Modeling and Optimization of Energy services in Net Zero Energy House

Dao Thi Thu Hang

Aalto University

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Modeling and Optimization of Energy services in Net Zero Energy House

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Abstract

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Abstract

The building sector consumes about 40% of primary energy in Europe, of which, residential building accounts for 26% - as the largest single energy consumption. As a result, the building sector plays a decisive role to reduce Europe's energy consumption. This led to the release of European Energy Performance Building Directive in 2010 known as EPBD recast 2010 which introduced the objective that all new buildings - and existing large buildings, by retrofitting – be Net Zero Energy Building (NZEB) from 2020 onwards.

As a result, this PhD thesis intends to contribute to the design of better policies that foster the implementation of NZEB concept or Net Zero Energy House (NZEH), as a subset, with a particular emphasis on residential building in Europe. In this context, Portugal and Finland are chosen as the cases of the two climatically distinct European countries (Mediterranean vs. Boreal/Sub-Arctic) that also possess a large socio-economic gap.

The thesis proposes that in order to develop policies that lead to the successful NZEH implementation in Europe, a clearly defined energy-service framework with numerical reference values for the residential energy services demand is required. As a result, the thesis proposes an energy service modeling framework for residential energy services: space heating and cooling, water heating, lighting, cooking, kitchen appliances and other media appliances. Additionally, a multi-objective optimization method that uses genetic algorithms is carried out, which can help to determine the optimal choice of energy systems to supply the demand energy services. The optimization objectives combine: minimize the energy system cost and minimize the energy demand. Furthermore, implications for future technology development and policy recommendations are defined with the emphasis on the end-use and demand side of residential energy services.

With respect to Portugal, the results are water heat pump is best suited for water heating, whereas biomass boiler is preferable for both water and space heating. Moreover, PV is found to be the best option for the electricity demand of media, cooking, and lighting. Of all the investigated options, geothermal remains the least cost-effective, whilst energy storage deployment needs more effective incentive mechanism to ensure cost feasibility. For Finland, it is found that a water heat pump is the most suitable means for water heating in detached houses, whereas district heat systems based on renewable energy resources offer the best option for water and space heating in an apartment building scenario. In contrast to Portugal, geothermal heat pumps offer a cost-effective alternative for space heating in the Finland's climate.

Keywords Net Zero Energy House, energy services, residential energy services, residential energy consumption, life-cycle cost optimal, multiple objectives optimization, genetic algorithm, renewable energy, residential energy system

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1 INTRODUCTION

1.1 Background of NZEH research

Building sector consumes about 40% of primary energy in Europe, of which, the residential building accounts for 26%, as the largest single energy consumption followed by the transportation sector (Bódis & Ossenbrink 2015). In Europe, energy consumption in the building sector increased 60% from 1990 to 2012, and by 2040 the growth is forecasted up to 37% of the global energy demand (Internaltional Energy Agency 2014b). Overall, the residential sector alone is estimated to contribute nearly 27% of all CO_2 emission worldwide (Nejat et al. 2015).

With the ongoing instability of energy-security, energy shortage and climate change threats, it is decisive that European countries to secure their energy supply and reduced energy consumption. In the efforts to curtail energy consumption, the building sector plays a clear role alongside transportation and industrial sector. Robust initiatives to increase energy efficiency in the residential sector were initially introduced by European Directive in 2006 (European Union 2006) which have brought a noticeable energy consumption reduction over the years. As a result, the total energy consumption in 2014 was 12.7% lower than in 2006 (Eurostat 2016). These efforts, however, have not been sufficient to meet the continuously higher climate goal and energy policy targets of Europe (European Commision 2014).

The release of the European Energy Performance Building Directive 2010 (also known as EPBD recast 2010) reflects a further step forward of European Union efforts. This update EPBD recast initiated the implementation of Net Zero Energy Building in Europe which is defined as - "*a high energy efficient building for residential purposes where all or nearly all the energy demand is covered by renewable energy produced on-site or nearby*" (European Union, 2010). Following the EPBD 2010 recast, European countries have taken their national actions to meet this objective. To date, since 2010, European countries have set up concrete plans and targets for new Net Zero Energy Building - NZEB in general, or Net Zero Energy House – NZEH in the residential sector.

This thesis focuses on buildings in the residential sector, and the term NZEH, as a sub set of NZEB, shall be used. However, most of the countries have not yet set specific numerical values as a benchmark for NZEH implementation. It should be noted that alongside the EPBD initiative, previous efforts have been made to develop low-energy buildings, for example, voluntary standards such as the "Passive-house" are used in certain countries such as Germany, Sweden (Müller & Berker 2013). These voluntary standards, however, do not define all the residential energy services demand such as lighting, or cooking but focus mainly on the energy consumption of space heating and cooling.

The EPBD recast has sparked a number of debate, research initiatives as well as case studies on NZEH which have revealed the multiple challenges and aspects to be addressed. For example, the question on how to define the principle of NZEH related to methodologies and definitions was discussed in literatures (Riedy et al. 2011, Sartori et al. 2012, Marszal et al. 2011). Regarding the technical issues, such as the role of technology such as modeling and simulation tools used in the NZEH designing process have been studied (Attia et al., 2012). In addition, comparative studies have also raised the discussion on the effectiveness of deploying renewables by on-site and off-site supply (Marszal et al., 2012). Noticeably, there are authors who strongly argue that the aim to have all buildings to be NZEH compliant is not likely to be either the lowest cost or the most sustainable approach in reducing energy use (Global Energy Assessment 2012).

In term of energy use, efforts have been made on increasing the residential building's energy efficiency on the European scale. There are also well-established regulations on the implementation of low-energy buildings for heating, cooling and water heating. The European Commission has also put effort to mandate the NZEB with more detailed guidelines under the draft technical report prEN 15603:2013 Energy performance of buildings (Technical Committee CEN/TC 2014). Portugal, however, has not been issued a reference benchmark to all residential energy services (such as lighting, cooking) in order to address the implementation of NZEB. Worldwide development, the USA has been one of the leading countries and has progressed toward a common definition of NZEB for different types of buildings including residential buildings (Peterson et al. 2015).

Overall, in order to address the energy use of residential energy in Europe, NZEH is one key solution to progress. However, to develop effective technical solutions that reach NZEH targets, all energy services consumed at the household level are needed to analyzed, and not only the heating, cooking and hot water that stem from the EPDB. It is also crucial to acknowledge the diverse nature of climate and socio-economic setting of European countries. In this context, this thesis provides a study of the alternative solutions for reaching NZEH targets in two European countries' context, Portugal and Finland, which have very different climate condition and socio-economics context.

1.2 Motivations

1.2.1 Energy service analysis

Analysis of the energy consumption in the residential sector show that the consumption accounts for 42.6% of Portugal's final energy (Estatisticas oficiais

2010), whereas contributes to 26% of Finland's final energy (Statistics Finland 2015c).

Investigations into the energy services show one of the main challenges that hinders the NZEH implementation is that the existing literature, in general, has not well-addressed the demand side of the energy. In fact, it is important to define energy-service demand in order to do load matching of the energy demand and energy supply, particularly when dealing with the intermittent resources of renewable energy. While, most of the European countries have not yet set specific numerical benchmark for NZEH in terms of breakdown energy service demand including lighting, cooking and media appliances. This is a critical requirement because those energy services (of lighting, cooking, media appliances) specifically account for 56% of the total residential electricity consumption in Europe (Bertoldi et al. 2012), and 57% in Portugal (Estatisticas oficiais 2010). To further illustrate the needs to define the energy services in residential buildings in Europe, an outline of the residential energy services term used in this thesis is defined in the following *section 1.3*.

1.2.2 Geographical analysis

According to climatic classification based on biogeographical region, Portugal belongs to Mediterranean climate featured by mild winters and hot summers, while Finland climate is the subarctic climate in a boreal region that undergoes a severe winter period. These two countries present two examples of the diverse climate available across the European continent as depicted in *Figure 1*.

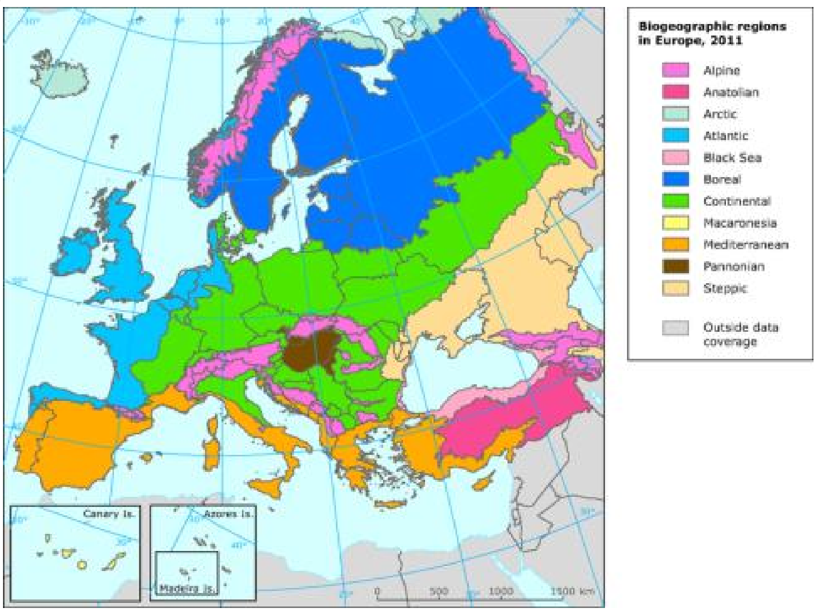


Figure 1 European Biogeographic and climate zones (European Environment Agency 2011)

In terms of energy use per capita, the Finns consume, in average, 3.3 times more electricity than the Portuguese (International Energy Agency 2013b), whilst annual Finland's household income per capita is 1.4 times higher than that of Portugal (Eurostat 2015b). Such country's background is important as it allows a better understanding of how NZEH implementation approaches can and should be varied to respond to such differences within Europe.

It is also worth emphasizing that, among the total of 300 reviewed documents listed in this thesis - which shall be discussed further in Chapter II - less than 5 literature addressed the NZEH topic directly to the residential sector in Portugal, and only 5 documents addressed the buildings in the Mediterranean climate, which Portugal is part of. Furthermore, the total number of NZEH case studies in Finland are also very few which comprise of less than 10. It is found that neither Portugal nor Finland has adopted an official obligatory guideline for NZEH development with the numerical targets and the low number of applicable literature highlights the need for more studies on the implementation of NZEH in both countries.

1.3 Definition of Terms

In this section, the following terms are defined in order to have a consistent use throughout the thesis: *Energy services, Net Zero Energy House – NZEH*. The *Energy balance* and the methodology used to evaluate the NZEH are also presented.

1.3.1 Energy services

According to the International Energy Agency - IEA (2007), *energy services* is a description of end uses. *Energy Services* is an expression that has been used over the last decade under various contexts and in referring to different meanings. *Energy Services*, however, in general is related to energy end use and energy efficiency contexts. In particular, two definitions are nowadays commonly associated with this expression:

- Energy services as a description of energy end-uses (IEA 2007)
- Energy services as a business activity related to the management of energy end-uses (Angelica; et al. 2010)

Though the definitions are different and somewhat disparate, both refer to the understanding of energy uses beyond the accounting of the energy used by an equipment or appliance. The definitions also suggest that energy service should enable the design and implementation of energy end-use in more energy-efficient manners.

In the context of this thesis, the definition of energy services as a description of energy end-uses (by following the IEA's definition) is considered. Energy services accounted for the residential sector is are categorized by the following items: space heating and cooling, water heating, cooking, lighting and electric appliances use (refrigerators, freezers, dish washer, washing machine, TV and other multimedia equipment).

The energy services accounting is done in useful energy, for example, will be independent from the technology and energy vector that is used. This is explained by the fact that the energy services demand vary by location and time period. For example, the water heating needs has traditionally been addressed by natural gas in most of the European countries, however, a steadily increasing trend in renewable energy usage, such as solar thermal for hot water has been observed (European Solar Thermal Industry Federation 2014). When accounting for primary energy, it is important to take into consideration the raise of renewable energy utilization in the energy systems, it however may hinder efficiency aspects regarding conversion of primary to final energy. Thus, this thesis proposes that the basic accounting in NZEH should be done in final energy, which is the actual energy consumed at the site.

1.3.2 Net Zero Energy House

As introduced in *section 1.1*, the generic definition of NZEH in the EPDB recast is "*a high energy efficient building for residential purposes where all or nearly all the energy demand is covered by renewable energy produced on-site or nearby"*. It is clear from the literature that the definition of NZEH depends on various characteristics and the goal of each component, for example: technology, construction, economic criteria, and political aim. Among a number of challenges, the debate over the lack of a consistent and comprehensive framework, lack of a commonly defined terminology and a too diverse number of evaluation methodologies for energy balance have been previously identified (Boermans, Hermelink, et al. 2011, Sartori et al. 2012). As Mlecnik (2011) pointed out, one of the major obstacles to have a general definition seems to be the linguistic, cross-regional and legislative confusion caused by the numbers and variety of definitions and their historical meaning.

Energy balance

In this context, this thesis proposes a boundary for the *Net Zero energy-service house* in which the residential energy services are: space heating and cooling, water heating, lighting, cooking, and media services including the electrical devices. The energy balance of the in-house energy services is taken into account, as depicted in the *Figure 2* and is further elaborated in Chapter II.

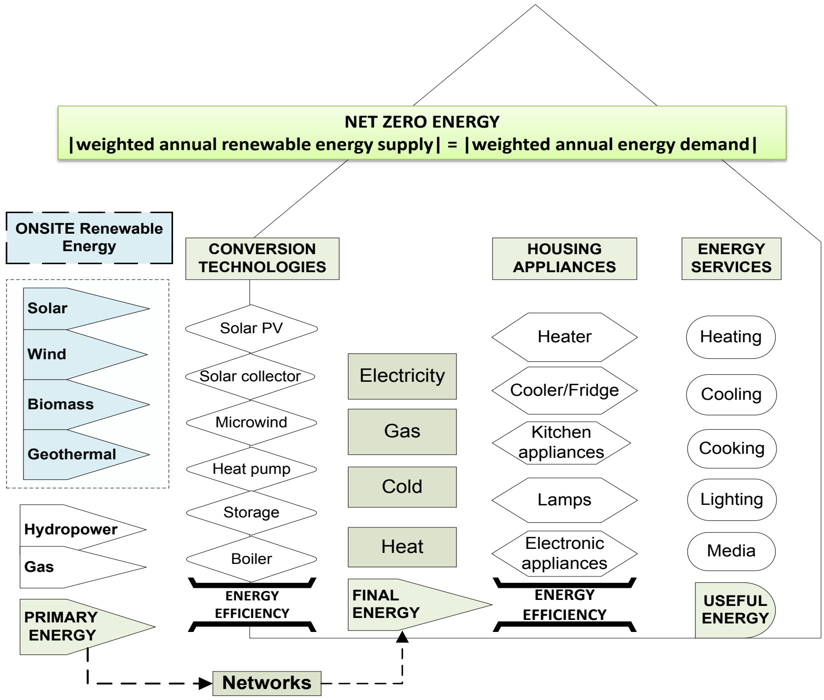


Figure 2 Residential energy services model

In the *Figure 2* , *Final energy* and *Useful energy* are defined using the principle of energy conservation as defined by the first Law of Thermodynamics. This principle is applied to energy economics when accounting for the energy flow from the primary sources to the consumer. These definitions are widely accepted by both International Energy Agency (European Environment Agency 2015a) and throughout the literatures (Madureira 2014). Final energy and useful energy can be understood as the followings:

- *Final energy* covers all energy vectors converted from all sources of energy (fossil fuels, renewables) that are available for consumption of the final consumers. The final consumers, in general, are broken down into the final end-use economic sectors (industry, transport, households, services and agriculture). At the household level, final energy consists of electricity, gas, heat, cold, or other energy carriers like wood or coal.
- *Useful energy* accounts for energy effectively made available to the end-users when the energy services are delivered by the equipment, such as the work performed by mechanical power, lighting, or heat generation.

As depicted in *Figure 2* , the net-zero-energy balance is defined as the *Site energy* balance in which it considers renewable energy produced at both *onsite* and from *distance*, and is formulated as: |*weighted annual renewable energy supply*| = |*weighted annual energy demand*|. The onsite renewable energy is for self-consumption and *not for export*. The extra energy services like those required for fire protection or energy for maintenance outside the energy service system are not included. The indicator of energy intensity per unit of area (kWh/m^2.year) is used.

No embodied energy is included in the building's life cycle and the building should also be allowed to connect to the grid for offsite or distanced renewable energy production. It is noted that, though energy life cycle assessment of the building construction is not included in this study, such a life cycle determination is critical in the broader evaluation spectrum of the building sector.

Methodology to evaluate NZEH

The recommended principles and methodology defined by EU guidelines (European Union 2010b) introduced a cost-optimal method for building energy-system performance which has also been conducted by authors such as Oliveira Panão et al. (2013). The following steps based on the guidelines are considered for the research in this thesis.

- Chosen reference buildings
- Define prerequisite energy efficiency measures
- Define the energy balance by final energy
- Calculate the lifecycle cost of energy system

Following these principles, the key indicators that are used in the context of this thesis are summarized in the *Table 1* and these indicators also form the recommendation that should be used for NZEH.

Table 1 Indicators used for the Net Zero Energy House definition

Key points to define	Indicators	Recommendation
Life cycle boundary	Building's embodied energy: before use during use after use	After use
Assessment methods and metrics	Primary energy Final energy CO_2 emission Energy cost	Final useful energy intensity
Timeframe	Zero energy balance of monthly annual and full lifecycle	Annually basis
Grid connection to renewables	Onsite Offsite	Both onsite or offsite renewables
Sectorial differences	Residential Commercial Industry	Focus on the residential and commercial until 2020
Building type	New buildings Retrofit existing buildings	Focus on new and Retrofit existing house
Spatial boundary	Individual to community scale City scale National scale	Individual to city scale
Conditional requirements	Energy efficiency Comfort standards Equipment's efficiency	Prerequisite meet standards of high energy efficiency

1.4 Research questions and contributions

In order to provide the answers of what is an NZEH among the available literature related to NZEH research and subsequently to contribute to a definition of NZEH thresholds, this thesis focuses on the residential energy service demands of both Portugal and Finland as an example of two European countries that have different climates and energy demand. Furthermore, the outcomes of the research give recommendations for NZEH development both for practical implementation and at the public policy level to foster the market development renewable energy technologies at the residential scale.

The thesis addresses the following research questions:

1. What types of energy services are applicable to NZEH?
2. What energy services reference values are applicable to NZEH in Portugal and Finland?
3. What is the life cycle cost-optimal of energy system for NZEH?

On the theoretical aspect, this research work contributes to the applied science of Energy management in Buildings. In particularly, the thesis provides solutions based on energy services and integrated optimization (of computer science) of services and technologies into the energy technology of the emerging NZEB concept development. The reasoning is that the understanding and application of NZEH concept requires an interdisciplinary knowledge of applied energy science and engineering, of architecture, construction, and residential energy consumption that contains behavioral science and life science. The conceptual model on residential energy services developed in this thesis could make the application of NZEH energy service concept more practical by the research community as well as to the policy makers.

The research also highlights the significance of systematic approach to the end-use energy usage in order to advance the cost-effective consumption of energy services in housing and building systems. The limitations of the research are acknowledged. In particular, this work does not address how to accurately model of the impact of the residential occupant behaviors of the energy consumption, one of the most difficult aspects to predict precisely predicted in the residential energy consumption.

1.5 Research methodology

Based on the above hypothesis and research questions, the study is carried out by recognizing energy use in residential building as an energy system that consists of system structure and the consumption factors of its occupants. Each consumption factor is considered as an input element in the energy balance and in the energy services model for the optimization.

The input data is collected by the direct measurement of the energy consumption by smart meters, complemented by the survey to the residential house both in Lisbon Portugal, and by an online survey on the energy consumption of the residential buildings in Helsinki Finland. The chosen sample population for survey conduction is further presented and discussed in the Chapter III and Chapter IV. Indirect data through literature review was also collected d for cross-reference throughout the thesis.

The data is analyzed by statistical analysis combined with theoretical and observational perspectives in Chapter IV. The results of Chapter V are both quantitative and qualitative. Following the proposed energy services model and the analytical results, an optimization model is set up to verify the proposed hypothesis and find out the mismatch caused by the consumption variation.

Finally, the validated models are used to determine the best energy systems to foster the implementation of NZEH, using a multi-objective optimization approach based on Genetic Algorithms that tries to minimize both the life-cycle cost of the energy systems and their energy demand. The results are presented and discussed in Chapter VI.

1.6 Thesis structure

The thesis comprises of six chapters, starting with the Introduction in Chapter I and background of the research area, which is followed by Chapter II to detail the available literature and the theoretical basis of the residential energy consumption research in order to develop an energy service model for the NZEH which is presented in Chapter III. The following chapter describes the actual energy consumption in both Portugal and Finland, and is subsequently analysed and discussed in Chapter IV. Based on the analysis, Chapter V outlines the results of optimization model for NZEH, and to conclude Chapter VI provides a discussion on technology development and public policies recommendation related to NZEH

Overall, this thesis comprises of the following segments:

Chapter I introduces the background of research area on NZEH, and proposes the research questions and describes the main contributions.

Chapter II presents a literature review on the NZEH research, NZEH case studies and the optimization method for NZEH studies.

Chapter III introduces and defines the energy service model for NZEH.

Chapter IV discusses the residential energy consumption in Portugal and in Finland using multiple data sources.

Chapter V presents the results of life-cycle cost optimization for NZEH using multi-objective optimization.

Chapter VI discusses the implications and recommendations on technology development and public policy for NZEH implementation.

2 LITERATURE REVIEW

This Chapter II presents an overview of regulations, policies and the implementation of NZEH among European countries including Portugal and Finland. The Chapter also provides a review on the design strategies and design techniques including optimization in NZEH design, in which multi-objective optimization technique is used in this research.

2.1 NZEH definitions

The literature has shown the emerging of various considering terms to describe NZEH based on different methods and calculation metric such as: the nearly zero energy, net zero energy, zero site energy, zero source energy, energy plus, zero carbon, zero emission, carbon neutral, climate neutral (Riedy et al. 2011, Sartori et al. 2012, Marszal et al. 2011).

Pan and Ning (2014) presented a comprehensive dialectics of sustainable buildings that have been coined since 1987. It has been seen that the dialectics cover a broad spectrum from environmental, social to technological features in the built environment. Those concepts of sustainable housing and building, green building, energy efficient building also indicate how the sustainable built environment has been evolved from low-energy to NZEH. Studies also debated about the discrepancy of NZEH setting in different climate and energy supply conditions (Deng et al. 2011, Stephens 2011). Since the definition of NZEH is mostly generic and unlikely practical throughout all locations within Europe, it is left to each member on setting up national adaptive definition of NZEB. This adoption means to be suitable for country's targets and local conditions.

From various definitions of NZEH that have been proposed in the literature and regulations, several definitions the author suggest could be highlighted and interpreted as below:

- *Net Zero Energy House*: general definition, the balance of energy demand and energy supply need to be defined
- *Net Zero Energy services house*: include all the energy services demand of the house, and the *energy services* need to be clearly defined
- *Net Zero embodied Energy house*: include all the embodied energy of the house in a clearly defined scope in which embodied energy counts for materials and construction
- *Net Zero life-cycle Energy house*: include energy balance in the whole life cycle of the house, and life-cycle boundary has to be defined

- *Autonomous or Non-autonomous Net Zero energy* house: could be considered as a subset of Net Zero energy services house without grid connection or allow to connect with the grid
- *Positive energy house:* produce more energy supply than the energy demand under certain defined scope

2.1.1 Energy balance definitions in NZEH

On the NZEH definition, one of the concerning factors, that slowdowns the practical implementation of NZEH, is the variation of the energy metrics in the calculation methods, particularly related to the boundaries of the system where the energy balance is made. There are several ways to define the NZEH energy balance based on its calculation methodology, that have been long discussed since the term Net Zero Energy Building was coined in early 2010.

The draft of the mandate standard " EN 15603:2013 Energy performance of buildings (Technical Committee CEN/TC 2014) issued by European Commission gives more detail on the building boundary of "on-site", "nearby" and "distant" renewable energy sources. The guiding definitions make the implementation more feasible in a way that it is clear on the energy balance calculation. This guideline on the boundary of renewable energy is particularly constructive for the countries that are still missing the mandatory target of renewable share.

On the balance metrics, other approach focused on the building lifecycle construction of a NZEH such as the calculation metric introduced by Berggren et al. (2013) and Cellura et al. (2014). However, the criteria in those mentioned studies mostly covered the energy demand for space heating and cooling but missing the other residential energy services of lighting, media appliances.

Concerning the weighting calculation methods for energy balance, among many debate issues, it exists a common agreement on making clear the energy boundary of NZEH as discussed by various authors. To this extent, Mohamed et al. (2014) for example articulated the energy balance by weighting imported and exported energy through a building's defined boundary. The "net zero" balance was calculated by the weighting factor of its energy carry, as presented in the following equation [1].

$$Net\ Weighted\ =\ Weighted\ energy\ imported-\ Weighted\ energy\ exported=0 \quad [1]$$

Where

$$Weighted\ imported\ energy=\ \sum_{k=1}^{n} Energy\ carrier_{k,imported}\ \times weighting\ factor_k \quad [2]$$

$$Weighted\ exported\ energy=\sum_{k=1}^{n} Energy\ carrier_{k,exported}\ \times weighting\ factor_k \quad [3]$$

It should also be noted that the weighting factors based on primary energy or final energy depend on its national regulations for energy performance. Therefore, it is not fully feasible to reach a common benchmark NZEH based on primary energy at European scale.

2.1.2 Considered energy services

The NZEH studies have mostly covered the energy demand for space heating and cooling but missing the other energy services, such as lighting and media appliances. These missing energy services were partly, say, stemmed from the European Standard guideline for global economic evaluation of building's energy system since 2006 (European Standard 2006). According to this standard, the energy and construction features should be put into evaluation are: building construction including envelops insulation and related system; HVAC system; domestic hot water; and operation and maintenance energy system of metering and pipeline.

2.2 Discussion on NZEH current definitions and regulations

2.2.1 NZEH and low-energy building standards

Following the national certification schemes stemming from the Directive 2010/31 (Bogdan Atanansiu, 2012), most of the European countries considered that a low-energy house consumes less energy than the energy consumption level defined for a reference house in the regulatory standards. And these low-energy standards vary according to national regulations and that, in general, standard of heating needs is less stringent than the Passive House standard. The Passive House is one of the most well-established voluntary standards in Europe to promote low-energy consumption building. The standard determines a maximum threshold for primary energy consumption as 120 kWh/m^2.year, and a maximum heat load as 15 kWh/m^2.year and an equivalent cooling load of 15 kWh/m^2.year if necessary. On this regard, *Table 2* presents a review of various low-energy standards used in Europe and worldwide.

From *Table 2*, it is possible to see that the UK has an approach to the standard not by energy use (final or primary energy) but by equivalent CO_2 emissions of the zero-carbon home. This approach is partly adopted in Australia – the zero-emission building. Albeit zero-carbon-home standard has been officially appeared in the UK policy, certain technical aspects still need to be defined on the clarification of CO_2 sources as some authors pointed out (Williams 2012).

Outside Europe, the concept of NZEH in Japan is considered as a very high energy-efficiency house focusing on the installation extremely high-efficiency appliances and equipment. In September 2015, USA national guiding has delivered common NZEB definition for different buildings including residential building (Peterson et al. 2015). Compared to most of the general definitions, the definition used by Australia is comprehensive as it includes all energy demand, energy embedded in the building fabric and infrastructure, and energy from renewable energy resources are included (Riedy et al., 2011). The integration of NZEH into a broader sustainability implication is also realized in the discussion outside European (Li et al. 2013). The NZEH house studies have been also moving further to tackle rebound effect (if any) (Bourrelle 2014).

In addition to *Table 2, Table 3* shows what the current requirements are for the low energy house in the selected European countries, and what the targets are up to 2020 for NZEH.

Table 2 Low-energy building regulations and standards worldwide

Definition	Organization	Target	Observations	Countries
Passive House	Passive house Institute	Primary energy < 120 kWh/m².year; heat load < 15 kWh/m².year	large residential building, commercial and public building	German, Sweden, Austria (Müller & Berker 2013)
Low-energy house	Buildings Performance Institute Europe	Depend on the maximum energy consumption level defined in the national building code	The energy performance must be lower than energy standard of national building code	Europe (Laustsen et al. 2011)
Zero-carbon home or Carbon-neutral home	Department of Energy and Climate Change	Emit no CO_2 during operation phase, no electricity import to the grid	Official released in the UK policies	United Kingdom (Department for Communities and Local Government 2014)
Zero-emission building	Australian Sustainable Built Environment Council	Zero annual emissions from operation phase and incorporated services	Compliance based on modeling of greenhouse gas emissions	Australia (Riedy et al. 2011)
High energy efficiency building	Japan Ministry of Municipal Affaires and Housing	Meet the maximum allowable consumption based on Design and Construction Guidelines	Having labelling standards of high efficiency equipment installed in house	Japan (Laustsen 2008)
Net zero energy building	U.S. Department of Energy	Annual delivered energy is less than or equal to the on-site renewable exported energy	The implementations vary among states and regions	USA state level (Peterson et al. 2015)
2000 Watt society	Swiss Federal Institute of Technology	2000 W/person or 17500 kWh/person.year in primary energy needs of all consumption	Target for multiple sectors	Switzerland (Marechal et al. 2005)

Table 3 From current residential energy consumption to NZEH targets in Europe

Country	Primary energy (Entranze 2013)		Primary goals from 2020 (J. Groezinger, T. Boermans 2014)		Share of renewable energy
	kWh/m².year	kWh/year	Numerical targets kWh/m².year	Applied to	
Austria	231	22139	160 – 200	New residential buildings or buildings with major renovation	-
Belgium	288	24089	< 45	Detached house	6 options proposed with minimum of 10 kWh/m² renewables: thermal solar, PV, Biomass (CHP), Heat pump, District heat, Renewable offsite
Denmark	190	21071	20	Space heating and cooling, ventilation, hot water	Expected: 51 – 56 % in 2020, but specified the sources
Finland	294	22709		Intention to issue technical description on NZEB in 2015	-
France	205	18799	50	Residential building	Proposed: Solar thermal, district heat 50%
Germany	232	19556	Focus on efficient house of primary energy less than 40% of reference building	Residential building	Made compulsory for heating of new building at minimum: Solar - 15%, biomass 30%, Geothermal - 50%. Combined heat-power – 15%
Netherlands	194	17514	EPC = 0	Based on Energy Performance Coefficient - EPC, non-dimensional number used as an indicator of the building's energy performance. EPC = 0.4 for low energy house	The RE percentage is increased in the EPC system but not specified
Sweden	240	21864	50-130 (final energy)	Residential building at various climate zone	RE in heating demand is recommended, no specific sources indicated
UK	256	19307	No indicator set for NZEH	Primary energy based on Energy Performance Certificate in the National - Calculation Methodologies	-
Portugal	90	9729			-

As seen from both *Table 2* and *Table 3* , few countries have either imposed or recommended the share of renewable energies in the regulation. Most of the existing low-energy house requirements do not specify the share of renewable energies. In addition, from *Table 3*, majority of the goals for 2020 are based on primary energy except Sweden and the values present, in general, a considerable reduction compared to 2013 values.

From *Table 3*, it can be seen that there is not yet an official quantitative definition of NZEH and numerical targets to be adopted in Portugal. So far, the regulation proposed a general definition: a NZEB is a building with low energy consumption with the implementation of renewable energy sources (produced on site wherever possible and/or as nearby as possible to cover a significant fraction to reduce building's energy needs. The general definition considers the energy needs of heating, cooling and domestic hot water only while other energy needs remained inexplicitly defined - Decree Law No 118/2013, 2013 (Ministério da Economia e do Emprego 2013).

In addition, the current studies on NZEH or nearly zero energy housing in Portugal have been mostly focused on building stock analysis and primary energy targets which are defined by building construction as stated in the national regulation. The residential energy services have largely left undefined in the regulations.

Compared to Portugal as shown in *Table 3*, Finland has made on progress on issuing technical description on the NZEH construction. The description gave recommendation and instructed planning to carry out number of pilots launched by Ministry of the Environment – MOE - with a target a share of 15% NZEH by 2015 (Ecofys 2013). Though the calculation for cost-optimal NZEH is underway, Finland has also planned to impose the renewable energy share in new building construction from 2015 onwards.

2.2.2 Energy demand in NZEH

In the Annex I of the Directive 2010 applied to household (European Union 2010), energy performance is determined by annual energy needs of space heating and cooling and domestic hot water. The technical system is recommended to cover at least heating system, hot water, air-condition and ventilation system.

The following *Table 4* describes the energy services that are considered to defined the primary energy goals in the regulation for the low-energy building performance in the countries that are indicated in *Table 3*.

Table 4 Energy services included in the primary energy (Erhvervs- og Byggestyrelsen 2011)

Country	Heating	Cooling	Hot Water	Lighting	Electricity - Ventilation fan	Electric Appliances cold
Austria	*				*	
Belgium	*	*	*	*		
Denmark	*	*	*		*	
Finland				*		*
France	*	*	*	*	*	
Germany	*	*	*		*	
Netherlands	*	*	*	*	*	
Norway	*	*	*	*	*	*
Czech Republic	*		*			
Sweden	*	*	*	*	*	*
UK	*		*	*	*	
Portugal	*	*	*			

It is seen from *Table 4*, not all energy services are included. In general, the low-energy standards include heating needs, hot water, cooling ventilation and lighting. Most countries (except Norway, Sweden, and Finland) still exclude electricity consumption from appliances and services such as cooking, laundry and entertainment devices (though media appliances or white appliances could be included in the electric appliances).

It is emphasized that most of the NZEB definitions account for the energy used in the operational phase and should therefore include all residential activities such as cooking, lighting and others. As an example, from the national survey of residential energy consumption in Portugal (Estatisticas oficiais 2010), the energy needs for cooking and kitchen activities and appliances accounts for 39% of final energy use. Therefore, the regulation framework of NZEH can be very limited if it does not include all the residential energy services.

2.2.3 Primary energy indicator

It could be said that recent guideline and regulations aiming for NZEH implementation have been focused mainly on primary energy metric. However, there are authors who disagreed with solely using primary principle. On the report of the common principles definition for NZEH Hermelink et al. (2013) stated that - *"It seems to be inappropriate to take primary energy as the only basis for creating benchmarks for nearly zero-energy buildings. We strongly recommend always adding the energy need for heating, cooling and hot water as well as the energy use for lighting. Later other performance indicators, e.g. for ventilation, auxiliaries and plug loads, may be added as 'bring to life' the energy performance indicator required by Annex I of the EPBD"*. (Hermelink et al. 2013, page 262).

The use of primary energy metrics is convenient to take into account the share of renewable energy in the overall energy matrix to estimate the corresponding green-house gas emissions by the country and by Europe. Thus, European energy policies have considered the primary energy metrics.

However, if using the primary objective is to decrease the amount of energy actually used in buildings, it is reasonable to lay out the reference values based on final energy used to provide the energy services. Another reason is that the NZEH implementation based on final energy of energy services is important for better energy demand management measures that have contributed to energy bill reduction up to 24% (Sheikhi et al. 2016).

To sum up, the up-to-date regulations on NZEH reflected through literatures and case studies have addressed diverse approaches to NZEH. Nonetheless, the incoherency still exists among European member states. To obtain more concrete numerical targets and practical standards, this thesis proposes residential energy services should be set as the framework for NZEH standards.

2.2.4 General guideline to further develop NZEH

Throughout literatures, it is widely agreed on the significance of making the integration of NZEH into the national building standards and regulations. This is mentioned by D'Agostino (2015) from a view in which deeper interdisciplinary cooperation is needed. Kylili & Fokaides (2015) also emphasized that the NZEB is has been largely recognized as a significant role in the strategic energy planning for smart cities. The NZEB needs to be included in smart grids development in which European cities are aiming for a considerable share of renewable energy of 27% as the minimum level by 2030 (European Commision 2014).

2.3 Net Zero Energy House implementation

2.3.1 Case studies in Europe and worldwide

European wide, more countries have moved forward to include NZEB requirement into the national building codes and building performance regulations. NZEH case studies have also been experienced a rapid growth worldwide, according to EnOB – Research for Energy Optimized Building (Leibniz-Institut GmbH 2013) as shown in *Figure 3*.

Figure 3 Net Zero Energy project worldwide (Leibniz-Institut GmbH 2013)

Figure 3 is the mapping of NZEH projects up to 2013 recorded worldwide with a result of 300 projects evaluation within IEA task 40 "Towards Net Zero Energy Solar Buildings" (International Energy Agency 2014a). The samples showed in *Figure 3* are focused on residential building including apartment building, detached house, and terrace houses. As it is appeared on the map, the concentration of European projects has surpassed North America according to IEA. On the energy supply side, there are increasing number of NZEH case studies that confirm the demand of energy storage to match the energy load as mentioned in the review by (Deng et al. 2014). A technical weighting factor for NZEH is also discussed to emphasize on biomass boiler, roof top PV and heat pump (Noris et al. 2014).

Following the EDBP 2010 recast, increasing number of pilot on NZEH and NZEB have been studied which are listed in detail by (Kurnitski 2013). It is noted again that, those mentioned studied have mainly focused on primary energy metric for European office building. As listed in *Table 2*, most of the current regulations are based on the primary energy factor. Some other countries' regulations are based on CO_2 emission equivalent such as the UK and Australia for zero carbon home, case studies were introduced in different studies (Berry et al. 2014, Heffernan et al. 2015, McLeod et al. 2012, Thomas & Duffy 2013a). The current Portugal and Finland building code and regulations are also based on primary energy weighting for building energy performance.

More of NZEH projects and case studies in different climate zone from Mediterranean, moderate to cold climate and North America are shown in *Table 5*. From *Table 5*, it is again shown that the majority of the energy balance is based solely on primary energy considerations and it is missing details of the energy services needed from the demand side.

Table 5 NZEH case studies for different climates

Energy services & renewable energy supply	**Mediterranean**			**Moderate to cold climate**					**North America**	
kWh/m².year	Cyprus	Italy	Spain	UK	Denmark	Serbia	Finland	Australia	USA	Canada
Floor area (m²)	130	96	129	75		52	143	100	252	225
Space heating and cooling	*	*	*	*	*		*	*	*	*
Water heating		*	*		*		*	*	*	*
Cooking										
Kitchen appliances			*						*	
Lighting	*							*	*	
Media appliances	*								*	
Final Energy										
Primary energy	40 - 65	75.5	120		33.3 (heat)	85	93 - 103		129	
PV	*	*	*	*		*	*	*	*	
Solar thermal	*									
Wind					*					
Geothermal		*			*					
Biomass	*			*						
Literatures	(Fokaides et al. 2014)	(Dall'O', Bruni, et al. 2013)	(Ferrante 2012, Gallo et al. 2014)	(Reeves et al. 2010)	(Nielsen & Möller 2012)	(Stefanović et al. 2014)	(Hamdy et al. 2013)	(Morrissey & Horne 2011) (Berry et al. 2014)	(Fanney et al. 2015, Elkinton et al. 2009)	(Zabaneh 2011, Hassoun & Dincer 2015)

2.3.2 Case studies of NZEH in Portugal and Finland

In Portugal, NZEH case studies have been focused on office building such as the Solar XXI building - a noticeable case study for its well-applied NZEH concept to building envelop (Aelenei & Gonçalves 2014), however limited case studies have been realized in the residential buildings. Nonetheless, a number of diverse studies on the NZEH particularly for Mediterranean climate including Portugal, Italy and Spain have been found. For example, study introduced a load matching model for its building energy balance (Cellura et al. 2015). Few case studies for detached house in Portugal have been carried out. One study suggested design solution for building in Lisbon with micro-generation of PV and wind turbines with heat pump to include in construction design (Kapsalaki et al. 2012).

The current energy consumption level of NZEH for Portugal could also be comparable with the reference case studied by Oliveira Panão et al. (2013) considered Mediterranean climate of Lisbon The study suggested the heating needs of 15.8 kWh/m^2.year and cooling needs of 2 kWh/m^2.year. The authors also suggested the total energy needs for NZEH load at 100-110 kWh/m^2.year and 70 kWh/m^2.year if solar heater was included.

Although an official regulation or a definition of NZEH has yet to be determined, Finland has taken a practical approach on the remark of FinZEB project or in the form of NZEH pilots, which includes apartment buildings, detached houses, schools and office buildings. The project was started in 2013, and its final report was released in March 2015 (FinZEB 2015) which emphasized a milestone toward an official NZEH legislation in Finland. However, most of the project information and the final report released, so far, are in Finnish only. The project's result has also drawn a noticeable implication that all utilized heat pump types are more cost efficient than district heating.

The installation of renewable micro-generation could also be found in the NZEH studies in Finland. For example, a heat demand of 103.3 kWh/m^2.year for a detached house was studied by Mohamed et al. (2014). It was also found in the studies by Hamdy et al. (2013) for detached house that the energy consumption (in primary-energy) was 47% lower than the Finns building standard (National building code of Finland 2012). Up to that reduction, energy needs for NZEH detached house could be 70 kWh/m^2.year in primary energy.

2.4 NZEH Design

In order to accommodate multiple criteria and indicators of energy use in building construction design, it requires more robust design techniques for NZEH in order to optimize all resources. Design parameters and design techniques in NZEH shall be discussed in this Chapter II.

2.4.1 NZEH design parameters

Cost-optimal principles

According to cost-optimal designed principles in the guide-lined framework recommended by the European Commission (Hermelink et al. 2013), three main principles are followed in this work:

- *Assess energy demand of the building and evaluate energy technology and cost in the building*
- *Specify maximum share of renewable energy in the energy supply*
- *Identify the role of renewable energy in the building system and its reference energy technologies and cost*

The optimal principle is the key to embed in the NZEH design process in order to balance the technology and its cost. Studies also suggested that the cost-optimal should be calculated as a part of or as an entire building's lifecycle costing calculation (Gustavsson & Joelsson 2010, Cabeza et al. 2014). This cost-optimal approach is aligned with the European Commission guideline (European Union 2012b).

It is worth recognizing that a building itself is a complex system. The building system is combined of its construction and its energy supply system which is associated with all energy services demand, and in particularly, the users are involved in those energy services. According to the economic evaluation procedure in buildings (European Standard 2006), in order to construct cost-optimal energy system, all the building's energy component need to be analyzed including building construction, HVAC system, energy costs, and other operation and maintenance costs. Common building energy performance and design models, however, have mainly focused on the thermal comfort but missed to include total residential energy services. That is also a gap to fill in load matching for energy services demand and energy supply.

Passive design and optimization techniques in NZEH

Following the EPBD recast, it is widely agreed that the NZEH firstly has to be first a high energy-efficient house in order to get fully renewable energy supplied. To this extent, a high energy efficiency design strategy is indispensable for cost optimization focusing on the renewable energy system. In this thesis, renewable energy system is considered as a part of active energy system of the building. The active energy system in the building, such as HVAC or lighting, is defined to require an external mechanical or electrical power to operate. Meanwhile passive energy system is, in practice, embedded into constructional and architecture design such as material, façade orientation. "Passive design" has been proved as one of the most effective techniques to minimize energy needs and maximize energy efficiency. Passive design could be established in well-designed and integrated strategies in the building, such as the daylight saving orientation which is resulted in energy loss reduction (Leach et al. 2014). Other passive practices including thermal massing, natural ventilating, and solar shading can also contribute to energy saving before reaching NZEH.

Passive solutions can be applied to different building's component and climates. The work done by Evola et al. (2014) for Mediterranean climate indicated that minor adjustment from the passive design of floor, roof, insulation could significantly reduce energy needs before deploying renewable energy system. This is also applied to the cold climate such as Denmark followed by the case studies of Marszal et al. (2012) and Marszal & Heiselberg (2011). The studies clearly indicated that energy-efficiency measures in design and construction process must be first implemented before doing cost-optimal in NZEH. High energy efficient measures have also been proved to be cost-saving during 25-40 years of energy system's lifetime, studied by Morrissey & Horne (2011). In addition, looking at the lifecycle payback period, the effectiveness of certain energy efficiency measures and alternative energy solutions on the return period could also supports the decision making process on cost-optimal, as pointed by Badea et al. (2014).

Therefore, it is crucial to first implement high energy efficiency measures in the buildings, such as passive construction in order to bring down the mismatch of the energy demand and the constraint of renewable energy supply.

Next step, it is significant to understand the basic criteria for choosing optimization technique in the building projects. When 100% renewable energy system is applied, it needs a combination of economical and technical aspects. As Milan et al. (2012) mentioned that the design of 100% renewable energy house is inevitably trial and error process which is necessary for optimal design solution. Other authors such as Dufo-López et al. (2007) also agreed on the control strategies for optimization process to find the best fit of energy technology for its energy services. Due to the complexity of the energy system integration and the inconsistency of the renewable energy resources, it is required robust optimization tool to examine the optimal setup. Comprehensive review also indicated the vitality of using building performance optimization with the suggestion that it should be considered as a standard activity in the NZEH design (Attia et al. 2013, Machairas et al. 2014).

Construction thermal transmittance

Regarding thermal performance in construction design, a basic construction parameter- thermal transmittance - U-value has to be met before having renewable energy integrated in the system. In addition, this U-value is also a factor that attributes to the energy building performance concerning occupants' thermal comfort level.

U-value: according to passive house standard the U-value has to be equal or lower than 0.15 W/m^2.K (Müller & Berker 2013). However, this recommended standard is aimed at applying to cold countries from 40^o-60^o North latitude. In Portugal, case studies showed that the U-value for building's walls could be from 0.5 W/m^2.K for less demand on cold climate insulation (Ferreira, Almeida, Rodrigues, et al. 2014). This reference value was also used in the studies by Congedo et al. (2015) for NZEH in warm climate of Italy. It should be also noted that U-value needs to comply with the national building codes and standards. For example, the Finns building code requires U-value for external walls and floor is 0.16 W/m^2.K. This U-value is mostly equal to passive house standard at 0.15 W/m^2.K. The Finns U-value for roof is 0.09

W/m^2.K which is even stricter than German passive house standards (MOE 2013). This U-value construction is based on the design facility of the building material as well as the building façade orientation as studies showed by Hermelink et al.(2013).

To sum up, in order to realize the full effectiveness of NZEH, certain parameters need to be assured during the design process. And, the above discussed design parameters of U-value are considered in the context of this thesis.

2.4.2 Retrofitting Net Zero Energy House

It should be noted that the guideline framework from the EDBP 2010 recast left unfilled on what should be the pathway for retrofit NZEH and how it could be done. While looking at European building stock in which 40% of residential buildings were constructed before the 1960s when limited building regulations were enforced. In Portugal, 31% buildings were built before 1960s and 37% buildings were built from 1961 – 1990 (Burger 2012). While in Finland, 40% building stock was built before 1970s (Statistics Finland 2014). Therefore, retrofit building to be NZEH has a large share in the building stock and it is needed further investigate.

In Portugal case studies have been done but remained scatted on retrofitted NZEB and NZEH. For example, studies by Barbosa et al. (2015) identified energy efficiency measure such as insulation and ventilation for the old houses. This study, however, did not reach a concrete NZEH target. Evaluate the investment return of energy efficiency measures for energy-retrofitted building using multi-objective optimization was studied by Sérgio Tadeu et al. (2015). In addition, studies have also discussed on how to reach NZEB from the old constructed buildings but mainly focused on office buildings such as the case studies in Italy. The study was done with a common technique of integrating photovoltaics passive house design (Sauchelli et al. 2014). Another retrofit case using sensor for thermal comfort was studied in Zurich (Nagy et al. 2014). Over times, it is appeared more emerging retrofitting cases for office building in the USA with façade and curtain wall redesign such as the studies by Aksamija (2015) and Patterson et al. (2014).

On the social and urban planning approach, noticeable studies by Ferrante (2014) proposed techno-economic feasibility assessment on the energy retrofit building to nearly zero. The approach was the integration of multiple aspects from socio-economics to energy issues and urban planning. Analysis of the literature listed in this thesis shows that there are less than cited 10 references that directly addressed the retrofitting of houses in either Portugal or Europe. This number highlights the challenges on NEZH retrofitting and the need for more robust case studies.

2.4.3 Optimization in energy system design for NZEH

The design of building and NZEH within the concept of sustainable built environment is the combination of multiple design aspects from engineering, architecture, aesthetics, and human health protection.

The building performance optimization could be defined in different ways according to the purpose of the optimization process. For example, it is understood as

"*The optimization objectives for Net ZEBs are to identify impacts on cost, energy, environmental impact (embodied energy, materials life cycle), comfort, and indoor air quality*." (Athienitis & Brien 2015, *page 175*).

It is undoubted that NZEH performance requires an optimal energy system from the outset to meet with technology challenges and to utilize multiple criteria for its performance. Therefore, it needs to focus on the optimal design process to combine cost-optimal principles and key design parameters. Since the last decade, multi-objective optimization has been utilized for building design and particularly for building energy performance (Wright et al. 2002, Diakaki et al. 2008, Negendahl & Nielsen 2015).

Conventional approach of the optimization solution for a regional or community renewable energy system is to minimize energy-system cost and CO_2 emission. Example are shown in the studies by Arnette & Zobel (2012) where the optimization was applied at a regional scale. Previous literatures also focused on sizing hybrid renewable system in the tradeoff with system's cost. The system that requires additional storage is constrained by economic criteria at the same time. Iverson et al. (2013) discussed the strategy on the levelized cost of energy and energy loss reduction from a controllable energy demand. Optimal design and performance for NZEH through simulation tools and numerical programming have been studied alongside gaining experiences with NZEH pilots. Many constraints, however, have been remained when accounting on defining residential energy services characteristics. More practical optimization model for NZEH from individual to community scale is required to cover complex factors that influence energy services consumption. The following discussion in this section shall introduce common optimization techniques that can be applied in NZEH design and to address the challenges of the discussed matter.

Single objective optimization - Linear Programming

Linear programing optimization in building energy system performance can be applied for single and simple objective matter. For example, it is used to maximize energy production or minimize energy demand, or to minimize CO_2 emission. Milan et al. (2012) identified cost-optimal installed capacity for residential renewable energy system by linear programing approach. In building energy performance, the constraint of linear programing is that, the program is limited within the less complex system by specific cases and objectives. With more complex input parameters that are required larger decision variables such as more number of people, more technology options and climate condition, the linear programing is not efficient to obtain optimal solution.

Single objective optimization - Trajectory optimization

Trajectory method applied in optimization is to optimize single objective function with defined constraint boundaries to find single global solution (Diener 1995). The applications of trajectory method are hill climbing and simulated annealing which can be inbuilt with other optimization methods. Simulated annealing is originally emulated by physical annealing process, where a high temperatures metal is slowly cooled down. Simulated annealing could be utilized on the optimize building's thermal comfort with automated system, studied by (Erdinc & Uzunoglu 2012). Its application, however, remains limited.

Multiple objective metaheuristic optimization

Multi-objective optimization method is able to combine multiple objectives including conflicting objectives such as to maximize the energy production and to minimize the energy cost. Multi-objective optimization, instead of one single solution, gives a set of optimal solutions called the Pareto front or non-dominated sorting. The optimization task therefore comprises of firstly the computing-based task on finding Pareto optimal solutions, secondly the decision-making task to choose the optimal solution based on initial setting criteria for the decision making. Applied in building energy, it can solve the metric of minimize system cost, or maximize energy production.

In multi-objective optimization, one of the most common and the fastest improved methods has been developed is the evolutionary optimization which was first developed in the 1960s. Evolutionary optimization adopts the principles of natural biological evolution into computational optimization process. The evolutionary optimization works with a set of initial population in a selection and searching process that is imitated biological selection in order to choose the best fit and best survival individual. The optimization process works by simultaneously searching for Pareto optimal solutions. The Pareto fronts give an advantage for the decision making process based on different setting criteria since it give a set of solution. Within the last decade, the evolutionary multi-objective optimization including Genetic Algorithm – GA, Particle swarm optimization – PSO, Ant colony optimization – ACO have been experienced a rapid development in both theoretical and practical application. The optimization has been applied in a wide range of industrial sectors including energy system, building and construction. Though the topic has only started since 1990s, it has been more than 10 books published within the topic so far (Branke et al. 2008). GA is extensively applied in energy system engineering (Konak et al. 2006). GA shall be further discussed and applied for optimization of energy system of NZEH in this research.

As one of the population-based approaches, GA is effective to solve multi-objective optimization problems in energy systems. The strength of GA is the simultaneous search for different regions which make it possible to find diverse set of solutions for complex problems with non-convex, discontinuous spaces**.** The GA crossover operator is able to exploit structures of solutions with different objectives to create new non-dominated solutions in unexplored parts of the Pareto front. Therefore, GA has been utilized as one of the most popular heuristic approaches to multi-objective energy system design and optimization. An iterative process in GA optimization involves consequential phases as depicted in *Figure 4*

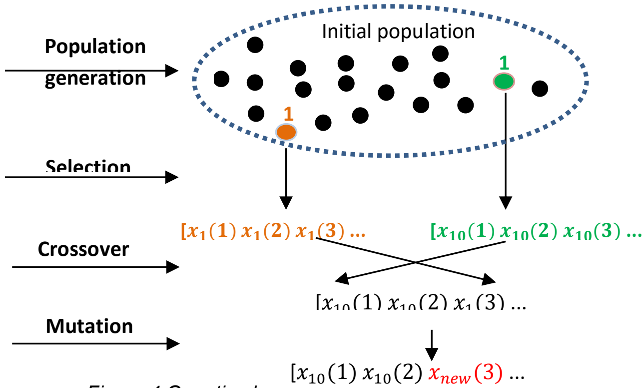


Figure 4 Genetic algorithm schemes

In which

Population generation: generate solutions in random to form the first population, followed by evaluate the fitness of solutions

Fitness assignment: Evaluate and assign a fitness value to each solution based on its objective function value and feasibility

Selection: Select *n* solutions (individuals) from the population based on their fitness and copy them

Crossover: Generate an offspring population by choosing two solutions based on the fitness values, and then crossover operators generate offspring and add them to the next population

Mutation: Mutate each solution with a predefined mutation rate

Stopping: If the stopping criterion is satisfied, terminate the search and return to the current population.

For building design and NZEH in particular, optimization using GA has gained significant practical application in defining design input for NZEH energy system. Studies have been found worldwide such as Lu et al. (2015), or Hamdy et al. (2013) studied the combined multi-stage optimization. Since decades, GA multi-objective optimization has been continuously improved to apply in building energy performance and environmental research as showed in studies by Alajmi & Wright (2014) and Huang & Niu (2015). A review introduced by (Fadaee & Radzi 2012) recommended GA and PSO the most used and promising methods in hybrid renewable energy system design. Recent optimization technique reviewed also confirmed the important contribution of the multi-objective optimization in hybrid renewable energy system including GA and PSO mainly focusing on cost reduction (Erdinc & Uzunoglu 2012). The artificial neutral network optimization was proposed in the energy industry as another possible approach. Artificial neutral network, however, still has limited application in the renewable energy system for building and residential sector since the last decade (Kalogirou 2000).

In better understanding of optimization application, *Table 6* summaries the optimization methods that have been utilized for building energy performance optimization and NZEH studies.

Table 6 Optimization methods applied for building energy performance and NZEH

Optimization methods	**Advantages**	**Limitations**	**Energy in building & NZEH application**	**Location**	**Literatures**
Single objective optimization					
Linear programming	Straightforward for programing	Limited decision variables	PV model and heat pump	Denmark	(Milan et al. 2012)
Trajectory method - Simulated annealing	Straightforward for programing Efficient in finding global optima Can combine with other algorithm	Limited decision variables	Building envelop design	USA	(Junghans & Darde 2015) (Huang & Niu 2015)
			Storage, grid-connected	Austria	(Velik & Nicolay 2015)
Multi-objective metaheuristic optimization					
Genetic algorithms	Multiple input parameters and objective functions	Relatively complex for programing	Cost-optimal design, maximize thermal comfort, maximize energy production		
			Energy system sizing and operation	Switzerland	(Evins 2015)
			Thermal and visual comfort	Italy	(Carlucci et al. 2015)
			Minimize energy consumption	Mediterranean	(Znouda et al. 2007)
			Solar system design	Canada	(Bucking et al. 2013)
			Renewable energy system sizing	Hong Kong	(Lu et al. 2014)
			Hybrid renewable energy design	Various areas including urban and remote	(Fadaee & Radzi 2012) (Machairas et al. 2014)
Ant colony optimization	Efficient for network optimization problems	Complex for programing	Distributed renewable energy system		
			Standalone micro-grid	Spain	(Marzband et al. 2016)
Particle swarm programming	Relatively straightforward for programing	Few decision variables	Automated building energy management	USA	(Hu et al. 2014)
			Thermal comfort and energy efficiency	The Netherlands	(Hurtado et al. 2015)

2.5 Concluding remarks

In order to have better picture of the literatures presented in this thesis, all the listed literatures are classified into 6 main subtopics in the energy and buildings which are: Energy services - Energy demand; Retrofitting NZEH; Energy supply system; Modeling and optimization of energy system, Policies on NZEH. The selection of the topics has the rational of using basic bibliometric techniques, in which the search is based on title and keywords related to the topics in the field. The mapping is presented in *Figure 5*:

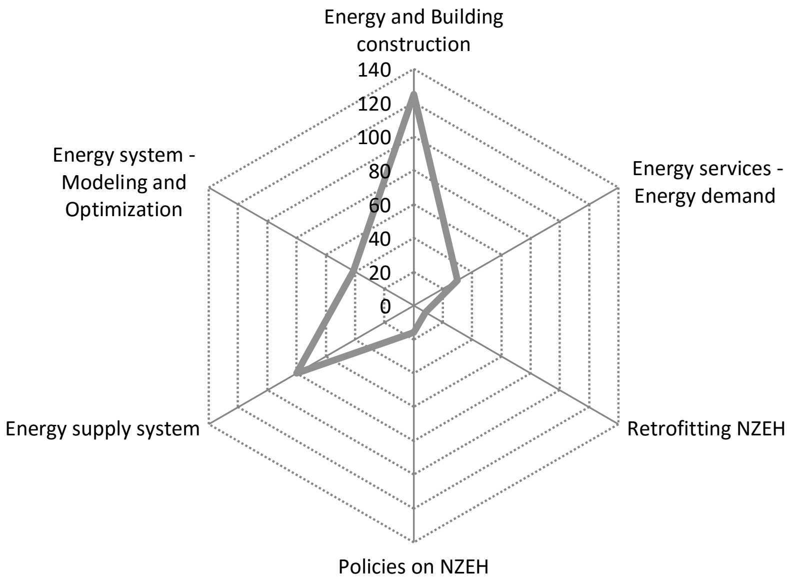


Figure 5 Literature review classified by topics

As seen in *Figure 5*, it confirms the needs of exploring the end-use demand side and the energy services in which this thesis is be emphasized. It is reminded that the passive design is pre-requisite for NZEH in design procedure as mentioned in the previous *section 2.4.1*. And this thesis focuses on building's active energy system which included technologies and equipment to supply energy services demand.

3 ENERGY SERVICE MODEL FOR NET ZERO ENERGY HOUSE

As discussed in Chapter I and II, following the European Directive on Energy Building Performance, the benefit of NZEH has been proved by tangible evidences and well-founded case studies. However, number of challenges have been identified, such as defining numerical targets of different energy services, in order to facilitate the NZEH design and setup. Looking at the energy end-use, many have remained uncertain on how residential energy demand is actually spent and consequently, how it can be reduced.

Studies on different aspects have agreed on the fact that there are large variations in residential energy consumption even when the households have identical physical structure. The factors related to energy consumption habit have not been fully identified (Morley & Hazas 2011, Fischer 2008). As part of the NZEH implementation, dealing with variations of residential energy demand has become even more significant in the emerging development of smart grid and the integration of renewable energy resources. Among recent literatures covering Portugal, the lack of comprehensive understanding on matching energy supply and demand of consumption characteristics is identified. It has also been found the missing quantification and qualification of all residential energy services as discussed in previous Chapter.

To formulate an energy services indicators for NZEH, it is needed to gain insight understanding of the entire energy services in the residential building including lighting, cooking, and media appliances, the services that are undefined by national regulations. The model-based regulations on residential energy performance have mostly focused on space heating and cooling, and water heating and have left unfilled the remaining consumption.

In sum, it is necessary to classify the variations of energy services demand to understand the factors that affect their variations. To identify consumption pattern, it certainly requires a time-series observation combined with analytical observation of the occupant consumption dynamics which is often time consuming, as previously proposed by Eidelson (1997a).

In light of identifying the residential energy services demand, this Chapter III shall introduce an energy services model based on physical principal. This model will later be used to support long-term NZEH implementation.

3.1 Residential energy consumption characteristics

Residential energy service in this thesis' context, as defined in Chapter I – *Section 1.3*, describes useful energy required to perform the services that satisfy occupants' basic needs and promote a higher welfare, such as space heating and cooling, water heating, cooking, lighting and other uses of electric appliances. As services to satisfy users' needs, the required service varies from user to user.

Well-documented studies on energy consumption habit concerning with price and energy availability were covered by various authors (Lutzenhiser 1992, Druckman & Jackson 2008). More specifically, residential energy consumption is relatively invisible compared to other household expense in goods such as food or car fuel. In literature, several authors have proposed factors that affect general consumption choices and habit in residential energy usage, such as the service availability and affordability, and others socioeconomic aspects, such as income that can influence occupant's attitude and awareness (Fischer 2008, Hens et al. 2010, Frederiks et al. 2015). Other authors have also proposed models of residential energy consumption behavior in which household lifestyle, building characteristics and housing appliances play the key roles that determine the consumption level (Van Raaij & Verhallen 1983, Dias et al. 2004). In addition Swan & Ugursal (2009) introduced a comprehensive review on the bottom-up and top-down models for energy used in the residential sector. Studies by Snape (2011) outlined a framework to model residential energy consumption behavior in relation to culture. In Snape's study, the author considered the transition of smart devices adoption and renewable energy integration as new practices. The challenges and the shortcoming in formulating residential energy consumption models were also raised for its lack of multi-disciplinary and dynamic approaches for socio-technical factors (Kavgic et al. 2010).

In current practices, residential energy performance is estimated by simplifying physical models and static analysis from the housing construction and its energy operation. It has been documented that this approach often leads to deviations of energy performance between designed operation and actual performances (Kolokotsa et al. 2011). Other studies discussed further on how the participation of energy-usage education program as an external factor effects individual behavior changes (Rue du Can et al. 2014, Frederiks et al. 2015). In fact, studies proposed that occupant' behaviors were conducted by their subjective and individual variables. These individual variables would have significant impacts on residential energy building's performance.

Previous literatures have also discussed determinant factors that affect energy-related consumption (Gouveia et al. 2012). The consumption characteristics are influenced by both factors which can be directly addressed by the user or policy on energy use - that are controllable in terms of energy, and by factors that cannot be directly addressed by action on energy consumption - that are not controllable. These characteristics form the consumption attitude and behavior surrounding energy usage. The attitude may vary among many aspects from energy price to personal comfort, from health-care concern to energy conscious of the consumers concerning for environmental impacts and energy sources saving. In this regards, *Figure 6* introduces a model of energy consumption characteristics which are divided into these two categories: *Controllable factors and Uncontrollable factors*.

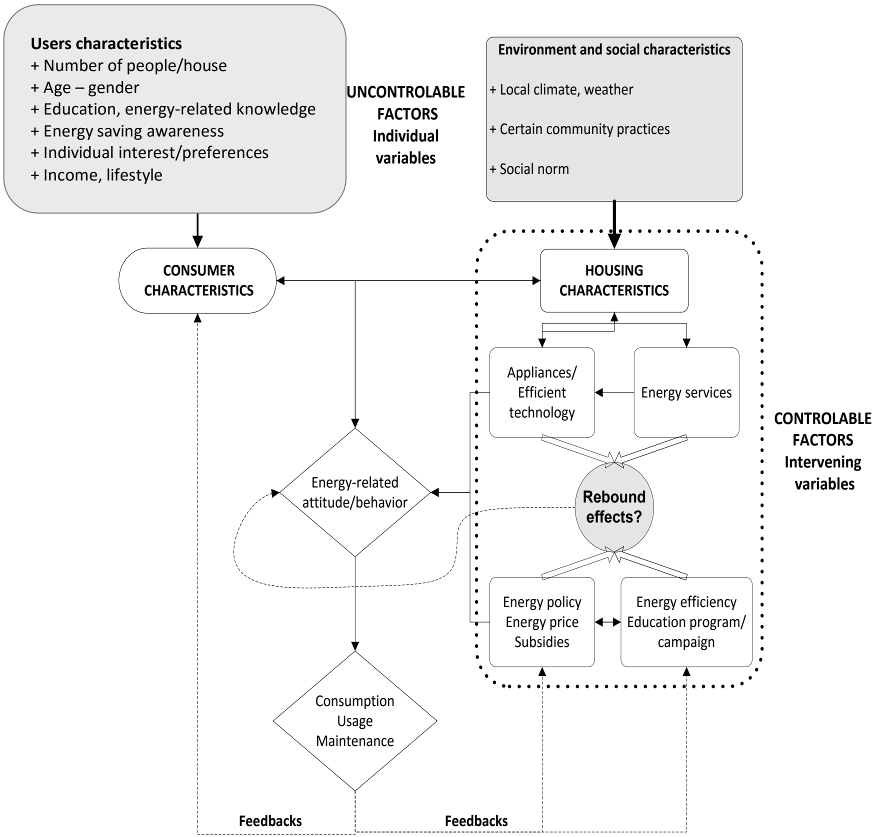


Figure 6 Residential energy consumption model

The controllable factors contain the "housing characteristic", such as the technologies and the services that are required, which can be changed by the user alone or supported by energy policies or energy saving programs. On the controllable factors, it is very important to take into account the rebound effect, one of the emerging behaviors related to residential energy usage. Past literatures have not considered comprehensively the emerging phenomena in residential energy usage called the rebound effects which recently reported to be more pronounced (Galvin 2014, Orea et al. 2015, Wang et al. 2016). From the end-user energy saving impacts, the question of whether the rebound effects would be experienced for the NZEH consumer has not been well-confirmed.

The uncontrollable factors include the "Users characteristics" which describe the socio-economic characteristics such as the number of occupant, their age, their education, the interests and preferences and the income and lifestyle. The uncontrollable factors also include the "environment and social characteristics", such the climate, the community practices and the social norm. All these factors end up by defining part of the consumer characteristics.

It is worth re-emphasizing that it is important to consider feedback loop in the model. For example, the knowledge and awareness about energy efficiency can be influenced by policies that support the implementation of energy efficiency measures or by effective education programs.

The presented energy end-used model is aligned with the theory and models previously proposed by Van Raaij & Verhallen (1983) and Dias et al. (2004). It has been also supported by case studies on the implementation a new NZEH (Lenoir et al. 2011). Since the residential system is a complex system, many studies have proposed simplified models to identify more accurate the energy demand. Up to date, methods on establishing such models were reviewed by several author such as by Zhao & Magoulès (2012). The accuracy between predicted and actual measure for energy performance was also discussed (de Wilde 2014).

Nonetheless, there is a knowledge gap in comprehensive understanding on how break-down residential energy consumption is concretely utilized or how occupants decide to firstly utilize energy efficiently, to go for more efficient choices, which is important to get to NZEH.

The next sections of this Chapter shall focus on the feature of energy services, as depicted in *Figure 6*, and how these are defined in the regulations of Portugal and Finland regulations. The services are defined in combination with efficiency of energy technologies. This discussion is the background in order to propose reference baseline to develop NZEH.

3.2 Residential energy consumption framework

Literatures have introduced various ways of classifying residential energy consumption based on engineering or physical model. Previous literature classified the residential energy demand by their status of predictable, non-predictable or moderate predictable mode (Wood & Newborough 2003). Studies also presented residential energy usage in electrical term such as standby, continuous, active cold, or active and passive mode based demand model (Subbiah et al. 2013), focused mainly on electricity demand (Kilpatrick et al. 2011)**.** Other studies classified the household appliances as movable appliances such as lamps, washing machine, plug-in units and fixed appliances such as heat pump, heater boiler (Nielsen 2009). Recent studies also discussed on the improvement of practical utilization of available data for residential appliances such as for updated versions of the appliances, when obliged to certain standards (Gruber et al. 2014).

It appears that in the demonstration projects that quite significant understanding has been gained regarding users' behavior by the experiences of the end users on residential energy-related practices. These projects, however, have been still insufficiently monitored and evaluated to obtain more practical and insight understanding on mentioned challenges of what is truly effective to influence users consumption (Brandemuehl & Field 2011). In addition, large variations of consumption level could hardly be explained solely by physical difference in construction. The same number of people living in identical houses can have large different amounts of energy consumption of which the variation can be up to factor of 40 with the average deviation of 50% (Morley & Hazas 2011).

In this context, the following proposing hypothesis is that residential energy service has two drivers: the household characteristics and the consumer characteristics, formulated as follows:

$$E_{household} = Household_{characteristics} + Consumer_{characteristics} \quad [4]$$

This concept is described in detail in *Figure 7* as the excerpt of model presented in *Figure 7*.

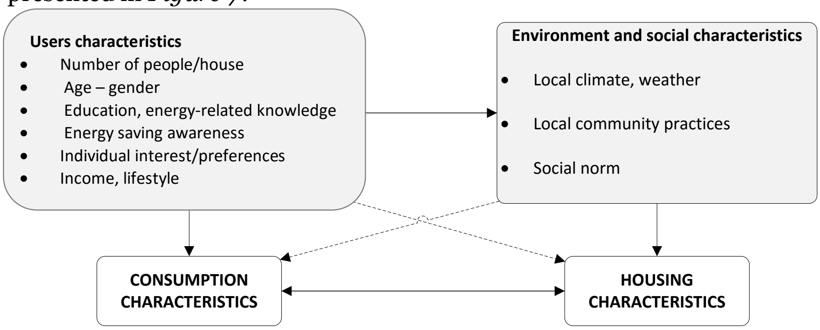


Figure 7 Characteristics of household energy consumption

The *household characteristics* refer to the floor area, number of occupants, and type of house, walls insulation or windows thermal transmittance. These features have significant impact on energy services of space heating and cooling and hot water. The impacts of these characteristics are well-understood, as it follows physical principles that has been documented (Biesiot & Noorman 1999). The household characteristic refers also to its location, taking into account of the climate that significantly influences the energy demand of heat and cold.

The *consumer characteristics* refer to the use that depends on the behavioral aspects of energy consumption, such as the occupants/users socio-economic status. These are shown in the users' response to information, their willingness or awareness to save energy, the environmental impacts concern or knowledge about energy efficiency. The assumption is that even with the same household characteristics, different occupants use energy differently and behave differently according to the context of use. The impact of these characteristics is recognized and discussed by different studies, for example (Guerra Santin et al. 2009).

In this extent, drivers for residential energy services consumption could be summarized as identified by International Energy Agency: Floor area; number of occupant; climate; income and energy costs (International Energy Agency 2007). The floor area mostly determines the needs of space heating and cooling. Number of occupants has impact on water heating, cooking and appliances. The climate is measured in Heating Degree Days – HDD. The income and energy costs can restrain the amount of energy use. Overall, considering the normalization by HDD values due to annual climate variations of country to country, the following conclusions are:

- *Floor Area*: There is an obvious relationship between residential floor area per capita and income. The floor is direct ratio to the income that has out pressure on per capita space heating and cooling needs;
- *Occupancy*: Average household occupancies have fallen in most of the developed countries - 2.6 to 2.8 people (OECD Family Database 2014). Energy needs of space heating and cooling are not necessarily reduced because of fewer people stay in a house;
- *Energy costs*: Higher energy costs are likely to restrain household energy consumption by encouraging more energy-efficient behavior and equipment purchases. Energy costs, however, continue to be a small proportion of household expenditure which falls between 2 and 3% for most European countries (Eurostat 2013);
- *Location*: Per capita energy consumption varies from country to country. In Europe 27, it is within the interval of 15 to 35 GJ per capita per year (normalized by HDD) (Eurostat 2016).

3.3 Evaluation of residential energy performance

A summary of selected online simulators used for residential in Portugal listed with other simulators can be seen in *Table 7*.

Table 7 Comparison of residential energy consumption models

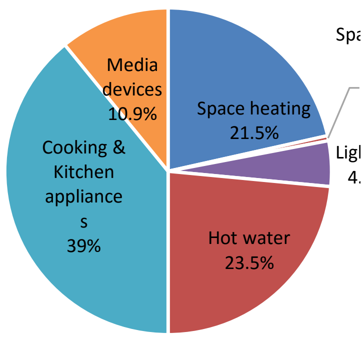
Model	**Developer**	**Estimation targets & features**	**Tariff bill**	**Equipment & devices**
Casa+	ADENE[1]	Housing energy class based on Portuguese regulation Nominal needs for heating, cooling and hot water Total CO_2 emissions		*
Simulator Billing Energy electric	ERSE[2]	Annual bill of electricity Monthly electricity consumption in the peak, and low-peak hour	*	
Simulator of potential billing	EDP[3]	Value of contracted power and tariff type (normal, bi-hourly, tri-hourly) Energy consumption by equipment's power Annual energy bill in different tariffs	*	*
Distributed Energy Resources Customer Adoption Model (DER-CAM)	LBNL[4]	Annual electricity and gas consumption Total annual energy cost Payback time of technology investment Graphic illustration of the cooling and heating water consumption	*	
The MIT Design Advisor – Version	MIT[5]	Primary energy consumption of heating, cooling and lighting Energy cost and CO_2 emissions Graphic illustration of indoor and designated temperature, Comparison of energy performance scenarios		*

[1]casamais.adene.pt, [2]simuladores.erse.pt, [3]edp.pt,[4]der.lbl.gov/der-cam,[5] designadvisor.mit.edu

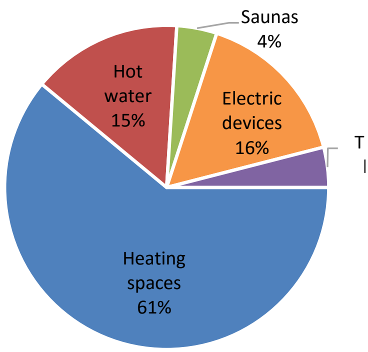
To support consumers on having better choices on residential energy use, a number of tools have been developed to evaluate building energy performance. It however, still requires better robust tools to access ambiguity in the consumption (Crawley et al. 2008). It can be seen from *Table 7* that most of the simulators cover the energy demand for space heating and cooling, water heating and CO_2 emission. Others energy services such as cooking and kitchen appliances are missing. Nonetheless, these tools could be well-suited for education purpose of consumers' awareness.

3.3.1 Residential energy consumption

It is clearly acknowledged that the residential energy consumption varies from country to country, particularly when the heating needs are very different due to climates, especially for countries like Portugal and Finland. The comparison of energy service consumption in Portugal and Finland is presented in *Figure 8*.



(a) – Portugal



(b) – Finland

Figure 8 Residential energy consumption in (a) Portugal and (b) Finland (Estatisticas oficiais 2010) (Statistics Finland 2015a)

It is shown from *Figure 8* that the main differences of residential energy demand of Portugal and Finland are the space heating needs. The energy needs for space heating accounts for 21.5% in Portugal and 61% in Finland. It is also noticeable that energy services are described differently from country to country. For example, in Finland electrical devices represents one group, while in Portugal, media appliances are separated from electrical appliances used in the kitchen. Furthermore, some services are very specific due to cultural practices, such as the use of saunas in Finland. These differences can be viewed in *Figure 10*

In the next section, more detail regarding energy services model, as described in the national regulations in both countries Portugal and Finland, shall be discussed.

Portuguese regulations

According to the Portuguese regulations on thermal performance of residential building defined in Decree Law n. 118/2013 (Ministério da Economia e do Emprego 2013), the main defined energy services are space heating and cooling, and water heating. The other energy services of lighting, cooking, and media appliances have remained undefined.

Finns regulations

According to Finns building code (MOE 2012a) and the Decree on improving building's energy performance (MOE 2012b), the calculation principle for building's energy service demand or energy performance is defined for space heating, cooling, ventilation, water heating, lighting and other appliances. Furthermore, the energy balance in the calculation for energy consumption with purchased renewable energy is also defined as shown in *Figure 9*.

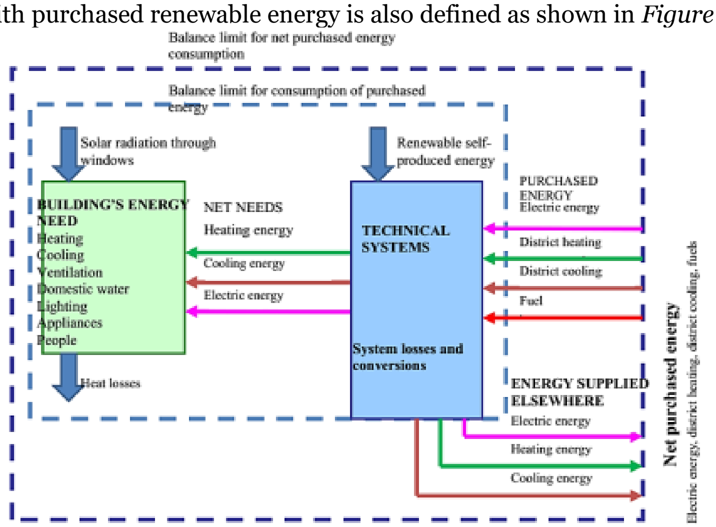


Figure 9 Energy balance for residential energy consumption with purchased energy in Finland (MOE 2012b)

The calculation principle in the Finland Building code as clearly seen from *Figure 9*, compared to Portugal, has been made more specific on the adding of electrical energy such as lighting.

3.3.2 Comparison of Portugal and Finland regulations

This section shall discuss the model of all residential energy services which will take into account of models to estimate energy needs to space heating and cooling, water heating, lighting, cooking, and media appliances. The models are presented in *Table 8*. In addition to the models that are applied to the energy needs defined in the Portuguese and Finns regulations, *Table 8* also presents the models applied to the undefined energy services by regulation. The purpose of this comparison, including the differences found in the previous sections to emphasize that the found differences contribute to a better understanding of how NZEH implementation approaches can and should be varied to respond to such differences within Europe. And that the general energy service model developed, presented in *section 1.3*, can be used in different context in Europe despite the differences of climate or other factors.

It can also be found in *Table 8* the suggested criteria to be applicable for NZEH and shall be used for this thesis context. In addition, the differences of energy services level defined in each country's regulation can be seen in the following.

Table 8 Comparison of residential energy services in the Portugal's and Finland's regulations

Energy services	**Portugal**	**Finland**	**Notes and NZEH considering**
Space heating	Heat loss through building component $Q_{SH} = \frac{(Q_{convection} + Q_{ventilation} - Q_{solargain})}{A}$ [5] $Q_{convection,i} = 0.024 \times GD \times H_{convection,i}$ [6] $H_{convection} = H_{ext} + H_{free} + H_{air} + H_{ground}$ [7] $H_{ext.} = \sum_i (U_i . A_i) + \sum_j (\varphi_j . B_j)$ [8] $H_{air} = b_{conduction} \times \left(\sum_i (U_i . A_i) + \sum_j (\varphi_j . B_j)\right)$ [9] $Q_{ventilation,i} = 0{,}024 \times GD \times H_{ventilation,i}$ [10] $H_{ventilation,i} = 0{,}34 \times R_{ph,i} \times A_p \times P_d$ [11] $Q_{solargain,i} = \eta_i Q_{heatgain,i}$ [12] $Q_{heatgain,i} = Q_{int.gain,i} + Q_{ext.gain,i}$ [13] $Q_{int.gain,i} = 0{,}72 q_{int.gain} \times M \times A_{int.}$ [14] $Q_{ext.gain,i} = G_{solar} \sum_j \left(X_j \sum_n F_{window,i} \times A_{window}\right) \times \Delta t_{heating}$ [15] $\gamma = \frac{Q_{heatgain,i}}{(Q_{convection} + Q_{ventilation})}$ [16] If $\begin{cases} \gamma \neq 1 \; and \; \gamma > 0 & : \; \eta = \frac{1-\gamma^a}{1-\gamma^{a+1}} \\ \gamma = 1 & : \; \eta = \frac{a}{a+1} \\ \gamma < 0 & : \; \eta = \frac{1}{\gamma} \end{cases}$ [17] $(i: component\ wall, celling, floor, door)$	. $Q_{SH} = Q_{space} - Q_{int.heat}$ [36] $Q_{space} = Q_{conduction} + Q_{airleakage} + Q_{supply\ air} + Q_{make\text{-}up\ air}$ [37] $Q_{conduction} = Q_{exterior\ wall} + Q_{ceiling} + Q_{floor} + Q_{thermal\ bridges} + Q_{door}$ [38] $Q_{conduction,i} = \frac{\sum U_i . A_i (T_{in} - T_{out}) \Delta t}{1000}$ [39] $Q_{thermal\ bridges} = \frac{\left(\sum \gamma_j + \sum \varphi_{j.B_j}\right)(T_{in} - T_{out}) \Delta t_{heating}}{1000}$ [40] $Q_{air\ leakage} = \frac{\rho_{air} . C_{p_{air}} . q_{v,air\ leakage} (T_{in} - T_{out}) \Delta t}{1000}$ [41] $q_{v,air\ leakage} = \frac{q_{50}}{3600.x} A$ [42] 1000 Converting factor to kWh 3600 Converting factor m3/h to m3/s x : *Factor for different storey building* $x = \begin{cases} 35\ for\ 1\ storey \\ 24\ for\ 2\ storeys \\ 20\ for\ 3\ storeys \\ 15\ for\ 5\ storeys \end{cases}$	The $U - value$ defined in the Finnish regulation can be used for the NZEH Heating system turns on when the outdoor base temperature falls below : $\begin{cases} < 15oC \text{ for Portugal} \\ < 10oC \text{ for Finalnd} \end{cases}$ NZEH should minimize thermal bridges: affects φ_j, B_j to zero. The majority of windows should be south-face by 15% of the floor area. The wall's height P_d is considered 2.5m Nominal air renovation rate is at minimum of $R_{ph,i}$=0.6 h^{-1} after the regulation NP1307 G_{solar}=117.05Wm^{-2} (PVGIS 2015) - vertical global irradiance. $q_{int.}$=4Wm^{-2}, and $X_j . F_{window} \geq 0.27$. a=1.8$W°K^{-1}$ for low thermal inertial buildings
Space cooling	. $Q_{SC} = \frac{(1-\eta_v) Q_{heatgain}}{A_p}$ [18] $Q_{convection,SC} = \frac{H_{convection}(T_{ref.} - T_{out}) \Delta t_{cooling}}{1000}$ [19] $H_{convection,SC} = H_{ext} + H_{free} + H_{ground}$ [20] $Q_{ventilation,SC} = \frac{H_{ventilation}(T_{ref.} - T_{out}) \Delta t_{cooling}}{1000}$ [22] $H_{ventilation,SC} = 0.34 \times R_{ph,v} \times A_p \times P_d$ [23] $Q_{heatgain,SC} = Q_{int.gain} + Q_{ext.gain}$ [24] $Q_{int.gain,SC} = \frac{q_{int.} \times A_p \times \Delta t_{cooling}}{1000}$ [25]	$Q_{SC} = (1 + \beta_{sca})\, Q_{ca} + (1 + \beta_{scw}) Q_{cw}$ [43]	In Finland, the cooling needs is considered too small base on the actual practice and consumption. Cooling needs is calculated from the net cooling energy need, considering losses from generation, storing, distribution.

<table>
<tr>
<td>Water heating</td>
<td>$Q_{DHW} = mC_p(T_{hot} - T_{cold})$ [26]
$m = n \times V_{DHW} \times f_{eh}$ [27]
$T_{hot} - T_{cold} = \begin{cases} 32\ ^\circ C\ (tankless\ system) \\ 42\ ^\circ C\ (storage\ system) \end{cases}$ [28]
$V_{DHW} = 40\ l/day$ [29]</td>
<td>$Q_{DHW} = \frac{\rho_w C_{p_w} V_{DHW}(T_{hot} - T_{cold})}{3600}$ [44]
$V_{DHW} = \frac{n.v_{DHW}\Delta t}{1000} = \frac{v_{DHW,net}\Delta t}{365.1000}$ [45]
$T_{hot} - T_{cold} = 50\ ^\circ C.$ [46]
$V_{DHW} = 50 - 60\ l/day$ [47]</td>
<td>The net heating need includes heating cold water to the temperature of the domestic hot water, excludes potential heat losses from the heating device.</td>
</tr>
<tr>
<td>Cooking and kitchen appliances</td>
<td>• Refrigerator and freezer
Energy class for new appliances by Energy Efficiency Index $EEI = \frac{AE_c}{SAE_c} \times 100$ [30]
SAE_c: standard annual energy consumption
$AE_c = 365 \times Consumption_{24h}$ [31]
$EEI: \begin{cases} A+++ for\ EEI < 22 \\ A++ for\ 22 < EEI < 33 \\ A+ for\ 33 < EEI < 42 \end{cases}$ [32]
• Dish cleaning and Clothes washing
$HW = W \times \rho \times C_p \times (T_{out} - T_{in})$ [33]
$W: Volume\ of\ hot\ water\ used.$</td>
<td>Consumption level regulated in the building code
<table>
<tr><th>SAE_c (kWh/year)</th><th>Apartment</th><th>House</th></tr>
<tr><td>Stove</td><td>340</td><td>520</td></tr>
<tr><td>Microwave oven</td><td>50</td><td>55</td></tr>
<tr><td>Coffeemaker</td><td>70</td><td>70</td></tr>
<tr><td>Dishwasher</td><td>170</td><td>250</td></tr>
<tr><td>Refrigerator/freezer</td><td>740</td><td>270</td></tr>
<tr><td>Ice box</td><td>330</td><td>330</td></tr>
<tr><td>Upright freezer</td><td>380</td><td>380</td></tr>
<tr><td>Washing machine</td><td>130</td><td>240</td></tr>
<tr><td>Clothes dryer</td><td>300</td><td>300</td></tr>
</table></td>
<td>Kitchen appliances and energy uses for cooking are not regulated in the Portuguese regulation. The listed calculation model bellow based on the guideline from European Union on energy efficiency and empirical formulation (European Union 2010a).
Dish washer AA++ consumes 1 kWh per utilization, including dryer and 10L of water, heated at 50ºC for 12 plates - 4 persons
Washing machine AA++ : requires 10L per Kg. Assume per capital: 3 Kg of clothes per week .</td>
</tr>
<tr>
<td>Lighting</td>
<td>Energy efficiency index - EEI
$EEI = \frac{P_{cor}}{P_{ref}}$ [34]
P_{cor} : corrected rated power (due to losses)
P_{ref}: Reference power (depends on luminous flux Φ)
$P_{ref} = \begin{cases} 0.88\sqrt{\Phi} + 0.049 & \Phi < 1300\ lumen \\ 0.07341\Phi & \Phi \geq 1300\ lumen \end{cases}$ [35]
For EEI < 0.11 is for A++
<table>
<tr><th>Lamp</th><th>EEI</th><th>Lifetime (h)</th><th>Lm/m²</th></tr>
<tr><td>LED</td><td>0.14 (A+)</td><td>15000</td><td>400</td></tr>
<tr><td>CFL</td><td>0.2 (A)</td><td>10000</td><td>600</td></tr>
</table></td>
<td>The energy consumption as electricity for lighting:
$W_{lighting} = \frac{\sum P_{lighting} A_{room}.\Delta t.f}{1000}$ [48]
Where
<table>
<tr><th>f</th><th>Control factor, lighting control mode</th></tr>
<tr><td>0.7 – 0.8</td><td>Sensor and daylight timer</td></tr>
<tr><td>0.75</td><td>sensor</td></tr>
<tr><td>0.9</td><td>room-specific switch</td></tr>
<tr><td>1</td><td>central ON/OF</td></tr>
</table></td>
<td>Finland: Room-specific switch for f = 0.9, Δt the running time for lighting residential building: 4 hour/day.</td>
</tr>
<tr>
<td>Media & electricity appliances</td>
<td>Appliances include: television, computer, aspirator, iron and printer

The detail consumption level are undefined in the regulation</td>
<td><table>
<tr><th>Appliances</th><th>kWh/year</th></tr>
<tr><td>TV</td><td>200</td></tr>
<tr><td>Video</td><td>95</td></tr>
<tr><td>PC</td><td>80</td></tr>
<tr><td>Sauna</td><td>8</td></tr>
</table></td>
<td></td>
</tr>
</table>

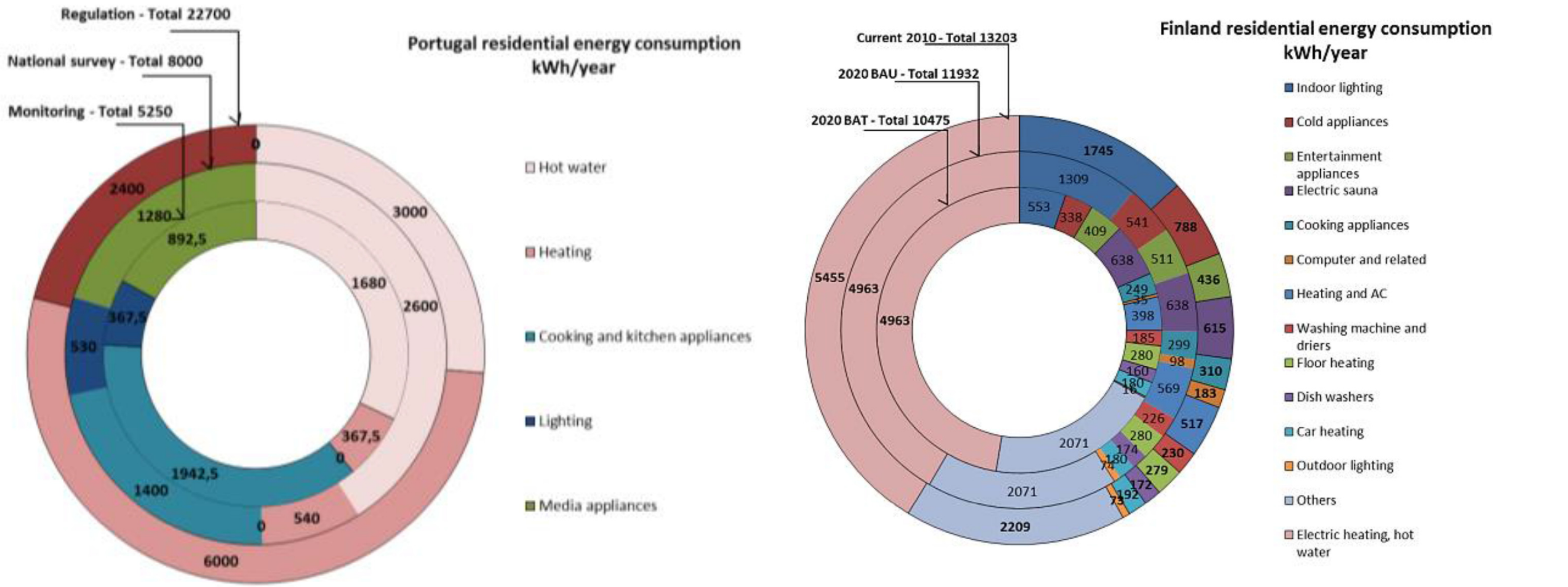


Figure 10 Comparison of residential energy consumption in Portugal and Finland

Overall, *Figure 10* depicts detail level of energy services defined in the Finns regulations in compared to what energy services are mainly defined in Portuguese regulation. It is confirmed the main services defined in Portuguese regulation have limited to hot water, space heating and cooling. This figure also shows that for Portugal these services are largely overestimated when compared to the 2010 national survey of energy use and to real data from a case study at the final energy use (taking into account the equipment efficiency). The detail energy services depicted in *Figure 10* shall be discussed further in Chapter IV.

It can also be seen from *Table 8* that the generic inputs for the thermal models in the Finland and Portugal resident are based on the same principles of heat transfer. The differences are found in the coefficients to calculate energy needs for service of heating, cooling and water heating due to temperature variations. This is also the background for generic model of NZEH optimization that shall be discussed in Chapter V. Based on the same principle, the decisive parameters could be limited and simplified to thermal transmittance U-value, which is also defined as a basic NZEH design parameter as presented in *section 2.4.1*.

Space heating and cooling

Overall, both countries' regulations on energy needs of space heating and cooling performance are based on principle of heat transfer/heat loss in a built environment and heat loss through convection, conduction and radiation.

The space heating and cooling needs calculation is based on Heating Degree Day/Cooling Degree Days method by European Environment Agency (European Environment Agency 2015b) with the note on its limitation that *"is a purely physical metric, which does not consider differences in technical, social and economic factors (housing quality, behavior, prices) between regions and their development over time."*

The calculation for space heating and cooling according to Portuguese regulation, as listed from equation [5] – [25] in *Table 8*, is a set of complex formulation and equation which mainly based on the physical building construction. These formulations are not fully reflected the aspects of actual consumption aspects as discussed in the earlier section of this Chapter.

In this comparison cooling needs is practically negligible for Finland. In Portugal, the cooling need is almost negligible (<0.5%). In fact, according to Finnish Meteorological Institute, the average temperature of the hottest month in Helsinki, Finland over the last 30 year is lower than 18℃ (Finnish Meteorological Institute 2010). For Portugal, the cooling needs are, in general, much lower than the heating needs and are mostly driven by the solar gains than the exterior temperature.

Another different feature in Finland's building regulation compared to Portugal is that the Finnish national building code requires minimum 30% heat recovery from the exhaust air. It is considered natural ventilation for Portugal which is also applied in this thesis context. In general, residential buildings in Portugal are naturally ventilated.

It should be noticed again that the U-value for residential building in Finnish are clearly defined as low as the level of Passive house. The comparison of U-value from current regulations can be seen in *Table 9*

Table 9 $U - value$ for constructed walls and window in Finland and Portugal

$U - value$ W/m^2.K	***Regulations***		**NZEH considered**	
	External walls	*Windows*	*External walls*	*Windows*
Finland (National building code of Finland 2012)	0.17	0.5	0.17	0.5
Portugal (RCCTE 2013)	0.6 – 0.8	0.7 – 0.8	0.3	0.5

Water heating

From *Table 8* it is clear that the formulation for energy needs of hot water from both countries' regulation are based on the same principle of water heat capacity. The difference is the maximum hot water temperature and the amount of water consumed per day which is 40 liters for Portugal and 50 – 60 liters for Finland.

Base on the formulation, it is estimated that for Portugal: The annual energy need water heating is 641.28 kWh/person.year for a storage system and 488.60 kWh/person.year for the tankless system. In Finland, the value is annual 1062 kWh/person.year.

An alternative model that is comparable with the estimation in the regulations could assume that hot water is used for mainly shower and bathing. The energy needs for shower is defined by:

$$HW = F \times D \times \rho \times C_p \times (T_{out} - T_{in}) \quad [49]$$

where

F - L/s *the flow of water*

D - s *time duration of the shower*

T_{out} *water temperature in the bath*

T_{in} *water temperature in the pipes*

Based on equation [49], a person takes a daily 8 minutes shower per day with a flow of 5L per minute - 40L/person.day, at a water temperature of 40°C, considering an inlet temperature of 20°C. So it would require the energy of 3.3MJ o**r** equal to 0.92 kWh per utilization. If consider only one utilization per day, the total annual amount would be 336 kWh/person.year. This amount is lower than the estimation from both Portugal and Finland's regulations however it could be considered comparative model for the NZEH.

Cooking and kitchen appliances

Kitchen appliances and energy uses for cooking are not regulated in the Portuguese regulations. The listed values based on the guideline from

European Union on energy efficiency and empirical formulation (European Union 2010a).

It is necessary mentioning that, it is not straightforward to define the energy consumption level of kitchen appliances and cooking. A quite obvious reason is that the cooking habits vary according to culture and cooking style. Nonetheless, the energy-related for cooking method is quite homogenous among European and developed countries (Hager & Morawicki 2013). For general kitchen appliances, it takes into account of ovens, microwave ovens, and stove.

If we consider electricity stove for cooking, an electric stove top burner typically comprises 4 heating elements. The capacity varies from 1000 W to 3000 W depends of the size. The estimation of average modern stove consumes 1500 W/hour of heating on medium to high mode. With the assumption of 2 hours per day spent on cooking and 1500 W = 3 kWh/day, it could estimate of an amount of energy by 6 kWh/day for a family spend on cooking.

Lighting

In both regulations, the standards for lighting service are also listed by the highest efficiency lamp In Portugal: Energy classes for lighting are calculated with energy efficiency index issued by European Union (European Union 2012a). According to the statistics 2010, 81% of Portuguese household used incandescent lamps (Estatisticas oficiais 2010). The replacement by LEDs, CFLs and more environmentally friendly design has been in place over the last years. Similar to other appliances, energy-efficiency class for lamps are classified A to G of. Today, LEDs lighting is classified as A+, CFLs is A class and halogen lamps is C class. In Finland regulation, the defined power ($P_{lighting}$) for lighting space is equal with the energy efficiency level CFL and LED lamp.

Media appliances

In Portugal regulations, the energy demand for media appliances is not yet regulated. Media devices and other electricity appliances consume about 32.9% of all electricity consumption according to the national inventory (Estatisticas oficiais 2010). Energy consumption for media appliances in Portugal residential is based on the guideline from European Union on high energy-efficiency equipment. Meanwhile, Finland has defined specific level of the consumption which are summarized in *Table 8*

3.4 Energy consumption targets for buildings in Europe

Table 10 below shows the energy consumption level for buildings of selected European countries, the low-energy requirements and their targets up to 2020

Table 10 Energy consumption and low-energy targets for buildings up to 2020 in Europe

Country Unit: kWh/m².year	Electric. consumption [1]	Primary energy consumption [2]	Primary energy requirement (2011)	Goals from 2020 [3]	Share of renewable energy in buildings 2020
Austria	52	231	*66.5 (final energy)*	**160:** new residential building 200: major renovation	-
Belgium		288	119-136	**45:** Primary energy - detached house	6 options proposed with minimum of 10 kWh/m² renewables: thermal solar, PV, Biomass (CHP), Heat pump, District heat, Renewable offsite
Denmark	40	190	52.5-60	**20:** Space heating and cooling, ventilation, hot water	Expected: 51 – 56 % in 2020
Finland	100	294	65 (heating)	Intention to issue technical description on NZEB in 2015	-
France	62	205	130-250 (electricity)	**50:** primary energy	Proposed: Solar thermal, district heat 50%
Germany	45	232	70	Focus on efficient house	Made compulsory for heating of new building at minimum: Solar - 15%, biomass 30%, Geothermal - 50%. CHP – 15%
Netherlands	40	194	130-250	Based on Energy Performance Coefficient (EPC) = 0 , non-dimensional index for building's energy performance	The share is supposed to increase but not yet specified
Sweden	117	240	110-150	50-130 (final energy) vary from climate zone	Recommended for heating (no specific share)
UK	64	256	100 (from CO_2)	Based on Energy Performance Certificate in the National calculation methodologies	No specific share
Portugal	33	90		Numerical indicators have not been stated	-

[1] (World Energy Council 2011), [2] (Entranze 2013), [3] (J. Groezinger, T. Boermans 2014)

Table 10 represents the electricity consumption and the primary energy consumption in comparison with the low-energy level requirement and the targets for buildings up to 2020. *Table 10* shows that the average energy consumption in final energy (and consequently of primary energy) is well above the required thresholds for primary energy for 2020. There are two reasons that could explain this gap. First, the regulations refer to the requirements for new houses or large refurbishments and mostly limit for primary energy, while the average consumption refers to all households. Second, the requirements do not include all the end uses including the lighting, cooking, electric appliances. *Table 10* also indicates that few countries have set the targets for renewable energy share in the building, while most of the rest have not released their targets.

3.5 Energy-service framework for NZEH

As discussed in Chapter II, the analysis of NZEH has, in general, been done using two principles: first, is to determine the energy demand, applying the highest energy efficient solutions; and second is to design an energy supply system, considering the use of renewable resources and primary energy sources to complement the amount of energy supply which is non-renewable energy. In fact, the appliances' efficiency from final energy to end-use useful energy needs to be taken into consideration to achieve the principle of designing the most efficient energy end-use.

As mentioned, the hypothesis proposed is that from NZEH design concept to its practical implementation, it is needed to go beyond the final energy use, and to explicitly consider the concept of energy end-uses (or energy services). This requires the NZEH design approaches - whether using simulation or optimization approaches – to consider not only supply technologies but also the appliances efficiency and the household characteristics.

The following section shall discuss on the generic benchmark for energy services in NZEH in which the analysis is more focused toward Portugal than Finland. This is due the differences in two countries' regulation on building energy performance and the definitions of services and electrical appliances (as presented) which consequently leads to different approach to NZEH from the regulations.

A general benchmark of energy services

NZEH projects have experienced an increasing number of studies worldwide since the last several years (Musall et al. 2010). According to Musall et al.'s overview, by far Germany is the leading country on the number of the NZEH projects implemented, and the second country is the US.

In Europe, the NZEH projects have been realized within climate clusters such as Mediterranean climate or extended to Southern Europe region, or Nordic cold climate's zone. Take Portugal and Southern Europe as an example: although the climate and socio-economic conditions are not similar, Cyprus and Italy can be reasonable case to compare within Mediterranean climate zone. Case study in Cyprus indicated that the average residential energy consumption of Cyrus' houses was reduced to 75 kWh/m^2.year since the mandatory adoption of the insulation measures was introduced (Fokaides et al. 2014). In addition, a class-A house in Cyprus is considered to consume not more than 60 kWh/m^2.year. The recommendation on the strategy plan and technical knowledge also suggested for Mediterranean climate including Portugal throughout pilot projects (Ferrante 2012). However, Ferrante's studies did not specify each energy service reference value.

The following discussion shall provide more calculation and reasoning on the reference benchmark for NZEH in Portugal on the basis of accounting for efficiency at the final energy use and energy services. The methodological approach to design NZEH is followed by the first step that is to determine an efficient consumption level which has been well-updated in the Finns regulations.

According to current low-energy target set by Portuguese regulation 2006 and an updated version in 2013, to get an A+ certificate the energy needs is equal or less than 25% of the total maximum primary energy needs of the house (Ministério da Economia e do Emprego 2006). Since the regulations only set the standard for heating, cooling and water heating, the total energy services needed presented in *Table 11* is calculated based on the actual values monitored by smart-meter project in Lisbon (more detail presented in Chapter IV) and based on the following assumptions*:*

a) Based on the national survey, all services (except 1, 2, 3) represent 60% of total final energy.

b) The efficiency of all electric appliances for other services (except 1, 2, 3) is 70%

*c) For renewable energy produced onsite, the conversion factor from final energy to primary energy is equal to 1*However, the services covered by the regulation as low-energy standard or the passive house could still be regarded as the reference values for a NZEH. For Finland, the calculation based on the national statistics of 2010.

Table 11 Current residential energy-services and targets

kWh/m^2.year	**Portugal** *(Base temperature 15^{o}C)*	**Finland**	**Passive house**
1. Hot water	20		
2. Space heating	5	87	15
3. Cooling	1		
Cooking		3.4	
Kitchen appliances	39[a]		
Lighting		19.4	
Media appliances		4.8	
Total final useful energy	65	146	
NZEH target in final energy	82[b]		
NZEH target in primary energy (A+)	82[c]		120

From *Table 11*, some important aspects could be drawn for Portugal. Along with that, the discussion shall go into detail of what should the baseline of energy consumption for NZEH in Portugal concerning all energy services demand, how the energy metric in final energy or primary need to be counted and the availability of the renewable energy share.

The first aspect is that the actual consumption in a household in the Lisbon area is 88.1 kWh/m^2.year. This level is lower than the passive house standard – 120 kWh/m^2.year. If we consider the use of biomass for space heating (and cooking), and that electric services are provided by local renewable electricity, the obtained value is under the passive house limit. From the described NZEH case studies in this section and in previous *section 2.3*, one can see that the proposed values are even higher than what is currently achieved for houses in Portugal.

Maximum space heating service

*Table **11*** *Table 11* proposes the values of final useful energy and primary energy use of the total energy demand needed for a low-energy house in Portugal. It appears that there is a gap between maximum regulated heating value and the actual value obtained by pilot project. This gap is partially explained by the required base temperature for heating needs and that when the outdoor temperature drops below the base temperature, the heating needs or heating system is considered to turn on. In the regulation RCCTE 2006, the base temperature is 20^{o}C and that temperature in the regulation 2013 is 18^{o}C. The 20^{o}C base temperature is also used by other authors when calculating the heating demand for Portugal based on HDD (Silva et al. 2009, Wiesmann et al. 2011) while 18^{o}C has been used by studies among Europe and North America (Mourshed 2012). However, based on the monitoring data, the reference temperature should be decreased to 15^{o}C. This 15^{o}C temperature has been used for Germany – which is a colder climate zone (Durmayaz et al. 2000).

For Finland, the space heating *(2)* shown in

Table 11 also includes the heat for hot water. As seen in *Figure 10*, the energy services for heating in *Table 11* do not include all the heating needs from extra heating need such as floor heating, and car heating. Nonetheless, the amount of energy for space heating in Finland indicates a far reaching to passive house standard.

Remaining energy services

The second important aspect to re-emphasize is that local renewable energy supply must fulfil all the energy services in a NZEH. Therefore, a reference value has to include not only the hot water, space heating and cooling, but also the services for lighting and cooking.

For Portugal, we consider values obtained in the national survey combined with the monitoring project as the reference values for the NZEH standard. For both countries, in fact, considering an increase efficiency of the technologies for the services such as lighting and cooking, it is expected that the future energy needs in 2020 shall be lower or eventually equal, even if there is an increase in the level of provided services. Furthermore, as raised in the previous section, the large variation of residential consumption is not fully identified. It is also necessary to consider the differences in types and model of many the electric appliances to introduce more valid threshold of each energy service (Wood & Newborough 2003).

Primary vs. final energy target

The third important aspect is the definition of the value in terms of primary and final energy. It is true that from a global energy management system perspective, to account for the environmental and economic impacts, the reference value should be given in terms of primary energy. However, taking into account the framework proposed for NZEH in *Figure 2*, defining a primary energy target significantly limit the options to implement a NZEH for the fact that technologies' efficiency and available resource vary significantly. For example, in Portugal, consider that the heating space service is totally provided in a NZEH using biomass with an efficiency of 25%. The total primary energy required for heating will be close to the Passive house limit and there is still missing the demand for the remaining services. However, from the standpoint of a NZEH, using biomass as a heating resource appears to be an excellent solution. Therefore, it is suggested that the benchmark for NZEH should be defined in final energy to allow a larger optimization space and better technological feasibilities of with more renewable penetration.

Local renewable energy supply

On the availability renewable energy supply resources for NZEH, it is no doubt that Portugal has one of the highest potential such as solar energy that could alone provide half of the energy demand for the proposed NZEH. For example, a minimum 1 kW PV (4 panels, 4m^2) and for 2 solar collector (4m^2), could generate between 1100 – 1330 kWh/kW$_p$ annually, which corresponds to 4 kWh/m^2.day and provides 13 kWh/m^2.year (Celik et al. 2009) (Šúri et al. 2007). Although storage may be required to match the demand load from the supply, certain level of renewable share is already covered in the update 2013 regulation of Portugal and the regulation on purchased renewable energy which have enforced the implementation of the renewable energy from the local supply.

In sum, despite the obstacles on finding a common framework for NZEH throughout Europe, several initiatives and implementations are found as good examples. Dall' et al. (2013) selected new houses built after 2007 in Italy with a heating energy demand range from 6.43 – 29 kWh/m^2.year. This heating need met the energy class A and A+ certificate. Case study in England was done for houses from 105-164 m^2 with a net consumption of 100 kWh/year. This means the NZEH meet or exceed their initial designed performance (Thomas & Duffy 2013). The author Aelenei also presented a series of NZEH project worldwide from North America to central Europe and Mediterranean in which the balance of net zero energy is reachable as from nearly zero with negative -34.5 kWh/m^2.year to positive energy of 24.6 kWh/m^2.year (International Energy Agency 2012). On the social acceptance level, more than half of the European citizens recognize and concern about energy efficiency in their houses (Eva & Kaisa, 2012). The major concern is to push up to policy level and to create market solutions.

3.6 Concluding remark for a general benchmark of NZEH

In conclusion, the Chapter proposed the boundary of *Net Zero energy services house* in which energy demand accounts for all energy services of: space heating and cooling, water heating, lighting, cooking, and entertaining and media services. The extra energy services such as fire protection or maintenance are not included. The standards should also be based on the bottom-up model which considers both housing characteristics and consumption characteristics.

The indicator of energy intensity (kWh/m^2.year) is used. There is no embodied energy included in the building's lifecycle. And the building should also be allowed to connect to the grid. Take Portugal as the case, the total maximum energy services require for residential in Lisbon area might be proposed as 100 kWh/m^2.year in final energy. However, it is critical and reasonable to set the NZEH targets in final energy as the services demand, as justified. The detail reference values for Finland shall be discussed in Chapter IV.

Initial policy recommendations regarding NZEH for Portugal are summarized below:

1 Use the low energy house standard as reference values for the NZEH services covered in the national regulations (beside hot water, space heating and cooling).

2 Define reference values for the remaining services (lighting, cooking, electrical appliances). These values may come from national surveys or pilot smart-meter project, but detailed studies on usages patterns should be done.

3 Define the reference values for NZEH in final energy, the reference values should be in kWh/m^2.year, also in kWh/person.year for hot water.

4 The concrete definition of nearly NZEH at the minimum of 50% renewable energy share according to principle of NZEH which ranges from 50 – 90% (Boermans, Hermelink, et al. 2011). Detached house could reach 100% renewable share. In the apartments or multiple houses, however, might not be possible for 100% renewable share due to the limited rooftop area for solar electricity production and heat generation. In these cases, the renewable energy supply can come from other areas.

5 The benchmarking should be done at the final energy level. Considering that in Portugal the current electricity supplied by renewable is 60% since 2012, the share of at least 50% would be achievable if consider that all services are provided by electricity. Thus the pure electrification of the energy services could lead to the NZEH alone, without further energy efficiency improvements.

4 RESIDENTIAL ENERGY CONSUMPTION

4.1 Portuguese residential energy service

4.1.1 Statistical data

Portugal has not issued an official regulation regarding the NZEH, nonetheless the topic has been closely followed by the national research community (Kapsalaki & Leal 2011, Wiesmann et al. 2011). To obtain more insights of NZEH-concept applicability in the Portuguese case, this section looks into 1) the Portuguese regulation (RCCTE) on building's energy performance and 2) the residential consumption data from two sources - a national survey and a pilot project on smart meters.

The RCCTE was originally introduced in 2006 and revised as REH in 2013. The RCCTE sets a methodology to evaluate the energy performance of residential buildings .Though not explicitly, the regulation provides a definition of the energy services for space heating, space cooling and hot water in considering the household characteristics (as defined in *section 3.1*). The regulation also evaluates primary energy consumption accounting for the end-use technologies efficiency, the climate (temperature and radiation), and other household characteristics such as the shape factor, floor area, materials, and number of people in the household.

In 2010, the National Statistics Agency and the National Directorate for Energy carried out a national survey on the residential energy consumption for Portugal (Estatisticas oficiais 2010) in which included detailed statistics of final end-uses. It should be noted that this national survey did not give results at the municipality level.

The author also had access to the data of a smart metering project (2011 - 2014) from a Portuguese utility that included not only electricity consumption but also gas consumption and covered the final energy vectors in the majority of the Portuguese houses. The project included 100 households from all the country, however most of the participants were located in Lisbon.

The comparison of energy consumption from the three sources of RCCTE regulation, national survey, and the smart meter project are shown in *Table 12*. A reference household is used (area of 108m^2 and average 3 inhabitants), where space heating is provided by electric heating with 100% efficiency and cooling is supplied by heat pump with a coefficient of performance - COP of 3.

Table 12 Residential energy consumption in Portugal

Final energy consumption kWh/m².year	**RCCTE (2006)**	**REH (2013)**	**National survey (2010)**	**Smart-meters (2012)**
1. Hot water	30	19	26	
2. Space heating	6.9[d]	69[e]	5.7	
3. Space cooling	1.1[d]	6[e]		
Cooking & kitchen appliances			30[f]	
Lighting			5.3	
Media appliances			13	
Total final energy			80	52[g]
Primary energy (1+ 2 + 3)	50.5[d]	81.5[e]	40.3	
Total primary energy services			198.7[f]	88.1

Table 12 is based on the following assumptions

d) The regulation – RCCTE 2006 considered that actual use of heating and cooling is 10% of the total needs.

e) The regulation – REH 2013 does not define a specific fraction of use per year. This number is the total needs off all services.

f) In the national survey, the cooking only represents 5% of the total final energy consumption (4 kWh/m².year). In Portugal, cooking is mostly done using gas, therefore considering cooking is supplied by gas and other kitchens appliances are supplied by electricity.

g) From RCCTE 2006 regulation, conversion factors from final to primary energy is considered as 1 for gas and 3.37 for electricity, and reduce to 2.5 in the 2013 regulation (grid became more efficient). So in total of 52 kWh, 24 kWh is from electricity and 28 kWh is from gas

The results in *Table 12* show that the final energy consumption in the national survey in heating, cooling and hot water services (1-2-3) is lower than the maximum admissible consumption of those services described in the RCCTE 2006 regulation.

The energy-service disaggregation also shows that the larger difference is from hot water service and the cooling needs. These two energy services are relatively small demand in the total demand of national scale since most of the houses have not yet had cooling equipment or do not use on frequent basis. The REH 2013 regulation actually shows a downward correction or lower consumption of hot water compared to RCCTE 2006. From the survey, it is observed that the energy consumed in space heating is mostly equal to the amount of energy used in lighting, and it is 5 times lower than the energy used for cooking and kitchen appliances.

It is recognized that the totally energy consumed by all services measured by smart meters is actually mostly close to the amount of energy needs by only three services of heating, cooling and hot water estimated by national survey and the regulation. In addition, it is also found that the actual energy use for space heating is only 5% and for hot water is 22% of the nominal values obtained from the RCCTE regulation (Magalhães & Leal 2014). According to Magalhães & Leal, even 80% of Portuguese residential has nominal heating needs higher than 100 kWh/m^2.year, the actual heating needs that are covered is still small portion. This over estimation of heating needs is also supported by other literature for resident in Portugal which indicated 84.3 kWh/m^2.year in final energy consumption of, and of 210.6 kWh/m^2.year in primary energy consumption (Balaras et al. 2007).

Since there is no central district heating tradition in Portugal (except for new development in one neighborhood in Lisbon), and the winter climate is less severe, this suggests that people are used to have colder houses and wear more clothes inside than in other northern European countries. In fact, people from northern countries spending winters in Portugal usually complain about the lower internal temperature when being inside the houses. Furthermore, the RCCTE regulation may overestimate the in-use duration of heating system in the winter. The regulation estimated the space heating needed in 16 weeks for 4-month winter from November to the end of February. Furthermore, the base temperature may be higher than reality in the regulation. As discussed, in the regulation RCCTE 2006, the base temperature is 20°C and that temperature in the regulation 2013 is 18°C. The 20°C base temperature is also used by other authors when calculating the heating demand for Portugal based on HDD (Silva et al. 2009, Wiesmann et al. 2011) while 18°C has been used by studies among Europe and North America (Mourshed 2012).

In Lisbon, the climate is characterized by mild winters and hot dry summers (Oliveira et al. 2011). In November, the average maximum temperature is 17°C and 14°C in January. In reality, people tend to use the heater only when the temperature is lower 10°C. The energy used for cooling demand could also be estimated higher than the average needs. The low energy demand for cooling is confirmed by the national survey in 2010 as seen in *Table 12*. This does not necessarily mean that the regulation is excessive which could be partly explained that despite energy efficiency concern, households must increase the energy consumption with heating service to increase the indoor thermal quality and thermal comfort.

Finally, in the national survey, the largest end-use in Portuguese residents is domestic hot water, followed by cooking (including the fridge) and the electric appliances for media (PC, TV, etc.). However, comparing the national survey data with the data from the smart-meters pilot, these energy services could also be overestimated. This clearly shows that a significant part of the energy needs by other services (rather than heating, cooling and hot water) is not considered in the regulation. This is consistent for other countries, when analyzing the weight of final electricity usage in colder climate such as Germany, Denmark or Sweden, where the space heating service if provided by district heating networks – as already shown in *Table 4*.

Data from smart-meters includes the information on the energy class of each household given by the available information of provided by each house. The energy class is divided from class A to D and their corresponding energy consumption are clustered by house size (T2 to T4 presents for number of bed room accordingly). The house energy class and the energy consumption are presented in *Figure 11*.

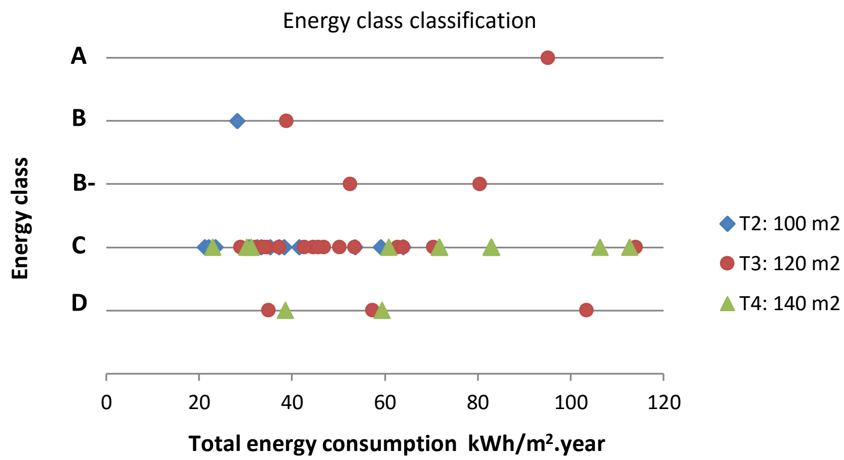


Figure 11 Energy consumption and energy class in the SMARTGALP Pilot

Figure 11 shows that for the same energy class, the size of the house does not appear to be a determinant driver of energy consumption. Most of all, the house with higher or better energy class are not the houses that consume less energy. On the other hand, the house with higher energy consumption is in fact in the group of lowest energy class. This suggests that other factors are not considered in the regulation to evaluate the energy class, such as consumption habit, are important drivers of energy consumption as described in Chapter III.

4.1.2 Smartgalp pilot

This section will discuss more about the Smartgalp pilot project of smart metering in Lisbon. In 2011 GALP ENERGIA - a Portuguese utilities – started a smart energy metering project, called SMARTGALP with the participation of 100 households in Lisbon area (GALP Energia 2013). The project's objective is to test the increase of energy efficiency in the residential building by providing detailed feedback of energy consumption on electricity and gas and energy efficiency tips to residential consumers. A smart meter is able to measure the electricity consumption up to hourly basis. The accounted energy of electricity and gas (as seen in *Table 12*) are in final energy.

In the Smartgalp pilot, the survey comprised extensive inventory on residential energy use by collecting information of equipment and electricity appliances used in the house. The information also included housing characteristics, such as the orientation and feature of doors and windows such as layers, shading. The survey tried to investigate more on the income level of the family by looking at, such as, the model of the appliances and number of cars in each house. To this extent the survey wanted to evaluate the residential energy demand based on their characteristics obtained and by occupants' habit and their activities' schedule such as when and how the energy appliances were used according to family schedule and family profile (such as number of kids and adults).

The physical determinant factors classified as household characteristics are the number of occupants and floor area. The indicators of energy intensity unit are kWh/m².year and kWh/m².person.year on the basis of floor area. Based on the house's area, 6 types of houses ranging from T1 to T6 were surveyed for annual energy consumption of electricity and gas. Out of 100 houses, 49 households of T2 to T4 are evaluated in this Chapter. The features of 49 houses are presented in *Table 13* .

Table 13 Type of surveyed house

House's type	Area (m²)	Average habitants	Number of house
T2	95 - 115	1 - 2	14
T3	105 - 135	2 - 4	23
T4	125 - 155	3 - 4	12
Reference house	*108*	*3*	

The energy consumption values in final energy measured by smart meters are validated by compared with the values obtained by a simulation tool. This simulation tool is developed from the input data of a comprehensive inventory survey on the electrical and gas appliances in the houses. Detail parameters and inventory of this survey are explained in the *Appendix 1*. The simulation tool is able to estimate the electric and gas demand for both block apartments and detached houses located in extended area of Lisbon.

It is noted that the monitoring values were given in the total annual gas and electricity consumption of Lisbon in 2012. The break-down of all residential energy service including water heating, space heating and cooling, cooking and kitchen appliances, lighting, and media are extrapolated from the simulation tool.

The weekly and monthly consumption of gas and electricity from 49 households are shown in the *Figure 12* and *Figure 13* and the total energy consumption is presented in *Figure 14*.

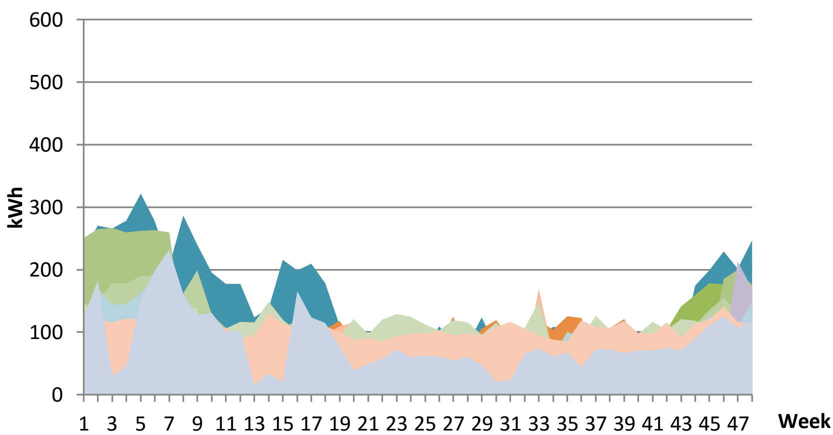


Figure 12 Weekly electricity consumption

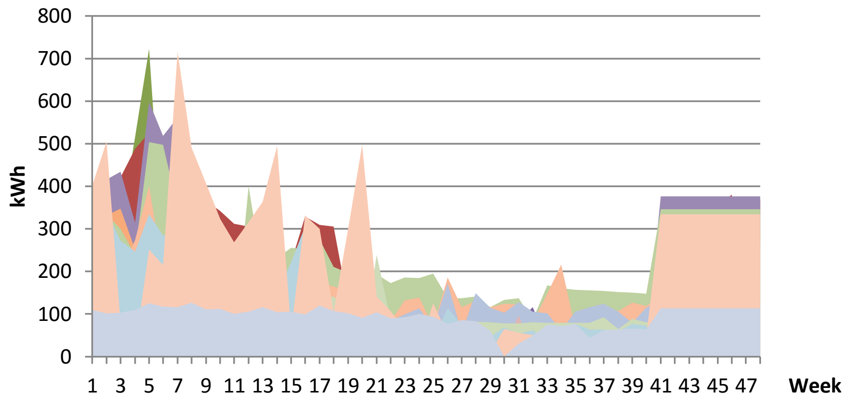


Figure 13 Weekly gas consumption

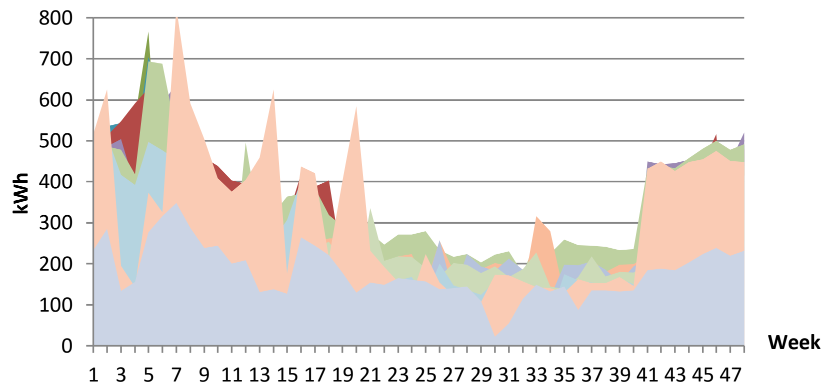


Figure 14 Total energy consumption

Figure 12 presents the weekly electricity consumption in which the pattern shows that most of the houses have a stable electricity consumption throughout the year which below 150 kWh/week. Only 6 out of 49 houses have the consumption exceed 150 kWh/week started from the second week of December to the last week of February which comprised 11 weeks in winter (less than 3 months).

It is seen that 45 households have the average weekly electricity consumption less than 100 kWh/week in which 23 households below 50 kWh/week. A consumption peak is observed on the first week of September. This peak is reasonable by the fact that most of the surveyed families are middle and high income household. Therefore, most of them had the summer holiday during August and come back in September.

The pattern seen from *Figure 12* shows that the electricity demand throughout the year is stably independent with the seasonal changing. The exception cases are from T4 houses where AC is used for space heating during winter time and the families that have 2-3 people stay at home during the day time.

Figure 13 adds the weekly gas consumption. There are two clear trends of gas consumption – a very high and a medium consumption group. There are 7 houses, equipped with central heating system, whose highest consumptions are larger than 200 kWh/week compared to remain houses. The winter gas peak started from the first week of November to the last week of February, which does not match with the winter electricity peak.

Figure 14 presents weekly total energy consumption. There are 19 out of 49 houses have energy consumption below 150 kWh/week. The very high consumption houses are mostly caused by the high gas consumption. The annual electricity consumption remains stable as mentioned.

4.2 Discussion on residential energy service data in Portugal

4.2.1 Residential energy services

This section shall continue the discussion in more detail of the residential energy service demand in Portugal by looking into the data obtained from 1 - Smartgalp smart-meter project, 2 - national survey and 3 – a simulation tool. The simulation tool as mentioned in previous section, was developed from the input data of a comprehensive inventory survey on the electrical and gas appliances in the houses. Detail parameters and inventory of this survey are explained in the *Appendix 1*. The simulation tool is able to estimate the electric and gas demand for both block apartments and detached houses located in extended area of Lisbon.

Table 14 , as an extract from *Table 13*, shows numerical values of each energy service estimated by national survey. And *Table 15* presents the breakdown in percentage estimated by the simulation tool. The results presented in these two tables shall be discussed in the next sections.

Table 14 Breakdown of the energy services consumption

kWh/m².year	National survey	Smart meters
Hot water	26	
Heating	5.7	
Cooling		
Cooking and kitchen appliances	30	
Lighting	5.3	
Media appliances	12.8	
Total final energy	80	52.5
Total primary energy	200	131

Table 15 Breakdown in percentage of the energy services consumption

Energy service	**Total energy**		**Electricity**		**Gas**	
(%)	Simulation	National survey	Simulation	National survey	Simulation	National survey
Space heating & cooling	19.80	6.82	14.87	10.7	17.50	3.1
Water heating	40.01	32.69		2.3	72.42	61.8
Cooking-kitchen appliances	32.41	37.74	65.71	40.5	10.33	35.1
Media	4.83	16.10	12.30	32.9		
Lighting	2.79	6.65	6.77	13.6		

Space heating and cooling

As seen from *Table 15*, a noticeable observation is that energy for heating indicated by the simulation (19.8%) is 3 times higher than the value obtained by national survey (6.8%). This again confirms of the mismatch between the simulation and the actual consumption due to overestimation of heating duration. As mentioned in previous sections, energy needs for space cooling is negligible compared with total energy needs. In addition, from the survey, 10 households were equipped with AC but the AC was rarely in-used for summer.

Water heating

Table 15 also shows the energy consumption by water heating is considerably matched between the simulation and the values obtained by the smart-meters and national survey. On monthly basis, there is no significant difference between the simulation values and the monitoring values. As seen in the *Figure 14*, there is an extract cluster that shows most of the houses have the water heating demand less than 80 kWh/person per month. From the survey, houses whose water heating is more than 80 are from the larger houses (T4 to T6).

Kitchen appliances and Cooking devices

The energy consumption for cooking demand shows no significant gap between the simulation and values obtained by other surveys. It is noted that there is no obvious trend in which larger family with more people would have higher energy demand for cooking. When it goes down to energy consumption per capita (kWh/person), the 5 highest energy consumption households belong to T4 house. Considering the same amount of time spent on cooking or the same amount of energy used by cooking devices, this is contrary with the intuitive understanding in which energy intensity per head for single person house is higher than those house with more people. Therefore, there is no obvious clue to conclude that energy used for cooking is mainly influenced by the number of people per house.

Furthermore, to date, there is limited available data for the residential energy consumption for cooking. Few literatures indicated that energy for cooking in developed countries ranges from 4 - 7% of total household energy consumption (UN-HABITAT 2008). For example in the UK, the energy demand for cooking even decreased from 6% to less than 3% during 1970s to 2000s (Palmer & Cooper 2012). On this thesis context, average of 5% energy demand for cooking only is therefore applied. Based on that consideration, cooking energy consumption is less than 40 kWh/month for most of the house in Lisbon.

Media appliances

Contrary with the heating, the energy used by media appliances estimated by simulation tool is 3 times lower than the values obtained by the national survey and 2 times lower than values obtained by the smart meters. This could be explained for the media case that the simulation applied for Lisbon context only while the national survey is applied for the whole Portugal. Looking into the energy intensity per capita, there is a trend that the highest consumption comes from bigger houses with more people. Meanwhile, it shows no clear correlation between the number of people per house and the amount of energy consumption. It is reminded that the media electric appliances do not include the fridge as the cold device.

Lighting

For energy used in lighting, it is found no significant gap between the simulation and the monitoring values. This could be explained by the fact that the electricity used for lighting is not easy to clearly separate from other electrical appliances. There is neither obvious trend that the bigger houses have higher energy demand for lighting. The highest and lowest consumption groups are equally distributed from T2 to T4 houses.

Literature suggests an average level of energy consumption lighting in Portugal by 380 kWh/year (Intelligent Energy Europe 2015). This level is comparable with the average consumption level in residential Lisbon which is 395 kWh/year obtained by the smart meters. Another factor worth noting is that living standard in Lisbon is relatively higher than the average Portugal, and the surveyed families are mostly from middle to high income group. Therefore, though having more energy efficiency light bulb, the energy demand for lighting in Lisbon is relatively higher than the rest of Portugal.

On a concluding remark, the comparison of the results obtained by simulation tool, the national survey and the smart-meter again show variations of residential energy consumption in Portugal. The unexplained variation is partly due to the missing values and incomplete information by the survey. It must be acknowledged the fact that the occupants do not know all correct information embedded of the installed appliances in their houses. The variation is also considerably affected by the individual lifestyle and family income. The variation factors include and how the occupants/users use and care for the appliances maintenance schedule, and how families saving efforts have been made. Diverse models and different efficient rate of household appliances also create large variations that the occupants themselves can hardly know the precise elements. Those factors are discussed in detail in previous *section 3.1*.

The above discussion and analysis gives an overall trend and pattern of the residential energy consumption in Portugal. The discussion is to provide further reasoning for the proposed value of each energy service for NZEH and that shall be discussed in the next section.

4.2.2 Renewable energy in Portuguese residential sector

As discussed in Chapter I and II, to develop an energy service model for NZEH under the building energy performance regulations, the available renewable energy resources also need to be defined. This section shall introduce the potential renewable energy resources that are used in residential in Portugal (for Finland, the resources shall be discussed in the next *section 4.4.3*)

Despite having advantage of being among warmest countries in Europe by its highest solar radiation intensity in Mediterranean (PVGIS 2015), Portugal still has a slow up-taking speed in the adoption of solar technology.

In the national grid sector, renewable energy is integrated mainly as hydropower (30%) and wind energy (25%) over the last 5 years. The total renewable energy in the grid has been average of 52%. That percentage is seen as a considerable share of renewable energy compared to average European countries which is only 11.8% (Eurostat 2015c).

In the residential sector, apart from the use of biomass, renewable energy has been integrated in the form of solar thermal systems for domestic hot water and solar PV for electricity. Still, these technologies have been adopted in less than 10% of the households (Direção Geral de Energia e Geologia 2014).

To reach NZEH in building sector, however, it is needed to go further beyond 50% renewable energy produced on-site, focusing on solar energy and/or biomass to substitute fossil-fuel based electricity and gas (natural of liquefied petroleum). Renewable energy needs to raise more significant role in energy planning and climate policy in Portugal residential sector given the advantage of good solar radiation (OECD 2011).

Solar PV and solar collector

According to Portuguese Energy Agency – ADENE, since 2009, a number of projects have been implemented to bring hot water solar collector to residential building in Portugal. Despite well-established studies that demonstrate the techno-and-economic feasibility of solar collector (Lamnatou et al. 2015), uncertainties remain on the policy and market creation. ADENE suggested an estimation of energy provided by solar system for Portugal is 11 kWh/m^2.year while the total hot water heating demand is estimated for reference case as 19 kWh/m^2.year, which means solar thermal technologies can cope with 60% of the total hot water demand. Study further showed the cost and high feasibility of solar collector among other passive strategy for residential building from (ADENE - Agência para a energia 2009).

Regarding solar PV, the productivity of solar PV systems is in Portugal is in average 1650 kWh/kW$_p$ (PVGIS 2015), while the average electricity consumption in Portugal has been 3600 kWh/household over the last years (Direção Geral de Energia e Geologia 2014).. This means that considering an annual balance, a 1 kW system is able to provide in average 45% of the electricity.

Wind energy

Wind energy accounts for more than 20% of electricity in Portugal's national grid. Portugal ranks among the top 7 countries with highest installed wind power capacity (Global Wind Energy Council 2015). However, micro generation by mini-wind turbine has still limited application to the residential sector despite its wind potential of larger than 5 m/s wind speed at 10 m height which is feasible for micro generation (Costa et al. 2006).

On one hand, it is observed an increasing attention on innovation for micro-wind turbine for building and residential sector (Bento & Fontes 2015, Abohela et al. 2013, Walker 2011). On the other hand, it is needed considering the fact that integrated micro-wind generation in urban areas and in building system remains challenges in compliance with technology, architecture and aesthetic combination. Nonetheless, micro-wind generation can be considered in the NZEH for detached house.

Biomass and biomass boiler

In Portugal, 30% of residential heating fuel comes from wood-based biomass (Estatisticas oficiais 2010). With its local biomass resource, biomass certainly remains an important source to serve heating demand. Studies have shown that in several regions of Portugal, switching heating system and domestic hot water, supplied by fossil fuels, to biomass system is environmentally and economically feasible (Fernandes & Costa 2010, Carpio et al. 2013). In addition, studies confirmed biomass wood pallet as the most competitive fuel to the end-use in Portugal, and its market has been growing (Nunes et al. 2016). Studies also pointed out that mix biomass pellet resource for the residential sector lack a systematic development and planning in Portugal (Nunes et al. 2014).

Geothermal and heat pump

In Portugal, there two power plants, which are located in São Miguel Açores island. In the main land, the available geothermal energy requires almost none superficial area. Among southern European climate countries, studies have shown that Portugal has a promising geothermal potential with solar assisted heat pump in the residential sector. And that the implementation of assisted heat pump geothermal resource in building sector could significantly bring the CO_2 reduction up to 90% in Portugal (Carvalho et al. 2015, Reda et al. 2015).

Geothermal energy resource can also be considered as a heat source for detached households.

4.3 Reference values of energy service in NZEH for Portugal

Space heating

Thanks to the energy efficiency improvement, since 1990 energy intensity used for space heating has been decreased 1.2% per year in Europe (Gouveia et al. 2012). However, this fact is exceptional for mild-winter countries such as Portugal because of the increasing demand of heating comfort (Estatisticas oficiais 2010).

It is noticeable that studies recommended Netherlands could be taken as a reference value for space heating as buildings in the Netherland have the lowest energy used for heating (Bertoldi et al. 2012). Other proposed the heating demand for zero house in Finland followed passive-house standard with 20.97 kWh/m².year and the normal standard is 64.39 kWh/m².year (Mohamed et al. 2014). These studies might be reasonable references of space heating values; however, studies are not comparable to Portugal's condition, as Portugal has much lower energy demand of space heating.

A more comparative look at NZEH studies among Mediterranean climate, for example a case study in Cyprus indicated a heating demand of 14.8 kWh/m².year in which biomass boiler satisfied 100% of the primary energy for space heating (Fokaides et al. 2014). Another case study in Lombardy, Italy introduced space heating demand for residential building in the range from 6.4 - 28.9 kWh/m².year (Dall'O', Belli, et al. 2013).

As mentioned in the previous section, for Lisbon, space heating demand is equivalent to 11.7 kWh/m².year in final energy (estimated by the simulation), and is equal to 5.2 kWh/m².year (measured by the smart meters). The differences are explained in the *section 4.2* which is due to the overestimated the heating period in the simulation. These values are already considered the fact that 25% household in the survey uses electricity for heating. The remained houses are heated by fireplace and central gas heating. In addition, other study for Portugal estimated the annual primary heating energy demand as 16.9 kWh/m² of which 11 kWh/m² are supplied by the solar system of a Passive house (Ferrante 2012).

Although it is not fully complete when comparing the condition of Lisbon area to the other countries, it is reasonable to observe the comparative level between Lisbon and the areas within their Mediterranean climate condition such as Cyprus and Italy. The cross-referenced value above of space heating are summarized in the *Table 16*.

Table 16 Cross-referenced values of the energy demand for space heating

Location	Finland	Cyprus	Italy	Portugal	Proposed NZEH
Primary energy kWh/m².year	20.97	14.8	6.4 - 28.9	16.9	10

This study proposes the value of energy demand for space heating in Lisbon area is less than 4 kWh/m^2.year in final energy which covers 4-month heating duration. Assume that 40% is the efficiency of the electricity system, the primary energy would be 10 kWh/m^2.year for space heating (reference house of 108 m^2, 3 people).

Water heating

The average demand for water heating is 873 kWh/person.year (or 20.5 kWh/m^2.year) in final energy obtained by the simulation and 738 kWh/person.year (or 24.3 kWh/m^2.year) measured by smart meters. Taking 75% energy efficiency for most of the water heater in the survey, these amounts are actually higher than the final useful energy amount obtained from the proposed model in the *section 3.3.2*. For that suggested model, an 80% efficiency water heater would consume 336 kWh/person.year or 9.4 kWh/m^2.year in final useful energy. As presented in *section 3.3.2*, according to Portuguese regulation, energy consumed by hot water demand of tank-less systems is 488.6 kWh/person.year or 13.6 kWh/m^2.year. The difference between those values could be explained by the loss in the pipeline system. The amounts of energy for water heating calculated by the suggested model is even lower compared to the simulation results for NZEH as given by other authors who studied a 129m^2 house in Germany with water heating need of-13.5 kWh/m^2.year, and in Madrid – the amount is 12.3 kWh/m^2.year and in Copenhagen - 14.2 kWh/m^2.year (Boermans, Hermelink, et al. 2011).

It should be noticed that, these energy consumption level for hot water in Portugal are relatively low compared to the colder countries such as the UK where the consumption is 1440 kWh/person.year with average 2.2 people per house compared 2.7 in Portugal. In addition, studies showed that showering and standby energy loss account for about 66% of the total energy used for hot water in the USA despite the common efficiency of the device is higher than 75% (Harvey 2010).

The comparison of energy demand for hot water from cross-reference can be seen in *Table 17*

Table 17 Cross-referenced values of the energy demand for water heating

Location	UK	Germany	Madrid	Copenhagen	Portugal	Proposed NZEH
Primary energy kWh/m^2.year	29.3	13.5	12.3	14.2	13.6	<15

As presented in *Table 17*, accounting for the efficiency improvement as well as reducing heat loss along the pipeline, this study proposes the level of water heating could be less than 15 kWh/m^2.year.

Cooking and kitchen appliances

It could be said that, energy used for cooking and kitchen appliances is not simple, as it is usually aggregated with other services. Past literatures attempted to separate the cold appliances including refrigerator and freezer from the cooking and other electric appliance used in the kitchen. It is noted that the survey in Lisbon includes cooking appliances such as stove, ovens and other appliances in the kitchen such as fridge, washing machine. In this way, appliances used in the kitchen are divided into two groups: appliances for cooking alone and the others are appliances such as refrigerator, washing machine, and microwave. There is, however, no strict classification for cooking devices in Portugal, for example microwave can also be used for cooking.

There is still limited available data for energy demand consumed by cooking in Europe except general surveys. Few studies discussed on the energy needs for cooking, for example Wood & Newborough (2003) and Palmer & Cooper (2012) conducted the case for the UK in which electricity for cooking needs is 460 kWh/year. Other author studied the case of Europe where most of cooking appliances are electrical devices with 16% of appliances is gas ovens and 36% is gas stoves (Hager & Morawicki 2013). While Harvey (2010) reported 25% of European household own the gas ovens. These fractions of gas oven are average lower than the numbers found in Portugal. In general, most of the cooking top using in Lisbon and Portugal as surveyed is gas stove (more than 90%).

According to the European standard, the minimum required energy efficiency for cooking devices is 52%. However studies found most of the current gas oven in the developed world have the efficiency about 40% (Hager & Morawicki 2013, Melbourne Energy Institute 2013). Therefore, there is still a need to improve higher energy efficiency in cooking devices. Recent studies also suggested replacing gas and electric stove by induction cook top to improve efficiency. Studies indicated the energy efficiency of the induction cook top can improve up to 70-84% which is about twice more efficient than the normal gas stove (Sadhu et al. 2010, Melbourne Energy Institute 2013). Summary of energy demand for cooking, and devices' efficiency requirement and the numbers are shown in the following *Table 18*.

Table 18 Energy demand for cooking and energy efficiency for cooking devices

Location	Europe	UK	Portugal
Energy demand for cooking (kWh/year)		460	317.4
Energy efficiency of cooking devices	40-52%		40%
Number	16% gas oven 36% gas stove		Nearly 100% gas stove

As seen from *Table 18*, for Portugal, the average monthly energy consumed for cooking is 317.4 kWh/year or 2.9 kWh/m^2.year - at the efficiency of 40%. Accounting for energy efficiency in cooking appliances to improve from 40% to 60% and maximum of 80%, the proposed level of energy needs for the cooking could be in the interval of 190 – 222 kWh/year.

Regarding kitchen appliances, most of new refrigerators and washing machine in Europe are labeled as A or A+ of energy efficiency for household appliances (European Union 2006). It is also observed that most of the kitchen appliances such as refrigerators and washing machine met the energy-efficient requirement except the cooking devices by gas as mentioned. Therefore, in terms of technology efficiency there is still a room for reducing the energy consumption of cooking appliances. However, there may not have much room for the rest of the kitchen appliances as mentioned the most updated energy efficiency appliances is being carried out. The reduction is, however, still possible when dealing with the consumer behaviors on using the appliances integrated with housing energy management system which could be assumed for a reduction of minimum 5%.

The average amount of energy consumed by kitchen appliances in the survey of Lisbon is 2084 kWh/year. Combined with the energy needs for cooking, total energy needs for kitchen appliances and cooking is 2170 – 2202 kWh/year or 20.1 – 20.4 kWh/m^2.year.

Multimedia appliances

It is not straightforward throughout the literatures to compare the amount of energy consumption by media appliances, since each study has different references for chosen electric devices and the operation mode, with a mixture of standby, continuous, and cold mode. On the energy efficiency, most of the current media appliances have met the EU requirement for energy efficiency on A to A+ of energy class. Therefore, it can also be said that to date there is not much space on reducing consumption of this appliance group but it is still possible on the behavior changes and on the living style that can reduce level of consumption.

For example, recent studies released that the amount of hours spent on watching TVs and using computers and electronic appliances has increased significantly over time from 1970 to 2000 in developed world. For example in the UK, this increase of hours spending on household multimedia have led to the increase of energy use more than 3 times over decades (Palmer & Cooper 2012). Portugal case appears as the same, with an increasing trend which is understandable for higher family income level (Gouveia et al. 2012). At European level, limited data appears from the bottom-up survey on energy consumption for residential media appliances. Nonetheless, studies have succeeded to estimate the level of energy consumption for multimedia appliances, such as for the UK of 1079 kWh/person per year (Palmer & Cooper 2012).

In our survey the average energy consumption of media appliances service is considered as 161 kWh/person per year or 4.5 kWh/m^2.year. It is proposed the threshold for NZEH as of below 4 kWh/m^2.year.

Lighting

In Europe, most of the current lighting standards have set the values for office building lighting - as can be seen in *Table 19*.

Table 19 Comparison of lighting energy efficiency standards

Efficient lighting standards	W/m²	Maximum Lux
French (office)	12	600
USA (office)	11	
Australia (office)	10	
Cyprus	0.44	300
(Fokaides et al. 2014)	1 W/m² = 683 lux	

Lighting standards for residential buildings have been left unregulated. Different works have discussed the standards for efficient lighting in European countries such as Spain and France for office lighting (Almeida & Martins 2014). Meanwhile, Portugal has not proposed energy consumption levels as lighting standards for low-energy performance buildings in the residential sector. For the services buildings with office, it has proposed a minimum of 32 kWh/m².year (for 500 lux).

There are, however, some studies that estimated the energy consumption for lighting in residential buildings at certain countries. For example, the electricity use for lighting in an average Norwegian household is 1050 kWh/year which accounts for 6% of total residential electricity (Rosenberg 2014). Portugal is also found in the range of European consumption level for lighting which is 8 to 11% of total energy consumption (Bertoldi et al. 2012, Palmer & Cooper 2012, Intelligent Energy Europe 2015). The energy consumption in lighting at selected countries are shown in *Table 20*.

Table 20 Energy consumption for lighting in Europe (Intelligent Energy Europe 2015)

Country	kWh/year	Energy intensity kWh/m².year
EU level	450	4.7
Austria	450	4.7
Cyprus	900	3.7
Netherlands	590	6.6
France	400	4.3
Spain	480	5.1
Sweden	890	9.8
Slovenia	350	4.4
Germany	280	3.3
Portugal	380	3.5
UK	600	8

According to Illuminating Engineering Society of North America (2000) there are different factors that affects the light illuminance required for working spaces to meet the human needs. They can be classified as different level of illuminance in lux unit - lx such as 100lx for simple visual task in living room and bedroom, 300 lx for moderate visual task such as reading in bedroom, 500 lx for working plane in the kitchen. In Europe, studies have indicated the same range of illuminance such as a case study in Belgium used 500 lx for the working plane in the kitchen, 150 lx in the living room, 100 lx in bedrooms, and 300 lx for the rest of the room (Bodart et al. 2009). Furthermore, these lighting standards have been recommended since several decades in Europe (Fischer 1973). Applied in NZEH study, a case study in Cyprus used the total housing lighting intensity of 300 lx (Fokaides et al. 2014).

In Portugal, few studies suggested a model framework for residential lighting in which the average number of light bulbs per house is 11.4, and most of bulbs are incandescent (Gouveia et al. 2012). In our study's survey, there is no dominance in certain types of light bulb among incandescent, fluorescent and LED. These types of light bulbs are equally distributed among the surveyed houses. This is also relevant to the fact that there are many renovated houses in Lisbon along with the new housing projects (Rodrigues et al. 2015).

For the purpose of simplifying the calculation, we assume that It can be considered that working plane at household as same level as the reading light. Therefore, the average of illuminance is taken as 250 lx. Assume the useful lighting area is 50% for the reference house.

Studies have also pointed out the trend of energy used for lighting in European residential increased by 1.4% per year between 1990 and 2002 (Intelligent Energy Europe 2015). From 2002, it started to decrease by 0.2% per year thanks to the efficient technology development. A potential of decreasing lighting energy consumption up to 50% by 2050 is possibly foreseen (Rosenberg 2014). Combine this energy reduction projection with the current level of usage in Portugal, the energy needs for lighting in high efficient NZEH is proposed to be less than 4 kWh/m^2.year.

4.4 Residential energy consumption data in Finland

4.4.1 Statistical data

Finland, unlike the warm and mild climate in Mediterranean countries, has much colder winter. Helsinki in the South of Finland has an annual average temperature of 5.4^{o}C (Finnish Meteorological Institute 2010). In the residential sector, Finland has the highest energy consumption per capita in final energy in Europe (Bertoldi et al. 2012). This high energy consumption is mainly due to the demand of space heating and water heating which accounts for about 80% of all residential energy consumption (Statistics Finland 2015a).

On residential building energy efficiency, there has been a significant improvement of U-values in all elements of Finns buildings. The U-values have dropped 27% for windows and up to 60% for walls during the last decade (Heinonen & Junnila 2014). Furthermore, it is found that energy efficiency provisions in 2010 were 30% more stringent than in 2003. Finland has largely followed international initiatives such as Energy Star and energy labelling of equipment. New regulations have been continuously adopted on improving new buildings' energy efficiency by 20% (Motiva Oy 2015).

Space heating demand and district heating system

Space heating is the major largest residential energy demand in Finland which accounts for 61% in final energy (Statistics Finland 2015a). District heating, accounts for 50% of heating market, is the most important heating distribution system in urban Finland. The district heating network is connected to 95% of apartment buildings and to most of the public and commercial buildings. However, only 7% of single-family houses or detached houses is connected to district heat system (Nussbaumer & Thalmann 2014). The district heating fuels include natural gas, coal, heat, peat, wood and an increasing amount of biogas. Energy for heat is produced by combined heat and power system or industrial waste heat. The heating services also provide for hot water heating and sauna heating system in the residential sector as partly seen in *Figure 8*.

Lighting and media appliances

According to VTT Technical Research Centre of Finland, the annual energy consumption for lighting is average 7.8 – 17 kWh/m^2 which vary from apartment buildings to detached houses (Evens et al. 2010). The efficiency for light devices has been continuously improved. The electricity for lighting in the apartment building accounts for about 20.9%, down to 13.2% for the detached house, the numerical values are depicted in *Figure 10*

Other work also considered annual electricity consumption of lighting was 7 kWh/m^2 for building in Finland (Mattinen et al. 2014). This value is average 2 times higher than the consumption in Portugal that was calculated in *section 4.3*. This could be explained for longer winter time therefore it needs longer lighting period during the day.

4.4.2 Online survey

Survey design

To get better understanding of the residential energy consumption in Finland, survey on residential energy consumption was carried out by the author from December 2014 to February 2015, by an online survey platform - *polldaddy.com*. The detail of questionnaire and more sample answers are attached in the *Appendix 2*. The following request was sent to the consumers/owners of the houses:

"This survey requires you to upload some files. Your household has a user account on the local energy company website for example Fortum or Helsinki Energia (verkkoyhtiö) that allows you to check your house's monthly and annually energy consumption. Please go to the company website and DOWNLOAD the summary files of your energy consumption in excel or PDF. Your name will not be included in these files neither on this survey"

The survey comprises of 13 questions including: basic features of the building such as floor area, the main energy services of heating with extra heating devices, and other occupancy feature such as number of adult and children in the house.

They survey was also able to obtain postal code of the respondent houses to show their location where are mapped in the *Figure 15*.

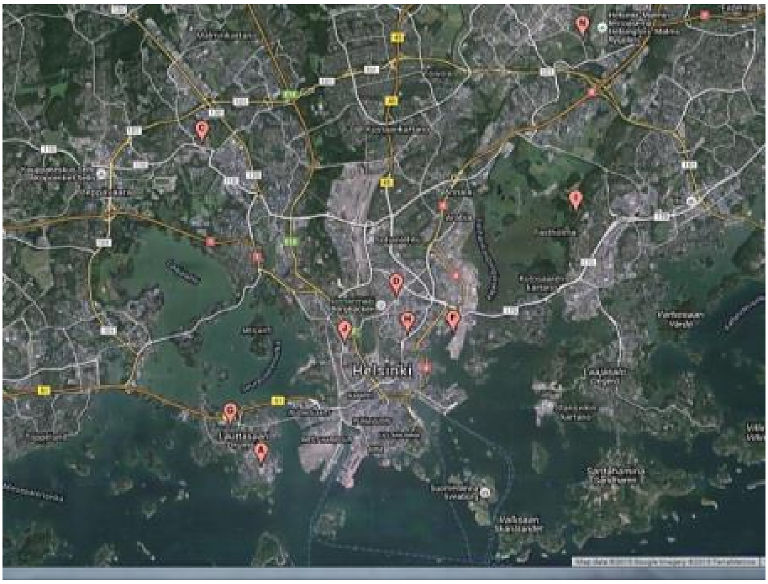
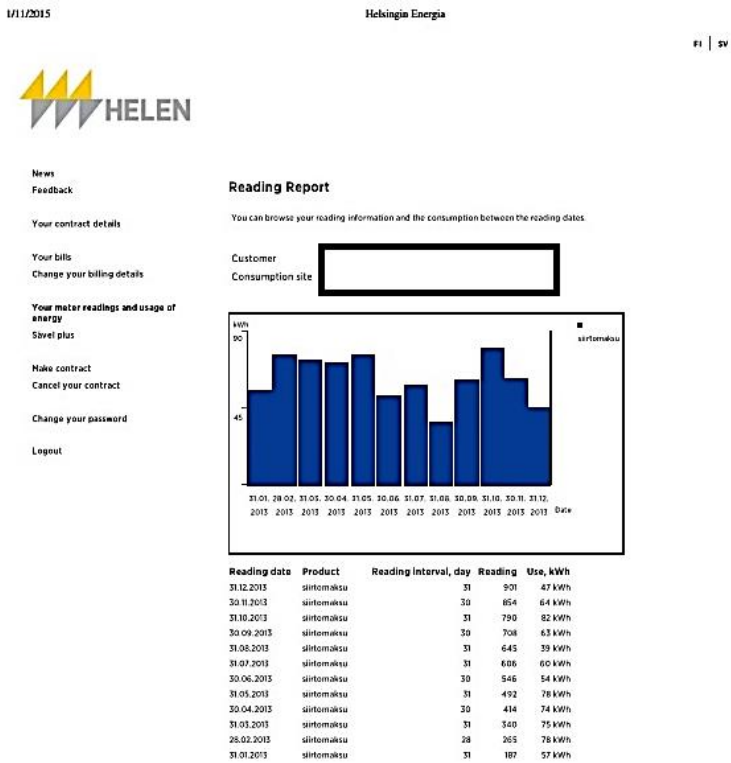


Figure 15 Location of surveyed houses on electricity consumption in Finland

There were 22 houses participated in the online survey, however, the acceptable responses were reduced to 16. The reason is that the survey requested consumers/users to login into their online account to download their household's records for electricity consumption. This task may not too simple and straight forward for some consumers.

An interesting finding of the survey is that majority of the consumer whom the author contacted directly said that they were aware of the smart-metering program installed in their houses but many had never checked their consumption that recorded in the online account provided by utility companies. Some consumers also shared that this was actually the first time they had login to their online account. Although, utility companies in Helsinki had completed the smart meter installation programs in Finland from late 2013 (Fortum 2015). This fact about lacking of consumer's engagement in the energy and smart-meter programs is aligned with study on the challenges of consumer engagement done by Intelligent Energy Europe (Koski et al. 2015). However, it can also imply the high trustability by the consumers to the utilities. Since, it should be noted that, the smart-metering programs provided by utilities companies in Finland allow consumers to access their personal account that is also linked to their bank account for auto monthly bill deduction. Consumers can access and check the information of their household consumption from annual, monthly to hourly consumption and the energy intensity as an example is showed in *Figure 16*.



Reading date	Product	Reading interval, day	Reading	Use, kWh
31.12.2013	siirtomaksu	31	901	47 kWh
30.11.2013	siirtomaksu	30	854	64 kWh
31.10.2013	siirtomaksu	31	790	82 kWh
30.09.2013	siirtomaksu	30	708	63 kWh
31.08.2013	siirtomaksu	31	645	39 kWh
31.07.2013	siirtomaksu	31	606	60 kWh
30.06.2013	siirtomaksu	30	546	54 kWh
31.05.2013	siirtomaksu	31	492	78 kWh
30.04.2013	siirtomaksu	30	414	74 kWh
31.03.2013	siirtomaksu	31	340	75 kWh
28.02.2013	siirtomaksu	28	265	78 kWh
31.01.2013	siirtomaksu	31	187	57 kWh

Figure 16 Interface of the online account shows consumption information

Survey results

The survey classifies all the surveyed buildings into 3 types of houses including detached house (one single building), terrace house (2-4 buildings in a group), and flat apartment house. These three types of houses are grouped in cluster according to its energy consumption as depicted in *Figure 17*. Furthermore, details of survey results are summarized in Appendix 6.

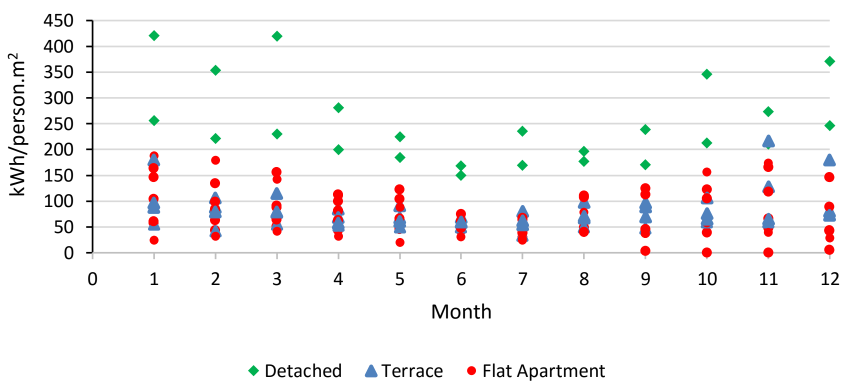


Figure 17 Grouping type of house and its energy consumption in Finland

As it is seen from *Figure 17*, the most dominant feature to the energy consumption is the floor area and the number of people in a house. This is no contradiction with common observation as indicated in the statistical data from previous section.

In terms of heating need, apart from the high energy heating demand due to cold climate, there is a particular addition with sauna usage in the winter and extra heating energy devices such as car engine heater and other internal heaters.

Additional freezer beside a fridge is also found in 4 families, which contribute to the raising energy consumption. The survey also asked the frequency of using electric dryer as a factor of high energy consumption devices. Different types of heating devices including devices to provide extra heating need are grouped according to their energy consumption as presented in *Figure 18*.

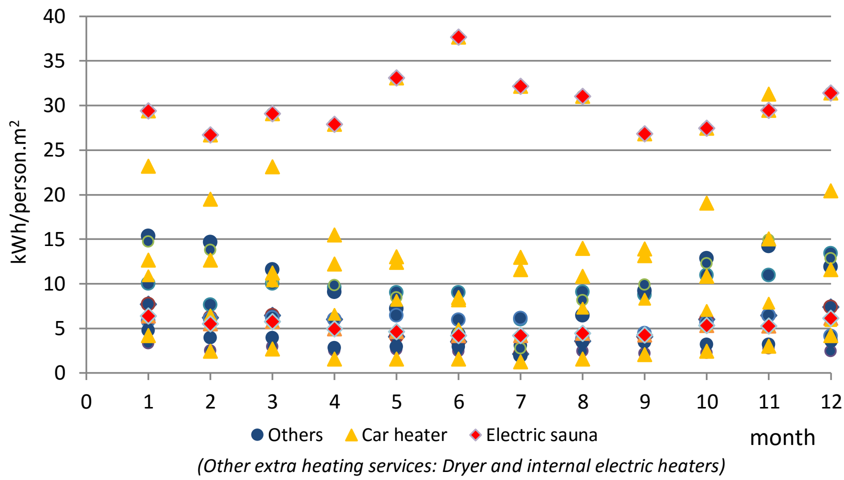


Figure 18 Electricity consumption based on type of heating device

It is seen from *Figure 18* that, there is no top runner of heating devices group that consume the largest energy. The highest energy consumption houses found are from detached houses due to larger floor area.

The overall electricity consumption obtained from the survey compared to statistics can be seen at *Figure 19,* in which detail of electricity consumption by the energy services and the appliances are presented.

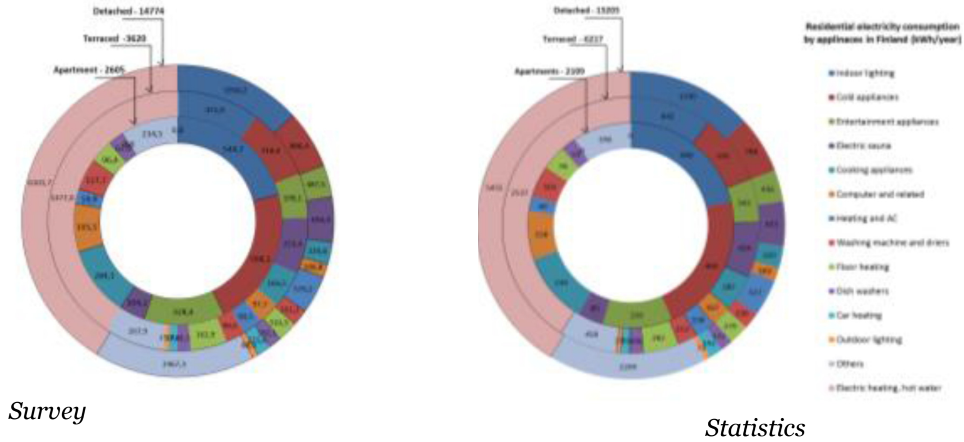


Figure 19 Comparison of Finland electricity consumption – national statistics and survey

As seen from *Figure 19* , the level of overall energy consumption by the survey is comparative to the statistics, except for the terraced house, since the survey appears to be lower than the values from the statistics. This can be explained by the nature of the large variation from house to house as explained in *section 3.1* . Another cause could be the fact that the surveyed families are considered high energy awareness consumers. Therefore, their energy saving effort is better than the average Finns families.

4.4.3 Renewable energy in Finns residential sector

Biomass and biomass boiler

The share of solid biomass in primary energy of Finland is 22% which is particularly high by compared to average 3% of IEA country (International Energy Agency 2013a). Biomass is one of the main heating renewable energy sources for residents in Finland, especially for sauna heating systems. Small scale biomass-based combined heat and power has been widely studied as an economically viable that recommended for buildings in Finland (Stephan & Stephan 2016, Salomón et al. 2011). Biomass can be from wood pallet and bio-waste.

Geothermal and heat pump

Since there are a number of residential buildings in Finland are not connected to district heating system, residential-scale heat pump is an alternative heating system to provide geothermal or ground source heat. In Finland, the installed numbers Heat pump alone (ground source or air source energy) have been increased since the last decade thanks to its cost effectiveness. Heat pump market already raise 30% in 2008 compared to 2007, and all of the consumers are from detached houses(Evens et al. 2010). Recent reports also showed the cost-effectiveness of ground source heat pump compared to district heat (VTT 2015).

Solar PV

Finland is not a solar-favor country, however, solar can still be utilized in Finland. Studies showed the average annual solar radiation (horizontal surface) is 940 kWh/m^2 in Helsinki. With an optimal direction, it could reach up to 1160 kWh/m^2 in Southern Finland (Pesola & Hagström 2011). Typical residential PV in range of 1–3 kW with a practical rule is 1 kW-installed capacity produces roughly 1000 kWh annual peak in Finland compared to 1300 – 1800 kWh in Portugal (Celik et al. 2009). In Finland, without subsidies, the disadvantage arises for solar PV by its uneconomical installation due to limited solar resource (Hirvonen et al. 2015, Zakeri et al. 2015). Solar PV, nonetheless, is not an input option for Finland covered in the context of this thesis.

4.5 From low-energy house to NZEH in Finland

As outlined in *section 4.4.1*, the energy consumption recorded by the smart meters in the author's survey of 2014 show comparative values to those derived from the 2010 statistics - *Figure 19* . However, the actually results obtained from the survey, in average are lower compared to the statistic values with the factor of 0.8, 0.6 and 0.7 for three types of house: apartment, terrace and detached house. Though this might not be fully representative for the Finns household in Helsinki, the results can partly show the electricity consumption reduction which reflects the improvement of energy efficiency measurement since 2010 to the late 2014. In addition, most of the surveyed households are from the faculty member and friends – who are relatively high awareness on energy saving.

It should keep in mind that, Finland is one of the leading countries in Europe for their continuously up-to-date energy efficiency policies and practices. To illustrate this improvement, *Figure 20* presents different scenarios of energy consumption reduction up to 2020 with BAU – business as usual scenario to BAT – best available technology for apartment, terrace and detached house.

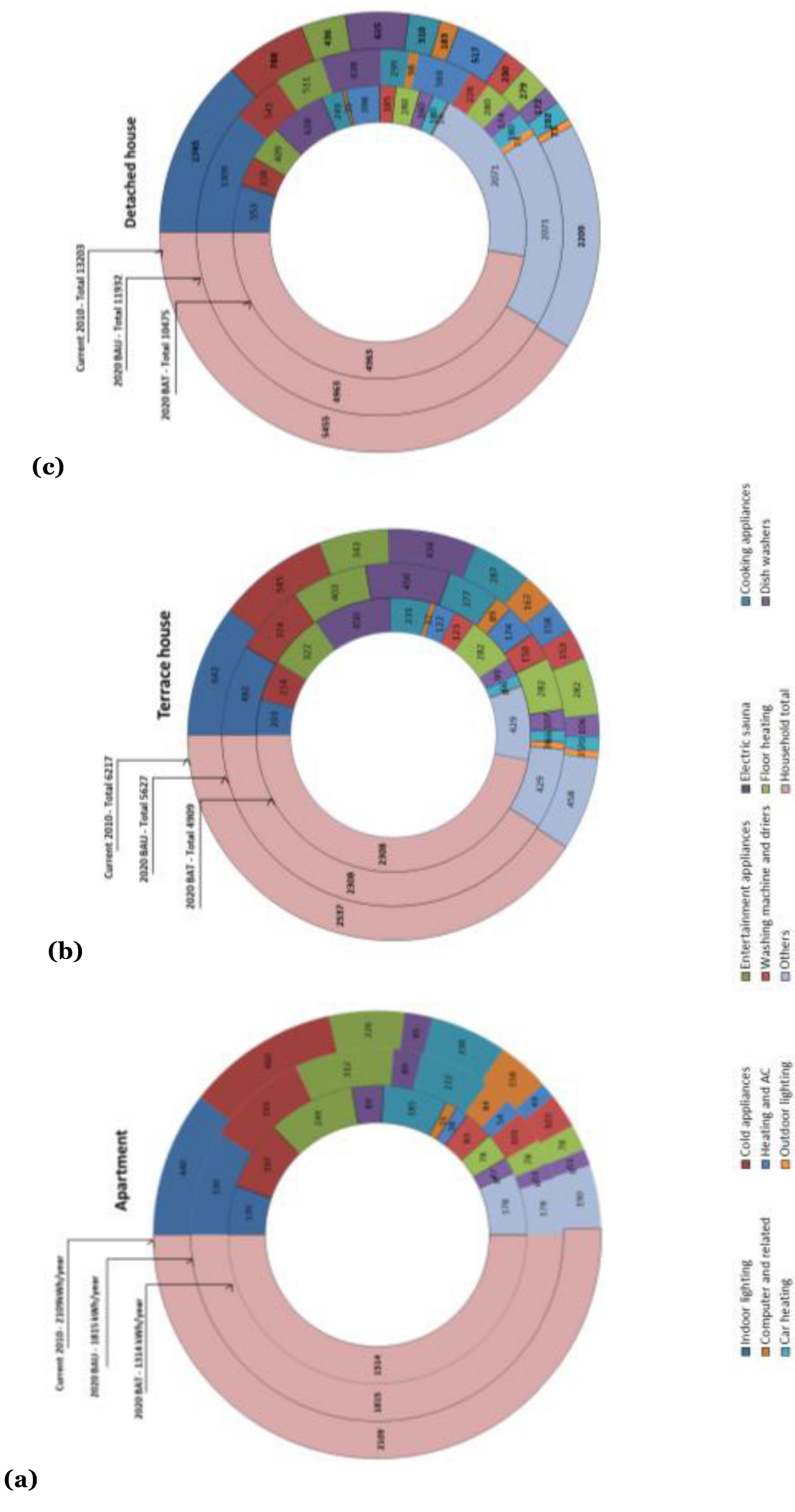


Figure 20 Scenarios for electricity consumption reduction in Finland
2010 Current consumption – 2020 BAU Business as usual – 2020 BAT Best available technologies

Figure 20 shows that the highest energy reductions are from lighting and cold appliances which show more than 3-fold reduction. Other appliances are foreseen as saturated energy-efficient innovation which is shown in small amount of energy reduction up to the best scenario. This reduction potential is aligned with what have been mentioned for Portugal and European wide. It is also seen that the heating demand will not either obtain a significant energy reduction in the 2020 scenarios. Nonetheless, the reduction for heating, as seen from *Figure 20,* can reach up to 10% by 2020.

As mentioned in *section 4.4.1*, the U-value required for building's construction has dropped significantly in Finland since last few decades. From the most updated Finland's building code in 2012, the U-value is 0.16 $W/m^2.K$ which mostly equal with passive house standard of 0.15 $W/m^2.K$. The roof U-value is even stricter than passive house German standards with 0.09 $W/m^2.K$ (MOE 2013). Therefore, NZEH case studies in Finland as introduced in *section 2.3* have mostly focused on the reconstruct energy system for space heating and water heating with more renewable energy but not the issue of improving U-value. Low U-values, enforced by the building code, have led to a significant heat-loss reduction and energy performance improvement (E-value) over the years. By the simulation for a reference house (ER 2012) of 4 people, 150 m² floor, the energy reductions by improvement of U-value are shown in *Figure 21* (Dao et al. 2016).

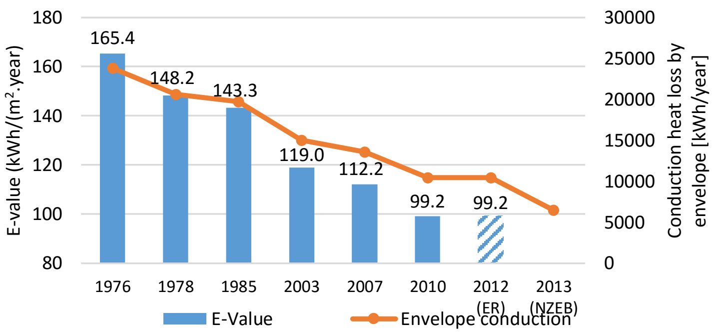


Figure 21 Improvement of U-value in the Finland's building code

As shown in *Figure 21,* E-value is used as an energy performance indicator by the building code. The lower E-value, the better energy performance the house achieves. It could be said that, the starting point for NZEH in Finland is basically different from Portugal in a way that Finns national regulations have met the high energy efficiency requirement of NZEH unlike the current situation facing in Portugal. Finland has updated regulations and enforcement to improve energy efficiency in both construction and household electricity devices. NZEH in Finland could be able to start with the design of 100% renewable energy. However, the regulation needs also to define concrete share of renewable energy from a proposed minimum level of 50%.

4.6 Concluding remarks

Chapter IV provides an analysis of residential energy service consumption in Portugal and Finland based on the national statistical analysis and direct consumer survey. The overview also gives the background of renewable energy resources and technologies could be applied in the NZEH which also be the reasoning for the model that further developed in the Chapter V.

Based on the above comparative analysis, national survey, national statistical data and the pilot smart meter project, results from the simulation in combination with NZEH cases studies in Europe, it can be laid out reference values of the energy services in NZEH in Portugal. The values are tabulated in the following *Table 21* and graphically depicted in *Figure 22* in comparison with Finland

Table 21 Reference benchmark for the energy service of NZEH in Portugal

Energy services	**kWh/m^2.year** (equal or below)
Space heating	7
Space cooling	1
Water heating	15
Lighting	4
Cooking and kitchen appliances	20
Media electrical appliances	4
Total	51

The low-energy consumption standards in Finns building code could be used as the reference value for NZEH in Finland. Stepwise evolvement of low-energy to NZEH in Finland can be summarized in the *Table **22*** and depicted in *Figure 22* , given space heating demand accounts for 61%.

Table 22 From low-energy to NZEH in Finland

	Apartment		**Terrace**		**Detached house**	
	kWh/year	kWh/m^2.year	kWh/year	kWh/m^2.year	kWh/year	kWh/m^2.year
Current	5408	83	10231	114	17194	132
2020	4654	72	9306	103	15510	120
BAT 2020	3369	52	8655	96	14247	109

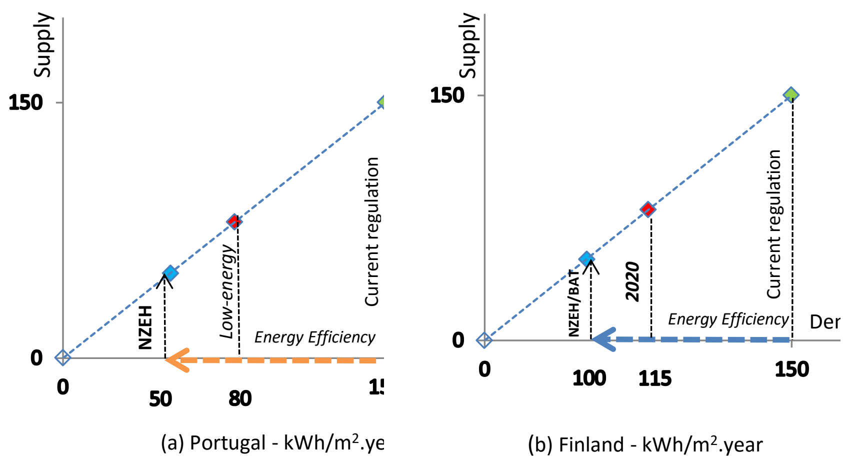


Figure 22 From low-energy to NZEH benchmark in (a) Portugal and (b) Finland

5 OPTIMIZATION OF ENERGY SYSTEM IN NET ZERO ENERGY HOUSE

5.1 Optimization of energy system for NZEH

The multi-objective optimization is discussed in this Chapter V, while the overview of the optimization methods is presented in Chapter II (literature review).

The optimization comprises of dual objective: The first objectives function is to minimize the energy-service demand. The second objectives function is to minimize the life cycle cost of energy technology.

In the end of this section the Chapter presents the results of the optimization using genetic algorithm.

5.1.1 Energy demand objective function

The energy demand input for NZEH optimization formulation based on the consideration as below:

- end-use energy or energy services demand calculated in final residential energy including heating, cooling, water heating, cooking, lighting and other media appliances
- embedded energy in the lifecycle construction, maintenance, renovation and demolition of the building are not included
- It is considered that the house was constructed with basic requirements to meet high efficiency as a low energy house or a NZEH. The energy demand calculation followed the updated Portuguese and Finns regulation on the thermal energy performance of the buildings. The detail adjustment and considered parameters used for both Portugal and Finland are presented in *Table 8* - Chapter III.

5.1.2 Life cycle cost objective function

Life cycle cost of energy technology

Life cycle cost - LCC indicates the sum of the costs over a lifetime for a given energy technology (Amer et al. 2013). In this work, LCC formulation is comprised of *investment cost, replacement cost, operation and maintenance* and is defined in equation [50 - 54].

$$LCC = I_0 + C_R + C_O + C_M \quad [50]$$

$$C_R = \frac{I_0}{(1+i)^{n/2}} \quad [51] \qquad C_O = ae \times t \times \left(C_{fuel} \times \frac{Q_{demand}}{\mu} + C_{base}\right) \quad [52] \qquad C_M = t \times C_{fuel} \times \frac{Q_{demand}}{\mu} \quad [53]$$

$$LCC = I_0 + C_R = \frac{I_0}{(1+i)^{n/2}} + ae \times t \times \left(C_{fuel} \times \frac{Q_{demand}}{\mu} + C_{base}\right) + t \times C_{fuel} \times \frac{Q_{demand}}{\mu} \quad [54]$$

Where

I_0	*Investment cost*
C_R	*Replacement cost*
$C_{O,M}$	*Operation and maintenance costs*
C_{fuel}	*Fuel price*
Q_{demand}	*Energy demand energy service in final energy*
i	*Real interest rate – 3% -* (IEA 2014)
n	*Life time of technology - 20 years*
t	*Analysis period – 30 years*
ae	*Discount factor - 2%, considered the energy-price escalation* (IEA 2014)
μ	*Energy efficiency of the technology*

Equation [51] [52] and [53] present respectively the *investment cost, replacement cost, operation and maintenance cost* without considering environmental disposal cost of the technologies. It is followed the principle of cost-optimal suggested by EDBP recast (European Union 2010). This cost-optimal principle of building's energy performance is based on the same principle have been studied by various authors (Boermans, Bettgenhäuser, et al. 2011, Zirngibl & François 2010, Aggerholm et al. 2011). The principle was also recent applied for studies on different European climate, which accounted for of energy cost and non-fuel operation and maintenance cost (Congedo et al. 2015).

It is worth noting that, the energy technology's operation and maintenance cost is calculated based on the energy demand required by the technology to provide a certain service, while previous studies focused on the LCC evaluation mostly from supply side. For example, a study evaluated the overall life cycle energy demand of residential buildings (Stephan & Stephan 2016) or another study focused on the embedded energy of the building or the LCC of the building's construction without including the technology and energy services (Hasan et al. 2008).

Another important point to mention is that, studies have also presented different approaches to LCC calculation based on cost optimal principle. For example studies by (Mohamed et al. 2015) (Hasan et al. 2008) indicated LCC formulation as presented in equation [55] *and* [56]

$$dLCC_{alternative} = LCC_{alternative} - LCC_{reference} \quad [55]$$

$$dLCC = dI_0 + dC_o + dC_R \quad [56]$$

From equation [55] and [56] we can see that the total LCC was not calculated but the differences produced by the alternative cases $dLCC_{alternative}$ compared to the reference cases $LCC_{reference}$ when an investment of a replacement and modification are made. This approach is mostly used for the replacement of construction component in the building. In this case, replacement cost was assumed constant and the LCC difference for operation cost was accounted by electricity price - e_p - and differences in electricity consumption (dE) is formulated in equation [57]:

$$dC_o = ae \times e_p \times dE \quad [57]$$

Furthermore, lifecycle costing method has been proved and widely applied in residential building by different approach but based on the same setting principle of net present value. The retrofitting case studies for Portugal were found based on cost-optimal EDPB 2010 recast method (S. Tadeu et al. 2015), the simulation cases for Finland (Takano et al. 2015) and the studies for Lebanon (Stephan & Stephan 2016). Those mentioned studies were all based on primary energy accounting.

The Input for LCC calculation in this study, as indicated in equation [54] are the following

- for the *investment cost,* consider the cost of the energy technology from market price of local suppliers;
- for *fuel price and base price,* consider the local market price and regulations and the base price is considered as the cost to connect to the network (electricity or heat)

Details of the cost considered in the work are listed in the *Appendix 7*.

5.1.3 Optimization alternatives

As mentioned in the *section 2.4.3*, linear programing has been used as one of the single objective optimization method. Linear programing optimization in this study is not able to give a set of optimal solutions. The program, however, was able to pre-select 22 technologies as summarized in *Table 23* out of 40 technologies input as indicated in *Appendix 7*. These are the pre-scanned technology options by the linear programing optimization before the next step of GA optimization. (The results of linear programing optimization are presented in SEB15 paper (Dao et al. 2015)).

Table 23 Technology input for optimization – applied for Portugal case

Energy Services	No	Technology	Efficiency	Investment cost (€)	Fuel costs (€/kWh)	Base price (€/year)
Water heating	1	Natural gas boiler	0.98	2295-2750	0.075	29.93
	2	Biomass boiler – storage tank	0.91	6226-7388	0.045	0
	3	Water heat pump	4.30 (**)	2250	0.15	72.42
	4	Electrical resistance heater	1.00	143-650	0.15	72.42
	5	Solar Circuit – storage tank	243 (*)	1990-3243	0	0
	6	Thermosyphon	217 (*)	1515-2370	0	0
Space heating	7	Air conditioner	3.90 (**)	790-1030	0.15	72.42
	8	Geothermal heat pump	4.66 (**)	15000	0.15	0
	9	Electric oil heater	1.00	90	0.15	72.42
	10	Wood furnace	0.70	904	0.045	0
Space cooling	11	Air conditioner	6.00 (**)	790	0.15	72.42
	12	Geothermal heat pump	4.66 (**)	15000	0.15	0
Space and water heating	13	Natural gas boiler - water radiators	0.85	2295-2750	0.07-0.08	29.93
	14	Natural gas Boiler - floor radiators	0.82	6226-7388	0.07-0.08	29.93
	15	Biomass Boiler - water radiator	0.79×0.87	6226-7388	0.048	0
	16	Biomass Boiler - floor radiator	0.79×0.84	6226-7388	0.048	0
	17	Solar Circuit - water radiators	264 (*)	1990-3243	0	0
	18	Solar Circuit - floor radiators	264 (*)	1990-3243	0	0
Space cooling and heating	19	Air conditioner	5.00(**)	790	0.15	72.42
	20	Ground source heat pump	4.66 (**)	15000	0.15	0
Other supply options	21	Photovoltaics	227 (*)	Depends on panel	0	0
	22	Wind turbine	Depends on hub height	Depends on hub height	0	0

(*) kWh/m², (**) COP: Coefficient of performance

5.1.4 Formulation

The mathematical model of two objective functions are given in the equation [58] and [59]

***Objective function* 1**: Minimize energy demand

$$y(1) = Q_{electricity} + \eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) - E_5 x(5) - E_6 x(6) + \eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \eta_{11} x(11) + \eta_{12} x(12) + \eta_{13} x(13) + \eta_{14} x(14) - E_{15} x(15) - E_{16} x(16) + \eta_{17} x(17) + \eta_{18} x(18) + \eta_{19} x(19) + \eta_{20} x(20) - E_{21} x(21) - \left(a_1 x(22)^6 + a_2 x(22)^5 + a_3 x(22)^4 + a_4 x(22)^3 + a_5 x(22)^2 + a_6 x(22)\right) +\ldots$$
$$+ \omega_{area}(x(5) + x(6) + x(15) + x(16) + x(21) - A_{roof})^2$$
$$+ \omega_{WH}(\eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) + E_5 x(5) + E_6 x(6) + \%_{wh}\eta_{11} x(11) + \%_{wh}\eta_{12} x(12) + \%_{wh}\eta_{13} x(13) + \%_{wh}\eta_{14} x(14) + \%_{wh}E_{15} x(15) + \%_{wh}E_{16} x(16) - Q_{wh})^2$$
$$+ \omega_{SH}(\eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \%_{sh}\eta_{11} x(11) + \%_{sh}\eta_{12} x(12) + \%_{sh}\eta_{13} x(13) + \%_{sh}\eta_{14} x(14) + \%_{sh}E_{15} x(15) + \%_{sh}E_{16} x(16) + \%_{shs}\eta_{19} x(19) + \%_{shs}\eta_{20} x(20) - Q_{sh})^2$$
$$+ \omega_{SC}(\eta_{17} x(17) + \eta_{18} x(18) + \%_{sc}\eta_{19} x(19) + \%_{sc}\eta_{20} x(20) - Q_{sc})^2 \quad [58]$$

***Objective function* 2**: Minimize lifecycle cost of technologies

$$y(2) = C_1 x(1) + C_2 x(2) + C_3 x(3) + C_4 x(4) + C_5 x(5) + C_6 x(6) + C_7 x(7) + C_8 x(8) + C_9 x(9) + C_{10} x(10) + C_{11} x(11) + C_{12} x(12) + C_{13} x(13) + C_{14} x(14) + C_{15} x(15) + C_{16} x(16) + C_{17} x(17) + C_{18} x(18) + C_{19} x(19) + C_{20} x(20) + C_{21} x(21) + 0.1575 x(22) + \cdots$$

$$+\omega_{area}(x(5) + x(6) + x(15) + x(16) + x(21) - A_{roof})^2 + \omega_{WH}(\eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) + E_5 x(5) + E_6 x(6) + \%_{wh}\eta_{11} x(11) + \%_{wh}\eta_{12} x(12) + \%_{wh}\eta_{13} x(13) + \%_{wh}\eta_{14} x(14) + \%_{wh}E_{15} x(15) + \%_{wh}E_{16} x(16) - Q_{wh})^2 + \omega_{SH}(\eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \%_{sh}\eta_{11} x(11) + \%_{sh}\eta_{12} x(12) + \%_{sh}\eta_{13} x(13) + \%_{sh}\eta_{14} x(14) + \%_{sh}E_{15} x(15) + \%_{sh}E_{16} x(16) + \%_{shs}\eta_{19} x(19) + \%_{shs}\eta_{20} x(20) - Q_{sh})^2 + \omega_{SC}(\eta_{17} x(17) + \eta_{18} x(18) + \%_{sc}\eta_{19} x(19) + \%_{sc}\eta_{20} x(20) - Q_{sc})^2 \quad [59]$$

Where

η_n	*Energy efficiency of the technology n*
n	*Number of technology*
a_k	*Adjusting coefficient k for wind production*
ω_{area}	*Penalty weight of roof area*
ω_{SC}	*Penalty weight of space cooling demand*
ω_{SH}	*Penalty weight of space heating demand*
ω_{WH}	*Penalty weight of water heating demand*
A_{roof}	*Roof area*
C_n	*LCC of technology n*
E_n	*Production of solar technologies (kWh/m^2)*
Q_{wh}	*Energy demand of water heating (kWh)*
Q_{sh}	*Energy demand of space heating (kWh)*
Q_{sc}	*Energy demand of space cooling (kWh)*

5.2 Optimization results

The outcome of optimization using genetic algorithm considering two objectives is able to give results in the form of Pareto front in assistance of decision making. Pareto front is a common analyze approach for multi-objective optimization in building design, which has been utilized by number of studies for building energy system using evolutionary optimization (Carlucci et al. 2015, Xu et al. 2015, Ascione et al. 2015, Liu et al. 2015).

The Pareto front gives out a set of energy technology options. In principle, the Pareto front curves are classified in two basic shapes: convex and non-convex curve. The convex curve is favorable for it gives larger decision making range in the trade-off of cost and demand. The convex curve results, in general, are better convergence of the optimizing programming. In this work, the Pareto front is divided into clusters which shall be discussed further in the following sections.

The simulation cases are performed for Portugal and Finland based on the constructed reference values presented in the previous Chapter III.

5.2.1 Portugal

Detail of simulation cases for Portugal is showed in *Table 24*

Table 24 Simulation cases for houses in Portugal

House type		**Apartment**	**Apartment**	**Detached house**
Number of people		2	3 - 4	2 - 4
Area	m²	75	95	120
Hot water	liter/day.person	40L	40L	40L
Heating and cooling room	m²	1	2 - 3	2 - 3
Heating area	m²	20	15-30	15-30
Lighting duration	hour/day	4	4	4
Lighting area	m²	28	45	45
Rooftop area	m²	5	20	20
Water heating	kWh/year	1282	1924 - 2850	1282 - 2850
Space cooling	kWh/year	31	61	61
Space heating	kWh/year	90	190	190
Media appliance + kitchen devices	kWh/year	1161	2333	2333
Total energy	kWh/year	2564	4508-5434	3866-5434

The results of the optimization given in the Pareto front are divided into different clusters of technology based on their LCC and energy consumption. The clusters are classified from A to D, in which each cluster comprises a set technology options. The set of optimal technology solution based on LCC and energy demand shall be analyzed in the flowing section and are presented in the legend. The results, clusters from A to D, are shown in *Figure 23* for different case studies.

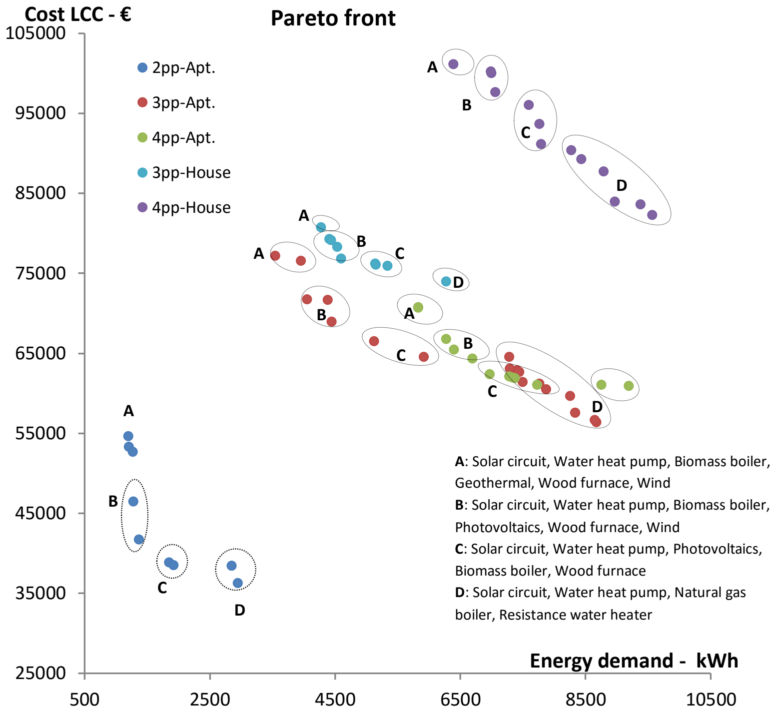


Figure 23 Pareto fronts of selected cases for Portugal

As shown in *Figure 23,* the most likely optimal options fall into the cluster B or C, which correspond to balancing the criteria of technology costing and energy demand. From *Figure 23*, it is possible to see that cluster D is the lowest cost option since it contains the fossil-fuel natural gas for space heating, heat pumps for cooling and solar thermal coupled with electric water heater for domestic hot water. Cluster C includes photovoltaics for electric appliances, wood furnace and biomass boiler for space heating. Cluster B includes mostly the same technologies of cluster C, together with the wind turbine. Cluster A is the highest cost option since it includes geothermal (ground-source) heat pump. The detail of the technology options in different clusters classified by the maximum share of renewable energy in each cluster are shown in *Table 25*

.

Table 25 Technology options and renewable energy share of different clusters

	2-pp Apart.	3-4 pp Apart.	2-4 pp house	SC	WHP	PV	BB	NGB	GHP	RWH	WT	TS	WF
	Max. RE	Max. RE	Max. RE										
A	80%	81%	100%	*	*		*		*		*		
B	83%	74%	100%	*	*	*	*				*		*
C	78%	71%	100%	*	*	*	*						*
D	78%	69%		*	*			*		*			

SC: Solar circuit
BB: Biomass boiler
WHP: Water heat pump
NGB: Natural gas boiler
PV: Photovoltaics
GHP: Ground-source heat pump
RWH: Resistance water heater
WT: Wind turbine
TS: Thermosyphon
WF: Wood furnace

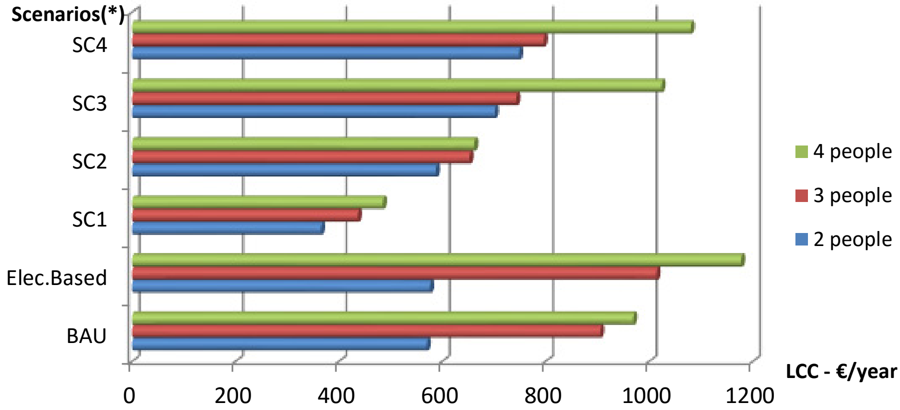
It is shown in *Table 25* that solar circuit - SC, water heat pump - WHP, PV and biomass boiler (BB) are the most favorable options that appear in 3 in 4 clusters.

These clusters of technology options provided by the Pareto front can be used to develop further scenario analysis. After identifying the most feasible technology options to meet with 100% RE supply, the following steps allow to choose what subsequent technologies can supply each energy service. The scenarios of different technologies shall be compared with the (1) the fossil-fuel BAU and (2) the electricity-based cost cases.

(1) The fossil-fuel BAU scenario is the current situation of using energy resources and the cost that is needed to provide the residential energy services. For Portugal case, natural gas provides energy for water heating and space heating and mixed energy sources of electricity from the grid provides energy for the rest of the energy service.

(2) The electricity-based cost assumes that all residential energy demand is supplied by electricity and accounted using the current electricity price of the national grid.

Different scenarios for a detached house compared to fossil-fuel BAU and electricity-based cost are presented in *Figure 24*. All the scenarios from SC1 – SC4 are 100% RE with different technology options without using batter as an energy storage for PV.



(*)Scenarios

***SC1**: Water heat pump - PV 8m^2- Wood furnace*
***SC2**: Biomass – PV 6m^2 – Wood furnace*
***SC3:** Solar circuit 5m^2 - PV 7 m^2*
***SC4:** Solar circuit 5m^2 - PV 6 m^2 – Wood furnace*
***BAU**: Fossil fuel business as usual*
***Elec. Based**: based on cost of electricity*

Figure 24 LCC scenarios with different technology for a detached house Portugal (without battery for PV)

It can be seen from *Figure 24*, LCC increases with larger number of people per house. Scenarios from SC1 – SC4 also show water heating service accounts for the highest LCC. It is reminded that water heating accounts for largest demand in Portuguese house energy service. Results from *Figure 24* also show SC1 as the lowest scenarios which comprise of water heat pump, PV - 8m^2 and wood furnace. Detail of the lowest LCC scenarios with according the technology and energy service is found in *Table 26* and depicted in *Figure 25*.

Table 26 Comparison of lowest LCC in different technology options

LCC (€/year)	**2 people**	**3 people**		**4 people**
Water heating	*water heat pump*	*water heat pump*		*water heat pump*
	199	222		225
Space cooling	*AC-PV*	*AC-PV*	*geothermal*	*AC-PV*
	59	60	624	63
Space heating	*wood furnace*	*wood furnace*	*geothermal*	*wood furnace*
	58	64	263	67
Media, cooking, lighting	50	91		100
PV battery	**533**	**733**	**667**	**933**
Panel area needed [m^2]	8	11	10	14

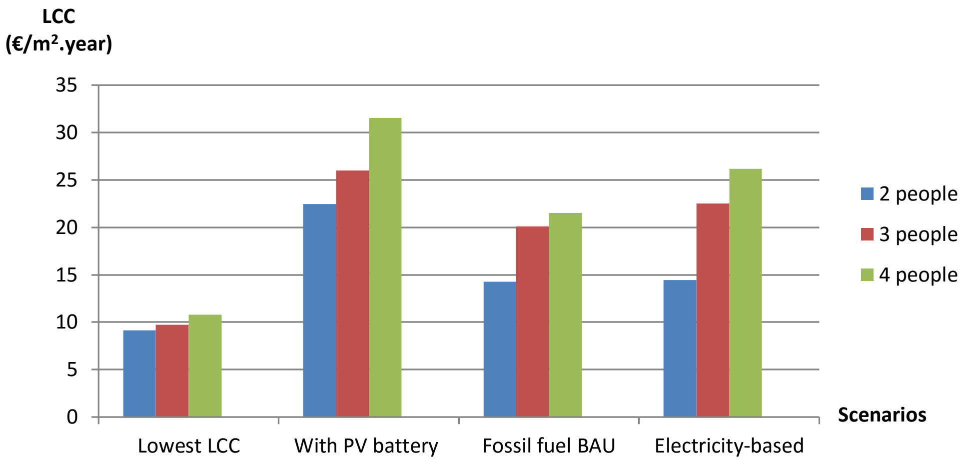


Figure 25 LCC of scenario with PV storage compared with other scenarios

From *Table 26* it is noticeable that in all cases of 2-4 people house, the lowest LCC is 54% of fossil-fuel BAU cost and 50% compared to the electricity-base cost (except when geothermal heat pump is included – taken the case of 3-people house). It is also seen the high cost of battery alone when it is used as the energy storage for PV. In addition, results from *Figure 25* find in all case that adding battery for PV raise a considerable cost the whole energy system. This suggests that the choice of technologies to meet the NZEH concept, with higher initial investment, can hardly be more economically interest to the end users. The following discussion will provide more detail about the high cost when adding battery as the PV storage and when utilizing geothermal in heat pump.

Battery as energy storage for PV

Additional battery for PV increases the energy system's cost by 1.7 times as compared to fossil-fuel BAU and it is 2.4 times higher than the lowest LCC case which consists of water heat pump, PV and wood furnace. The comparison showed in *Figure 25* also indicates that, in the lowest LCC case, larger number of people in the house, the more cost-investment benefit in terms of per capita unit of LCC energy technology.

Ground-source heat pump and mini wind turbine

From *Table 26,* it is noticed that, the geothermal ground-source heat pump and mini-wind turbine are the possible options for apartment building as the optimization selected. This is due to the highest cost of LCC cases resulted when the options include geothermal or mini-wind turbine for the detached house, taking 3-people house example as seen in *Table 26* (in which geothermal or mini-wind to supply energy for space cooling and space heating, compared to house that uses PV to provide electricity for AC space cooling and wood furnace for space heating).

It is clear that LCC is highly increased if geothermal heat pump is used. In this case, the lowest LCC including geothermal is 1200 €/year and 1267 €/year with mini-wind turbine. These cases show the less advantage of geothermal and mini-wind compared to the case without the two technologies whose LCC costs 437 €/year in choosing the option of water heat pump for hot water, wood furnace for heating and 11 m² PV to provide electricity. It is understandable for the less advantage of ground-source heat pump system because of its high initial investment cost.

5.2.2 Finland

The simulation cases for apartment buildings, terrace house and detached house in Finland are summarized in *Table 27*.

Table 27 Simulation cases for residential in Finland

House type		**Apartment**	**Apartment**	**Terrace - House**
Number of people		2	3	2-4
Area	m²	65	90	120-140
Hot water	l/day.person	40	40	40
Heating area	m²	60	75	120-140
Lighting duration	hour/day	4	4	4
Lighting area	m²	30	35	60-70
Water heating	kWh/year	1526	2290	1526 - 3053
Space heating	kWh/year	3607	6426	6426 -7322
Media appliance + kitchen devices	kWh/year	1161	2333	2333
Annual demand	kWh/year	6295	8949	9114 - 12709
Annual intensity	kWh/m².year	97	99	76 - 91

Following the same systematic approach as with the case of Portugal, Pareto fronts of different scenario are obtained for Finland and graphically depicted in *Figure 26*.

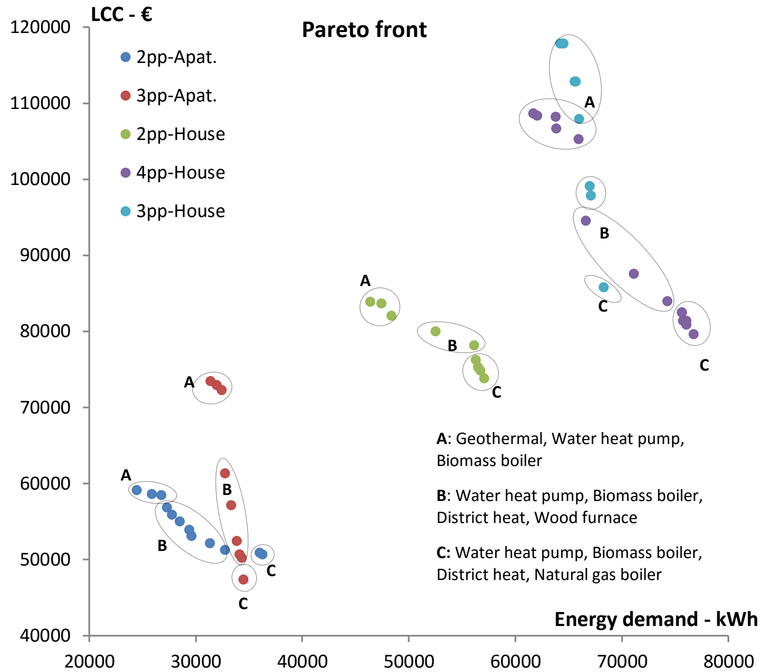


Figure 26 Pareto fronts of selected cases for Finland

As seen from *Figure 26* for Finland, the technology clusters are divided in 3 from A to C, instead of 4 as in Portugal case. The reason is that, as mentioned, PV and mini-wind turbine are not considered for Finland's case and district heat is taken in place.

Nonetheless the same pattern appears in the options of which geothermal heat pump is the highest cost option in all cases. The same pattern also found for the detached houses as larger number of people in house would require higher LCC is.

Water heat pump, biomass boiler and district heat are the most favorable options. The lowest-cost option is due to the selection of natural gas boiler which is also found similar to Portugal. The 100% renewable energy options with their lowest LCC compared to other scenarios of fossil fuel BAU and electricity-based cost are shown in *Figure 27*. The case of 3-people house with geothermal heat pump option is taken as a case to compare with other cases without geothermal is also presented in *Figure 27*. The 100% renewable energy options with their lowest LCC compared to other scenarios of fossil fuel BAU and electricity-based cost are also tabulated in Table 27

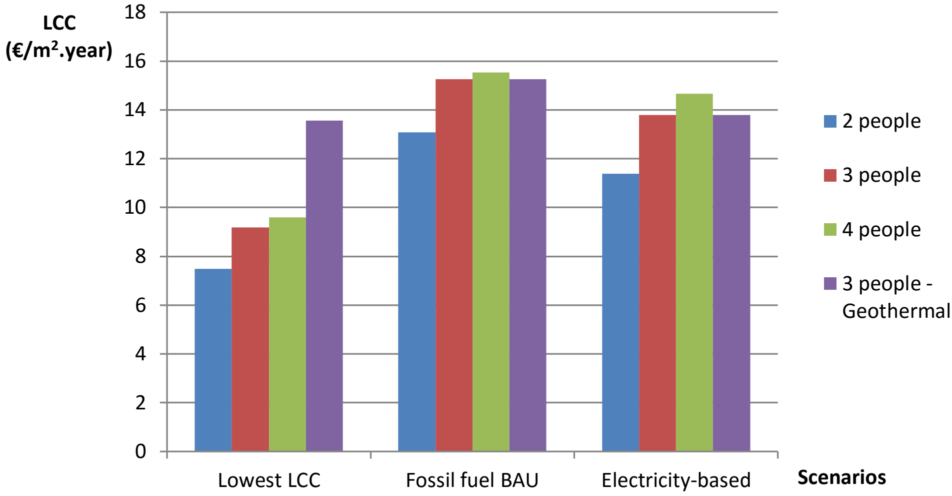


Figure 27 Different LCC scenarios for detached houses in Finland

As seen from *Table 28,* in Finland case, the NZEH could reach 100% RE only when considering that the district heating is from RE resource such as biomass waste.

Table 28 Lowest LCC compared with different scenarios in Finland

(€/year)	**2 people**	**3 people**		**4 people**
Space heating	District heat/biowaste	District heat/biowaste	Geothermal	District heat/biowaste
	482,38	549,09	1118,4	549,09
Water heating	Water heat pump			
	240,86	295,15		349.96
Media, cooking, lighting	Electricity			
	174,14	350,03		350,03
Lowest LCC	897,38	1194,26	1763,574	1248,57
BAU Fossil fuel	1570,60	1983,65		2018,92
Electricity based	1367,16	1791,93		1906,44

The high energy demand of space heating certainly affects the high investment cost. Space heating requires highest energy demand in Finland which accounts for highest LCC investment for energy supply. While in Portugal, the largest energy demand and the highest LCC come from water heating. The analysis shows that the lowest alternative LCC case, including water heat pump and district heat and biomass boiler, is cost competitive with the fossil-fuel BAU and electricity-based case. However, this cost competitiveness is only feasible for detached house. In all detached houses, the 100% renewable energy district-heat scenario has LCC 40% lower than fossil-fuel BAU and electricity-based cost. It is reminded that in the case of fossil fuel BAU natural gas is used for water heating, and non-renewable electricity is used for space heating.

For Finland apartment buildings, the LCC of alternative options do not change compared to the BAU cost since the main space heating source is also from district heat and electricity. From *Figure 27,* it is clear that unlike Portugal, geothermal heat pump option is cost competitive for detached houses in Finland. When district heat is replaced by geothermal heat pump, total LCC will increase 1.5 times and when biomass boiler is replaced, the LCC increases 1.3 times.

5.3 Discussion

This section shall further discuss each technology cluster and its economical feasibility to provide energy service in considering 100% renewable energy scenarios.

5.3.1 Portugal

As identified in *section 5.2* for households in Portugal, the technologies include solar circuit, water heat pump, PV, and biomass boiler are the most favorable options that appear in all clusters except cluster D.

Space heating and cooling

In all cases, the results show that wood furnace can reach the lowest LCC option for space heating in which wood furnace cost is 15% of biomass boiler cost. It is, however, needed to consider the fact that wood furnace is not always feasible in all houses as the apartment building. For that reason, for either detached house or apartment building, the biomass boiler used for combination of water heating and space heating should be utilized. The option of biomass boiler is cost benefit since the space heating only requires a maximum 16 weeks or 4 months in Portugal. In reality, the heating duration is needed only 12 weeks or less which vary from year to year. In terms of fuel cost-effectiveness, this result is aligned with other study for Lisbon and other Iberian cities that showed the use of wood pallets can reach 70% of cost-saving compared to natural gas (Carpio et al. 2013). However, this study did not specify the technology cost. Furthermore, within Portugal, research showed the potential and economic viability of biomass residues for small-scale heating (Fernandes & Costa 2010). The biomass boiler option for both space heating and water heating is also found in case studies at Northern Portugal residential that indicate the most cost-effective renovation solution is small biomass boiler (Ferreira, Almeida & Rodrigues 2014). It is worth noting that biomass boiler technologies have been long proved of a maturity energy efficiency technology and environmental quality. As studies shown, European market, in general, still needs better economic incentives (Verma et al. 2009).

In fact, the energy-system cost is added less than 10% when biomass boiler is used for combined water and space heating. The optimization results also suggest using AC with PV-electricity supplied. Though, the AC-PV is not the lowest cost scenario, the option can be the solution when PV is deployed for both space cooling and services that need electricity such as media, lighting and kitchen devices. In that case, wood furnace can be utilized space heating backup option in the winter time when solar PV does not supply enough energy.

Water heating

Water heating is the largest energy demand in residential Portugal which accounts for 33% listed by national statistic (Estatisticas oficiais 2010) or up to and 40% by actual monitoring (Dao et al. 2014). The optimization results also indicate LCC of water heating technology accounts for highest cost by an average 55% of total LCC of the energy-system.

As showed in *Table 26*, water heat pump appears as the most economical option for water heating service in all apartment building and detached house cases in Portugal. In order to supply the same amount of energy demand, the cost of water heat pump (included PV-assisted for electricity) is equal 50% of biomass-boiler cost and is only 35% of solar-circuit cost.

Biomass boiler and solar circuit using solar thermal are also listed as feasible options for water heating. The solar circuit cost is 1.5 times higher than biomass boiler. The disadvantage of solar circuit is the needs for available rooftop area which consequently become more feasible for detached houses. The optimization results show the minimum panel is 5 m^2 for 2-people house and the maximum area is 12m^2 for 4-people house. Recent studies also showed solar circuit using solar thermal has been increased in numbers, cost saving and CO_2 reduction, particularly for Mediterranean climate such as in Greece (Martinopoulos & Tsalikis 2014).

Media, lighting and cooking

Solar PV and wind turbine are two basic options to provide electricity demand by the media devices, lighting and other cooking devices. From the analysis, solar PV is the most cost-feasible option. The cost of PV panel alone (inverter included) accounts for 7-13% of the whole system without the battery as an energy storage. Studies on a renovation measure for Portugal´s building also indicated adding up PV panel does not affect economical optimal solution in the renovation options (Ferreira, Almeida, Rodrigues, et al. 2014). In our cases, the most costly portion appears when the PV battery is used as an energy storage which would add up to the system cost from minimum of 1.7 times. It is also supported by other studies on the high cost of energy storage which suggest that the market is still far from mature concerning the heavy portion of PV storage (Carvalho et al. 2011).

PV with battery as the energy storage

In this study, the LCC of the PV panel is calculated separately from the cost of battery used as energy storage. On one hand, it should be emphasized that the needs of electricity storage for NZEH is crucial. Adding up to system cost is the main constraint of the storage but it mostly impossible for NZEH without the energy storage support that also found by other study (Maclay et al. 2011). On the other hand, in reality, appears more successful implementation case of energy storage for NZEH. Recent studies showed sizing the storage system for residential is not a most difficult obstacle to overcome either in cold or warm climate (Leadbetter & Swan 2012) (Rosen 2015). Though it is not considered in this thesis, it is needed more studies on the impact of the grid-connection by the residential-scale energy storage for Portugal in both cost and grid interaction by relevant usage of storage (Santos et al. 2014). Other studies proved the needs of fuel-cell storage, for example, in Japan (Hamada et al. 2011).

In addition, more studies have showed the positive cost-effective of adding PV storage such as a study concluded that PV-based heat pump is cost-competitive without public subsidies based on the net present value analysis in Turin, Italy (Ghafoor & Fracastoro 2015). In fact the solar radiation in Turin is lower than in Lisbon. Another study in Spain resulted in positive lifecycle cost of energy - LCOE of 0.1301 and 0.141 for PV energy storage (Talavera et al. 2011). In Portugal, the extension of PV mini-grid by its cost optimal could be a good start for NZEH at community level in Portugal.

A worth-noting study done for residential buildings in Belgium indicated that PV-battery is already cost-effective without subsidies (Mulder et al. 2013). This study was carried out in a resident of average 4500 kWh energy consumption per year (which is compatible with detached house in Portugal) and the battery cost was compared with electricity price. In addition, study showed that electricity price needs to rise up to 4% for quicker attraction of resident PV-battery and investment return. It is also agreed by the IRENA study on the fast decreasing of PV installation cost at residential level from 3.8 – 5.8 USD/W in 2011 to 2.9 – 4.1 USD/W in 2015 (International Renewable Energy Agency 2014). Another positive picture clearly showed, in German market, a system's profitability when including PV energy storage (Naumann et al. 2015). The study used Monte Carlo simulation for levelized cost of energy storage.

Total LCC of energy system

As shall be seen in *Table 29* in the comparison of different LCC scenarios, the lowest LCC cases, without PV energy storage, is equal to 40% the cost of fossil-fuel BAU and to 50% cost of electricity-based. The adding-up cost arises when PV storage is included. In that case, total LCC (including PV storage) is higher than the fossil-fuel BAU 1.5 times and 1.3 times to the electricity-based cost.

It is reminded that in our study, LCC analysis is included fuel price and the base price for network connection. Therefore, it is reasonable to compare these

LCC costs, including PV storage, to the actual residential expense on energy as shown in *Figure 28* - the household energy expense for selected European countries.

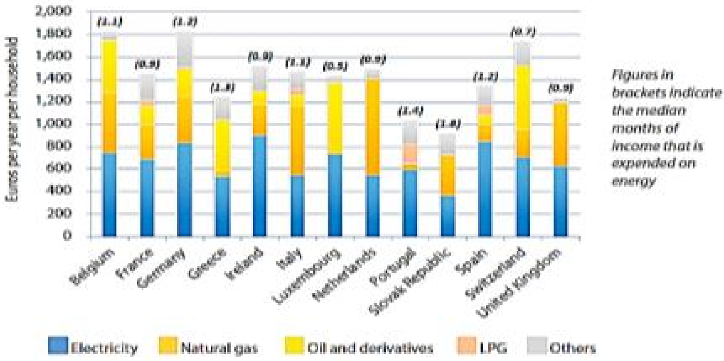


Figure 28 Annual European household expense on energy (BPIE 2013)

As seen from *Figure 28*, the expense for Portuguese residential on energy is average 1100 € per year which is higher than our calculation of average from 815 - 923 € per year. If compared to annual household energy expense 1100 € per year, the LCC with a PV storage for 2-people family, which is 899 € per year, is actually lower that expense. In our study, the expense only increases with an amount of 70 € per year in 3-people family, and for 4-people family. The most costly option with geothermal ground-source heat pump will increase the expense to 70% or 767 € per year. Summary of LCC comparison with the energy expense of a reference house in Portugal is shown in *Table 29*.

Table 29 Comparison of different LCC scenarios in Portugal

(€ per year)	2pp	3pp	4pp	3pp-with geothermal
LCC of PV without battery	365	437	485.6	1200
LCC of battery for PV	533	733	933	667
LCC of PV with battery	899	1170	1419	1867
LCC of Fossil fuel BAU	571	905.6	969	720
LCC of Electricity-based cost	577	1014.4	1178	1014
Roof area needed (m^2)	8	11	14	10
Compared to reference non-NZEH house 108 m² – 3 pp: 6000 – 8000 kWh/year				
Fossil fuel BAU cost	1150 - 1480			
Electricity-based cost	1350 - 1800			
Current average annual expense on energy	1100			

Table 28 also shows the cost-competitiveness of NZEH utilizing battery as energy storage with the electric price base case. In addition, Portugal is among the countries having highest electricity price and gas in Europe, which is higher than UK, Finland, Sweden (Eurostat 2015a). Increasing trend of both electricity demand and electricity price in Portugal is also foreseen (Gouveia et al. 2012). It is also needed considering that the cost of energy storage technology have been decreasing rapidly especially solar PV storage system

and geothermal heat pump for the market-driven both centralized and distributed domestic consumption as studies showed (Agnew & Dargusch 2015) (Internaltional Energy Agency 2014a).

Therefore, it is positively foreseen the investment of energy storage for NZEH is steadily cost-competitive with the price trending of the current fossil-based fuel.

5.3.2 Finland

In Finland, the largest energy consumption in residential buildings are space heating and water heating which also demand a considerably large share of renewable energy in order to reach NZEH.

Space heating

As district heat is feasible for apartment building and terrace house in Finland with 97% of apartment building is already connected to district heat network. Therefore, as mentioned, in order to get 100% renewable energy for space heating in apartment building and terrace, the district-heat fuel must be from renewable resources such as biomass waste. This implementation has been increasingly more feasible in Finland. The renewable energy share in the electricity and heat accounts for 46% of all renewable energy in which half of this amount comes from wood (Statistics Finland 2015b). Moreover, the utility companies in Finland, especially in Helsinki are now transferring to higher penetration of wood pallet district heat (Helen Helsinki 2015), it could be more feasible with the support of new biomass fast pyrolysis in combined heat and power as studies showed (Kohl et al. 2014). Recent study also pointed out that with current energy demand of all sector, the renewable energy share in Finland could reach to 70% in the energy mix (Zakeri et al. 2015). This would also help to increase higher percentage of renewables share in the district heat.

For detached houses, geothermal heat pump appears to be cost-effective beside biomass boiler or district heat option. This provides more renewable energy option for space heating in Finland. Previous studies also proved positive cost-effective of the geothermal heat pump system in Europe using LCC method (Keçebaş et al. 2013). In addition, Finland is in the world’s top five of installed geothermal capacity in 2011 (J. W. Lund et al. 2011). The fast growing installation of geothermal in Finland would certainly increase the share of renewable energy in space heating while the heating demand have been kept lower or even decreasing. This decreasing trend of heating demand is indicated by the findings that annual energy demand space heating and ventilation supply in Finland will decrease by 20–40% by 2100, as study showed (Jylhä et al. 2015). It is also agreed by comparative studies in Italy and Finland that it needs more market instrument and support policies for better geothermal heat pump penetration in the small to medium residential in Europe (Giambastiani et al. 2014). Meanwhile others suggested that the capital cost of geothermal heat pump in warmer climate in Europe could be reduced through the implementation of smaller units though the author did not layout a specific cost (Self et al. 2013).

Water heating

From our study, heat pump is the best cost-effective option for water heating compared to biomass boiler. This is aligned with the NZEH case studies in Finland indicated that heat pump is cost-efficient than district heating (Häkämies et al. 2015, Sulpu 2015). For both water heating and space heating, recent LCC-based studies also listed ground source heat pump with PV integrated is the most economical viable for district energy system compared to heat pump alone (Ristimäki et al. 2013). Studies also confirmed a leading heat pump market of Finland among European countries with the second highest output and third rank in number of installation thanks to its competitive pricing mechanism with gas fire (Hannon 2015).

More studies appeared to support the increasing number of water heat pump. For example, a study concluded that recharging strategy of excess renewable electricity to a hot water storage tank by one-day volume was technically and economically more effective than using electrical battery in reducing annual mismatch (Cao et al. 2013). In our study, LCC of water heat pump system for detached house is equal 50% LCC of biomass boiler. The issue needs to resolve is how to match the heat pump electricity demand with the solar assisted or wind assisted for the pump.

Media devices and other services

It is shown that the construction as well as energy performance in residential building Finland have obtained much better energy efficiency compared to other European countries including Portugal (Pikas et al. 2015). Media devices, cooking and other services accounts for about 20% of total residential energy needs. Therefore, it is crucial for Finland to transfer electricity production with higher penetration of renewable energy. Studies even further show the possibility for air source heat pump to be applied for energy saving lamps lighting (Evens et al. 2010).

5.4 Concluding remarks

The proposed optimization method is able to identify the sets of technology with optimal cost considering overall LCC and energy demand. Different scenarios allow choosing the cost - feasible technology with its renewable energy option, and comparing them with fossil-fuel based price and current electricity price. The optimization results are able to classify and cluster the technology options with the cost to supply energy in NZEH in Portugal and Finland with the following technology sets:

Portugal

- Water heat pump for water heating
- Biomass boiler for water heating and space heating with wood furnace backup

- PV should be applicable to provide electricity demand of media, cooking, lighting but needs pricing mechanism for energy storage in the PV system is needed
- Geothermal heat pump remains the least cost-effective option compared to water heat pump and biomass boiler for space heating

Finland

- Water heat pump should be used for water heating in detached house, further implementation would be the integration of PV or wind assisted to the heat pump
- District heat from renewable energy resource is adequate for water heating and space heating for apartment building
- Geothermal heat pump is cost-effective for space heating

To conclude, it is acknowledged the limitations of the study on how to fully address the load mismatching and sensitivity analysis which is recommended for further study. Other studies have also pointed out with the case in Italy and Netherlands case that summer load profiles will be affected by PV and electric vehicles (Dagdougui et al. 2012). And the winter profiles will be determined by the penetration levels of heat pumps, CHP units and electric vehicles (Asare-Bediako et al. 2014). Further sensitivity analysis of the demand for residential energy services in the integration of PV storage is significant (Wilkerson et al. 2013). This is one of the principal to compensate the mismatch of the demand and supply as mentioned in the literatures such as the mismatch compensation factor (H. Lund et al. 2011). As study agreed the sensitivity analysis of the energy services demand is necessary due to the fact that people keep wanting for more indoor thermal comfort. This sensitivity analysis is significant to evaluate and adjust the reachable goal for NZEH. Other authors emphasized on the high variation of residential consumption that it is not simple to fully identify (Firth et al. 2008). It is also needed considering the dynamic of all the electric appliances by introducing more valid threshold of each energy service and storage adjustment (Wood & Newborough 2003).

6 POLICY RECOMMENDATIONS AND CONCLUSIONS

6.1 Main findings

This thesis addresses the research questions on 1 – What types of energy services are applicable to NZEH? 2 – What energy service reference values are applicable to NZEH in Portugal and Finland? 3 - What is life cycle cost-optimal of energy system for NZEH? The following findings are concluded:

A need for an energy-service framework of NZEH

Recent literature has showed from a number of studies on NZEH that there is a gap on defining a framework which can clearly layout the implementation pathway for energy demand in NZEH. This thesis finds this missing link from the studies of Portugal and Finland cases. The thesis argues that NZEH needs an energy-service framework and needs to define a stepwise benchmark – from overall services to each energy service - to reach a mass NZEH implementation in Europe based on their climate and socioeconomic conditions. The thesis' research contributes to this by developing an energy services framework.

For Portugal, the past regulations on energy performance in residential building have not precisely reflected actual energy consumption. The actual residential energy consumption is lower than the estimated calculation by the Portuguese regulations and its national statistics – as presented in Chapter III. This mismatch has made NZEH more seemingly impractical for residential building on how to bring down the energy consumption to the low-energy level of NZEH.

For Finland, Finns regulations on residential energy performance have closely followed the up-to-date European regulations on high energy efficiency. The Finnish NZEH pathway is certainly different from Portuguese approach by their variation of climatic and socio-economics. NZEH in Finland could be able to start with the design of 100% renewable energy house. However, the Finns regulations also need to define concrete share of renewable energy which should be 50% as the minimum.

Reference values of the energy services for NZEH

As discussed, the thesis also draws the pathway and reference values as the energy service benchmark for NZEH in Portugal and Finland. The values are presented in Chapter IV.

Life-cycle cost optimal of energy technologies for NZEH

The results of optimization program using genetic algorithm show the life-cycle cost optimal of energy technologies by different technology options which can be applied to NZEH in Portugal and in Finland. Different life-cycle cost optimal scenarios are compared with fossil fuel business as usual (BAU) scenarios and the electricity-based cost. The fossil-fuel BAU scenario is the current using of current energy resources and their costs that needs to provide for the residential energy service. The electricity-based cost assumes that all residential energy demand is supplied by electricity and accounted by current electricity price of the national grid. The sets of technologies are also drawn up as listed in *section 5.5*.

6.2 Implications and recommendations

To stronger facilitate and mobilize the mass implementation of NZEH, the following implications and recommendations are drawn up.

Focus on end-use from energy service demand

European wide, national regulations on residential energy use needs to specify the residential energy services including heating, cooling, water heating, lighting, and cooking and kitchen appliances. This specification can also play a critical role for energy technology developments focusing on end-use as well as building up the users' consumption consciousness. On the public policies that need to focus on residential customer is also supported by Pellegrino et al. (2015). The public policies should also include the energy-efficiency service to be provided for faster adoption of NZEH as a prerequisite. Including of energy efficiency service to the policy is also supported by other study (Labanca et al. 2015).

Invest on energy storage technology at residential scale

Technology is no longer the main barrier for the penetration of renewable energy into the NZEH. A deep leapfrog in the energy storage technology at residential scale is required. The development need to further focus on solar PV, residential-scale energy storage and reliable smart-metering application. Particularly, non-cost diffusion of batteries and storage is required to ensure economic viability, suggested by Lang et al. (2016). These developments can support to create a robust environment for microgeneration to apply in the residential scale, the development that has been experienced a positive exponential growth over decades, as studies showed (Herrando & Markides 2016).

Provide cross-sector training and knowledge dissemination on NZEH

It is clear that the building and construction sector is an extremely multiple stakeholder sector with various connections involved in the energy consumption process. The actors and connection could be named from companies, authorities to the final end use called tenants or users (Antink et al. 2014). Therefore, the solutions are undoubtedly required multiple aspects and innovative approaches.

In recent years, common challenges in building sector associated with NZEH implementation have been identified among all European countries. As mentioned in previous discussion, the emphasis on construction alone need to be revised, for example U-values and materials have been focused more than the energy performance quality by consumer or users' interaction (Emta et al. 2008). This focus has led to the fact that stakeholders including owners, investors, constructors concern only about the initial investment cost but not the total life-cycle energy performance of the house. This has also led to a challenge of market formation for high energy efficiency technology. Another challenge is the lack of access to resources, information and knowledge in building sector from multidisciplinary approach. Therefore, it is needed to fill the knowledge and skill gap among various-disciplinary (Brunsgaard et al. 2014). Training and knowledge dissemination through cross sectors are to equip multi-stakeholders with the knowhow while working on the customers' side. The main aims is to encourage the willingness of the residential users switching to a more residential sustainable energy systems, also emphasized by other authors (Michelsen & Madlener 2016).

Promote innovative business model on NZEH and retrofitting buildings

To obtain faster adoption of NZEH market, in addition to high technologies and high energy efficiency appliances development, better market-orientation incentive mechanism from public policies, together with innovative business models are needed. NZEH can be achieved through a better choice of energy system. The net energy balance can be reached economically through more robust incentive mechanism for investment of residential-scale energy technologies. For example, studies by pointed out that integrated design, and performance based design helps to address financial, technological and cultural challenges and to extend the market (Zhao & Pan 2015). It is also proved that the more innovative business models that are put into practice the less risk for public policies in the new growth phase of renewable energy market – the experiences learned from European countries such as Spain, Germany, and Belgium (De Boeck et al. 2016).

Policy recommendations

Policymaking: A more stimulating incentive mechanism is needed for faster renewable penetration into building and construction sector focusing on residential end-use to activate the market formation. It also requires from public policy approach that more practical guidelines on NZEH design should be put on place. These guidelines can enable more efforts and solutions to obtain energy performance targets with cost-effective manner design. Public policies should also give reasonable incentives to NZEH retrofitting market to incentivize innovative business models in renovating old building stock in Europe

Industry and technology development: Top-down policy development policies on renewable energy and energy efficiency indeed are needed to pave the way for technology innovation focusing on residential PV batteries and storage, and reliable smart meters.

Academia: For its nature of multidisciplinary and multidimensional aspect of the energy used in building and construction sector, the academia and educational institutes are also required to integrate cross-discipline training and education on sustainable energy system, energy efficiency into building, constructions, and design professionals. A more proactive academia and education initiatives shall support to enable multi-stakeholders to access practical training and information in releasing NZEH concept.

6.3 Suggestions for future studies

The future research can be focused on to facilitate research in developing more systematic study toward end-use energy services in the residential sector. The future research could also support policy makers in energy and building sector in formulating more robust energy policies toward energy technology developer (especially the residential energy storage), and finally to the end-use consumer in a cost-effective choice of energy system for the residential energy services.

The future works to extend this study can be carried out as the following:

- On the energy use in building stock: focus on retrofitting old buildings to be NZEH. This research can support the adoption of solutions during the retrofit of the building sector in Europe with its large number of old buildings.
- On the scale of energy system: extend the optimization of energy services to the NZEH at community scale and micro-grid scale. The micro-grid NZEH community can play a significant role in the development of smart city and sustainable urban environment from multiple aspects including the utilization of sustainable energy resources.
- On the energy storage development in the building: explore extensively the cost-optimal of energy system when integrated different energy storage technologies at individual scale and community scale. This development would facilitate better and faster energy storage market at residential scale by realizing the energy storage technology application in actual implementation.
- On the energy system techno-economic aspect: consider the optimization model incorporated with incentive mechanisms for energy storage deployment at residential level. This research can support the policy making process in delivering better mechanism to incentivize the NZEH development as well as reducing the market-failure risk.

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Abbreviations and Nomenclature

International Energy Agency	IEA
Net Zero Energy Building	NZEB
Net Zero Energy House	NZEH
Energy Performance Building Directive	EPBD
Energy Efficiency Index	EEI
Genetic Algorithm	GA
Genetic Algorithm Optimization	GAO
Particle swarm optimization	PSO
Ant colony optimization	ACO
Ministry of the Environment	MOE

Nomenclature	***Unit***	
A	*m²*	*Floor area*
A_i	*m²*	*Surrounding element area*
A_p	*m²*	*Interior area*
A_{room}	*m²*	*Illuminated area*
A_{window}	*m²*	*Window area*
B_j	*m*	*Thermal bridge linear development*
$b_{conduction}$		*Contact reduction coefficient*
$C_{p_{air}}$	*Ws/kg.K*	*Air specific heat capacity - 1000*
C_{p_w}	*kJ/kg.K, or* $\frac{cal}{g.°C}$	*Specific heat capacity of water*
F_{window}		*Window obstruction factor*
f		*Lighting mode control factor*
f_{eh}		*Hydro efficiency factor - 0.9*
GD	*°C /day*	*Heating degrees*
G_{solar}	*kWh /m².month*	*Monthly solar irradiation (on vertical south-oriented surface)*
H_{air}	*W/ °C*	*Ambient heat transfer coefficient*
$H_{ext.}$	*W/ °C*	*External wall heat transfer coefficient*
H_{free}	*W/ °C*	*Heat transfer coefficient (unused contact thermal bridge)*
H_{ground}	*W/ °C*	*Ground heat transfer coefficient*
n		*Number of people*
P_d	*m*	*Wall height*
$P_{lighting}$	*W/room.m²*	*Total power of the illuminated area per room*
P_{cor}	*W*	*Lighting corrected rated power*
P_{ref}	*W*	*Lighting reference power*
$q_{int.}$	*W.m²*	*Internal heat gain per unit area (equal to 4)*

q_{50}	$m^3/h.m^2$	*Air leakage number (equal to 4)*
$q_{v,air\ leakage}$	$m^3/h.m^2$	*Air leakage flow*
Q_{SH}	$kWh/m^2.year$	*Total energy needs of space heating*
Q_{SC}	$kWh/m^2.year$	*Total energy needs of space cooling*
Q_{DHW}	$kWh/year$	*Energy needs of hot water*
$Q_{convection}$	kWh	*Heat transferred by convection or convection heat loss*
$Q_{\ conduction}$	kWh	*Heat transferred by conduction or conduction heat loss*
$Q_{ventilation}$	kWh	*Heat transfer by ventilation or ventilation heat loss*
$Q_{solargain}$	kWh	*Internal solar heat gain*
$Q_{heatgain,i}$	kWh	*Total heat gains*
$Q_{int.gain,i}$	kWh	*Internal heat gain*
$Q_{extgain,i}$	kWh	*External solar heat gain*
$Q_{\ air\ leakage}$	kWh	*Air leakage heat loss*
$Q_{\ supply\ air}$	kWh	*Heating needs for supply air*
$Q_{\ make-up\ air}$	kWh	*Heating needs for make-up air*
$Q_{heating,space,net}$	kWh	*Net energy needs for space heating*
$Q_{\ space}$	kWh	*Energy need for heating area*
$Q_{int.heat}$	kWh	*Heat loads recovered for heating*
Q_{ca}	$kWh/year$	*Annual cooling energy used by ventilation cooler battery*
Q_{cw}	$kWh/year$	*annual cooling energy used by room units*
$R_{ph,i}$	h^{-1}	*Air renovation rate*
T_{in}	^oC	*Indoor air temperature*
T_{out}	^oC	*Outdoor air temperature*
$T_{ref.}$	^oC	*Reference temperature over which cooling is needed*
T_{hot}	℃	*Hot water temperature*
T_{cold}	℃	*Cold water temperature*
U_i	$W/m^2.K$	*Heat transfer coefficient or Thermal transmittance factor of component i*
V_{DHW}	m^3	*Volume of water consumption per day*
v_{DHW}	*Litter*	*Volume of water consumption per day*
v_{DHWnet}	m^3/m^2	*specific consumption of domestic hot water per year*
X_j		*Orientation factor*
x		*Factor for different storey building*
$W_{lighting}$	kWh	*Electric consumption for lighting*
$\Delta t_{heating}$	*Hour*	*Period of heating*
$\Delta t_{cooling}$	*Hour*	*Period of cooling*
Δt	*day*	*Time period*
Φ	*lumen*	*Luminous flux*
φ_j	$W/m.K$	*Linear thermal transmission*

		coefficient of the thermal bridge j - d by joints between building components
γ_j	W/K	*Additional conductance caused by joints of building components*
β_{sca}		*Thermal, condensation and air-side losses factor*
β_{scw}		*Thermal water-side losses factor*
ρ_{air}	kg/m^3	*Air density 1.2*
ρ_w	kg/m^3	*Water density 1000*
η_i		*Usage rate of heat gains*

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APPENDIX

Appendix 1 *Detailed household inventory items for energy usage*

Electricity	Inventory items		Running schedule
Space heating and cooling -	Portable heater Wall heater Central heating system Portable Air-conditioner Dehumidifier	Portable and wall heater: 1.5 kW Bathrooms Heaters: 1.2 kW Air-conditioning: 2 kW Portable air-conditioner: 1 kW Dehumidifier: 0.25 kW	Heater: 16 weeks in 4 months winter from November-February Air-conditioned: 8 weeks in 2 Months summer Morning: an 1h/day, Night several hours: 3 h/day Occasionally: 15 mins/day
Water heating	Boiler capacity	50 – 80 – 100 – 150 – 200- 300 L	Daily – 7 days/week Almost every day – 5 days/week Weekend-2 days/week Occasionally – 15 mins/day
Multimedia	Television TV box Laptop Desktop	Recent: 20-40-50 W, within 1 year New: 50-100 W, 1 – 5 years Old: 100 W, 5 - 10 years Very old: 100W , more than 10 years	Until an 1 h/day Several hours: 3 h/day Occasionally: 15 mins/day
Cooking and kitchen appliances	Fridge Freezer Washing machine Dishwasher Drying machine Electric oven	Induction/electric plate Microwave Toaster Vacuum cleaner Iron	Daily – 7 days/week Almost every day – 5 days/week Weekend-2 days/week Occasionally – 15 mins/day Except Fridge 24 hours/day
Lighting	Ceiling light Reading light Kitchen Bathroom Office Hallway	*Kitchen ceiling:* Fluorescent: 32 W Halogen: 75 W Incandescent: 150 W Dining room ceiling: LED : 11 W Fluorescent: 23 W Halogen: 75 W Incandescent: 90 W *Bathrooms and hallway* Fluorescent: 19 W, Halogen: 65 W Incandescent: 75 W *Reading lights:* LED: 3 W Fluorescent: 9 W Halogen: 35 W Incandescent: 40 W	Until 1 h/day Several hours: 3 h/day Occasionally: 15 mins/day
Gas			
Cooking and kitchen electric appliances	Gas stove Gas oven	4 kW	Every day for gas stove
Water heating	Gas heater: 11L – 19.2 kW Gas boiler: 28kW	Efficiency rating Recent – with 1 year: 85% New – 1-5years: 75% Old – 5-10 years: 65% Very old: more than 10 years: 50%	
Heating	Portable heater: 2.8 kW Central heating system 23.7 kW		

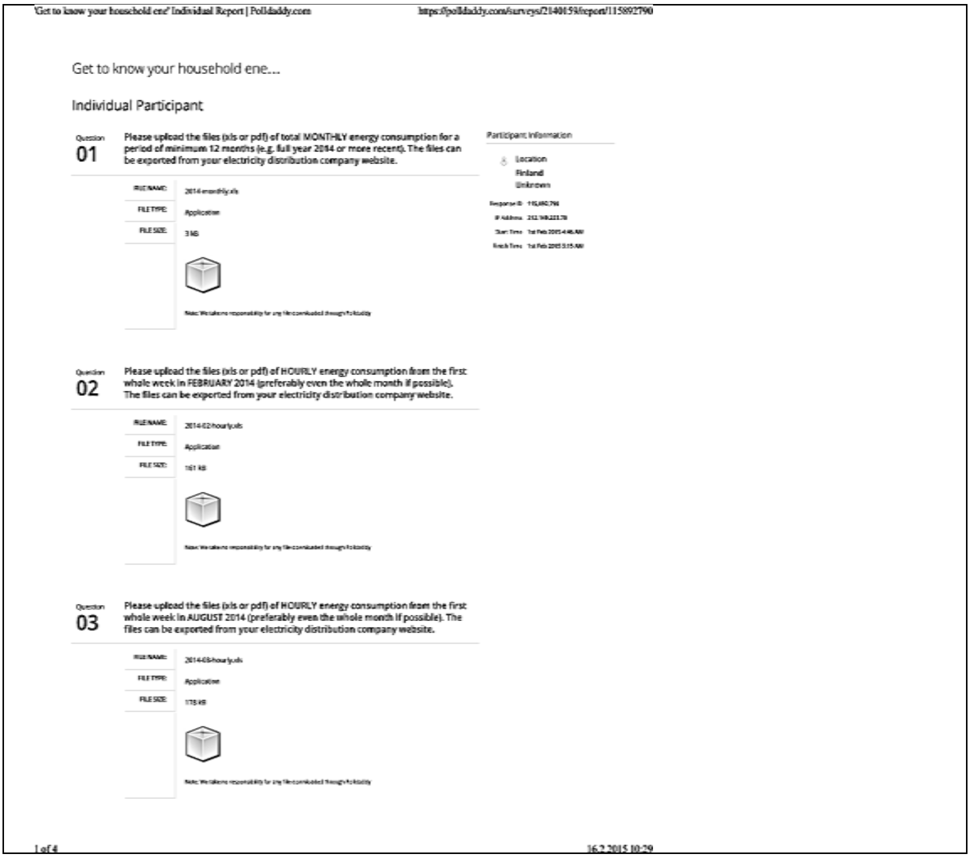
Appendix 2 ***Survey on energy and electricity consumption in Helsinki, Finland***

English version	**Finnish version**
Get to know your household energy consumption START PAGE	Tervetuloa vastaamaan kyselyyn!
We are conducting a research as a part of PhD thesis on household energy consumption in Finland. Please proceed to the survey IF you use OIL HEATING, WOOD PELLET HEATING, WOOD BASED CENTRAL HEATING or DISTRICT HEATING SYSTEM for your house. This is a joint PhD research of Aalto School of Business, Aalto University and Instituto Superior Técnico, University of Lisbon. We greatly appreciate your support in providing information on the energy consumption of your household Please visit http://laica.fi/tutkimus-asumisen-energiankulutuksesta/ for further information. If you have any question or concern about the survey, please feel free to contact Hang Dao - PhD candidate (hang.daothithu@aalto.fi) and Dr. Jouni Juntunen (jouni.juntunen@aalto.fi)	Keräämme tietoa asuintalojen energiankulutuksesta Suomessa osana väitöskirjatutkimusta. Ota osaa kyselyyn, jos talosi lämmitys perustuu öljylämmitykseen, pellettilämmitykseen, puu(klapi)keskuslämmitykseen tai kaukolämpöön. Tutkimus tehdään yhteistyössä Aalto yliopiston kauppakorkeakoulun ja Lissabonin yliopiston Superior Técnicon kanssa. Antamasi tiedot auttavat meitä ymmärtäään paremmin asumisen energiankulutusta ja sen vaihtelua. Lisätietoja tutkimuksesta http://laica.fi/tutkimus-asumisen-energiankulutuksesta/ sivuilla. Lisätietoja antavat Hang Dao - Väitöskirjatutkija (hang.daothithu@aalto.fi) ja KTT Jouni Juntunen (jouni.juntunen@aalto.fi)
PLEASE READ THIS BEFORE STARTING	**LUE TÄMÄ ENNEN**
Please proceed to the survey IF you use OIL HEATING, WOOD PELLET HEATING, WOOD BASED CENTRAL HEATING or DISTRICT HEATING SYSTEM for your house. This survey requires you to upload some files. Your household has an user account on the local energy company for example Fortum or Helsinki Energia (verkkoyhtiö) website that allows you to check your monthly and annually energy consumption. Please go to the company website and DOWNLOAD the summary files of your energy consumption in excel or PDF. Your name will not be included in these files neither on this survey. Thank you very much for your support!	Ota osaa kyselyyn, jos talosi lämmitys perustuu öljylämmitykseen, pellettilämmitykseen, puukeskuslämmitykseen tai kaukolämpöön.. Kysely vaatii joidenkin kulutustietotiedostojen lataamista sähkönjakeluyhtiöstäsi. Sinun tulee ladata nämä tiedot oman yhtiösi verkkopalvelusta tietokoneelle ja ladata ne kyselykaavakkeelle. Kysely tehdään nimettömänä, joten älä liitä nimeäsi tiedostoihin.
Page 1 Q.1 File Upload * Please upload the files (xls or pdf) of total MONTHLY energy consumption for a period of minimum 12 months (e.g. full year 2014 or more recent). The files can be exported from your electricity distribution company website.	**Page 1** **Q.1** **File Upload *** Talleta tiedosto sähkön kuukausikulutuksesta 12 kuukauden ajalta (xls-, csv- tai pdf-tiedosto, joka sisältää ainakin koko vuoden 2014, mutta voi sisältää myös vanhempaa tai uudempaa tietoa). Voit ladata tiedoston tietokoneellesi sähkönjakelijayhtiöstäsi.
Q.2 File Upload Please upload the files (xls or pdf) of HOURLY energy consumption from the first whole week in FEBRUARY 2014 (preferably even the whole month if possible). The files can be exported from your electricity distribution company website.	**Q.2** **File Upload** Talleta tiedosto sähkön tuntikulutuksesta viikon ajalta koskien helmikuun 2014 ensimmäistä viikkoa (xls-, csv- tai pdf-tiedosto, joka voi sisältää pitemmänkin ajan, esim koko kuukauden tai vuoden). Voit ladata **tiedoston tietokoneellesi sähkönjakelijayhtiöstäsi.**

Q.3 File Upload Please upload the files (xls or pdf) of HOURLY energy consumption from the first whole week in AUGUST 2014 (preferably even the whole month if possible). The files can be exported from your electricity distribution company website.	**Q.3** **File Upload** Talleta tiedosto sähkön tuntikulutuksesta viikon ajalta koskien elokuun 2014 ensimmäistä viikkoa (xls-, csv- tai pdf-tiedosto, joka voi sisältää pitemmänkin ajan, esim koko kuukauden). Voit ladata tiedoston tietokoneellesi sähkönjakelijayhtiöstäsi.
Q.4 File Upload Please upload the files (xls or pdf) of HOURLY energy consumption from of the whole year 2013, 2014 The files can be exported from your electricity distribution company website.	**Q.4** **File Upload** Talleta tiedosto sähkön tuntikulutuksesta 12 kuukauden ajalta (xls-, csv- tai pdf-tiedosto, joka sisältää ainakin koko vuoden 2013, 2014 mutta voi sisältää myös vanhempaa tai uudempaa tietoa). Voit ladata tiedoston tietokoneellesi sähkönjakelijayhtiöstäsi
Q.5 Multiple Choice * The heating system using in your house? BE REMINDED again: if you use electricity for heating your house, please do not continue the survey • Oil heating • District heating • Wood pellet heating • Wood based central heating	**Q.5** **Multiple Choice *** **Talouden lämmitysjärjestelmän päälämmönlähde on?** • Öljylämmitys • Kaukolämpö • Puupellettilämmitys • Puukeskuslämmitys
Q.6 Multiple Choice * What type of the house? • Detached • Terrace • Flat apartment building • Other	**Q.6** **Multiple Choice *** **Talotyyppi?** • Omakotitalo • Rivitalo • Kerrostalo • Other
Q.7 Free Text * Floor area of your house in m²	**Q.7** **Free Text *** **Asumispinta-ala (m²)**
Q.8 Multiple Choice * Please select if you use electricity for the following heating services • Electricity for water heating • Electric sauna • Car engine heater • Other electric indoor heaters • I don´t use extra heating services	**Q.8** **Multiple Choice *** **Käytetäänkö taloudessa seuraavia lämmitysratkaisuja**: • Käyttöveden lämmitys sähköllä • Sähkösauna • Auton lohkolämmitin ja/tai sisätilalämmitin • Muu sähkölämmitys sisätiloissa (patteri tai lattialämmitys) • En käytä sähkölämmittimiä tai lämmitystä lainkaan
Q.9 Multiple Choice * Please select if you have or use following electrical appliances which consume a lot of electricity • An addition freezer • An electric dryer • Use electric dryer more than 3 times per week • I don't use	**Q.9** **Multiple Choice *** **Onko taloudessa seuraavia sähkökäyttöisiä laitteita:** • Useampi kuin yksi pakastin • Kuivausrumpu • Käytetäänkö kuivausrumpua enemmän kuin kolme kertaa viikossa • En käytä
Q.10 Free Text	**Q.10** **Free Text**

Please list any other appliances that you think consume a lot of electricity in your house Page 3	**Onko taloudessa muita laitteita jotka mielestäsi kuluttavat paljon sähköä?**
Q.11 Multiple Choice * How many adults are living in your house?	**Q.11** **Multiple Choice *** **Aikuisten lukumäärä taloudessa?**
Q.12 Multiple Choice * How many kids are living in your house (under 18)?	**Q.12** **Multiple Choice *** **Lasten lukumäärä (alle 18v)?**
Q.13 Address Postal code?	**Q.13** **Address** **Postinumero**

Appendix 3 ***Sample of survey's answer***


'Get to know your household ene' Individual Report | Polldaddy.com https://polldaddy.com/surveys/2140159/report/115892790

Get to know your household ene...

Individual Participant

Question 01
Please upload the files (xls or pdf) of total MONTHLY energy consumption for a period of minimum 12 months (e.g. full year 2014 or more recent). The files can be exported from your electricity distribution company website.

FILE NAME: 2014-monthly.xls
FILE TYPE: Application
FILE SIZE: 3 MB

Participant Information
Location
Finland
Unknown

Question 02
Please upload the files (xls or pdf) of HOURLY energy consumption from the first whole week in FEBRUARY 2014 (preferably even the whole month if possible). The files can be exported from your electricity distribution company website.

FILE NAME: 2014-02-hourly.xls
FILE TYPE: Application
FILE SIZE: 161 KB

Question 03
Please upload the files (xls or pdf) of HOURLY energy consumption from the first whole week in AUGUST 2014 (preferably even the whole month if possible). The files can be exported from your electricity distribution company website.

FILE NAME: 2014-08-hourly.xls
FILE TYPE: Application
FILE SIZE: 178 KB

1 of 4 16.2.2015 10:29

'Get to know your household ene' Individual Report | Polldaddy.com https://polldaddy.com/surveys/2140159/report/115892790

Question
13 Postal code?

00510

View Larger Map

Appendix 4 Sample of online answer

1/11/2015 Helsingin Energia

FI | SV

HELEN

News
Feedback

Your contract details

Your bills
Change your billing details

Your meter readings and usage of energy
Sävel plus

Make contract
Cancel your contract

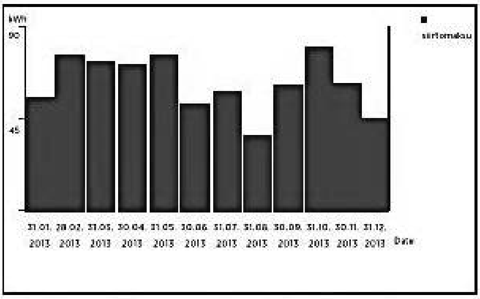
Change your password

Logout

Reading Report

You can browse your reading information and the consumption between the reading dates.

Customer
Consumption site



Reading date	Product	Reading interval, day	Reading	Use, kWh
31.12.2013	siirtomaksu	31	901	47 kWh
30.11.2013	siirtomaksu	30	854	64 kWh
31.10.2013	siirtomaksu	31	790	82 kWh
30.09.2013	siirtomaksu	30	708	63 kWh
31.08.2013	siirtomaksu	31	645	39 kWh
31.07.2013	siirtomaksu	31	606	60 kWh
30.06.2013	siirtomaksu	30	546	54 kWh
31.05.2013	siirtomaksu	31	492	78 kWh
30.04.2013	siirtomaksu	30	414	74 kWh
31.03.2013	siirtomaksu	31	340	75 kWh
28.02.2013	siirtomaksu	28	265	78 kWh
31.01.2013	siirtomaksu	31	187	57 kWh

10 latest 2014 2013 2012 2011 2010 2009

Appendix 5 ***Finland energy consumption according to VTT statistics***

2010	**APPARTMENTS**	**TERRACED HOUSES**			**DETACHED HOUSES**		
kWh		ALL	No electric heating	Electric heating	ALL	No electric heating	Electric heating
Indoor lighting	440	642	687	569	1745	1856	1619
Cold appliances	460	545	574	508	788	855	713
Entertainment appliances	226	343	370	300	436	464	404
Electric sauna	85	434	436	423	615	589	645
Cooking appliances	230	287	303	269	310	321	300
Computer and related	158	167	180	138	183	201	164
Heating and AC	49	158	156	162	517	770	234
Washing machine and driers	103	153	156	154	230	236	223
Floor heating	78	282	204	408	279	152	421
Dish washers	51	106	114	92	172	179	164
Car heating	0	70	52	100	192	181	204
Outdoor lighting	0	35	38	31	73	84	62
Others	190	458	479	423	2209	3757	477
Household total	**2109**	**3681**	**3749**	**3577**	**7748**	**9643**	**5630**
Electric heating. hot water	0	2537	0	6654	5455	0	11564
TOTAL	**2109**	**6217**	**3749**	**10231**	**13203**	**9643**	**17194**
BAU scenario by 2020	**APPARTMENTS**	**TERRACED HOUSES**			**DETACHED HOUSES**		
kWh		ALL	No electric heating	Electric heating	ALL	No electric heating	Electric heating
Indoor lighting	330	482	516	427	1309	1393	1215
Cold appliances	316	374	393	348	541	587	489
Entertainment appliances	312	403	434	352	511	544	474
Electric sauna	89	450	452	439	638	611	668
Cooking appliances	222	277	293	260	299	310	290
Computer and related	84	89	96	74	98	108	88
Heating and AC	54	174	172	178	569	847	257
Washing machine and driers	101	150	154	151	226	231	219
Floor heating	78	282	204	409	280	152	422

Dish washers	51	107	115	93	174	181	166
Car heating	0	66	49	94	180	170	192
Outdoor lighting	0	36	38	31	74	85	62
Others	178	429	449	397	2071	3521	447
Household total	**1815**	**3319**	**3366**	**3253**	**6969**	**8739**	**4990**
Electric heating. hot water	**0**	**2308**	**0**	**6053**	**4963**	**0**	**10520**
TOTAL	**1815**	**5627**	**3366**	**9306**	**11932**	**8739**	**15510**
BAT scenario by 2020	**APPARTMENTS**	**TERRACED HOUSES**			**DETACHED HOUSES**		
kWh		ALL	No electric heating	Electric heating	ALL	No electric heating	Electric heating
Indoor lighting	139	203	218	180	553	588	513
Cold appliances	197	234	246	218	338	367	306
Entertainment appliances	249	322	347	281	409	435	379
Electric sauna	89	450	452	439	638	611	668
Cooking appliances	185	231	244	216	249	258	241
Computer and related	31	32	35	27	35	39	32
Heating and AC	38	122	120	124	398	592	180
Washing machine and driers	83	123	126	124	185	190	180
Floor heating	78	282	204	409	280	152	422
Dish washers	47	99	106	86	160	167	153
Car heating	0	66	49	94	180	170	192
Outdoor lighting	0	8	9	7	16	19	14
Others	178	429	449	397	2071	3512	447
Household total	**1314**	**2601**	**2605**	**2602**	**5512**	**7109**	**3727**
Electric heating. hot water	**0**	**2308**	**0**	**6053**	**4963**	**0**	**10520**
TOTAL	**1314**	**4909**	**2605**	**8655**	**10475**	**7109**	**14247**

Appendix 6 *Finland residential electricity consumption survey*

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16
Jan	208	208	1371.7	175	511	114.17	215.43	47	374	292	359	327	120	192	841.35	333
Feb	167	167	1246.02	175	443	84.97	16383	64	357	268	211	196	125	158	707.22	312.5
Mar	175	175	1359.05	155	459	101.4	21543	82	283	180	229	310	127	158	838.03	231.5
Apr	162	162	1303.05	169	398	86.4	20.	63	221	224	135	198	124	113	562.21	222.5
May	110	110	1544.53	180	369	90.51	93.5	39	176	208	134	244	132	120	449.13	192
Jun	94	94	1758.21	117	335	83.52	1935	60	106	94	136	149	122	119	298.05	100
Jul	57	57	1500.18	160	338	74.87	129	54	48	78	107	133	126	123	469.68	63
Aug	96	96	1449.25	193	354	83.86	196.08	78	157	213	134	219	79	140	392.85	185
Sep	110	110	1251.96	192	340	75.9	188.34	74	225	224	176	249	91	138	477.06	224.5
Oct	162	162	1282.74	150	424	77.68	236.07	75	313	244	211	210	116	128	690.77	278.5
Nov	175	175	1375.09	432	421	93.84	236.07	78	346	330	255	236	132	129	546.08	338
Dec	200	200	1466.81	160	491	82.74	288.96	57	290	291	358	175.93		145	741.40	290.5
Annual total	1716	1716	16908.59	2258	4883	104986	2462.61	771	2896	2646	2445	2646.93	1379	1663	7013	2771
Aldults	2	2	3	2	2	2	4	2	2	2	2	2	2	1663	7013.83	2771
Kids (<18)	0	0	0	3	0	0	2	0	1	2	0	2	0	2	2	2
Area (m2)	54	54	140	69	160	68.5	129	32	73	120	171	120	41	80	145	90.5

Appendix 7 *Technology input for linear programing*

	Fuel	No	**Technology model**	**Efficiency**	**Investment cost (€)**	**Fuel costs (€/kWh)**
Water heating						
Storage	Natural gas	1	Gas water heater	0.88	595-1760	0.0746-0.0791
	Propane	2	Gas water heater	0.88	595-1760	0.0986-0.1020
	Biomass	3	Boiler	0.91	6226-7388	0.0412
	Electricity	4	Electrical water heater	1.00	143-650	0.1528
		5	Heat Pump	4.30	2250	0.1528
	Solar radiation	6	Forced circulation system	0.52	1990-3243	0.0000
		7	Thermosyphon	0.46	1515-2370	0.0000
Instantaneous heating	Natural gas	8	Gas geyser with ambient	0.88	256-283	0.0746-0.0791

			exhaustion			
		9	Gas geyser with vented exhaustion	0.87	334-388	0.0746-0.0791
		10	Sealed gas geyser	0.92	450-509	0.0746-0.0791
	Propane	11	Gas geyser with ambient exhaustion	0.88	256-283	0.0986-0.1020
		12	Gas geyser with vented exhaustion	0.87	334-388	0.0986-0.1020
		13	Sealed gas geyser	0.92	450-509	0.0986-0.1020
Space heating						
Boiler with storage	Natural gas	14	Condensed boiler	0.98	2295-2750	0.0746-0.0791
		15	Boiler with air exhaustion	0.93	1705-2343	0.0746-0.0791
		16	Sealed boiler	0.95	2003-2458	0.0746-0.0791
	Propane	17	Condensed boiler	0.98	2295-2750	0.0986-0.1020
		18	Boiler with air exhaustion	0.93	1705-2343	0.0986-0.1020
		19	Sealed boiler	0.95	1820-2458	0.0986-0.1020
Storage	Solar	20	Forced circulation	0.52	1990-3243	0.0000
	Biomass	21	Boiler	0.91	6226-7388	0.0412
Tank-less boiler systems	Natural gas	22	Condensed boiler	0.98	1750	0.0746-0.0791
		23	Boiler with air exhaustion	0.93	1343	0.0746-0.0791
		24	Sealed boiler	0.95	1458	0.0746-0.0791
	Propane	25	Condensed boiler	0.98	1750	0.0986-0.1020
		26	Boiler with air exhaustion	0.93	1343	0.0986-0.1020
		27	Sealed boiler	0.95	1458	0.0986-0.1020
Electrical heaters	Electricity	28	Mono-split air conditioner	3.9	790	0.1528
		29	Multi-split air conditioner	3.8	1030	0.1528
		30	Oil convection heater	1.00	90	0.1528
		31	Infrared heater	1.00	24	0.1528
		32	Electrical resistance heater	1.00	145	0.1528
Geothermal heating	Geothermal	33	Probe sole	4.66	18000	0.1528
		34	Horizontal sole	4.66	15000	0.1528
Biomass heater	Biomass	35	Wood furnace	0.70	904	0.0049
Oil heater	Oil	36	Portable space heater	0.80	968	0.0986-0.1020
Space cooling						
Electrical coolers	Electricity	37	Mono-split air conditioner	6.00	790	0.1528
		38	Multi-split air conditioner	5.80	1030	0.1528
Geothermal cooling	Geothermal	39	Probe sole	4.66	18000	0.1528
		40	Horizontal sole	4.66	15000	0.1528

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