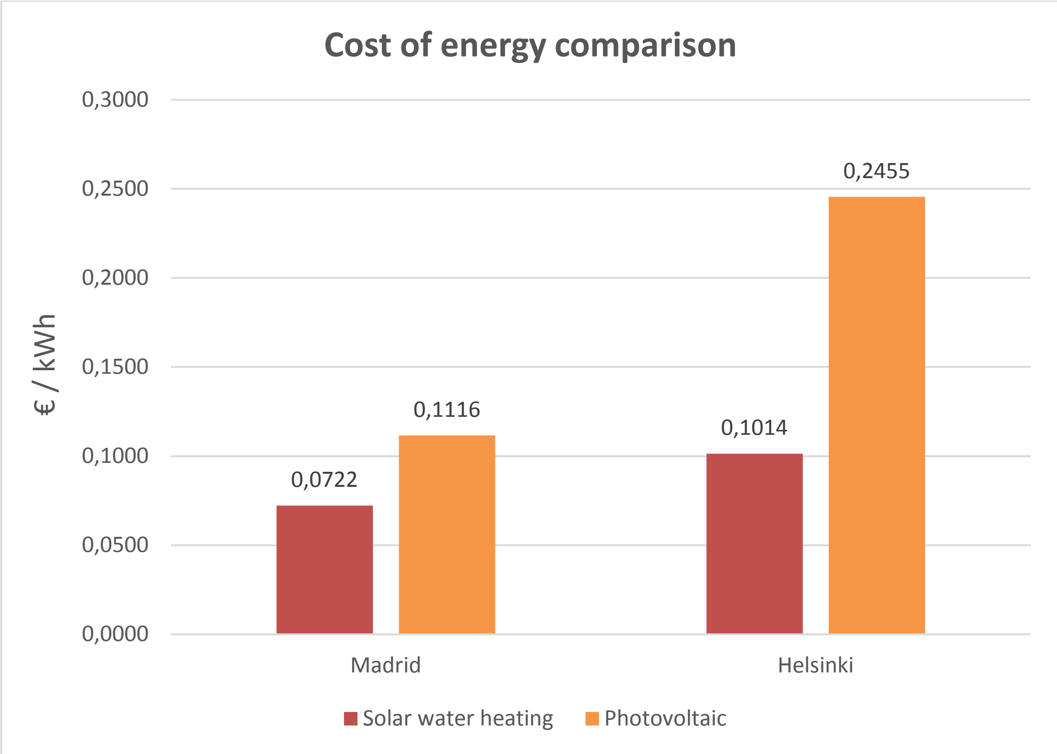

Figure 5.19. *Solar water heating and photovoltaic energy costs for Spain and Finland.*

As it was expected, Spanish energy costs are lower than in Finland due to the higher radiation levels. Photovoltaic technologies are not as developed nor efficient as thermal solar systems, therefore, costs are higher for PV energy in both locations. This suggests to prioritize the solar thermal collectors, respect the PV-panels, in the nZEB design and the methodology applied.

Solar thermal energy costs appearing in Figure 5.19 consider installation costs and thermal energy produced. However, users are more interested in how much energy is saved due to a new system, instead of just how much energy it produces. For this reason, Figure 5.20 shows solar thermal energy costs contemplating the net produced energy of different heating systems.

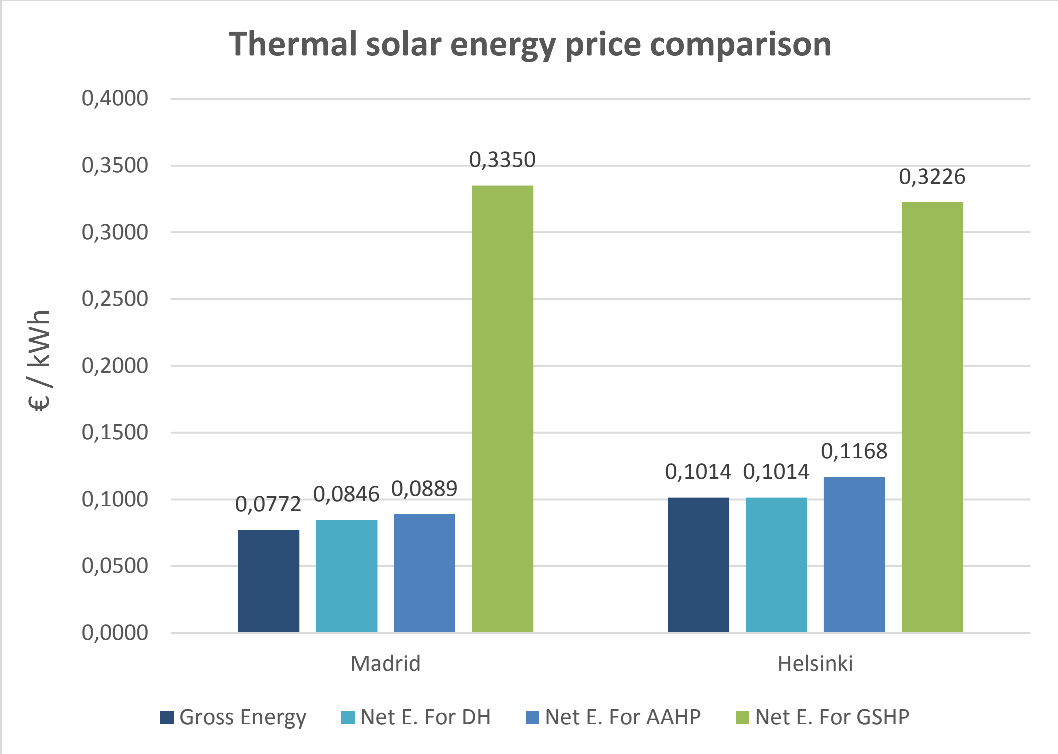

Figure 5.20. *Solar thermal energy prices in Madrid and Helsinki considering the net energy of different heating systems.*

Figure 5.20 shows how energy costs are very similar to district heating and air-to-air heat pumps disregarding the type of efficiency considered. However, prices are much higher in the case of the GSHP when considering net energy. Table 5.11 showed a low net efficiency for solar collectors in GSHP systems due to the high COP of heat pumps, which could heat domestic water. For the same reason, prices in Figure 5.20 rise up until 0.33 €/kWh for this heating system.

5.5. Analysis of nZEB cost-optimal solutions

Once presented most of the results obtained from the calculations, a detailed analysis of the cost-optimal buildings is going to be carried. In the first place, in Figure 5.21, it is shown the proportionate path towards the nearly zero-energy building concept. Buildings presented are cost-optimal and the most efficient solutions with PV-panels necessary to reach 50 kWh/m^{2}a, considered as nZEB qualification.

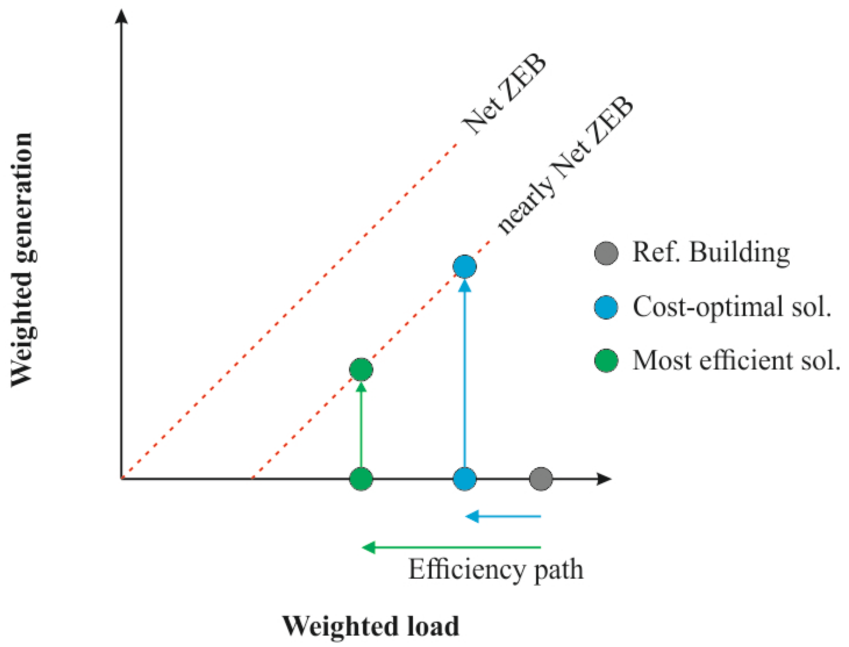

Figure 5.21. *Path towards Finnish nZEB solutions.*

It can be appreciated how energy savings in the best performance solution are more than twice those of the cost-optimal solution. Therefore, cost-optimal solution does not benefit from the energy measures as much as possible. The same situation appears in Spain, the reason, as commented before, is that the investment in better envelope packages is not paid back within 30 years.

As commented before, only costs considered in this study are those related to energy measures and energy consumption. In Figure 5.22, costs can be compared depending on their origin. Results are shown both for cost-optimal nZEB and reference building with air-to-air heat pump system. It is worth to remind that the annual global costs were 27.95 and 15.98 €/m^{2}a for reference buildings in Finland and Spain, respectively, while for nZEB solutions they were 27.96 and 12.96 €/m^{2}a.

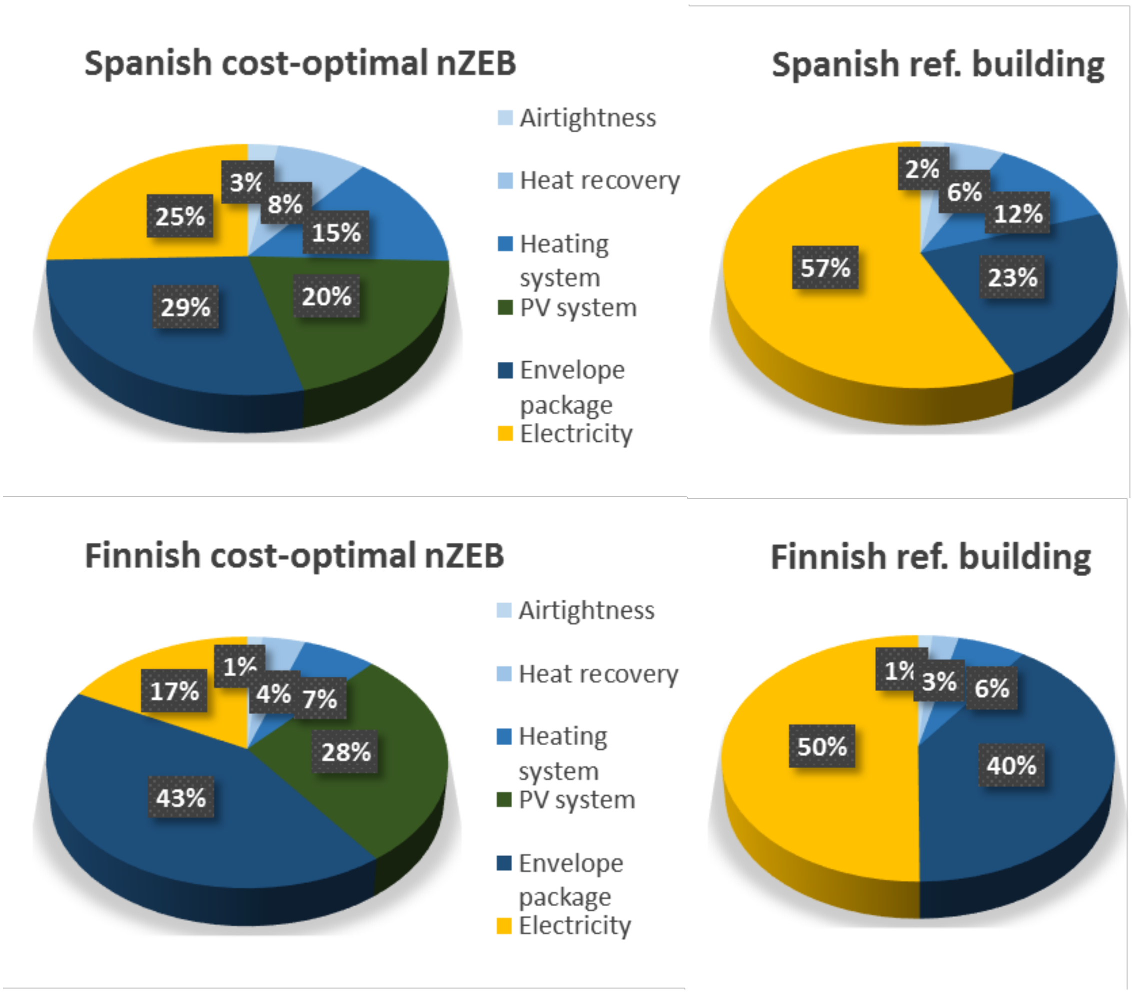

Figure 5.22. *Cost comparison of different items for cost-optimal nZEBs and reference buildings.*

Annual costs are mainly caused by energy expenses and investments in envelope packages and PV systems. Heating systems do not represent a big share in these cases because buildings implement air-to-air heat pumps, however for the other heating systems the importance is higher. Low-energy solutions reduce annual electricity expenses thanks to costly energy saving measures and photovoltaic systems. For this reason, in reference buildings, electricity represents more than half of the annual costs while it is a forth or less in nZEB solutions. Investment costs represent the majority of annual costs in nZEBs, being the photovoltaic system share the second bigger after the envelope package.

Finally, another interesting concept in the study of nearly zero-energy buildings is the temporal match. As has been explained before, ZEBs must offset an annual energy balance but also try not to be an extra stress for the electric grid. To solve this problem, buildings should increase the match between their load and generation, promoting self-consumption. A proper temporal match study requires a self-consumption model, not implemented by DBES. However, some results can be provided with the means available. In Figure 5.23 and Figure 5.24, it is illustrated this energy match for cost-optimal buildings in both locations.

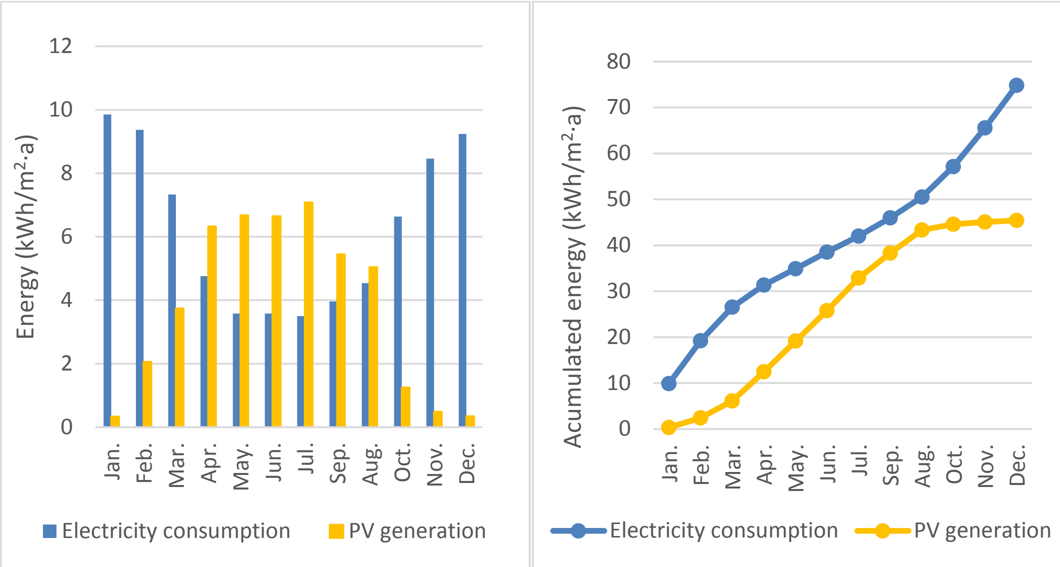

Figure 5.23. *Electricity consumption and photovoltaic generation during the year for cost-optimal Finnish nZEB.*

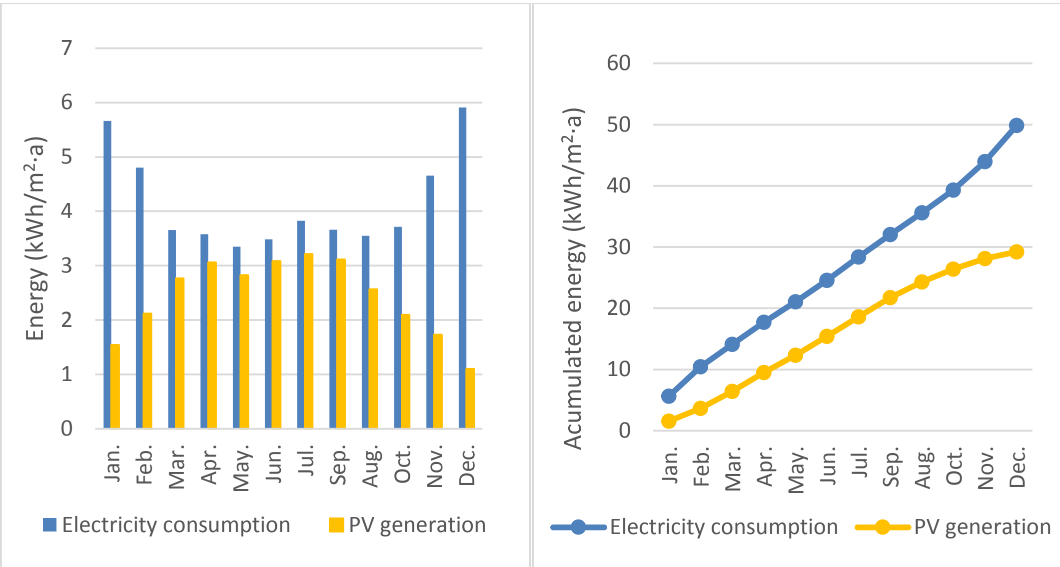

Figure 5.24. *Electricity consumption and photovoltaic generation during the year for cost-optimal Spanish nZEB.*

Results are presented for nZEB, which annual balance is not zero but negative, with a primary energy of 50 kWh/m^{2}a. For this reason, in both cases, the line representing PV generation never crosses the line related to the consumption. This could be wrongly interpreted as if all energy produced in the panels would be self-consumed. Therefore, this kind of graphic is not very truthful. However, these graphs are more meaningful in the case of studying zero-energy buildings or, specially, of having a self-consumption model.

Zero-energy building solutions are out of the scope of this thesis due to the unnecesarly big costs involved in their construction in Finland. Under the applied design, cost-optimal ZEB solution in Finland would have 85 m^2 PV-panels and 36 m^2 in the case of Spain. Nevertheless, this building was simulated in Spanish conditions to present a proper temporal match graphic in Figure 5.25.

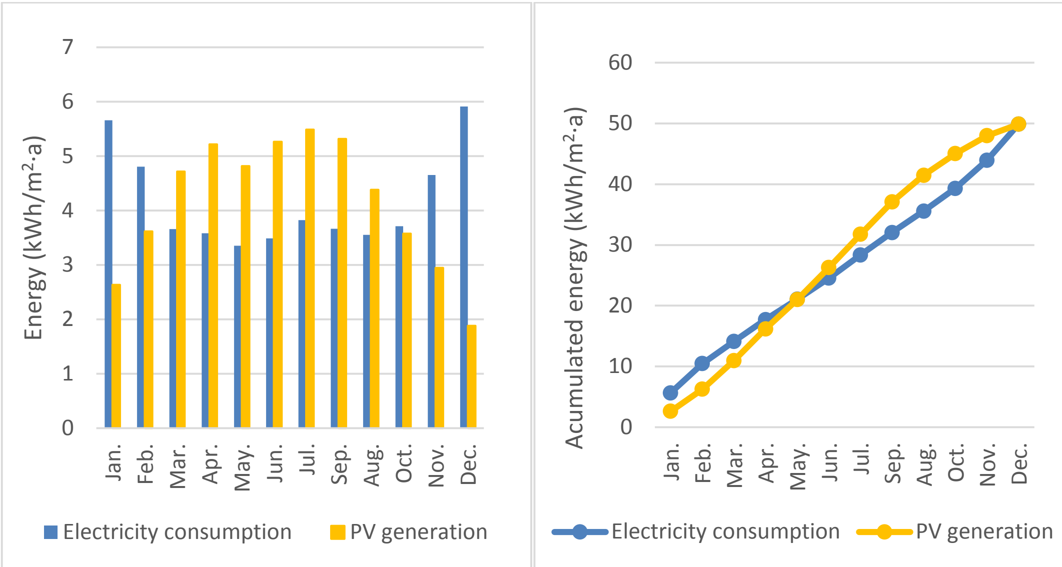

Figure 5.25. *Electricity consumption and photovoltaic generation during the year for cost-optimal Spanish ZEB.*

Figure 5.25 shows how in summer months there is a big amount of exported electricity in order to offset the annual balance at the end of the year. The flatter the curves formed by monthly consumptions are, the smaller is the stress introduced into the grid. Again, it is worth to mention, that results would be more representative in the case of applying a self-consumption model.

5.6. Sensitivity analysis

Multiple simulations have been run to show the impact on the results of several financial parameters. Parameters considered in this sensitivity analysis include energy and installation prices, interest rate and life-cycle duration. Moreover, other significant parameters, such as the weighting factors and the escalation-rate of energy prices, have been studied. The main purpose of the analysis is to check how these parameters influence the shape of Pareto curves and, therefore, the cost-optimal solutions. As well, it will be evaluated the effect on the size of the PV system needed to reach nZEB qualification.

Stage 1 results depend only on the thermal behavior of the building. Although costs can vary, the main results of the stage do not change when modifying any of previously cited parameters. On the contrary, Stage 2 results depend on these values. However, results prove to be robust as the cost-optimal system does not change when slightly varying prices or financial parameters. As it is shown in Figure 5.26, Pareto curve becomes flatter when the interest rate decreases in Finland, and conversely.

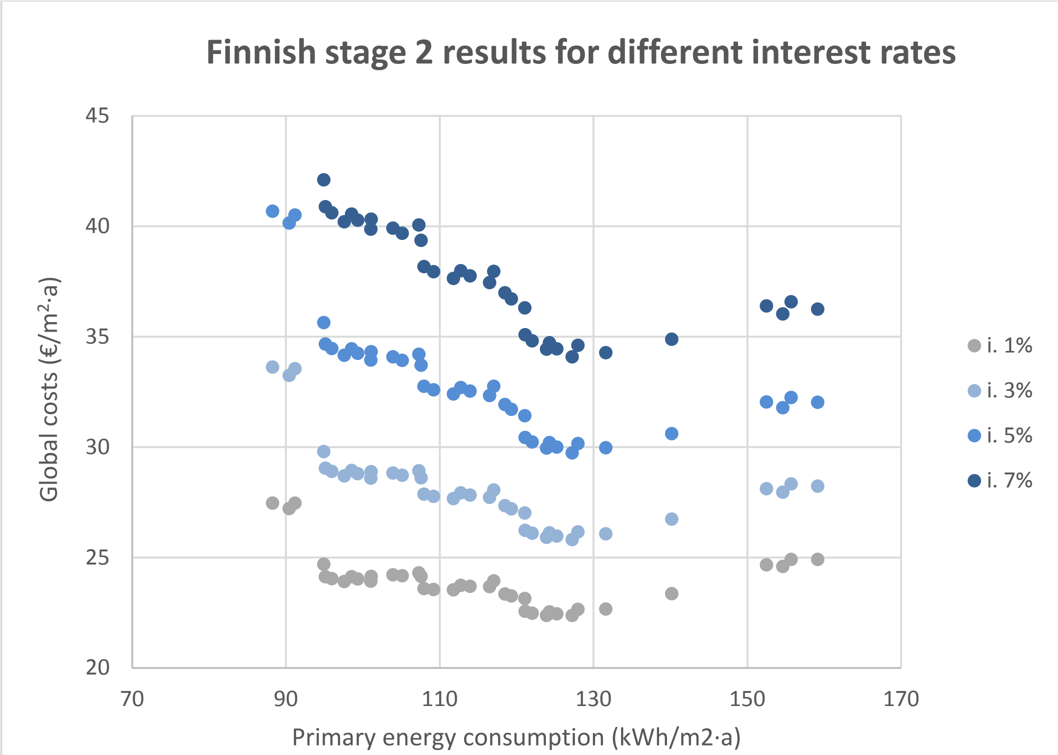

Figure 5.26. *Global costs and primary energy consumption of Stage 2 Finnish candidate buildings under different interest rates.*

Design variables such as envelope packages were not cost-efficient in basic conditions. However, if their price is decreased while energy prices remain, they move closer to cost-efficiency. As a consequence, the curve corresponding to an interest rate of 1 % is flatter.

Stage 3 results are considerably sensitive to the variation of photovoltaic system prices or the interest rate. For levels higher than 4.5 % interest rate, PV-panels stop being cost-effective in Spain. The situation is the same in Finland, but in the other direction. By decreasing the interest rate under 2.5 % or just lowering the installation prices, photovoltaic systems start to be cost-efficient and nZEBs cheaper.

By running multiple simulation, it was sought which variation of the financial parameters influenced which candidate is the cost-optimal solution. This variation resulted to be considerably high. For example, a rise of 30 % in Finnish electricity prices makes cost-optimal solution switch to district heating systems. A decrease of 40 % in district heat prices in Spain, due to a possible wider implantation of the system, was simulated as well. However, this situation does not have any effect on the final cost-optimal solution.

Instead of incrementing the price of one energy carrier for all the time period, it is possible to apply an energy price increase rate. In order to do that, the present value of an increasing income is calculated using Equation (7) and annualized.

$$PV = \frac{P}{r-g}\left[1-\left(\frac{1+g}{1+r}\right)^{n}\right] \tag{7}$$

where P stands for the price in the first period and g for the growth rate of this price. The terms r and n stand for the interest rate for applying the discount and the number of periods, respectively. For example, after calculations, it is found that it is needed an increase rate of 6 % per year on the energy price before cost-optimal solution in Finland switches to district heat systems. Results are shown in Figure 5.27 and compared with those without energy price increase.

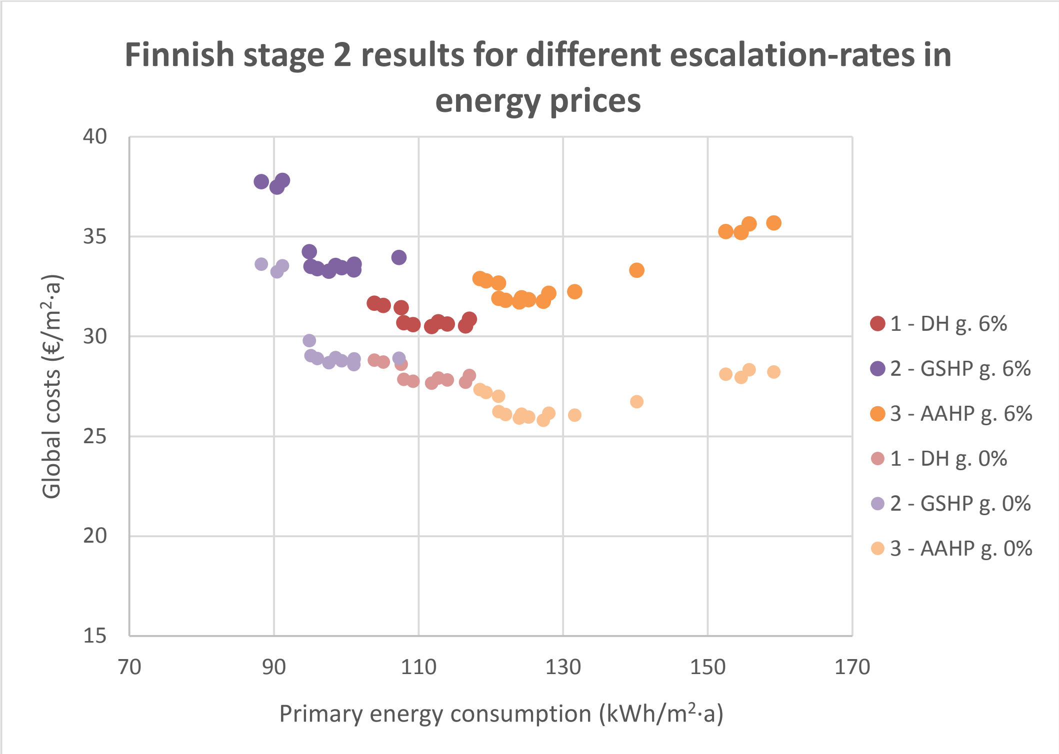

Figure 5.27. *Global costs and primary energy consumption of Stage 2 Finnish candidate buildings under different energy price escalation-rates.*

In the case of Spain, an unrealistic growing rate of 15 % would be needed for any change in cost-optimal solutions.

During all the calculations, it was assumed that the selling price of exported electricity was the same as the price of the imported one. This assumption is slightly unrealistic, at least in the current situation in Spain. On the other hand, some Finnish electricity providers assure market prices for surplus electricity [108], while others offer prices around 25 % of the buying price [109]. Moreover, a variation on this selling price influences the feasibility of photovoltaic systems, as considered in [110]. For example, if the selling price of exported electricity is decreased to 55 % or less of the buying price, photovoltaic panels stop being cost-effective in Spain.

Weighting factors are other of the biggest assumptions made for the calculations. Although, the official values of each country were applied, these values are not completely objective. In addition, they affect severely the results. An increase of 0.1 points of district heat weighting factor changes the heating system of the most efficient building from district heating to ground source heat pump in Spain.

Moreover, the variation of electricity weighting factors affects the area of PV-panels needed to obtain a nZEB in Spain, as shown in Figure 5.28. This effect is less remarkable in Finland due to the small size of the variation compared with bigger areas of panels. Figure 5.28, shows the needed area for weighting factors increasing from the Spanish official value, 2.432, to the value proposed for European countries, 3.14.

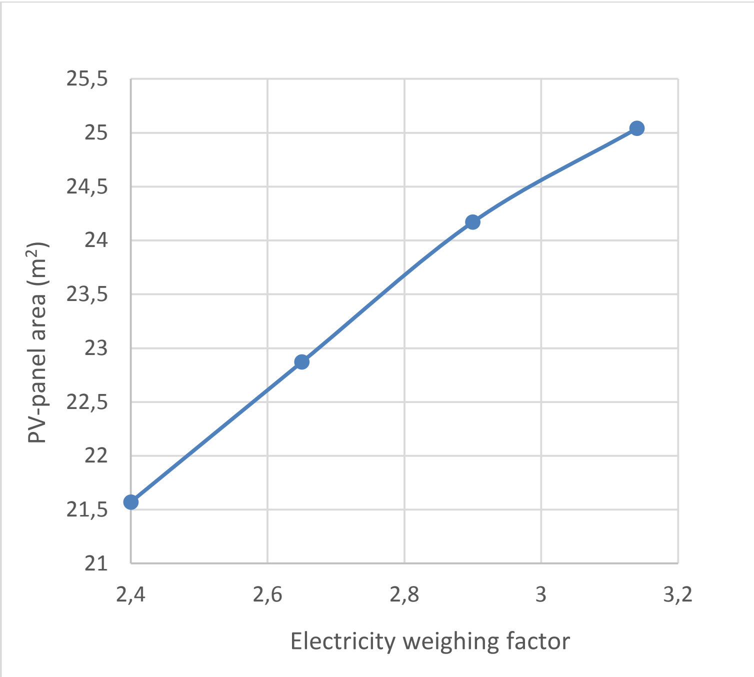

Figure 5.28. *Influence of electricity weighting factor over the PV-panel area needed to reach nZEB qualification in Spain.*

The nearly zero-energy building qualification applied consisted on allowing a primary energy net consumption of 50 kWh/m^{2}a. Increasing electricity weighting factor, means that the electricity consumption allowed is lower. Therefore, more electricity needs to be produced and more PV-panels installed.

Summarizing, the area of the photovoltaic panels and the cost-efficiency of the PV systems are the most sensitive results. However, the rest of the results, such as which heating systems is included in the nZEB solution, seem to be robust when financial parameters are varied.

6. CONCLUSIONS

This study presents findings regarding to a cost-optimal approach of nearly zero-energy buildings in Finland and Spain. This is achieved by simulating multiple single-family house configurations with DBES model in order to understand how design variables affect energy performance and global costs. Cost-optimal results are analyzed and compared with reference buildings, which implement minimum requirements in the regulation of each country.

Studied design variables include envelope insulation, windows structure (U-value and solar transmission), airtightness and heat recovery unit efficiency. Results confirm that investing in the last two variables is cost-efficient due to considerable savings in energy expenses. However, calculations reveal that costs of improving the envelope insulation or installing high quality windows are too high. The improvement in the energy performance compared with reference buildings does not lead to savings that could justified the investment. A reasonable explanation for this is that regulation requirements, which are specially focused on thermal transmittances of the envelope, are the result of previous cost-optimal studies.

Regarding to the HVAC systems in nearly zero-energy buildings, air-to-air heat pumps prove to be the most attractive choice. Ground source heat pumps and district heating systems, despite their lower primary energy consumption, result to be too expensive nowadays in Finland and Spain. Nevertheless, a future decrease in the installation costs of these systems could promote changes in nZEB cost-optimal solutions.

Renewable energy sources were considered in this study as well. Results confirm the convenience of implementing solar thermal collectors for heating domestic water and improving the efficiency of HVAC systems. Photovoltaic panels result to be cost-efficient only in Spain, where their electricity production is considerable higher compared to Finnish locations. Nevertheless, the technology could be soon economically attractive in Finland as only slightly lower installation costs are needed, under the considered financial context.

Cost-optimal designs reveal lower primary energy consumption and annual costs compared with reference buildings, even before the implementation of PV-panels. Approximated reductions of 27 and 18 kWh/m^{2}a and 8 and 6 % lower costs were found in Finland and Spain, respectively.

Photovoltaic panels are needed in order to achieve nZEB, understood as the standard of 50 kWh/m^{2}a primary energy consumption. The necessary area of PV-panels is 50 m^2 in Finland and 20 m^2 in Spain. Investment in this technology makes annual global costs similar to those of the reference building in Finland. In the case of Spain, the annual costs remain 19 % lower than reference building's due to the cost-efficiency of photovoltaic technology in this location.

The sensitivity analysis carried confirms a high dependency of the PV sizing and cost-efficiency on several financial parameters, such of the selling price of surplus electricity. However, results seem to be robust for the reasonable variations of this and the rest of parameters.

The results of this thesis show how energy savings are highly conditioned by the search of cost-optimal solutions. Further studies might focus on the appropriate funding that governments should provide to save energy beyond cost-optimal.

Future steps to be taken related to this study would include the implementation of a self-consumption model into DBES software. Thus, additional studies could be carried, with more specific conclusions. It would be constructive to add additional heating systems to DBES model, so the study could include, for example, gas or biomass boilers. As well, it would be interesting to apply genetic algorithm calculations in the optimization methodology. As a result, more defined Pareto curves could be obtained. Nonetheless, the initial goals were fulfilled under the chosen approach.

REFERENCES

[1] E. C. Eurostat, "Energy, transport and environment indicators - 2013 edition," Publications Office of the European Union, Luxembourg, 2013.

[2] I. E. A. -. IEA, "IEA Sustainable Buildings Centre," 2014. [Online]. Available: http://www.sustainablebuildingscentre.org/. [Accessed 12 December 2014].

[3] E. Parlamient, "EPBD recast (2010), Directive 2010/31/EU," *Official Journal of the European Union,* May 2010.

[4] A. Marszal, H. P., J. Bourrelle, E. Musall, K. Voss, I. Sartori and A. Napolitano, "Zero Energy Building - A review of definitions and calculation methodologies," *Energy and Buildings,* vol. 43, pp. 971-979, 2011.

[5] U. E. I. Administration, "Annual Energy Outlook 2013 with Projections to 2040," April 2013.

[6] L. Pérez-Lombard, J. Ortiz and C. Pout, "A review on buildings energy consumption information," ELSEVIER, March 2007.

[7] D.-G. o. E. a. T. European Commission, "Green Paper on Energy Efficiency. How to Do More with Less?," Office for Official Publications of the European Communities, 2005.

[8] U. Department of Energy, *Building Technologies Program,* 2008.

[9] E. Commission, "Energy Performance of Buildings Directive 2002/91/EC (EPBD)," European Parliament, 2002.

[10] P. Torcellini, S. Pless, M. Deru and D. Crawley, *Zero Energy Buildings: A Critical Look at the Definition,* US: National Renewable Energy Laboratory and Department of Energy, 2006.

[11] I. Sartori, A. Napolitano, A. Marszal, S. Pless, P. Torcellini and K. Voss, "Criteria for Definition of Net Zero Energy Buildings," in *International Conference on*

Solar Heating, Cooling and Buildings, 2010.

[12] J. Kurnitski, F. Allard, D. Braham, G. Goeders, P. Heiselberg, L. Jagemar, R. Kosonen, J. Lebrun, L. Mazzarella, J. Railio, O. Seppänen, M. Schmidt and M. Virta, "How to define nearly net zero energy buildings nZEB - REHVA proposal for uniformed national implementation of EPBD recast," *REHVA Journal*, vol. May, pp. 6 - 12, 2011.

[13] I. Sartori, J. Candanedo, S. Geier, R. Lollini, A. Athienitis, F. Garde and L. Pagliano, "Comfort and Energy Performance Recommendations for Net Zero Energy Buildings," in *EuroSun 2010*, Gratz, AT, 2010.

[14] I. Sartori, A. Napolitano and K. Voss, " Net zero energy buildings: A consistent definition framework," *Energy and Buildings*, vol. 48, pp. 220-232, 2012.

[15] D. Crawley, S. Pless and P. Torcellini, "Getting to net zero," *ASHRAE Journal*, vol. 51, pp. 18-25, 2009.

[16] K. Voss, I. Sartori and R. Lollini, "Nearly-zero, Net zero and Plus Energy Buildings - How definitions & regulations affect the solutions," *REHVA European HVAC Journal*, vol. 49, pp. 23-27, 2012.

[17] A. Marszal, J. Bourrelle, E. Musall, P. Heiselberg, A. Gustavsen and K. Voss, "Net Zero Energy Buildings – Calculation Methodologies versus National Building Codes," in *EuroSun Conference*, Graz, Austria, 2010.

[18] I. Sartori and A. Hestnes, "Energy use in the life cycle of conventional and low-energy buildings: A review article," *Energy and Buildings*, vol. 39.3, pp. 249-257, 2007.

[19] K. Voss, I. Sartori, E. Musall, A. Napolitano, S. Geier, M. Hall, B. Karlsson, P. Heiselberg, J. Widen, J. Candanedo and P. Torcellini, "Load matching and grid interation of net zero energy buildings," in *EuroSun 2010*, Graz, Austria, 2010.

[20] J. Grözinger, T. Boermans, A. John, F. Wehringer and J. Seehusen, "Overview of Member States information on NZEBs, Background paper – final report," Ecofys, October 2014.

[21] J. Grözinger, T. Boermans, A. John, F. Wehringer and J. Seehusen, "Overview of Member States information on NZEBs. Working version of the progres report - final report," Ecofys, October 2014.

[22] M. Gonzalez Álvarez, "Nueva Directiva relativa a la Eficiencia Energetica de los Edificios, Directiva 2010/31: Edificios de Consumo de Energía Casi Nulo," in *Edificios de consumo energético casi nulo, de la investigación a la construcción real*, Barcelona, May 2010.

[23] *Código Técnico de la Edificación (CTE) Documento Básico de Ahorro de Energía (DB-HE)*, BOE 08/11/2013, September 2013.

[24] *Código Técnico de la Edificación (CTE) Documento Básico de Ahorro de Energía (DB-HE)*, BOE 28/03/2006, 2006.

[25] D. M. Aitor, "Implementing the Energy Performance of Buildings Directive (EPBD) - Featuring country reports 2012," in *EPBD implementation in Spain: Status at the end of 2012*, ADENE, 2013, pp. 173-180.

[26] M. Haakana, P. Kalliomäki and J. Kauppinen, "National plan for increasing the number of nearly zero-energy buildings in Finland," Ecofys, Köln, Germany, May 2013.

[27] M. Haakana and P. Laitila, "EPBD implementation in Finland: status at the end of 2012," in *Implementing the Energy Performance of Buildings Directive (EPBD)*, ADENE, 2013, pp. 173-180.

[28] "Finland's national plan to increase the number of nearly zero-energy buildings," European Commission, October 2012.

[29] "iPHA - The International Passive House Association," International Passive House Association, [Online]. Available: http://www.passivehouse-international.org/. [Accessed 2 February 2015].

[30] E. Musall, "Net Zero Energy Buildings - Worldwide," Bergische Universität Wuppertal, December 2013. [Online]. Available: http://batchgeo.com/map/net-zero-energy-buildings#. [Accessed 2 February 2015].

[31] "Nollanergia," [Online]. Available: http://www.nollaenergia.fi. [Accessed 2 February 2015].

[32] J. Jormalainen, "Implementing zero energy buildings in harsh Nordic climate conditions," SPU Insulation, 2011.

[33] "Lanttitalo," [Online]. Available: http://www.lanttitalo.fi/. [Accessed 02 February 2015].

[34] "Afrisol," Ministerio de Ciencia y Educación, [Online]. Available: http://www.arfrisol.es/. [Accessed February 03 2015].

[35] J. Ferrer, "Proyecto Arfrisol," Unidad de Investigación sobre Eficiencia Energética en edificación del CIEMAT, 2012.

[36] "Research Demo-container of the Building 70 CIEMAT," PSE-ARFRISOL.

[37] H. R. E. Strategies, "Sede de ACCIONA SOLAR primer edificio “cero emisiones” de España," [Online]. Available: http://www.pvdatabase.org/pdf/Acciona-Solar_Building_es.pdf. [Accessed 03 February 2015].

[38] "Acciona-energia," [Online]. Available: http://www.acciona-energia.es/media/318837/Edif%20CERO%20EMISI%20ESP%20OK.pdf. [Accessed 03 February 2015].

[39] O. Hernandez, "Elithis Tower in Dijon, France," *REHVA Journal*, vol. May, pp. 53-57, 2011.

[40] New Buildings Institute - nbi, "Gilman Ordway Building at the Woods Hole Research Center (Woods Hole Research Center)," [Online]. Available: http://buildings.newbuildings.org/overview.cfm?projectid=257. [Accessed 03 February 2015].

[41] "Autodesk Design Academy," [Online]. Available: http://academy.autodesk.com/library/building-science/trombe-wall-and-attached-sunspace. [Accessed 9 February 2015].

[42] S. Kalogirou, Solar Energy Engineering: Processes and Systems, Academic Press, 2013.

[43] E. Rodriguez-Ubinasa, C. Monter, M. Porteros, S. Vega, I. Navarro, M. Castillo-Cagigal, E. Matallanas and A. Gutiérrez, "Passive design strategies and performance of Net Energy Plus Houses," *Energy and Buildings*, vol. 83, p. 10–22, 2014.

[44] R. McDowall, Fundamentals of HVAC Systems, Elsevier, 2006.

[45] W. Turner and H. Awbi, "Experimental investigation into the thermal performance of a residential hybrid ventilation system," *Applied Thermal Engineering*, vol. 77, pp. 142-152, 2015.

[46] M. Russell, M. Sherman and A. Rudd, "Review of Residential Ventilation Technologies," Ernesto Orlando Lawerence Berkeley National Laboratory, 205.

[47] W. Grondzik, Air Conditioning System Design Manual, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2007.

[48] E. Fabrizio, F. Seguro and M. Filippi, "Integrated HVAC and DHW production systems for Zero Energy Buildings," *Renewable and Sustainable Energy Reviews,* vol. 40, pp. 515-541, 2014.

[49] F. I. f. S. E. Systems, "Photovoltaics report," Franhoufer ISE, Freiburg, July 2014.

[50] H. Häberlin, Photovoltaics: System Design and Practice, Electrosuisse, 2010.

[51] G. Masson, S. Orlandi and M. Rekinger, "Global Market Outlook For Photovoltaics 2014-2018," European Photovoltaic Industry Association, 2014.

[52] D. C. Jordan and S. R. Kurtz, "Photovoltaic Degradation Rate - An Analytical Review," National Renewable Energy Laboratory (NREL), June 2012.

[53] E. Skoplaki and J. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," *Solar Energy,* 2008.

[54] B. Marion, J. Adelstein, K. Boyle, H. Hayden, B. Hammond, T. Fletcher, B. Canada, D. Narang, A. Kimber, L. Mitchell, G. Rich and T. Townsend, "Performance parameters for grid-connected PV systems," in *Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE*, January 2005.

[55] M. Raisul Islam, K. Sumathy and S. Ullah Khan, "Solar water heating systems and their market trends," *Renewable and Sustainable Energy Reviews,* vol. 17, p. 1–25, 2013.

[56] Z. Wang, W. Yang, F. Qiu, X. Zhang and X. Zhao, "Solar water heating: From theory, application, marketing and research," *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 68-84, 2015.

[57] K. Januševičius and G. Streckienė, "Solar Assisted Ground Source Heat Pump Performance in Nearly Zero Energy Building in Baltic Countries," *Environmental and Climate Technologies*, vol. 11, pp. 48-56, 2013.

[58] A. Allouhi, T. Kousksou, A. Jamil, P. Bruel, Y. Mourad and Y. Zeraouli, "Solar driven cooling systems: An updated review.," *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 159-181, 2015.

[59] M. Abdeen, "Ground-source heat pumps systems and applications.," *Renewable and Sustainable Energy Reviews,* vol. 12.2, pp. 344-371, 2008.

[60] R. Curtis, J. Lund, B. Sanner, L. Rybach and G. Hellström, "Ground source heat pumps–geothermal energy for anyone, anywhere: current worldwide activity.," in *Proceedings World Geothermal Congress*, Antalya, Turkey, 2005.

[61] S. Self, B. Reddy and M. Rosen, "Geothermal heat pump systems: Status review and comparison with other heating options.," *Applied Energy,* vol. 101, pp. 341-348, 2013.

[62] G. Huttrer, "Geothermal heat pumps: an increasingly successful technology.," *Renewable Energy,* vol. 10.2, pp. 481-488, 1997.

[63] G. Florides and S. Kalogirou, "Ground heat exchangers - A review of systems, models and applications.," *Renewable Energy,* vol. 32.15, pp. 2461-2478, 2007.

[64] M. Omer, "Ground-source heat pumps systems and applications.," *Renewable and Sustainable Energy Reviews,* vol. 12.2, pp. 344-371, 2008.

[65] J. Lund and T. Boyd, "Direct Utilization of Geothermal Energy 2015 Worldwide Review," in *2015*, Melbourne, Australia, Proceedings World Geothermal Congress 2015.

[66] L. Lu and K. Sun, "Wind power evaluation and utilization over a reference high-rise building in urban area.," *Energy and Buildings,* vol. 68, p. 339–350, 2014.

[67] A. Peacock, D. Jenkins, M. Ahadzi, A. Berry and S. Turan, "Micro wind turbines in the UK domestic sector," *Energy and Buildings,* vol. 40, p. 1324–1333, 2008.

[68] D. Ayhan and Ş. Sağlam, "A technical review of building-mounted wind power systems and a sample simulation model," *Renewable and Sustainable Energy Reviews,* vol. 16, p. 1040– 1049, 2012.

[69] E. Dayan, "Wind energy in buildings: Power generation from wind in the urban environment - where it is needed most," 2006.

[70] A. Lahimer, M. Alghoul, K. Sopian, N. Amin, N. Asim and M. Fadhel, "Research and development aspects of pico-hydropower," *Renewable and Sustainable*

Energy Reviews, vol. 16, pp. 5861-5878, 2012.

[71] P. Maher, N. Smith and A. Williams, "Assessment of pico hydro as an option for off-grid electrification in Kenya," *Renewable Energy,* vol. 28, p. 1357–1369, 2003.

[72] A. Haidar, M. Senan, A. Noman and T. Radman, "Utilization of pico hydro generation in domestic and commercial loads," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 518-524, 2012.

[73] E. Michaelides, Alternative Energy Sources, Springer, 2012.

[74] S. (. d. E. BESEL, "Biomasa: Edificios," IDAE (Instituto para la Diversificación y Ahorro de la Energía), Madrid, 2007.

[75] D. d. B. y. R. d. IDAE, "Guía técnica de instalaciones de biomasa térmica en edificios," IDAE (Instituto para la Diversificación y Ahorro de la Energía), Madrid, 2009.

[76] The Austrian Energy Agency (E.V.A.), Instituto para la Diversificación y Ahorro de la E and Energy and Environment Consulting, "Biomasa. Calefacción sostenible para edificios públicos," Instituto para la Diversificación y Ahorro de la Energía (IDAE), Madrid, 2002.

[77] V. Verma, S. Bram and J. De Ruyck, "Small scale biomass heating systems: Standards, quality labelling and market driving factors – An EU outlook," *Biomass and Bioenergy,* vol. 33, pp. 1393-1402, 2009.

[78] G. Inc., *Google Earth 7.1.2.2041,* 2013.

[79] "Weather Base," Canty and Associates LLC, 2015. [Online]. Available: http://www.weatherbase.com. [Accessed 15 March 2015].

[80] Eurostat, "Housing statistics," [Online]. Available: http://ec.europa.eu/eurostat /statistics-explained/index.php/Housing_statistics. [Accessed 19 May 2015].

[81] M. Viot and J. Hilpinen, "Dynamic Building Energy Simulation: Presentation of the Matlab-model," Tampere University of Technology (TUT), Tampere, 2014.

[82] I. E. E. P. o. t. E. Union, "Entranze Project: Policies to Enforce the Transition to Nearly Zero Energy buildings in EU-27," [Online]. Available: http://www.entranze.eu/. [Accessed 16 March 2015].

[83] A. P. Dobos, "PVWatts Version 5 Manual," National Renewable Energy Laboratory (NREL), Denver, September 2014.

[84] "Building Energy Software Tools Directory," U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy, 1 September 2011. [Online]. [Accessed 15 March 2015].

[85] G. Mitalas and J. Arseneault, "Fortran IV program to calculate z-transfer functions for the calculation of transiet heat transfer through walls and roofs.," National Resarch Council of Canada, Ottawa, 1972.

[86] A. Aittomäki and T. Kalema, "TASE: Tietokoneohjelma rakennusten lämpötaseen laskemiseksi (In Finnish)," Technical Research Center of Finland, Otaniemi, 1976.

[87] A. Aittomäki, T. Kalema, T. Haapala and J. Tala, "TASE: Tietokoneohjelma rakennusten lämpötaseen laskemiseksi (In Finnish)," Technical Research Center of Finland, Otaniemi, 1976-1989.

[88] T. Haapala and T. Kalema, "TASE: Tietokoneohjelma rakennusten lämpötaseen laskentaan versio 2.0 (In Finnish)," Tampere University of Technology, Tampere, 1989.

[89] T. Kalema, "Thermal analysis of buildings - Verification and further development of the TASE program," Tampere University of Technology, vol. 87, 1992.

[90] "NREL: System Advisor Model (SAM)," The National Renewable Energy Laboratory (NREL), [Online]. Available: https://sam.nrel.gov/. [Accessed 10 October 2014].

[91] "PVWatts Calculator," The National Renewable Energy Laboratory (NREL), [Online]. Available: http://pvwatts.nrel.gov/. [Accessed 10 October 2014].

[92] D. Aron P., "PVWatts Version 1 Technical Reference," National Renewable Energy Laboratory (NREL), Denver, October 2013.

[93] J. R. C. I. f. E. a. T. (IET), "Photovoltaic Geographical Information System (PVGIS)," [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#. [Accessed 5 November 2014].

[94] N. R. E. L. (NREL), "PvWatts Calculator," [Online]. Available: http://pvwatts.nrel.gov/. [Accessed 5 November 2014].

[95] P. SA, *PVSyst Photovoltaic Software V. 6.32,* November 2014.

[96] "EnergyPlus Energy Simulation Software: Weather Data Sources," U.S. Department of Energy, 12 February 2015. [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm#IWEC. [Accessed 17 March 2015].

[97] A. Mohamed, A. Hasan and K. Sirén, "Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives," *Applied Energy,* vol. 114, pp. 385-399, 2014.

[98] I. p. l. D. y. A. d. l. E. IDAE, "Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector edificios en España," Ministerio de industria, energía y turismo, 2014.

[99] M. Ferrera, E. Fabrizio, J. Virgone and M. Filippi, "A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings," *Energy and Buildings,* vol. 84, pp. 442-457, 2014.

[100] C. Becchio, P. Dabbene, E. Fabrizio, V. Monetti and M. Filippi, "Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target," *Energy and Buildings,* vol. 90, pp. 173-187, 2015.

[101] M. Viot and J. Hilpinen, "Dynamic Building Energy Simulation: Results," Tampere University of Tampere, Tampere, 2014.

[102] M. Hamdy, A. Hasan and K. Siren, "Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings," *Building and Environment,* vol. 46, pp. 109-123, 2011.

[103] "Kaukolämmön hinnat tyyppitaloissa eri paikkakunnilla," Energiateollisuus, 11 Feb 2015. [Online]. Available: http://energia.fi/tilastot/kaukolammon-hinnat-tyyppitaloissa-eri-paikkakunnilla. [Accessed 24 March 2015].

[104] "Los tipos de interes practicados por las entidades," Banco de España, 2014. [Online]. Available: http://www.bde.es/clientebanca/tipo/entidades.htm. [Accessed 25 March 2015].

[105] M. Hamdy, A. Hasan and K. Siren, "A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010," *Energy and Buildings,* vol. 56, p. 189–203, 2013.

[106] A. Saari, T. Kalamees, J. Jokisalo, R. Michelsson, K. Alanne and J. Kurnitski, "Financial viability of energy-efficiency measures in a new detached house design in Finland," *Applied Energy,* vol. 92, pp. 76-83, 2012.

[107] T. Huld, A. Jäger Waldau, H. Ossenbrink, S. Szabo, E. Dunlop and N. Taylor, "Cost Maps for Unsubsidised Photovoltaic Electricity," European Commission, 2014.

[108] "Selling surplus electricity," Helen Ltd, [Online]. Available: https://www.helen.fi/en/households/services/new-energy-products/own-solar-power-plant/selling-surplus-electricity/. [Accessed 1 April 2015].

[109] "Tuntispot-hinnat Sähköpörssissä," Vattenfall, 13 April 2015. [Online]. Available: http://www.vattenfall.fi/fi/tuntispot-hinnat-sahkoporssissa.htm. [Accessed 13 April 2015].

[110] E. Pijas, M. Thalfeldt and J. Kurnitski, "Cost optimal and nearly zero energy building solutions for office buildings," *Energy and Buildings*, vol. 74, pp. 30-42, 2014.

APPENDICES

Appendix A: Added code to DBES model

In this appendix, functions added to DBES in order to process multiple buildings and perform the cost-optimal calculation are presented. No additional explanation is needed to that included in the comments of the code.

PVWatts implementation function

```
function [ pv_generation] = pvwattsgenpoa( power, city, poa)

% This function runs PVWatts in order to calculate the electricity generated
% by the installed photovoltaic panels.

% Inputs
    % Power: installed capacity
    % City: location of the building
    % Poa: Plane of array irradiance

% Moving to the solar tool folder
oldfolder=pwd;
cd(strcat(oldfolder,'\','solar\SAM - sdk\languages\matlab'));

% Main solar script
SSC.ssccall('load');

% Create a data container to store all the variables
data = SSC.ssccall('data_create');

% Selection of the weather file
if strcmp(city,'Helsinki')
     weatherepw = '../../weatherdata/HelsinkiTMY3own.csv';
elseif strcmp(city,'Madrid')
    weatherepw = '../../weatherdata/ESP_Madrid.082210_IWEC.epw';
else
    weatherepw = '../../weatherdata/HelsinkiTMY3own.csv';
    disp ( 'Helsinki conditions selected for PV generation calculations');
end
```

```
% Setup the system parameters
SSC.ssccall('data_set_string', data, 'file_name', weatherepw);
SSC.ssccall('data_set_number', data, 'system_size', power);
SSC.ssccall('data_set_number', data, 'derate', 0.825); % DC too AC efficiency
factor, updated according to PVWatts V5 Manual
SSC.ssccall('data_set_number', data, 'gamma', -0.47); % Temperature
coefficient
SSC.ssccall('data_set_number', data, 'track_mode', 0);
if strcmp(city,'Madrid')
    SSC.ssccall('data_set_number', data, 'tilt', 40);
else SSC.ssccall('data_set_number', data, 'tilt', 60);
end;
SSC.ssccall('data_set_number', data, 'azimuth', 180);
SSC.ssccall('data_set_number', data, 'enable_user_poa', 1);
SSC.ssccall('data_set_array', data, 'user_poa', poa);

% Create the PVWatts module
module = SSC.ssccall('module_create', 'pvwattsv1');

% Run the module
ok = SSC.ssccall('module_exec', module, data);
if ok,
    % if successful, retrieve the hourly AC generation data and print
    % annual kWh on the screen
    pv_generation = SSC.ssccall('data_get_array', data, 'ac');
    disp(sprintf('pvwatts: %.2f kWh',sum(pv_generation)/1000.0));
else
    % if it failed, print all the errors
    disp('pvwattsv1 errors:');
    ii=0;
    while 1,
        err = SSC.ssccall('module_log', module, ii);
        if strcmp(err,''),
            break;
        end
        disp( err );
        ii=ii+1;
    end
end

% Free the PVWatts module that we created
SSC.ssccall('module_free', module);

% Release the data container and all of its variables
SSC.ssccall('data_free', data);
```

```
% Unload the library
SSC.ssccall('unload');

% Moving back to the main folder
cd(oldfolder);

end
```

Building creator for Stage 2

```
function [] = buildingcreator2st(SH)

% This function creates building input files that can be read by
% run_DBES. These buildings are created using parametric inputs.

% Inpus:
    % SH is 1 for floor heating and 0 for radiators.
    % "envelopePackages.mat" Defined as:
        % Columns 1:4 = floorheating packages for FI
        % Columns 5:8 = radiator packages for FI
        % Columns 9:12 = floorheating packages for SP
        % Columns 13:16 = radiator packages for SP
    % "sel2stage.mat" includes the number identifying the selected
        %candidates from the first stage.
    % "input.xlsm" includes the reference building definition and location.

% Variables:
    % Heating systems best size, defined along the funcition
    % Range of values for the design variables
```

```
% Error if no heating system specify
if nargin<1
    beep;
    error...
      ('You must specifiy a heating system, 1=floor heating, 0=radiators');
end
% Variables:
q50=[4 2 1 0.5];
heatRec=[0.45 0.65 0.75];
% Loading necessary inputs
load('sel2stage.mat');
```

```
load('envelopePackages.mat');
xlsfile=uigetfile('input.xlsm')

tic % Starts timer

% Reading global properties
[globalNum, globalTxt] = xlsread(xlsfile,'Global','C40:C65');
% Readings for the building and profiles
[buildingNum, buildingTxt] = xlsread(xlsfile, 'Building', 'C30:K45');
[timeprofilesNum, timeprofilesTxt] = xlsread(xlsfile, 'TimeProfiles',
'C4:AW23');
% Reading room properties
[room1Num, room1Txt] = xlsread(xlsfile, 'Room1', 'C60:L101');
[room2Num, room2Txt] = xlsread(xlsfile, 'Room2', 'C60:L101');

% Location and spaceheating selection
if strcmp(globalTxt(1),'Madrid')==1 % Location given in "input.xlsm"
   location='SP';
   sp=1;
else
   location='FI';
   sp=0;
end
if SH==1 % Input of the matlab function
    spaceHeatingB='Floor heating';
    spaceHeatingS='fl'; % Tag for the name of the output file
    ra=0;
elseif SH==2
    spaceHeatingB='Radiators';
    spaceHeatingS='ra'; % Tag for the name of the output file
    ra=1;
end

filecounter=0; % Tag for the name of the output file
```

```
% Creating buildings
for p=1:4 % Writing envelope data for both rooms
        envelopePackage=p;
        room1Txt(1:14,1)=envelopePackages(1:14,p+8*sp+4*ra);
        room2Txt(1:14,1)=envelopePackages(15:28,p+8*sp+4*ra);
    for i=1:4 % Writing airtightness data
        buildingNum(3,7)=q50(i);
        for j=1:3 % Writing heat recovery data
            buildingNum(1,8)=heatRec(j);
```

```
            filecounter=filecounter+1;
            for heatingSystem=1:3 % Writing heating system data
                switch heatingSystem
                    case 1 % District heating + solar
                        SHeti='DH'; % Tag for the name of the output file
                        SHeti2=spaceHeatingS;
                        globalTxt(12)=cellstr...
                            ('District heating with solar collector');
                        globalTxt(13)=cellstr(spaceHeatingB);
                        if sp==1 % Set optimum values depending on location
                            globalNum(7)=300;
                            globalNum(8)=2;
                        else
                            globalNum(7)=400;
                            globalNum(8)=5;
                        end
                    case 2 % Ground source heat pump
                        SHeti='GHPD';
                        SHeti2=spaceHeatingS;
                        globalTxt(12)=cellstr...
                            ('Ground HP with DHW storage + solar');
                        globalTxt(13)=cellstr(spaceHeatingB);
                        if sp==1
                            globalNum(7)=300;
                            globalNum(8)=2;
                            globalNum(9)=6;
                        else
                            globalNum(7)=400;
                            globalNum(8)=5;
                            globalNum(9)=6;
                        end
                    case 3 % Air-to-air heat pump
                        SHeti='AA';
                        SHeti2='';
                        globalTxt(12)=cellstr('Air to air HP + solar');
                        globalTxt(13)=cellstr('Air heating');
                        if sp==1
                            globalNum(7)=300;
                            globalNum(8)=2;
                            globalNum(9)=3.5;
                        else
                            globalNum(7)=400;
                            globalNum(8)=4;
                            globalNum(9)=3.2;
                        end
```

```
                end
                % Creating variable with design variables values
                ZEB_info=struct('location',location,'ZEB_counter',...
                    filecounter,'q50',i,'heatRec',j,'heatSys',...
                    heatingSystem,'envelopePackage',p);
                % Creating output file name
                fileName = ['2stage-ZEB','-',location,'-n',...
                    int2str(filecounter),'-e',num2str(envelopePackage),...
                    '-q',num2str(q50(i)),'-hr',num2str(heatRec(j)),'-',...
                    SHeti,SHeti2,'.mat'];
                % Saving outputfile if the candidate was selected in Stage 1
                if find(sel1stage==filecounter)>=1
                    save(fileName, 'globalNum', 'globalTxt', ...
                         'buildingNum', 'buildingTxt', 'timeprofilesNum',...
                         'timeprofilesTxt','room1Num', 'room1Txt',...
                         'room2Num', 'room2Txt','ZEB_info');
                end
            end
        end
    end
end
disp([num2str(toc/60),' min']); % Showing elapsed time
end
```

Script for multiple building simulation

```
% This script runs DBES model over multiple files chosen by the user

% Chosing files to simulate
files=uigetfile('input.mat','MultiSelect','on');
disp('Multiprocessing:')
disp(files);
if isa(files,'char') % For the case of only one building simulated
    files={files};
end
```

```
% Running simulations
progress=0;
waitingbar=waitbar(progress,['MetaZEB calculating... (' num2str(progress)...
    '/' num2str(length(files)) ')']); % Creating waiting bar for the process
for i = 1:length(files)
    progress=progress+1/length(files);
```

```
    tic % Starting timer
    file=char(files(i));
    disp('Procesing');
    disp(file);
    % Running DBESmodel
    [buildingResults, roomsResults, heatingSystemResults] =
run_DBES_ZEB(file);
    sound(1); % Warns about ending the simulation
    b(i)=toc;
    disp(['Time ',num2str(b(i)/60),' min']); % Showing elapsed time
    close(waitingbar);
    waitingbar=waitbar(progress,['MetaZEB calculating... elapsed time '...
        num2str(round(sum(b)/60)) ' min (' num2str(i) '/'
num2str(length(files)) ')']);
end
close(waitingbar);
disp(['Total time ', num2str(sum(b)/60),' min']); % Showing total elapsed time
```

```
% Warning the user about the end of the simulations
    % Sound
    sound(1);sound(1);sound(1);sound(1);
    % Dialog
    d = dialog('Position',[300 300 250 150],'Name','My Dialog');
        txt = uicontrol('Parent',d,...
                    'Style','text',...
                    'Position',[20 80 210 40],...
                    'String','Simulations are finished');
        btn = uicontrol('Parent',d,...
                    'Position',[85 20 70 25],...
                    'String','OK',...
                    'Callback','delete(gcf)');
```

Cost calculation function

```
function [ Cost DetailedCosts ] =
CostCalcZEB(ZEB_info,building,heatingSystemResults)
% This function calculates the cost of the energy measures of a building

% Inputs
    % ZEB_info: values of the design variables
    % Building: general data about the building
```

```
    % heatingSystemResults: results of the simulation for the heating system
```

```
% Defining variables
q50=ZEB_info.q50;
heatRec=ZEB_info.heatRec;
heatSys=ZEB_info.heatSys;
envPack=ZEB_info.envelopePackage;
PVcap=building.PVcapacity;
if PVcap==0
    PVinst=0;
else
    PVinst=1;
end
DHcons=sum(heatingSystemResults.Q_districtHeating);
ElecCons=sum(heatingSystemResults.TotalElec_consumed);
PVgen=sum(heatingSystemResults.PV_gen);
location=building.city;

% Loading prices for the specific location
load('pricesData.mat');
if strcmp(location,'Madrid')==1
    prices=PricesSP;
else
    prices=PricesFI;
end
```

```
% Calculating energy measures cost
q50p=prices.q50(q50);
heatRecp=prices.heatRec(heatRec);
envPackp=prices.envPack(envPack);
heatSysp=prices.heatSys(heatSys);
PVcapp=prices.PVcapXX(1)*PVcap+prices.PVcapXX(2)*PVinst; % Photovoltaic panel
and installation

% Calculating energy costs
DHconsp=DHcons/1000000*prices.DHcons;
ElecConsp=ElecCons/1000000*prices.ElecCons-PVgen/1000000*prices.PVgen;

% Total Cost
Cost=(q50p+heatRecp+envPackp+heatSysp+PVcapp+DHconsp+ElecConsp)/building.areaF
loor;
DetailedCosts=struct('Infiltration',q50p,'heatRec',...
                   heatRecp,'envPack',envPackp,'heatSys',heatSysp,'PVinst',...
```

```
                   PVcapp,'DHcons',DHconsp,'ElecCons',ElecConsp);
end
```

Primary energy calculation function

```
function [PrimEC ElecToProduce] = PrimEC( heatingSystemResults, building)
% This function calculates the primary energy consumption of a building. In
% addition, it calculates the electricity that is necessary to produce for
% achieving an specified nZEB peformance level.



% Inputs:
    % HeatingSystemResutls: results of the simulation for the heating system
    % Building: results of the simulation for the heating system
    % nZEBconsumption: primary energy consumption value for a nZEB
        nZEBconsumption=50; %kWh/m2/a
```

```
% Setting the weighting factors according to the location
if strcmp(building.city,'Madrid')==1
    WF_DH=0.7;
    WF_EL=2.423;
else
    WF_DH=0.7;
    WF_EL=1.7;
end

% Calculating the primary energy (output in kWh/a/m2)
PrimEC=(sum(heatingSystemResults.Q_districtHeating)*WF_DH+...
    sum(heatingSystemResults.TotalElec_consumed)*WF_EL-...
    sum(heatingSystemResults.PV_gen)*WF_EL)/1000/building.areaFloor;

% Calculating electricity to produce (output in kWh/a)
ElecToProduce=(sum(heatingSystemResults.Q_districtHeating)*WF_DH+...
    sum(heatingSystemResults.TotalElec_consumed)*WF_EL)/1000/WF_EL-...
    nZEBconsumption*building.areaFloor/WF_EL;
end
```

Photovoltaic energy generation function

```
function [] = pvchanger3stage( mode )

% This function calculates the generated energy by photovoltaic panels for
% the selected candidates of Stage 2. It can also calculate the necessary
% panel area achieving nZEB qualification.

% Inputs
    % mode: 1 for several capacities, '' for the optimal solution.
    % Capacities to study:
        capacities=[0 2 4];
    % "sel3stage.mat": includes the number identifying the selected
        % candidates from the second stage
```

```
% Chosing files from Stage 2
files=uigetfile('input.mat','MultiSelect','on');
tic % Starting timer

% Creating the list of files. Only including candidates appearing in sel3stage
filecount=1;
load('sel3stage.mat');
for i = 1:length(files)
    load(char(files(i)));
    sel3stageindex=find(sel3stage(:,1)==building.ZEBinfo.ZEB_counter);
    for k=1:length(sel3stageindex)
       index=sel3stageindex(k);
       if sel3stage(index,2)==building.ZEBinfo.heatSys
          selfiles(filecount)=files(i);
          filecount=filecount+1;
       end
    end
end

% Mode selection
if nargin<1
    numberofcapacities=1;
else
    numberofcapacities=length(capacities);
end
```

```
% Photovoltaic energy calculation
for j=1:numberofcapacities
```

```
    for i = 1:length(selfiles)

        % Loads file.mat and creates names for future files
        load(char(selfiles(i)));
        [~,fileName,~]=fileparts(char(selfiles(i)));
        fileXls=strcat(fileName,'.xlsx');

        % Loads PVWatts results for the specific location
        if strcmp(building.city,'Madrid')==1
            load('SpanishPVgen.mat');
            hourlyPVgen=SpanishPVgen;
            PV_1kW=sum(SpanishPVgen);
        else
            load('FinlandPVgen.mat');
            hourlyPVgen=FinlandPVgen;
            PV_1kW=sum(FinlandPVgen);
        end

        % Calculates new PV capacity and creates new output files
        if nargin<1 % Case of optimal capacity mode
            [~,ElecToProduce]=PrimEC(heatingSystemResults, building);
            PVcapacityNew=ElecToProduce*1000/PV_1kW;
            outMAT=['3stage-' fileName,'-
PVopt',num2str(round(PVcapacityNew)),'.mat'];
            outXLS=['3stage-' fileName,'-
PVopt',num2str(round(PVcapacityNew)),'.xlsx'];
        else
            PVcapacityNew=capacities(j);
            outMAT=['3stage-' fileName,'-PV',num2str(PVcapacityNew),'.mat'];
            outXLS=['3stage-' fileName,'-PV',num2str(PVcapacityNew),'.xlsx'];
        end

        % Calculates new hourly PVgen
        heatingSystemResults.PV_gen=hourlyPVgen*PVcapacityNew;

        % Sets new PVcapacity in building variable
        building.PVcapacity=PVcapacityNew;

        % Writes new XLS results file
        copyfile(fileXls,'monthly_results.xlsx'); % Overwrite
        xlswrite('monthly_results.xlsx', PVcapacityNew, 'Building inputs',
'C64');
        HeatingSystemMonthlyResultsToExcel(heatingSystemResults,...
            heatingSystemInput.spaceHeating.type,building.areaFloor,...
            building, heatingSystemInput.heatSources.solarCollector.area,...
```

```
            heatingSystemInput.spaceHeating.systemID, heatingSystemInput,...
            buildingResults, roomsResults);

        % Calculates and writes new primary energy consumption and costs

heatingSystemResults.PrimEnerConsump=PrimEC(heatingSystemResults,building);
        [heatingSystemResults.BuildingCosts building.costs]=...
            CostCalcZEB(building.ZEBinfo,building,heatingSystemResults);
        ZEB_info_writer(heatingSystemResults);

        % Creates new result files and saves new monthly results
        copyfile('monthly_results.xlsx',outXLS); % Overwrites
        save(outMAT, 'building', 'heatingSystemInput', ...
        'buildingResults', 'roomsResults', 'heatingSystemResults');
         movefile(outXLS,'Stage3');
         movefile(outMAT,'Stage3');
    end
end
disp(['Total time ', num2str(toc/60),' min']); % Showing elapsed time
end
```

Result extraction function

```
function [] = zebdataextractor()

% This function extract those results needed for the cost-optimal
% calculation

% Input:
    % Files to analyze.

% Chosing input files
files=uigetfile('input.mat','MultiSelect','on');
tic % Starting timer
disp(files);
if isa(files,'char')
    files={files};
end

% Creating output empty matrix
dataZEB=cell(length(files),8);
```

```
% Extracting data
for i = 1:length(files)
    load(char(files(i))); % Loads file to analyze
    [~,name,~]=fileparts(char(files(i))); % Extracts its name
    [waste name]=strtok(name,'Z');
    dataZEB(i,1)={name};
    dataZEB(i,2)={building.ZEBinfo.ZEB_counter};
    dataZEB(i,4)={building.ZEBinfo.q50};
    dataZEB(i,5)={building.ZEBinfo.heatRec};
    dataZEB(i,6)={building.ZEBinfo.heatSys};
    dataZEB(i,3)={building.ZEBinfo.envelopePackage};
    dataZEB(i,7)={building.PVcapacity};
    dataZEB(i,8)={(sum(buildingResults.heating)/1000+...
        sum(buildingResults.vHeating)/1000)/building.areaFloor};
    dataZEB(i,9)={(sum(buildingResults.cooling)/1000+...
        sum(buildingResults.vCooling)/1000)/building.areaFloor};
    dataZEB(i,10)={sum(buildingResults.solarGain)/1000};
    dataZEB(i,11)={heatingSystemResults.PrimEnerConsump};
    dataZEB(i,12)={heatingSystemResults.BuildingCosts};
end

% Writing output matrix in an Excel file
range=strcat('A2:L',num2str(length(files)+1));
success=xlswrite('ZEB_analysis.xlsx',dataZEB,'Sheet1',range);

disp(['Total time ', num2str(toc/60),' min']); % Showing elapsed time
end
```

Appendix B: Price table applied in DBES cost calculations

	Finland	Spain
VAT not included, except for energy prices.		
Structures		
External wall insulation [I]	1.48 €/cm·m²	1.41 €/cm·m²
Roof insulation	1.80 €/cm·m²	0.59 €/cm·m²
Floor insulation	1.87 €/cm·m²	1.83 €/cm·m²
Windows	$138.9 \cdot U^{-1.168}$ €	$225.6 \cdot U^{-1.168}$ €
Infiltration (q50 = 4 | 2 |1 | 0.6)	550 | 850 1680 | 2210 €	550 | 850 1680 | 2210 €
HVAC-systems		
Ventilation unit		
Heat recovery efficiency (45% | 65% | 75%)	1566.8 | 2100 | 2366.6 €	2109.11 | 2394.5 | 2537.2 €
District heating system		
Connection cost	2177 €	2177 €
District heating unit	3145 €	3145 €
Installation	400 €	400 €
Solar collectors system [II]	2777 €	2957 €
Ground source heat pump system		
GSHP unit (6kW)	5700 €	6225 €
Other equipment and installation	2016 €	3722 €
Borehole (180m)	5040 €	2957 €
Solar collectors system	2540 €	2957 €
Air-to-air heat pump system		
Heat pump unit and installation [III]	1551 €	1720 €

Other		
Photovoltaic installation		
PV-panels	2700 €/kW	1750 €/kW
Installation	700 €	700 €
Energy		
Electricity import/export	154 €/MWh	160 €/MWh
District heat	68 €/MWh	100 €/MWh

[I] Prices are an average of the specific cost as the price of the mineral wool depends on the thickness of the panels.

[II] Solar collector system costs depend on the size of the installation. As mention before, this size is the optimal for the specific HVAC system and so is its price.

[III] Once again, these cost depend on the capacity of the specific heat pump