Optimization of integrated renewable energy system supplied for Net Zero Energy Buildings

Ulrike Ellen Eilhauer

Thesis to obtain the Master of Science Degree in Engineering Physics

Supervisor: Prof. Carlos Augusto Santos Silva

Examination Committee

Chairperson: Prof. Luís Filipe Moreira Mendes
Supervisor: Prof. Carlos Augusto Santos Silva
Member of the Committee: Dr. Laura Aelenei

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To my parents

Living the concept of net zero and auto sustainability
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This thesis is dedicated to my parents, Marika Fedtke e Gerhard Winzer, for giving me the opportunity to study and for supporting me not just as parents, but also as friends during my whole life.

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ABSTRACT

As energy demand in the residential building sector is constantly increasing, it is important to explore different energy sources and efficiency measurements. The European Union launched the EU Directive 2010/31, which states that all new buildings have to be nearly Net Zero Energy Buildings (NZEBs) by December 31st 2020. However, each member state has to take its own approaches in order to define NZEB term, as well as how to implement these buildings.

The main interest of this work is to study possible NZEB implementations for Portugal and to define a valid framework for the term. To do so, an optimization algorithm for energy services in a given household is developed in MATLAB. It chooses the best technologies by minimizing energy consumptions and costs. The input of the algorithm via user-friendly interface takes behavioral aspects of energy consumption and available space for renewable onsite production into account.

To test the constructed algorithm, different case study scenarios were performed and analyzed. It is demonstrated that the percentage of renewables present in the energy household consumption depends on the given house type and on the number of members. Thus nearly net zero apartments should include 60-65% of renewables and standalone houses 75-80%. Furthermore, it is concluded that water heating is the energy service with most unrealized saving potential and that solar thermal systems are an essential technology option to become nearly net zero.

Keywords: net zero buildings, optimization, renewable supply, energy services
RESUMO

Com o consumo de energia a aumentar constantemente no sector residencial é importante explorar vários recursos e possibilidades de poupança energética. A União Europeia lançou a Directiva 2010/31, a qual define que todas os imóveis novos têm de ser edifícios de balanço energético nulo (EBEN) até 31 de Dezembro de 2020. Contudo, cada estado membro tem de definir “balanço energético nulo” e as medidas para a sua implementação.

O interesse principal desta tese é o estudo de possíveis implementações de EBEN em Portugal e o desenvolvimento uma metodologia válida. Para isso, foi criado um algoritmo que optimiza os serviços de energias de uma dada casa em MATLAB. O código escolhe a melhor tecnologia para os serviços, minimizando o consumo energético e custo. As variáveis iniciais do programa, que são introduzidas através de uma interface, têm em consideração o comportamento das pessoas e o espaço disponível para energias renováveis.

Para testar o programa, foram analisados diferentes cenários, tendo-se mostrado que a percentagem de renováveis utilizadas no consumo de uma casa depende do tipo de casa e do número dos habitantes. Para um apartamento com balanço energético quase nulo é surgerido o valor de 60-65% para um apartamento e de 75-80% para uma moradia. Além disso, é possível concluir que o aquecimento de águas sanitárias é o serviço com maior potencial de poupança e que os sistemas solar térmicos são uma tecnologia essencial para uma casa se tornar um EBEN.

Palavras-chave: edifícios de balanço energético nulo, optimização, fornecimento de energia renovável, serviços de energia
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**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>%RE</td>
<td>Percentage of renewable energy present in the total household consumption</td>
</tr>
<tr>
<td>%RE(_{\text{grid}})</td>
<td>Renewable energies in the total electricity production</td>
</tr>
<tr>
<td>AC</td>
<td>Air conditioner</td>
</tr>
<tr>
<td>ACO</td>
<td>Ant colony optimization</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of performance</td>
</tr>
<tr>
<td>EPBD</td>
<td>Energy performance building directive</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
</tr>
<tr>
<td>HOMER</td>
<td>Hybrid optimization of multiple energy resources</td>
</tr>
<tr>
<td>HP</td>
<td>Heat pump</td>
</tr>
<tr>
<td>LCC</td>
<td>Life cycle cost</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized costs of energy</td>
</tr>
<tr>
<td>LCOT</td>
<td>Levelized cost of technology</td>
</tr>
<tr>
<td>LP</td>
<td>Linear programming</td>
</tr>
<tr>
<td>NZEB</td>
<td>Net zero energy building</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle swarm optimization</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>RE</td>
<td>Renewable Energy</td>
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<tr>
<td>SC</td>
<td>Space cooling</td>
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<td>SH</td>
<td>Space heating</td>
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<tr>
<td>WH</td>
<td>Water heating</td>
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1 INTRODUCTION

1.1 Motivation

It is foreseen that global energy demand will increase about one third from 2011 to 2035. This corresponds to circa 4250 Mtoe more energy and the related CO₂ emissions will rise by 20%, reaching 37.2Gt [1]. Reasons for the increasing energy demand are mainly a tremendous population growth and an increasing income in the developing countries. The income increase may influence people’s behavior as they might spend more money on energy uses, such as thermal comfort. As Asia is experimenting in these decades a huge technological and demographical increase, it contributes essentially to this statistics. In order to satisfy the demand, all types of energy resources might have to be explored – Figure 1-1 [1].

![Figure 1-1: Growth in primary energy [1]](image)

The European Union (EU) has surprised the International Energy Agency by reducing its foreseen energy demand for 2035 from an increase of 23% to only 13% (from 2012 Outlook to 2013). These 10% reduction could be achieved principally due to faster growth of renewables in power generation and increased building’s energy efficiency [1]. In fact, nearly 40% from the final energy consumption is attributed to the private and public building sector [2]. The EU has launched some energy policies that will help to satisfy the future energy demand. One of these policies, the EU Directive 2010/31, known as EPBD (Energy Performance of Buildings Directive) recast 2010, includes the so called Net Zero Energy concept for buildings [3]. This directive states that all new buildings have to be nearly Net Zero Energy Buildings (NZEB) by December 31st 2020 (December 31st 2018 for public authority buildings)[4].

To achieve such objective, each EU member state has to study its theoretical potential in order to define the term of nearly NZEB. To do so, local conditions, optimization and modeling techniques play a significant role.

Not only EU politics is concerned about the increasing energy demand and the predictable related topics, such as climate change, shortage of fossil-based energy resources and increasing energy prices. For already existing buildings it will be certainly an economical and environmental issue to transform them to nearly NZEB. Becoming a NZEB may have economical advantages for the owners and can also contribute to future competitiveness in the energy market, which is going to be a flexible exchange between the produced and needed energy.
1.2 Objectives

The objective of this thesis is to study Portugal’s potential for residential NZEB implementation. To do so, the thesis encounters the study of NZEB optimization implementation, an own framework modulation, the respective code and its analysis. The framework is based on the concept of energy services and optimizes different technologies and onsite renewable supply options for specific cases. Two different optimization approaches (linear programming and genetic algorithm) are studied and used as a hybrid model. MATLAB software helps to compute the desired. The optimization minimizes the energy consumption and costs. A comparison between different scenarios shows the best technologies for given energy services and the potential of onsite renewable implementation in Portugal.

1.3 Contributions

This thesis contributes to the evaluation of NZEB implementation in Portugal. It suggests the best suited technologies for a given household and the potential of renewable onsite production. To do so, this work includes a developed program with a user-friendly interface that uses an optimization algorithm to determine the solution.

1.4 Structure of the thesis

The thesis is structured in five main chapters. This first chapter gives a brief introduction to the theme and presents the main objectives of this work.

The second chapter gives an overview of the NZEB implementation situation. The chapter contains the NZEB definition as well as political aspects from the EPBD 2010 recast. The state of the art for NZEB implementations with optimization techniques is presented. It is given a short overview of Portugal’s primary energy production, possible renewable onsite and available technologies for given energy services.

The programming model for the code is presented in the third chapter. This chapter involves mostly the calculations and assumptions needed to determine all relevant parameters.

The fourth chapter discusses the optimization approach and is divided into: linear programming and genetic algorithm. Results to given case studies are presented in the fifth chapter. The conclusion and further discussion points about this work can be found in the fifth chapter.

The code structure and the objective functions layout of the MATLAB code can be found in annex.
2 NET ZERO ENERGY BUILDINGS

2.1 Net Zero Energy Buildings definition

The term Net Zero Energy Buildings refers to buildings with highly decreased energy needs through efficiency achievement such that the balance of energy demand can be fully supplied by renewable technologies [2]. As buildings are considered the energy efficiency sector with the most unrealized economic potential, current policies should be adapted to technological advance in order to achieve the full potential [1]. The EU Directive 2010/31 may be one of the first steps in this direction. In order to satisfy the EPBD recast, the European member states are adopting different solutions. This effect is a result of an inconsistent framework related to different evaluation methods for the energy balance that is required to establish the NZEB definition. The main obstacles for NZEB implementation appear due to cross-regional and legislative confusion about a proper definition [4]. Worldwide the term of NZEB encounters around 75 different balance methodologies [5]. It is possible to find four main definitions of NZEB in the literature [3]. The most intuitive one appears to be Net Zero Site Energy which balances the produced renewable energy with the consumed energy. In this definition, all energy is generated and consumed onsite, that is, within the buildings system boundary. Figure 2-1 [3] includes the connection between buildings and energy grids. NZEBs need a low energy generation (red line) which then is weighted with the delivered or exported grid energy (green line). Based on this principle, other NZEB definitions can be established. One is the Net Zero Source Energy which weights the consumed energy with produced renewable energy, which can come from out site the buildings boundary. Therefore, this definition includes in the term of consumed energy the energy that is needed to deliver the renewable energy to the site. Net Zero Energy Cost and Net Zero Energy Emissions indicate already from their name that their weighting system is not energy based. The Net Zero Energy Cost definition balances the total energy purchase costs with the sold energy to the grid. Finally, the Net Zero Energy Emissions balances the CO$_2$ emissions coming from energy consumption with the avoided emissions from renewables production.

![Figure 2-1: Four main established energy balances][3]
2.2 Policy aspects – EU Directive 2010/31

The EU Directive 2010/31 defines the implementation of nearly NZEBs in 2020 in order to reduce greenhouse gas emissions and energy consumption. Within this directive, other important aspects are stated and should be taken into account for this work.

2.2.1 Guidelines

Each member state should define how it will implement the action plan, this means to define how to calculate the energy performance of a building. However, the EPBD recast gives some guidelines to do so: the energy performance of the building should be calculated annually and not seasonal, the action-plan should achieve the cost-optimal balance between involved investments and energy costs saved throughout the lifetime of the building, the buildings should meet minimum energy performance requirements adapted to the local climate, which is basically to say that energy needs are reduced first and then renewable energy supply systems are implemented as depicted in Figure 2-2. Of course, all implementations should be verified with certifications by authorized institutions [6].

![Figure 2-2: Reaching Net Zero Energy in Buildings [3]](image)

2.2.2 Energy performance calculation

The calculation methodology for the energy performance is presented in annex 1. The established methodology should take thermal characteristics of the house into account, which are thermal capacity, insulation, passive heating, cooling elements and thermal bridges. Additionally heating installation and hot water supply, as well as air conditioning, natural and mechanical ventilation, built-in lighting installation, design and orientation of the building should be included in the framework. Furthermore, outdoor and indoor climate conditions as well as passive solar systems and solar protection such as internal loads shall be considered. The analyzed buildings should be classified into groups such as single family house, apartment, educational buildings, hotels and others [6].

The energy consumption in the building can be characterized as seen in Figure 2-3. Primary energy is coming from the various energy sources (power plants, renewable generation and others) and is delivered to the building. In the building, energy is used to provide desired energy services. To do so, different technologies
with different efficiencies can be implemented. Also should the building, in order to reach nearly Net Zero, be equipped with onsite renewable resources which can deliver thermal or electrical energy.

The system losses of a building are related to the installed technologies which provide the desired energy services. The percentage of renewable energy present in the total energy consumption of a building depends strongly on the availability of onsite renewables and on the percentage of renewables present in the primary energy.

Figure 2-3: Energy classification of energy consumption (adapted from [5])

### 2.2.3 Cost-optimum calculation

The calculation methodology for the cost-optimum level is presented in annex 3 of the directive. For the cost-optimum calculation, outdoor climate conditions, investment costs, building category, earnings from produced energy and maintenance and operating costs should be taken into account. The discount rate should be assumed between 2% to 4%. The building’s lifetime is at least 30 years. The established framework should first define a reference building, then the energy efficiency measurements, the final and primary energy need of the building and finally calculate the costs.

These are the main suggestions from the EPBD recast. In this work, it is intended to satisfy most of these approaches and in further chapters exact assumptions are presented.

### 2.3 Portugal’s potential for NZEB implementation

From the EPBD recast, each member state has to identify a concept of NZEB, define compatible laws and establish a compatible framework. The suggested tasks from the European Union can be found summarized in
As described in section 2.1, the NZEB definition depends on the chosen balance methodology and thus European member states have different approaches to define the term.

Portugal does not have defined a proper definition yet; however the country has taken some actions in order to save energy and to increase renewable onsite production. In terms of developing highly efficient buildings, a methodology for energy demand calculation (which will be used in section 3) [7] and an evaluation strategy for certifying buildings energetically was established. The certificate for the buildings works with the concept of energy classes from A+ to G, being A+ the most energy efficient building and G the worst. A study done by [8] concluded that with this policy more than 50% of the new constructed buildings is included in class A or higher (Figure 2-5).

Figure 2-5: Study of the improvement of energy efficiency in the Portuguese building sector [8]

In terms of implementing renewable onsite generation, there have been promoted some programs for solar systems. In these programs the government supported around 50% of the acquisition costs for solar thermal systems and the installation of photovoltaics, through the implementation of feed-in tariffs. From [5], it is possible to summarize the current state of implementation of onsite renewables and other measures in Europe to help to achieve NZEB in Table 2-1.
Table 2-1: Possible technologies for NZEB and their actual impact in different European regions (adapted from [5])

In general, it can be said that Portugal has a very high potential to implement NZEB. Due to its climate conditions the country favors renewable energy production. Portugal has already established a framework for increasing energetically efficient buildings and the first NZEB examples from Portuguese institutions can be found, such as the building Solar XXI from the Laboratório Nacional de Energia e Geologia (Figure 2-6).

In order to follow all required tasks of EPBD recast, it is still needed to identify a more concrete and better defined concept for the NZEB implementation and consistent framework.

2.4 Optimization methods for NZEB – State of the art

Optimization is the search for the best solution or the set of best solutions for a given problem. Mathematically, optimization is defined as “finding inputs of a function that minimizes or maximizes its value, which may be subjected to constraints [10]”. Generally, this function is called objective function, which is the function that is going to be maximized or minimized. The objective function is written in terms of variables and
indicates how much each variable contributes to the value to be optimized in the problem. Often these variables present constraints, which also need to be satisfied. Notice that the objective function can have more than one minimum or maximum and that optimization methods are intended to find the global extreme value. One of the main challenges consists of defining an objective function that describes the problem and the best suited method to solve it.

During the last decade, the number of papers of optimization methods for renewable energy implementation in households increased exponentially. This also means that innumerous different optimization methods have been applied to the topic, depending on the approach and the chosen objective function [10].

In this section it is given an overview of different optimization methods used in the past, following references [11] and [10].

### 2.4.1 Traditional optimization methods - Linear Programming

Traditional optimization methods such as linear or quadratic programming are possible to solve analytically. The difficulty resides in defining a linear or quadratic cost function, which describes the problem and the set of variables that needs to be optimized. In the NZEB case, these variables can be the energy demand, the energy production, the costs or the CO$_2$ emissions. The authors of [12] have developed a linear optimization (LP) approach, which is suitable to identify the optimal installed capacity of a renewable energy supply system in terms of the overall costs. Their formulation takes only three energy supply systems into account and needs further development. The considered technologies are solar thermal installation, photovoltaics and a heat pump. As traditional optimization methods are related to quite specific cases, they are not universal.

### 2.4.2 Meta-heuristic optimization

By considering more complex problems, that is, assuming more variables and minimizing and maximizing more than one parameter, the traditional optimization methods are not suited anymore. Heuristic methods may not provide necessarily the optimal solution, but a satisfactory one. Meta-heuristic optimization models differ from heuristic ones, as they can be applied to a wider set of problems, without modifications. Many of these optimization methods are based on natural observations and named after them. The runtimes of these programs can be very long and so it is reasonable to reduce the complexity of these methods.

The input data of meta-heuristic methods regarding NZEB are normally the climate conditions, unit prices of the projected renewable system components, including installation and maintenance costs and some constraints (such as available space for the renewable energy installation). The objective function in these methods is often called fitness function.

#### 2.4.2.1 Trajectory methods

Trajectory methods are single objective methods that describe a trajectory that minimizes or maximizes an objective functions within prescribed constraint boundaries. Most of these methods are extensions of iterative procedures that include techniques to enable the algorithm to escape from local extreme values, finding a
The main methods of this category are hill climbing and simulated annealing. These methods often are inbuilt in other methods.

For NZEB optimization, simulated annealing has been used most frequently regarding the trajectory methods. It is an optimization method based on the process of physical annealing, where a metal at high temperatures is slowly cooled down. At high temperatures, the atoms of the metal are located at higher states and can easily rearrange themselves into other structures. During the cooling process the probability that the atoms rearrange decreases until reaching the ground state. For the computational approach it is normally used the Metropolis algorithm, which is based on Monte Carlo method. Simulated annealing starts from an arbitrary high temperature (possible solution), which is slowly lowered by a probability acceptance criterion (given by the Boltzmann distribution) until reaching the global optimum. Due to the acceptance criterion it is able to jump out of local optima solutions and to find the global one.

Regarding NZEB implementation, this method was used in literature to find the optimum design of a PV-wind-battery system and for a renewable-hydrogen storage combination [10] [11].

2.4.2.2 Multi-objective optimization

Multi-objective optimization uses a population that evolves during the iteration process, giving a set of possible solutions. This possible set of solutions is also called Pareto set. This type of optimization methods is the most used in studying the implementation of renewables for NZEB. Especially evolutionary algorithms, which are based on biological processes, have made the most success. The big advantage of these methods is the possibility to use various objective functions and to maximize or minimize all the desired parameters [10] [11]. The two most used algorithms are the genetic algorithm (GA) and the particle swarm optimization (PSO). One still developing algorithm probably suitable for NZEB optimization is the ant colony optimization (ACO). All three are part of the evolutionary algorithms and provide solutions to complex real world problems.

GA is an optimization method based on the genetic process in biological systems. After defining the input, GA consists of an iterative process, which includes five components: a random population generator, a fitness evaluation unit and genetic operators for “selection”, “crossover” and “mutation”. Normally for NZEB, the random initial population offers random sizes for the renewable system constituents in order to satisfy the load demand. Each solution is then evaluated due to the fitness function. The genetic operator “selection” chooses the population according to their fitness. The “crossover” operator provides possible new solutions when it is needed to achieve higher fitness values by mixing existing solutions and the “mutation” operator prevents the algorithm from getting stuck at a local minimum. The biggest benefit of this method is its easiness to code many different parameters. Furthermore, GA will not get stuck at local optima and stays diverse even when found the global optimum. If GA codes become too complex, the computation time increases significantly.

GA is the most used optimization method in implementing hybrid systems, which are a combination of various renewable energy sources and is used by many authors. The authors [11] and [10] refer that this algorithm was used to optimize the economical design of stand-alone hybrid systems, which included as energy sources PV cells, wind turbines and fuel cells. Furthermore, [10] states that GA was used to find the optimal site for the maximum capacity outcome of wind turbines and also to evaluate costs, power production and efficiency of
wind farms. The authors of [13] mention the use of GA optimization in PV systems in order to find the minimum area and maximum storage. It was also used to maximize the power point from the current-voltage characteristic of a PV cell. Additionally, [13] refers GA use to maximize thermal comfort, optimize power system at islands and hybrid PV-diesel systems.

PSO is the second most used optimization method used in NZEB implementations after GA. The method is based on the movement and intelligence of swarms. The input data is similar to other meta-heuristic process. The iterative process is based on stochastic optimization procedure, where each potential solution is called a particle, which can be presented with a position and velocity vector. Each possible solution (particle) is initialized by a random velocity and moves within the possible space of solutions. At each iteration, each particle moves toward an optimum solution, obtaining the global best solution considering all final solutions from all particles. The PSO has some advantages over GA as its approach is simplified, involving fewer operators, which are easier to implement. Thus the computation time is usually shorter than for GA. As the PSO is based on coordinate definition of particles, it usually does not have more than three components (such as three renewable energy supply options).

The authors of [11], [10] and [13] state that PSO optimization was used in stand-alone wind-PV systems in order to minimize costs. PSO is also used to optimize renewable energy sources in a micro-grid. Additionally, the authors [10] mention the use of PSO to optimize the energy demand of a residential area.

ACO optimization method is inspired by the observation of ant colonies. Ant colonies use specific paths to find food. When a path is not needed anymore, the smell of pheromone, which is used to mark a path, vanishes. As a consequence, the probability of the path being used in the future decreases. The best path (the most used and shortest) to the food is the highest possible value of performance index in terms of optimization criteria. The input variables are similar to the processes referred earlier, differing mainly in the iteration procedure. An ant colony (possible implementations) travels in space, where the space dimensions are the possible parameters. The search for the global minima is similar to the search for food described above. Just when the fitness function is satisfied, the iteration process stops, otherwise the ‘ants’ continue their search. For lower number of components, this optimization method is perfectly suitable. This method was used to optimize wind and photovoltaic capacity [11]. All in all, it relies in the approach chosen by the system designer which optimization technique is the most satisfying for his problem.

2.4.3 Further approaches

There exists also commercially available software for hybrid system sizing (such as HOMER or RETSCREEN) that make it easier to size a given system. They require initial information about the available energy resources, economical and technical constraints, energy storage requirements and system control strategies. In addition, the component type, capital, replacement, operation and maintenance costs, efficiency, operational life, etc. can also be defined and introduced in the software. Unfortunately, the developed programs only consider electrical technologies and can not exactly simulate every chosen implementation site [11]. Furthermore the software was developed to cover only the supply option and not the demand options. Comparing HOMER software results to results obtained from different algorithms for a given site can be helpful to understand the
feasibility of the developed algorithm. Notice that other useful approaches have been made. GenOpt, a Java application has been developed and can be associated to almost all external simulation programs such as TRANSYS or EnergyPlus. In Table 2-2, the most used optimization methods for NZEB and their advantages and disadvantages are demonstrated.

<table>
<thead>
<tr>
<th>Optimization process</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Implemented for NZEB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single objective methods</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear programming</td>
<td>Easy to code</td>
<td>Few decision variables</td>
<td>Minimum overall costs for 3 supply options</td>
</tr>
<tr>
<td><strong>Trajectory methods</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated annealing</td>
<td>Easy to code and efficient in finding global optima, many studied examples</td>
<td>Few decision variables</td>
<td>Optimal design for renewable hybrid combinations</td>
</tr>
<tr>
<td><strong>Multi-objective programming</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Genetic algorithms</td>
<td>Suitable for problems with a great number of parameters</td>
<td>Relatively harder to code</td>
<td>Optimal economical design, maximized thermal comfort, maximized capacity output</td>
</tr>
<tr>
<td>Ant colony optimization</td>
<td>Efficient for network optimization problems</td>
<td>Relatively harder to code</td>
<td>Optimization of photovoltaic and wind turbine capacities</td>
</tr>
<tr>
<td>Particle swarm programming</td>
<td>Relatively easy to code</td>
<td>Few decision variables</td>
<td>Optimal cost, demand, renewable energy sources</td>
</tr>
</tbody>
</table>

Table 2-2 – Optimization methods used for NZEB implementations

2.5 Energy services in households

The term of energy services is related to all basic energy needs for a given household. These needs include usually warm water, thermal comfort, food cooling, cooking and lighting. Of course, in a modern world approach these needs also include the access to electricity for media appliances.

In Portugal space heating consumes 21.5% of the total household consumption and that water heating has a higher value with 23.5% [14]. Therefore these two energy services can be considered the two biggest energy consumers. The considered energy services will be further described in section 3.

2.6 Available technologies to satisfy household needs

The available technologies to perform water and space heating are represented in Table 2-3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Heat generation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional heaters</td>
<td>Combustion</td>
<td>Biomass, Fossil fuel</td>
</tr>
<tr>
<td></td>
<td>Joule effect /Infrared</td>
<td>Electricity</td>
</tr>
<tr>
<td>Heat pump</td>
<td>Ambient heat</td>
<td>Air, Water, Ground + Electricity</td>
</tr>
<tr>
<td>Solar heater</td>
<td>Ambient heat</td>
<td>Solar radiation</td>
</tr>
</tbody>
</table>

Table 2-3: General classification of water and space heaters

[14] performed an analysis about which equipment is most used in Portugal’s households for certain energy services. The most used for space heating was an independent electrical heater (oil heater or infrared heaters)
and the second most used technology was a wood furnace (see Figure 2-7). Notice that households can have more than one technology to perform the same energy service.

The same analysis was done for water heating systems, and it was concluded that instantaneous gas water heaters are the most common heating option. They are followed by the electrical water heaters and boiler systems. Just few households include a solar thermal system (see Figure 2-8). Ventilation was the most used approach to cool spaces, followed by air conditioning systems.

2.6.1 Conventional heaters

Conventional heaters can be classified into two types. The first developed devices to deliver heat worked with combustion. To do so these devices require biomass or fossil fuels. Biomass is a more common option for space
heating than for water heating. The most traditional space heater can be found in wood furnaces. Wood was the first heating fuel and is still very common in Portugal representing 42.3% [14] of all space heating options. Wood furnaces exist in many different shapes and sizes with different efficiencies and prices. Furthermore, the efficiency of these appliances depends also on the used wood.

Fossil fuels are more used for water heating. It exist the option to store water in a proper tank or to heat it instantaneously. For both cases, conventional water heaters are suited. Natural gas is the most used fuel in Portuguese cities, while propane can be bought in bottles and has more practice in rural areas [14]. From Figure 2-8 one can clearly conclude that the instantaneous water heating option is most used. Natural gas and propane water heaters operate basically the same way. For the instantaneous heating, a gas burner heats normally a copper pipe where the water flows by. The copper pipe is the best option due to its high thermal conductivity. The heated water flows then directly to the water draw-offs. In these systems gases are produced from the combustion and there exist three different ways to treat them. They can leave the inside from the house by ambient, vented or sealed exhaustion. Vented or sealed exhaustion is normally installed when the buildings are localized in a denser population zone (with more buildings around them). Notice that these three options have different efficiencies (Figure 2-9).

![Figure 2-9: Exhaustion options of tankless gas systems: Left-ambient; Middle-vented; Right-sealed [15]](image)

In the storage tank, a gas burner heats the water in the tank, a process which is regulated with a thermostat. Unfortunately storage tanks have heat losses and thus these systems require energy even when no hot water is demanded. The system gases in the storage option are released in a sealed chimney. Fossil fuels are also very used for central heating boiler systems. Boiler systems work in the same manner. Again their efficiency depends on how the exhaustion gases are treated. These systems present the possibility to use the heat from the exhaustion gases by condensing them before releasing. But there exist also the ambient and sealed exhaustion as for the instantaneous heaters.

When electricity conquered the market, electrical heater became the most common heating option (see Figure 2-7). There are different ways to convert electricity into heat, being the most common one the electrical resistance. The electrical resistance heats up, when current passes through it due to Joule’s effect. In its most pure form, the electrical resistance heats directly air or water and the heat is spread due to convection. Other options such as heating first oil in a ceramic body with a resistance and then the oil convection passes heat to the surrounding air are also common space heating options.
Infrared heaters use also electricity as energy source. They differ from the previous heaters as they do not use Joule’s effect to heat air. These devices emit infrared radiation which heats directly all surrounding bodies such as the walls, floor, people and furnishings.

2.6.2 Heat pumps

The heat pump system is another option to heat water or air with electricity. These devices are very diverse as they can be used with different sources (surrounding air, water and ground). For this reason they received their own category amongst the heating types and differ from other electrical options due to their high efficiency. As they are not generating heat directly, these devices can achieve efficiencies greater than any other devices. The heat pump is constituted by four basic elements: an evaporator, a compressor, a condenser and an expansion valve. Inside these machines a transport fluid with a high thermal conductivity is used, which passes through all these elements in order to heat the desired air or water. Inside the evaporator the transport fluid receives heat from the surrounding heat source (air, water or ground) and thus it evaporates. The gas then passes into the compressor pump where its temperature is increased. Afterwards the transport fluid transfers its heat to the desired by passing through the condenser, where it becomes liquid again. The expansion valve controls the flow of the fluid. The cycle repeats itself (Figure 2-10). For air space, it can be operated reversely and therefore used to cool the air.

![Heat Pump Working Principle](image)

2.7 Renewable energy technologies

Efficient behaviour and the implementation of renewable energy systems is the only way to reach Net Zero households. In order to understand better which renewable resources could be used for onsite production, this section gives an overview of the available renewable technologies nowadays. Renewable energies resources are defined as “energy resources that are inexhaustible considering the time horizon of humanity [16]”. They can be divided into three main groups: energy prevailing from the sun, due to gravitational effects and from geothermal processes. Solar energy can be divided into direct and indirect energy. Indirect solar energy contains phenomena such as wind, plant growth and water flow in rivers. Technologies that permit to extract these energy resources are for instance wind turbines, biomass combustion and hydro plants. Direct solar
energy can be converted into heat or electricity with thermal solar equipment or photovoltaics, respectively. Geothermal energy refers to heat from the Earth’s interior which can be extracted with different technologies and can be used as heat and/or electricity source. Gravitational relations between Earth and Moon create tides, whose energy can also be extracted with proper devices (see Table 2-4).

<table>
<thead>
<tr>
<th>Renewable Resource</th>
<th>Technologies</th>
<th>Provided energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Indirect energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind power</td>
<td>Wind turbine</td>
</tr>
<tr>
<td></td>
<td>Hydro power</td>
<td>Hydro turbine</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td>Heating plant,</td>
</tr>
<tr>
<td></td>
<td>Ocean current</td>
<td>Wave power plant</td>
</tr>
<tr>
<td></td>
<td>Direct energy</td>
<td>Solar radiation</td>
</tr>
<tr>
<td></td>
<td>Solar radiation</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar collectors</td>
</tr>
<tr>
<td>Moon</td>
<td>Gravitation</td>
<td>Tides</td>
</tr>
<tr>
<td>Earth</td>
<td>Isotopes decay</td>
<td>Geothermal</td>
</tr>
</tbody>
</table>

Table 2-4: Available renewable energies

The next section will present renewable energy production in Portugal and the percentage associated to renewables in the Portuguese grid. After this, renewable onsite production options are considered. Taking into account the advancement of renewable technologies it is proper to say that for an onsite production we should consider thermal solar collectors, photovoltaics, wind turbines, geothermal heat pumps and biomass combustion.

2.7.1 Renewables present in the Portuguese grid system

Renewables coming from primary energy are normally included as electrical energy in the grid. The renewable resources are mainly hydro and wind energy in Portugal with 29.4% and 23.7% of the total electricity production for Portugal in 2014, respectively - Figure 2-11. In the past years, Portugal’s percentage of renewable energies in the total electricity production (%RE\textsubscript{grid}) has been increasing. In 2010 the %RE\textsubscript{grid} was around 40%; in 2014 this value went up to around 62%. This is due to an increasing renewable capacity installation, but also due to favourable weather conditions [17], in particular to rainfall above average. With an average annual daytime temperature of 17.92°C [18], the energy needs for space heating are low compared to northern European countries or more continental climates.

Given these values, the electricity that clients in Portugal buy includes already about 52% (average from 2010 to 2014) of renewable energy sources. Seen in terms of a bigger percentage of renewables present in the energy household consumption, energy services that can be realized by electrical appliances should substitute appliances that need other fuels such as natural gas, propane or butane. However, in order to reach a Net Zero household, it is necessary to generate additionally renewable energy onsite. Taken into account that Portugal is one of the sunniest European countries with 2500 to 3200 annual sun hours (see Figure 2-12) [19], sun energy is an attractive option for onsite production. Besides this renewable, biomass and wind energy are interesting options that will be studied in this work.
Also some more expensive investment options are interesting to be considered such as geothermal energy. Not always one needs to go really deep in order to avail this energy source. Space heating and cooling systems are able to work with a lower depth by circulating air from the ground, which maintains a constant temperature over the year.

Figure 2-12: Conditions in Europe for solar energy production [18]

2.7.2 Solar Thermal collectors

The designation of thermal sun energy is a large range, which includes solar thermal power plants, photolysis systems for fuel production, and solar collectors for water heating and passive solar heating systems. As this work is focused on onsite production for residential buildings, the two available systems for flat solar collectors are considered. There exist also more efficient collectors as vacuum sealed collector tubes, however they are more expensive and usually don’t pay off [20].

Flat solar collectors are the most common devices used for residential water heating. They are constituted out of a black painted metal (normally copper or aluminium) under which are installed black collector tubes. At the back and at the sites of the construction a proper isolation helps to keep the heat inside the collector. The
construction is closed by a transparent non-reflecting glass. It is possible to purchase two options for flat solar water heating devices: a forced circulation system and a thermosyphon system. The thermosyphon system distinguishes from the circulation system as it does not need any pump in order to perform heat movement (Figure 2-13) and thus it does not require additional electrical energy.

![Figure 2-13: Left side – thermosyphon system | Right side - circulation system[16]](image)

Thermosyphon systems are only used for the energy service of water heating, having for this purpose their own storage tank associated. The associated collector fluid is the water itself or a collector fluid such as glycol, which is an anti-freeze solution. The forced circulation system heats a water storage tank, which is eventually heated additionally by other technologies. The collector fluid in these systems is not necessarily water as the fluid in the tubes is not used, but just serves to provide the heat exchange. Therefore the forced circulation system can also help to provide space heating with irradiation [20].

### 2.7.3 Photovoltaics (PV)

As mentioned in the previous section, Portugal is one of the sunniest countries in Europe, which is why sun energy is especially interesting for renewable onsite production (Figure 2-12). Not just hot water can be obtained with solar irradiation, but also electrical current. This process is denominated photovoltaics. In 2014, Portugal has generated 588GWh of photovoltaic energy [21].

A PV solar panel is constituted by semiconductor modules and a support system, which includes the wiring, the DC/AC inverter (for systems connected to the electrical grid) or battery and a charge controller (for standalone systems). The PV evolution went mainly down on silicon cells. More recently, PV technologies with thin films are produced. Furthermore, there are also interesting investigations in these areas such as organic photovoltaic modules that present some promising outcomes.

The so called conventional PV technologies dominate with 87% of the global share the PV market in these days. They are made out of silicon crystals, which can be classified into three different types: Monocrystalline silicon, multicrystalline silicon and silicon tapes. Silicon tape technology evolves a production process in where silicon is melted and pushed. It only represents 3% of the total market and will not be considered an option for this project [22]. The technology for monocrystalline PV modules is obtained from cutting a bar of pure monocrystalline silicon (Figure 2-14).
This type of solar panel has the highest power-to-area ratio with efficiency between 135-170W/m². It has a bigger performance in cooler regions and presents conversion efficiency over 18%. The panels are generally long living with over 25 years. Today this type of panel represents 35% of the total PV market [23].

The so-called polycrystalline silicon modules, which are obtained from cutting a bar of silicon with many crystals (Figure 2-14), have a lower efficiency with values between 120-130W/m². Their price is cheaper than the monocrystalline silicon panels. The lower efficiency is due to the discontinuous structure, which hinders the electron movement. The panels are also generally long living with over 25 years. This type of panel represents today 49% of the total PV market [22].

The principle of energy production in the silicon crystal is based on the phenomena of photoelectric effect. The atom of silicon presents fourteen protons and fourteen electrons, being four of them valence electrons. A silicon crystal is formed from silicon atoms that align in a web structure, where they connect with their four valence electrons between each other. Thus if a photon (coming from the sun) with enough energy hits one electron, it will jump from the valence band to the conduction band, leaving a hole in the valence band. This hole behaves as a positive charge and one says that the photon created an electron-hole pair [22].

In order to create electrical current it is needed to have an applied electrical field, otherwise the electrons would recombine. Using the doping process, which consists in including different material into the silicon to alter its electrical properties, it is possible to create two layers in the crystal. One layer called p (created with boron), which has an excess of positive charges and the other one called n (created with phosphor), which has an excess of negative charges regarding the pure silicon. A doped crystal is called semiconductor and the region where the two layers were formed is called the p-n junction. In this region the electrical field is created that is needed to generate the current. The electrical field separates the electrical charges: The electrons are sent to negative terminal and the holes to a positive. The terminals are connected to an exterior closed circuit, where due to this process will circulate direct current (DC) [22].

It is possible to obtain higher efficiency (up to 25%) by the use of solar concentration systems. These consist in optical systems (Fresnel lens or mirrors) in order to concentrate the solar radiation on the solar panel. Solar tracking systems are also considered to be part of this class, as they try to obtain the maximum solar radiation. These systems, which follow the sun’s motion during the day, are very efficient solutions in order to increase
the available energy from the sun that can be transformed into electrical energy. There are two types of solar tracking systems: they can rotate in one direction (following the sun during the day) or in two (following the sun during the day and obtain the optimal angle during the year). The two-axes tracking systems presents an average efficiency increase of 20% in relation to the normal panel efficiency and the one-axe tracking systems increase the efficiency in average about 15% [24].

2.7.4 Wind turbines

Wind turbines experienced a tremendous growth in the past years (Figure 2-15). This is mainly due to the new installed capacities in Asia. However, in Europe many countries are also increasing their installed capacities. In Portugal onshore wind power became an important energy producer. At the end of 2014, Portugal is the seventh country in the European Union (EU 28) with most installed wind power capacity, with a total of 4914MW [25]. The possibility to install this renewable resource also offshore permits higher wind speeds and more energy production. Unfortunately the offshore production has several drawbacks for Portugal, which is why Portugal chose an onshore implementation. The nonexistent of shallow waters makes it much harder to install a stable wind turbine. In addition, the energy delivery from the sea to the land is complicated and also the visual impact done on Portugal’s beaches could be considerable.

![Figure 2-15: Cumulative installed wind capacities worldwide](image)

There are two types of wind turbines, which can be divided into vertical and horizontal axis rotors. The big difference relies in the fact that vertical rotors rotate always perpendicular to the wind, while the generator itself is fixed. In the horizontal wind turbines rotate with the wind direction and their generator is not fixed [22]. This is the configuration of virtually 100% of the wind installed capacity in the world.

Vertical wind turbines work due to the wind flow on their blades. The shape with the biggest efficiency is called Darrieus-rotor. The Darrieus-rotor can be constituted of two or three blades and can reach efficiencies up to 40%. This type of wind turbine is most adequate in regions with lower wind speeds. Generally, the vertical turbines are cheaper than horizontal ones, but their efficiencies do not reach for now the high efficiency from the horizontal turbines. Thus normally it compensates to install horizontal wind turbines, which is why this type is the most used and known (Figure 2-16).
The rotors with multiple blades are most used in the agricultural sector for water pumps. These wind turbines experience their maximum power outcome with weak winds and can reach an efficiency of 30%. Today the three blades rotors are most used for electricity production. Even that these wind turbines would reach higher efficiencies with two blades; the three blade format is more stable, which permits the construction of wind towers higher than 100m. They can reach efficiencies up to 45%. Notice that the theoretical limit for wind turbine efficiencies is set by Betz limit and cannot pass the 59.3% [26].

For household needs, it is possible to purchase small horizontal wind turbines with up to a power of 1kW. In urban environment it is complicated to see wind turbines as certain energy deliver due to the strong changes in the wind speed in these areas. However, it is an interesting study option as onsite production as this renewable normally is more suitable for large wind power parks.

2.7.5 Biomass

The biomass concept involves products of animal or vegetable origin, which can deliver heat, electrical energy or fuels. It is the most diverse renewable energy, as it can be produced from various different sources and is the only renewable source that can be converted into heat, electrical energy or fuel. Solid biomass can be transformed directly into heat by combustion. This process is the available one for onsite usage in form of wood furnaces for space heating or biomass boiler for water and space heating. The biomass boiler works with the combustion of pellets. Pellets are compressed wood chips, but they can also be produced out of olive seeds, coconut shells or similar residuals. The combustion process can also be implemented industrially as in coal power plants [20]. Other industrial processes as presented in Figure 2-17 will not be further discussed in this thesis.
2.7.6 Geothermal energy

The word “geothermal” comes from the Greek words γη, which means Earth, and θερμος, which means heat. Thus the word itself identifies this energy resource. It is the extraction of heat from the interior of the Earth. Natural phenomena of this energy source can be observed in volcano, geysers and similar. The average geothermal flux is around 0.06 Wm$^{-2}$. In principle this energy resource is available over the whole planet. There are, however, regions that are more favourable than others. These regions are created due to the non-uniformity of the Earth’s crust and permit a higher geothermal flux than usual. Frontiers between tectonic plates are especially good regions for the heat extraction [28].

Generally, heat is extracted by a water flow, which delivers hot water or vapor to the surface. There are several processes which permit to transform the delivered into electricity or to use the heat directly. For now, the geothermal resource is not that relevant as it just produces 0.12% (167TWh) from the annual global energy (Figure 2-18) [29]. The biggest energy geothermal energy producer are the United States and the country with the highest potential do grow is New Zealand. However, this resource is interesting because of its availability in the whole world. In Portugal, there are only two power plants, which are located in the island of São Miguel Açores with a total installed capacity of 29MW.

Geothermal energy can also be used directly as heat source for single or district households. There are three possibilities to extract the heat from the Earth in minor scale [30]. First, it is possible to use a deep drilling where the heat exchange occurs deep under the building. This method gets more expensive and efficient the deeper the drilling enters the crust. In general, deep drilling has the biggest investment costs of the three possibilities. It is however, at some sites the only available opportunity for geothermal energy as requires almost none superficial area.
Second, the heat exchange can occur in circa 1.5m depth, which requires a higher area in order to perform the exchange. This method is called ground collector and is only available for houses with a respective garden. It is important to notice that the surface over the collector cannot be used.

For last, the heat exchange can be realized in water. The water can be situated in the ground or superficial. Both ways works, but the superficial approach has several drawbacks as bigger fluctuations in temperature. All three possibilities (see Figure 2-19) require normally the help of a heat pump. Thus for the residential energy sector, this work will not consider that the geothermal option is 100% renewable.
3 MODEL PROGRAMMING

To achieve NZEB implementation, three main goals have to be taken into account. The first one is to clarify the ambiguous definition as already discussed in previous sections, the second one concerns the development of a supporting methodology to compute the energy balance for different sites [31] and the third one is the cost efficiency of the solutions. The modeling process involves specifying all assumptions and necessary calculations made in order to formulate the goals to maximize or minimize. It also permits to present mathematically all variables and their associated constraints. In order to reach (nearly) NZEB, it should be first implemented energy efficiency measures in order to decrease energy consumption and then determine energy supply from renewable resources that match those needs. Simulating such a process is quite complex as not only the choice of renewables that are possible to install onsite as supply systems are important to develop an algorithm, but also the specific energy services, which are defined in this work as energy end-uses – Figure 3-1 [4], and the technologies to provide these services.

Figure 3-1: Model of residential end-uses and possible available energy sources [4]

The energy consumption in the considered building will depend on the required energy services and on the occupant’s behavior. On the other hand, producing energy from renewables is a strongly climate dependent process and depends also on the area availability [10]. Other important considerations as investment and maintenance costs have also to be considered. Taking all these variables into account, it is hard to take the right decisions for each site. Thus, to study NZEB implementations for a given site, optimization methods, which have been presented in section 2.4, are required [10]. This chapter will present the estimation of the energy consumption for a given household, the available technologies in the market to perform a given energy service and possible renewable energy onsite installations. This data is needed to optimize the available technologies and renewables for a given case.
3.1 Evaluating technologies for demand and supply

In order to compare and to choose the best suited option between different technologies for providing an energy service and to convert the renewable resources in another energy source, efficiency and optimum cost level should be considered.

3.1.1 Efficiency

Efficiency $\eta$ for a device is generally defined in equation (3-1).

$$\eta = \frac{E_{\text{produced}}}{E_{\text{consumed}}}$$  \hspace{1cm} (3-1)

where $E_{\text{produced}}$ is the produced energy and $E_{\text{consumed}}$ is the consumed energy. Thus the devices receive energy in one form and transform it into another form. During this process, not all energy can be used for the energy service due to irreversibility associated with any physical process.

Normally, efficiency is given in percentage, but there are some devices that have efficiencies higher than 100% like heat pumps as described in section 2.6.2. To distinguish those cases, heat pump efficiency values are called Coefficient Of Performance - COP. It is possible to calculate the COP for performing space heating or cooling as shown in equation (3-2). In case of cooling, the efficiency is also called Energy Efficiency Index – EEI (see equation (3-3)).

$$COP_{\text{heating}} = \frac{Q_h}{W'}$$  \hspace{1cm} (3-2)

$$COP_{\text{cooling}} = \frac{Q_c}{W'}$$  \hspace{1cm} (3-3)

where $Q_h$ is the heat supplied to the reservoir, $Q_c$ is the heat removed from the reservoir and $W'$ is the work that heat pump needs to exceed to do the heat transfer. The special characteristic of heat pumps is that the electrical energy $W'$ used in the whole process is less than the energy obtained in heat form $\Delta Q$.

The efficiency or COP value can be normally obtained directly from the developer. Notice that there are other approaches of efficiency measuring depending on seasonal effects or the chosen unit definition such as the American energy factor.

3.1.2 Cost approach

Often people tend to analyze just the initial purchase costs when deciding which technology they are going to buy. However, in order to optimize costs, in general it is important to consider not only the investment costs $I_o$, but also the fuel costs $C_{\text{fuel}}$ and the operation and maintenance costs $C_{\text{O&M}}$.

As for instance in [32], costs are normally analyzed with the Life-cycle-cost methodology. As it is a very common practice, this thesis will also consider this approach. Additionally, it is developed an alternative cost analyses, the levelized cost of technology.
3.1.2.1  Levelized cost of technology (LCOT)

The levelized cost of energy LCOE is a metric that is used in order to estimate the cost at which electricity must be generated in order to reach financial payback after a chosen period. This period is normally assumed to be the lifetime of a plant so that LCOE gives minimum value at which electricity should be sold. For its calculation all lifetime costs such as construction costs, fuel costs, taxes, operation and maintenance costs, insurances and others are taken into account and then divided by all energy produced in this time period. LCOE is a good comparison indicator between different generation options, thus it is very common to use LCOE when comparing overall costs of generated energy from a given source to others. In Europe it is normally measured in €/kWh or €/MWh [33].

In this work, this idea of LCOE is used in order to compare energy conversion technologies and their according devices for a given energy service. That is, the unit price per kWh that one needs to pay for a given technology in order to reach payback inside the technologies lifetime. The levelized cost of technology LCOT can be calculated with equation (3-4).

\[
LCOT = I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t} \sum_{i=1}^{n} M_t, e = (1 + i)^t
\]

where \(t\) is the year of lifetime, \(i\) the real interest rate in percentage, \(n\) the economic operational lifetime in years, \(A_t\) the annual total expenses in € in year \(t\) and \(M_t, e\) the consumed quantity of energy in year \(t\) in kWh. For this cost analyses, the annual total expenses are represented by the fuel or electricity costs over the year. The LCOT value will be calculated for the lifetime of the appliances which is assumed to be \(n=15\) years. For the onsite renewables, the lifetime is taken to be \(n=20\). The interest rate is \(i=3\%\) as the suggested value from the European Union [6].

3.1.2.2  Life cycle costs (LCC)

As defined by [34], life-cycle cost (LCC) is the numerator of equation (3-4) only. To be a little more specific, LCC is as the name indicates the sum of all costs over a lifetime for a given technology. This value can be more or less specified and it depends on the author how exact it is determined. For this work, LCC is given in equation (3-5) [32].

\[
LCC = I_0 + C_R + C_{O&M}
\]

with \(I_0\) as investment cost, \(C_R\) as the replacement cost and \(C_{O&M}\) as the operation and maintenance costs.

The replacement costs of given technological equipment can be obtained with

\[
C_R = \frac{I_0}{(1+i)^{n/2}}
\]

where \(i\) is the real interest rate and \(n\) is the calculation period. The real interest rate is taken 3\% and calculation period is 30 years; values which are suggested in the EPBD recast 2010.

The operation and maintenance costs can be calculated as
\[ OC = ae \times C_{\text{fuel}} \]

where \( ae \) is the discount factor taken energy price escalation into account and \( C_{\text{fuel}} \) the fuel price \[32\]. Therefore, the factor is given as

\[ ae = \frac{1 - (1 + i_e)^{-n}}{i_e} \]

The real interest rate taking energy price escalation into account is given as

\[ i_e = \frac{i - e}{1 + e} \]

The energy price escalation is assumed to be 2%.

In order to get the pretended unit, the obtained value is divided by the required energy during the calculation period. The costs for the onsite renewables are calculated as indicated in section 3.8.

### 3.1.3 Percentage of renewables

The factor of percentage of renewables \( \% \text{RE} \) is another relevant parameter. In the model, this factor will be important in order to evaluate when the chosen technologies reach net zero. Hence all renewable devices count with 100%, electrical devices connected to the grid with \( \% \text{RE}_{\text{grid}} \) with a value of 51.91% as it is the average value from 2010 to 2014 and fuel devices with 0%. Depending on how much energy is produced by the technologies, \( \% \text{RE} \) is weighted. This parameter will be essentially used to evaluate when the house is reaching a net zero balance. Notice that no energy export to the grid is considered.

### 3.2 Water heating

Water heating is considered one of the largest energy services in the European Union with a total consumption (EU-27) of 2156 PJ which corresponds to 124 Mt of \( \text{CO}_2 \) emissions per year. 20% of the expected savings for 2020 will come from efficiency measurements for water heating. In numbers this represents 450 PJ or 26 Mt \( \text{CO}_2 \) \[35\]. It appears that in the past years people’s behaviour in buying water heaters has been directed towards the initial purchase cost rather than life cycle cost. This is also due to few available information and most people miss their opportunity to install an effective water heater with which they could save money and reduce environmental impact in later years.

In \[35\] one can read about the most general approach to classify water heaters. The mentioned types can be classified as instantaneous water heating option or with a storage system. One action that the European Union decided to start in September 2015 is the labelling of all different kind of water heaters. The labelling will help clients to choose the best water heater not just from an economical point of view, but also regarding the ecodesign (more efficient, less noisy, less \( \text{CO}_2 \) emissions). Water heaters will be classified first from G to A, where A is the most efficient device, and until 2020 from G to A+++. It is foreseen that the labels A++ or A+++ can be only required from devices that include at least 50% of their energy source from a renewable option \[35\]. In order to distribute the energy labels among all water heater options, the European Union designed test load
profiles for the models and explained how the manufactures have to calculate the related efficiency. The efficiency for conventional water heaters and heat pumps $\eta_{WH}$ is given by equation (3-6).

$$
\eta_{WH} = \frac{Q_{\text{ref}}}{(Q_{\text{fuel}} + CC \times Q_{\text{elec}})(1 - SCF \times \text{smart}) + Q_{\text{acor}}}
$$

(3-6)

where $Q_{\text{ref}}$ is the sum of all useful energy content of water draw-offs, $Q_{\text{fuel}}$ and $Q_{\text{elec}}$ the daily fuel and electricity consumption, $CC$ the conversion coefficient, $SCF$ and $\text{smart}$ quantities relate to efficient usage of the equipment due to additional technology controls or environmental friendly behaviour and $Q_{\text{acor}}$ the ambient correction term which depends on the water heater model used. The efficiency for the solar water heater was defined by equation (3-7).

$$
\eta_{WH} = \frac{0.6 \times 366 \times Q_{\text{ref}}}{Q_{\text{total}}}
$$

(3-7)

where $Q_{\text{total}}$ is the total annual energy consumption and 0.6 the percentage of 366 days (one year) in which the solar water heater was able to perform its service. For Portugal this value seems a little rough. Furthermore, the EU did set the maximum rated heat output of 70kW and for storage systems a volume ≤ 500l. Biomass water heating systems were not yet considered due to a lack of information [35].

As this law is not yet implemented, it is not easy to get the needed consumption information (fuels and electricity with or without smart controls) from the manufactures for efficiency calculations. Thus, for this work there are only considered water heater types that one can purchase in Portugal.

In Table 3-1 all the considered water heating options and related data are displayed. The technologies were chosen essentially from two main Portuguese water heater producers: Vulcano and Junkers [15][36]. Both offer conventional water heater types and solar devices. Biomass is a quite unusual option thus the data was taken from Zantia and Viessmann.

The annual energy needed to heat water for a given household can be obtained from the well-known relationship between heat and temperature change $\Delta T$ [37]

$$
Q_{WH} = m c_p \Delta T
$$

(3-8)

where $m$ corresponds to the mass of water that is heated and $c_p$ is the specific heat of water which corresponds to $c_p = 11.62 \times 10^{-3} \frac{kWh}{kg\cdot^\circ C}$. The mass $m$ of heated water per day is given by

$$
m = 40 \times n \times f_{eh}
$$

(3-9)

where 40 is the number of litres of hot water needed per day for one person, $n$ is the number of persons in the household and $f_{eh}$ is the factor for hydro efficiency. $f_{eh}$ is 0.90 when considering an efficient behaviour or equipment and 1.00 otherwise. This efficient behaviour can be achieved from savings done by the persons living in the respective house or due to respective equipment.
Assuming that the annual average ambient temperature for Portugal is 18°C and that the heated water reach maximum temperature of 50°C (a value higher than 35°C, the defined minimum value for sanitary hot water [37]), \( \Delta T=32°C \) for a tankless system. In a storage system the temperature difference needs to be higher than the assumed as it losses heat while storing the water thus taking \( \Delta T=42°C \). Independent on the source, the energy that the water heating requires has to be produced. For a smart storage system the calculated value is 641.28 kWh/(year×person) and for the tankless systems it is 488.60 kWh/(year×person).

<table>
<thead>
<tr>
<th>Considered type</th>
<th>Fuel</th>
<th>Model</th>
<th>Variable for mathematical analysis</th>
<th>Efficiency ((^1))</th>
<th>Investment cost (€)</th>
<th>Fuel costs (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage systems</strong></td>
<td>Natural gas</td>
<td>Gas water heater</td>
<td>( x_{1AA} )</td>
<td>0.88</td>
<td>595-1760</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Gas water heater</td>
<td>( x_{1AB} )</td>
<td>0.88</td>
<td>595-1760</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td>Boiler</td>
<td>( x_{1BA} )</td>
<td>0.91</td>
<td>6226-7388</td>
<td>≈0.0412</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>Electrical water heater</td>
<td>( x_{1CA} )</td>
<td>1.00</td>
<td>143-650</td>
<td>≈0.1528</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heat Pump</td>
<td>( x_{1CB} )</td>
<td>4.30</td>
<td>2250</td>
<td>≈0.1528</td>
</tr>
<tr>
<td><strong>Solar radiation</strong></td>
<td></td>
<td>Forced circulation system</td>
<td>( x_{1DA} )</td>
<td>0.52</td>
<td>1990-3243</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermosyphon system</td>
<td>( x_{1DB} )</td>
<td>0.46</td>
<td>1515-2370</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>Instantaneous heating systems</strong></td>
<td>Natural gas</td>
<td>Gas geyser with ambient exhaustion</td>
<td>( x_{2AA} )</td>
<td>0.88</td>
<td>256-283</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Natural gas</td>
<td>Gas geyser with vented exhaustion</td>
<td>( x_{2AB} )</td>
<td>0.87</td>
<td>334-388</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Natural gas</td>
<td>Sealed gas geyser</td>
<td>( x_{2AC} )</td>
<td>0.92</td>
<td>450-509</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Gas geyser with ambient exhaustion</td>
<td>( x_{2BA} )</td>
<td>0.88</td>
<td>256-283</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Gas geyser with vented exhaustion</td>
<td>( x_{2BB} )</td>
<td>0.87</td>
<td>334-388</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Sealed gas geyser</td>
<td>( x_{2BC} )</td>
<td>0.92</td>
<td>450-509</td>
<td>0.0986-0.1020</td>
</tr>
</tbody>
</table>

Table 3-1: Considered Water heater options

### 3.3 Central heating options

Devices that perform space and water heating can be found in Table 3-2. Boiler systems as well as the thermal forced circulation system can perform both energy services or water heating separately, which is why they are presented in both tables. The hot water or transport fluid flows can pass through the floors or walls and irradiate heat to the desired area. For the biomass boiler it was considered the use of pellets.

\(^1\) Units according to technologies – see individual technology description for further details
The devices chosen for this analysis are presented in Table 3-2.

<table>
<thead>
<tr>
<th>Considered type</th>
<th>Fuel</th>
<th>Model</th>
<th>Variable for mathematical analysis</th>
<th>Efficiency (¹)</th>
<th>Investment cost (€)</th>
<th>Fuel costs (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boiler systems with storage</strong></td>
<td>Natural gas</td>
<td><strong>Condensed boiler</strong></td>
<td>Y_{1AA}</td>
<td>0.98</td>
<td>2295-2750</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Boiler with ambient exhaustion</strong></td>
<td>Y_{1AB}</td>
<td>0.93</td>
<td>1705-2343</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sealed boiler</strong></td>
<td>Y_{1AC}</td>
<td>0.95</td>
<td>2003-2458</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td><strong>Propane</strong></td>
<td></td>
<td><strong>Condensed boiler</strong></td>
<td>Y_{1BA}</td>
<td>0.98</td>
<td>2295-2750</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Boiler with ambient exhaustion</strong></td>
<td>Y_{1BB}</td>
<td>0.93</td>
<td>1705-2343</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sealed boiler</strong></td>
<td>Y_{1BC}</td>
<td>0.95</td>
<td>1820-2458</td>
<td>0.0986-0.1020</td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td>Solar radiation</td>
<td><strong>Forced circulation system</strong></td>
<td>X_{1DA}</td>
<td>0.52</td>
<td>1990-3243</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td><strong>Boiler</strong></td>
<td>X_{1BA}</td>
<td>0.91</td>
<td>6226-7388</td>
<td>0.0412</td>
</tr>
</tbody>
</table>

| **Tankless boiler systems** | Natural gas  | **Condensed boiler**                       | Y_{2AA}                            | 0.98           | ≈1750               | 0.0746-0.0791      |
|                            |              | **Boiler with ambient exhaustion**         | Y_{2AB}                            | 0.93           | ≈1343               | 0.0746-0.0791      |
|                            |              | **Sealed boiler**                          | Y_{2AC}                            | 0.95           | ≈1458               | 0.0746-0.0791      |
| **Propane**               |              | **Condensed boiler**                       | Y_{2BA}                            | 0.98           | ≈1750               | 0.0986-0.1020      |
|                            |              | **Boiler with ambient exhaustion**         | Y_{2BB}                            | 0.93           | ≈1343               | 0.0986-0.1020      |
|                            |              | **Sealed boiler**                          | Y_{2BC}                            | 0.95           | ≈1458               | 0.0986-0.1020      |

Table 3-2: Water and space heaters

### 3.4 Thermal comfort

Space heating is considered the biggest energy consumer with 16% of the total energy consumption in the European Union (EU-27). Savings for 2020 are foreseen to be 1900 PJ or 110 Mt CO₂. Space heaters are undergoing the same procedure as water heaters in the European Union labelling policy. Just as them, space heaters need to be better classified so that the client is able to choose properly. For labelling space heaters the classifications will vary from G to A, where A is the most efficient device, and until 2020 from G to A++. It is foreseen that the labels A+ to A+++ can be only required from devices that include cogeneration and renewables. Heat pumps will also be included in the A class as their efficiency is higher than 115%. Once again, biomass heating options were excluded for now [38].

¹ Units according to technologies – see technology description for further details
Space cooling is a smaller energy consumer than space heating and not all actual Portuguese households perform this energy service [14]. Normally, this energy service is performed only by natural ventilation or with a heat pump. When installing a heat pump for space heating it is just convenient to use it also for space cooling. In order to know when space heating or cooling is required, Lisbon temperature data from the last six years was analyzed [19] (Figure 3-2).

To determine the heating and cooling needs, a simple calculation method can be applied using degree-days [39]. Summing all the values of temperature over 25°C and all the values of temperature beneath 15°C will give us the sum of all heating and cooling degrees respectively needed in these six years. One then can easily obtain the number of heating or cooling degree days for an average year. Thus the number of heating degree days is 476.83°C.day and number of cooling degree days is 56.83°C.day.

![Figure 3-2: Temperature data and reference temperature](image)

![Figure 3-3: Required heating and cooling degrees for Lisbon](image)
From Figure 3-3 it is trivial to see that a lot more space heating is required over the year than space cooling. However, the energy needs for these services do not just depend on the outside temperature. Building constructions as well as habitant’s behaviour influence the demand. Energy needs for space heating $Q_{SH}$ and space cooling $Q_{SC}$ are calculated as defined by [37].

### 3.4.1 Space heating

To determine the space heating needs, we will follow the general methodology defined for Portugal [39]. As the analysis is quite complex, all relevant parameters and their corresponding units are defined in Table 3-3.

| $Q_{SH}$ | kWh m⁻² year⁻¹ | Energy demand for space heating |
| $Q_{tr,i}$ | kWh | Heat transfer via buildings surroundings |
| $Q_{ve,i}$ | kWh | Heat transfer by ventilation |
| $Q_{gs,i}$ | kWh | Heat earnings due to solar radiation |
| $A_p$ | m² | Interior pavement area |
| $GD$ | ºC day⁻¹ | Numbers of heating degrees |
| $H_{tr,i}$ | W ºC⁻¹ | Global heat transfer coefficient due to heat transmission |
| $H_{ve,i}$ | W ºC⁻¹ | Global heat transfer coefficient due to ventilation |
| $R_{ph,i}$ | h⁻¹ | Nominal air renovation rate |
| $P_d$ | M | Wall height |
| $\eta_i$ | | Usage rate of thermal gains |
| $Q_{g,i}$ | kWh | Total thermal gains |
| $Q_{int,i}$ | kWh | Thermal gains due to internal heating sources |
| $Q_{sol,i}$ | kWh | Thermal gains due to outside solar radiation |
| $q_{int}$ | Wm⁻² | Internal thermal gains per unit area (defined as 4Wm⁻²) |
| $M$ | Month | Duration of the heating season |
| $G_{sul}$ | kWh m⁻² month⁻¹ | Average month sun irradiation value on a vertical south orientated surface |
| $X_j$ | | Orientation factor |
| $F_{s,ln,j}$ | | Obstruction factor of the window n with orientation j |
| $A_{s,ln,j}$ | m² | Area of window n with orientation j |
| $H_{ext}$ | W ºC⁻¹ | Heat transfer coefficient through walls in contact with the ambient |
| $H_{enu}$ | W ºC⁻¹ | Heat transfer coefficient through elements in contact with not used space |
| $H_{adj}$ | W ºC⁻¹ | Heat transfer through elements in contact with surrounding buildings |
| $H_{ecs}$ | W ºC⁻¹ | Heat transfer through elements in contact with the ground |
| $U_i$ | Wm$^{-2}$ºC$^{-1}$ | Heat transfer coefficient through element $i$ from the buildings surroundings |
| $A_i$ | m$^2$ | Area of element $i$ from the buildings surroundings |
| $\varphi_j$ | Wm$^{-1}$ºC$^{-1}$ | Linear thermal transmission coefficient of the thermal bridge $j$ |
| $B_j$ | M | Linear development of thermal bridge $j$ |
| $b_{tr}$ |  | Reduction coefficient due to contact with another building |

**Table 3-3: Variables and units used to calculate energy demand for space heating**

The energy needed to satisfy space heating $Q_{SH}$ can be calculated using

$$Q_{SH} = \frac{(Q_{tr,i} + Q_{ve,i} - Q_{gw,i})}{A_p} \quad (3-10)$$

The first term determines the value for the heat losses $Q_{tr,i}$ due to the buildings envelopes. The heat losses depend on the heating needs and can be presented by the equation (3-11).

$$Q_{tr,i} = 0.024 \times GD \times H_{tr,i} \quad (3-11)$$

$GD=476.83$ºC.day in average was estimated for the annual heating season for a building in Lisbon area. The global heat transfer coefficient through the buildings envelope can be obtained by

$$H_{tr,i} = H_{ext} + H_{enu} + H_{adj} + H_{ecs}.$$  

As it is not known the exact structure and orientation of the building, the heat transfer with the ground and empty spaces is neglected. Thus $H_{tr,i}$ depends on the heat transfer from the envelope in contact with the exterior or other buildings.

$$H_{ext} = \sum_i [U_i \cdot A_i] + \sum_j [\varphi_j \cdot B_j]$$

$$H_{adj} = b_{tr} \times \left( \sum_i [U_i \cdot A_i] + \sum_j [\varphi_j \cdot B_j] \right)$$

Given the consideration of a NZEB, effects due to linear thermal bridges $\varphi_j, B_j$ are not desired and thus not considered. The heat transfer coefficient $U_i$ for a NZEB can be assumed to be $U=0.15$ Wm$^{-2}$ºC$^{-1}$ for an isolated wall and $U=0.50$ Wm$^{-2}$ºC$^{-1}$ for windows [40]. The g-value (solar transmittance) for the windows is about 50% [40]. Notice that these values are just assumptions and may not correspond completely to real heating and cooling needs. The majority of windows should face south and their area should at the most be 15% of the floor area [41][42]. $b_{tr}$ reduces about 40% of thermal transmission when the wall is contact with other buildings or room, that is $b_{tr}=0.6$. With this information, it will be possible to determine the heat transfer losses. However the value will be approximate as each house is a special case.

Ventilation is an important aspect for the house comfort as it renews the air, which permits new O$_2$ supply and has the effect that this new air is quicker heated or cooled due to convection. Furthermore, this aspect is, when
not regulated by technological options, a strongly behavioural parameter. The value of ventilation heat transfer can be estimated by equation (3-12).

\[ Q_{ve,i} = 0.024 \times GD \times H_{ve,i} \]  
\[ (3-12) \]

\[ H_{ve,i} = 0.34 \times R_{ph,i} \times A_p \times P_d \]

The height of the walls \( P_d \) is considered to be 2.5m. The nominal air renovation rate should take at least the value \( R_{ph,i}=0.6 \text{ h}^{-1} \) after NP1307[39]. At last, the value of sun irradiation is determined (equation (3-13)). This value helps to decrease the energy demand for this energy, especially in Portugal with its many sun hours.

\[ Q_{sun,i} = \eta_{i} Q_{g,i} \]  
\[ (3-13) \]

\[ Q_{g,i} = Q_{int,i} + Q_{sun,i} \]

\[ Q_{int,i} = 0.72 q_{int} \times M \times A_p \]

\[ Q_{sun,i} = G_{sun} \sum_{j} \left[ X_j \sum_{n} F_{s,inj} \times A_{s,inj} \right] \times M \]

The vertical global irradiance is taken \( G_{sun}=117.05 \text{ Wm}^{-2} \) [18]. From [37] it is defined that \( q_{int}=4 \text{ Wm}^{-2} \), and that \( X_j.F_{s,inj} \geq 0.27 \). In order to calculate the usage rate of thermal gains \( \eta_{i} \), it is defined \( \gamma = \frac{Q_{g,i}}{(q_{tr}+Q_{ve})} \). Depending on this value, the rate of thermal gains can be calculated with equation (3-14).

\[ \gamma \neq 1 \text{ & } \gamma > 0 \quad \eta = \frac{1 - \gamma^a}{1 - \gamma^{a+1}} \]  
\[ (3-14) \]

\[ \gamma = 1 \quad \eta = \frac{a}{a+1} \]

\[ \gamma < 0 \quad \eta = \frac{a}{a+1} \]

where the value for low thermal inertial buildings is \( a=1.8 \text{ W}^{\circ} \text{C}^{-1} \).

For a house with 100m² and two envelope sites in contact with another building, the calculation gives a value of 174.11kWh/year. The value of space heating depends essentially on the chosen isolation. If the heat transfer coefficient is not that efficient as assumed here, the space heating demand for 100m² is about 850kWh/year. This value is consistent with the analysis done by [4]. All considered space heating devices can be found in Table 3-4. For this analysis, the chosen biomass option for a common furnace is pine wood. Notice that to the equipment efficiencies are added the distribution efficiencies, depending on how the heat is ultimately delivered.
<table>
<thead>
<tr>
<th>Considered type</th>
<th>Model</th>
<th>Variable for mathematical analysis</th>
<th>Efficiency ( (%) )</th>
<th>Investment cost (€) ( (4) )</th>
<th>Fuel costs (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical heaters</strong></td>
<td>Mono-split air conditioner</td>
<td>( z_{1AA} )</td>
<td>3.9</td>
<td>=790</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Multi-split air conditioner</td>
<td>( z_{1AB} )</td>
<td>3.8</td>
<td>=1030</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Oil convection heater</td>
<td>( z_{1B} )</td>
<td>1.00</td>
<td>=90</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Infrared heater</td>
<td>( z_{1C} )</td>
<td>1.00</td>
<td>=24</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Electrical resistance heater</td>
<td>( z_{1D} )</td>
<td>1.00</td>
<td>=145</td>
<td>0.1528</td>
</tr>
<tr>
<td><strong>Geothermal heating options</strong></td>
<td>Probe sole</td>
<td>( z_{2AA} )</td>
<td>4.66</td>
<td>=18000</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Horizontal sole</td>
<td>( z_{2AB} )</td>
<td>4.66</td>
<td>=15000</td>
<td>0.1528</td>
</tr>
<tr>
<td><strong>Biomass heater</strong></td>
<td>Wood furnace</td>
<td>( z_{3} )</td>
<td>0.70</td>
<td>=904</td>
<td>0.0049</td>
</tr>
<tr>
<td><strong>Propane</strong></td>
<td>Portable space heater</td>
<td>( z_{4} )</td>
<td>0.80</td>
<td>=968</td>
<td>0.0986-0.1020</td>
</tr>
</tbody>
</table>

**Table 3-4: Considered options for Space Heaters**

### 3.4.2 Space cooling

It is to note that this calculation is similar to the space heating approach, which is why some variables used in both calculations are not presented again in table Table 3-5.

| \( Q_{SC} \) | kWh m² year\(^{-1} \) | Energy demand for space cooling |
| \( Q_{g,v} \) | kWh            | Total thermal gains            |
| \( \eta_v \) | kWh            | Usage rate of thermal gains    |
| \( \theta_{v,ref} \) | °C            | Reference temperature over which cooling is needed (25°C) |
| \( \theta_{v,ext} \) | °C            | Outside average temperature in cooling season |
| \( L_v \) | h             | Duration of cooling season (2928h) |

**Table 3-5: Variables and units used to calculate energy demand for space cooling**

The energy needed for space cooling can be calculated by

\[
Q_{SC} = \frac{(1 - \eta_v) Q_{g,v}}{A_p}
\]  
(3-15)

To calculate the usage rate of thermal gains \( \eta_v \), it is again defined \( \gamma = \frac{q_{g,v}}{(q_{tr} + q_{ve})} \). Depending on this value, the rate of thermal gains can be calculated with equation (3-16).

---

3 Units according to technologies – see technology description for further details  
4 Depends on the required heating area (Single rooms or whole house)
\[ \gamma \neq 1 \& \gamma > 0 \quad \eta = \frac{1 - \gamma^a}{1 - \gamma^{a+1}} \tag{3-16} \]

\[ \gamma = 1 \quad \eta = \frac{a}{a + 1} \]

\[ \gamma < 0 \quad \eta = \frac{1}{\gamma} \]

With \( a = 1.8 \, W^\circ C^{-1} \) which is the value for low thermal inertial buildings.

Thus, first the heat transfer via ventilation and building transfer has to be calculated with equations in (3-17) and (3-18). The assumptions made for space heating are also valid in this case.

\[ Q_{tr,v} = \frac{H_{tr,v}(\theta_{v,ref} - \theta_{v,ext})L_v}{1000} \]

\[ H_{tr,v} = H_{ext} + H_{enu} + H_{ecs} \]

\[ H_{ext} = \sum_i [U_i \cdot A_i] + \sum_i [\varphi_i \cdot B_i] \] \tag{3-17}

\[ Q_{ve,v} = \frac{H_{ve,v}(\theta_{v,ref} - \theta_{v,ext})L_v}{1000} \]

\[ H_{ve,v} = 0.34 \times R_{ph,v} \times A_p \times P_d \] \tag{3-18}

Then the total thermal gains can be estimated with the set of equations (3-19).

\[ Q_{g,v} = Q_{int,v} + Q_{sol,v} \]

\[ Q_{int,v} = \frac{q_{int} \times A_p \times L_v}{1000} \] \tag{3-19}

\[ Q_{sol,v} = \sum_j [G_{solj} \sum_n F_{x,v,nj} A_{x,v,nj}] \]

Also the space cooling value was confirmed with the study performed by [4]. For a not isolated house, the value for a cooling area of 100m\(^2\) is about 245kWh/year. When considering however a NZEB (altering the U value), this value deceases to 133.86kWh/year. The cooling options can be seen in Table 3-6. In this table air conditioners (AC) and geothermal heat pumps are considered.

<table>
<thead>
<tr>
<th>Considered type</th>
<th>Model</th>
<th>Variable for mathematical analysis</th>
<th>Efficiency ((^{\circ}))</th>
<th>Investment cost ((\text{€}))(^5)</th>
<th>Fuel costs ((\text{€}/\text{kWh}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical coolers</td>
<td>Mono-split AC</td>
<td>(z_{1AA})</td>
<td>6.00</td>
<td>(\approx 790)</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Multi-split AC</td>
<td>(z_{1AB})</td>
<td>5.80</td>
<td>(\approx 1030)</td>
<td>0.1528</td>
</tr>
</tbody>
</table>

\(^5\) Units according to technologies – see technology description for further details

\(^6\) Depends strongly on the required heating area (Single rooms or whole house)
## 3.5 Food cooling

Another important energy service is food cooling. The storage of food and its fresh-keeping is essential for today’s households. Even there exist some alternative food cooling systems such as clay pots, in this work there are considered the most usual option. Additionally, both fridge and freezer are essential installation options. There are different methods how to install these two appliances. 58.5% of Portuguese families have a combined fridge which has a compartment that is a freezer and 47.6% has a separate freezer [14]. The second option is more used in bigger families. There are also more high-tech fridges, the so-called American fridges; they normally have two doors, where one is a fridge and the other a freezer. They also provide crushed ice directly, however they consume a lot and thus they are not available in efficiency classes A+++

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Symbol</th>
<th>Considered type</th>
<th>Price (€)</th>
<th>Yearly consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+</td>
<td>$O_{a1}$</td>
<td>Simple fridge + freezer</td>
<td>$≈$678.5</td>
<td>$≈$432.5</td>
</tr>
<tr>
<td></td>
<td>$O_{b1}$</td>
<td>Combined Fridge</td>
<td>$≈$539.5</td>
<td>$≈$288.0</td>
</tr>
<tr>
<td></td>
<td>$O_{c1}$</td>
<td>American Fridge</td>
<td>$≈$1049.5</td>
<td>$≈$434.5</td>
</tr>
<tr>
<td>A++</td>
<td>$O_{a2}$</td>
<td>Simple fridge + freezer</td>
<td>$≈$1568.0</td>
<td>$≈$347.0</td>
</tr>
<tr>
<td></td>
<td>$O_{b2}$</td>
<td>Combined Fridge</td>
<td>$≈$774.0</td>
<td>$≈$268.5</td>
</tr>
<tr>
<td></td>
<td>$O_{c2}$</td>
<td>American Fridge</td>
<td>$≈$1799.0</td>
<td>$≈$348.0</td>
</tr>
<tr>
<td>A+++</td>
<td>$O_{a3}$</td>
<td>Simple fridge + freezer</td>
<td>$≈$2198.0</td>
<td>$≈$236.0</td>
</tr>
<tr>
<td></td>
<td>$O_{b3}$</td>
<td>Combined Fridge</td>
<td>$≈$1024.5</td>
<td>$≈$160.5</td>
</tr>
</tbody>
</table>

Table 3-7: Considered food cooling options

Most of the chosen options in Table 3-7 are taken from Siemens. The efficiency classes for fridges and freezers range from G to A+++, where G is the least efficient class. In this work the considered options range from A+ to A++ with the most economical friendly. Refrigerator appliances are sorted into the efficiency classes by calculating their Energy Efficiency Index (EEI)[43]. The EEI is calculated by equation (3-20).

$$EEI = \frac{AE_c}{SAE_c} \times 100, \quad (3-20)$$

where $AE_c$ is the annual energy consumption of the refrigerator, which is obtained by measuring the energy consumption for 24 hours and multiplying by 365 and $SAE_c$ the standard annual energy consumption which is a reference consumption based on the storage volume and type of refrigerator. EEI values lower than 22 identify refrigerators with A+++ class, between 22 and 33 A++ class and between 33 and 42 A+ class.

The analysis for the refrigerators is different from the previous sections as energy consumption is a given parameter for each option. Thus this work compares the technologies $O_x$ based on price $P_x$ and consumption $Q_x$ with equation

$$O_x = P_x \times \sum_{n=1}^{15} \frac{0.1528 \times Q_x}{(1+i)^n}, \quad x \in \{a1, a2, a3, b1, b2, b3, c1, c2\}$$

where 0.1528 is the actual electricity price in €/kWh and $i$ the discount rate.
Efficiencies are not considered separately in this analysis as they are already present in the energy consumption value.

### 3.6 Lighting

Similar as for food cooling, lamps are being classified into energy classes from A to G. Today, LEDs are able to be included in the class A+, CFLs in class A and halogen lamps in class C, which is not that better than incandescent lamps [44].

Similar as refrigerators, the classes are established with energy efficiency classes \((EEI)\) [45]. In this case, the classes can be calculated with equation (3-21).

\[
EEI = \frac{P_{cor}}{P_{ref}}
\]

where \(P_{cor}\) is the corrected (due to gear losses) rated power and \(P_{ref}\) the reference power. The last one depends on the measurement of the luminous flux \(\Phi\). The reference power can be obtained by equation (3-22).

\[
P_{ref} = \begin{cases} 
0.088\sqrt{\Phi} + 0.049 & \Phi < 1300 \text{ lumen} \\
0.07341\Phi & \Phi \geq 1300 \text{ lumen}
\end{cases}
\]

For EEI values lower than 0.11, the energy efficiency class will be A++.

For this work, the lamps analysis is limited to LEDs and CFLs as they seem to be the lamps with most net zero potential. Their main characteristics are summarized in Table 3-8.

<table>
<thead>
<tr>
<th>Lamp</th>
<th>EEI</th>
<th>Price (€)</th>
<th>Power (W)</th>
<th>Lifetime (h)</th>
<th>Lm/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED</td>
<td>0.14 (A+)</td>
<td>≈10</td>
<td>≈6</td>
<td>15000</td>
<td>400</td>
</tr>
<tr>
<td>CFL</td>
<td>0.2 (A)</td>
<td>≈16</td>
<td>≈12</td>
<td>10000</td>
<td>600</td>
</tr>
</tbody>
</table>

**Table 3-8: Chosen options for lighting**

To calculate the annual energy consumption for lighting, the area that is to illuminate has to be indicated and how many hours the illumination is used in average.

### 3.7 Other appliances

Consider other appliances in final optimization have to be considered in order to get as close as possible to a real household needs. The appliances most used in this sector are television, computer, aspirator, iron and printer. Also the electricity consumption of washing machines, which already contribute for water heating should be considered. These devices consume about 32.9% of all electricity consumption [14]. From [4] it is possible to assume the annual energy consumption of these appliances with 13kWh/m². This estimation is however rough, once this value is strongly behavioral. Therefore, the questionnaire includes some questions about the kitchen and washing appliances, considering the dishwasher, cooker system, washing machine and dryer. Furthermore, the program is not just considering these values, but it is also possible to choose the appliances with the lowest LCOT.
3.8 Renewable implementation onsite

As biomass and geothermal energy are included in the demand technology options and their supply can be considered infinite in storage, they are not further considered in this section. Solar and wind supply systems are sized. In order to know how much energy can be produced from such renewable implementations, it is important to estimate how much energy is available from the resource.

3.8.1 Available solar resource

As already discussed in section 2.7, the available solar energy in a certain region can be estimated by the physical quantity irradiance $G$, which gives us the amount of power available per square meter. Therefore the available energy $H_i$, also called exposure, is directly proportional to the irradiance (equation (3-23)).

$$H_i = G_{average} \Delta t$$  \hspace{1cm} (3-23)

where $\Delta t$ is the amount of time measured in hours (for instance: a year has 8760 hours). Irradiance depends strongly on the position of the Sun-Earth system and on local weather conditions [46] (Figure 3-4).

![Figure 3-4: Irradiance depending on weather conditions and Sun-Earth position [46]](image)

Global irradiance is the sum of the direct sun irradiation and the diffuse irradiation. Moreover, the irradiance also depends on the position between the Sun and the Earth and therefore is a strongly angle depend value. The higher the value of irradiance, the higher will be the value of available energy and the more energy the PV panel can convert. The inclination of the PV panel will affect the value of the captured irradiance and thus it is important to study different panel inclinations.

The optimal inclination depends also on the time of the year. In Figure 3-5 the optimal angle for Lisbon was simulated [18]. However, as the NZEB analysis is performed in annual values, the overall best angle has to be determined.
It was possible to obtain data to analyze the best angle position over the year for Lisbon [18]. In Figure 3-6 the results are displayed.

For a fixed inclination system the best angle for yearly production is 34° and south faced (0° as azimuthally angle). This fixed angle is chosen one for solar thermal systems and fixed photovoltaics. For these solar options, the algorithm will optimize the used area, taken available roof area into account.

### 3.8.1.1 Solar Thermal systems

The description about the available solar thermal technologies can be found in section 2.7.2. The efficiency $\eta$ of solar water heaters can be calculated by

$$\eta = \eta_0 - k_1 \frac{(T_m - T_o)}{G} - k_2 \frac{(T_m - T_o)^2}{G}, \quad (3-24)$$

where $\eta_0$ is optical efficiency, which is the maximum efficiency without considering any heat losses, $k_1$ and $k_2$ are the first and second order heat loss coefficients respectively, $T_m$ is the mean temperature of the collector fluid, $T_o$ the mean ambient temperature and $G$ the global irradiance (Figure 3-7). $\eta_0$, $k_1$ and $k_2$ are normally given by the manufacture [16].
Figure 3-7: Collector efficiency at different irradiances and temperature difference (adapted from [16])

$T_a$ and $G$ can be estimated by [18] which gives the average yearly values for Lisbon of $T_a=17.92 ^\circ C$ and $G=467.51 \text{Wm}^{-2}$ considering the optimal inclination angle of $34 ^\circ$. $T_m$ is considered to be $50 ^\circ C$ for solar water heating systems [47].

These devices may however not be enough to produce the required heat over the whole year. The EU indicated the rough value of 60% [35] of the water heating needs that can be satisfied with thermal solar systems, which seems imprecise taking the number of people and the two distinguished technologies of the solar circuit system and thermosyphon into account. In order to estimate how much energy the solar option is able to produce over the year from the total required heat just for water heating $\%_{SUN}$, the produced energy from the solar heater is divided by the households energy needs for this service (see equation (3-25)).

$$\%_{SUN} = \frac{\eta \times A \times G \times h}{Q_{WH}} \quad (3-25)$$

where $A$ is the aperture area of the panel, $h$ the hours of sun irradiation per day and $Q_{WH}$ the energy needed for water heating. The results can be seen in Figure 3-8. In this calculations the storage capacity and number of panels are confirm the suggested values from the manufacture [15][36].
The obtained values are taken into account in the further development of the project. Notice that even the forced circulation system should not be considered a 100% renewable due to its pump which requires additional electrical energy. As the value is so low, thus for simplicity it is taken zero.

Other assumptions can be found in Table 3-1 and Table 3-2.

3.8.1.2 Photovoltaics

The technology of Photovoltaics (PV) is described in section 2.7.3. For the PV analysis, it was considered an monocrystalline PV panel from Sunpower with an efficiency of 20% [48]. Notice that the specific technological choice does not influence much the optimization outcome, once the modules are sold for ≈1€/Wp.

It is essential to know how much energy can be delivered per installed area of PV and how much it would cost. The produced energy $E$ from a PV system can be calculated with equation (3-26).

$$E = \eta_{inv}(P_{DC}) \sum_{i=1}^{n} P_{DC}(G,T) \Delta t_i,$$

where $\eta_{inv}(P_{DC})$ is the inverter efficiency, which is depend on the value of the maximum power $P_{DC}$, which for its site is depend on irradiance $G$ and temperature $T$. $\Delta t_i$ is the considered time interval and $n$ the number of considered periods. As equation (3-26) is highly panel depend and the optimization procedure so far not able to perform so much detail, equation (3-27) will be used.

$$E = \eta_{inv} H_{aver} \eta^r A,$$

where $\eta_{inv}$ is assumed to be 80%, $H_{aver}$ is the average annual exposure for the surface of 34°, $\eta^r$ is the efficiency of the panel at STC and $A$ the panel area [22]. From [18] it was possible to calculate that the average available annual energy in Lisbon at a 34° surface is 2032kWh/m². Considering the systems losses and the chosen solar panel, the actual usable energy is 227kWh/m².

For solar energy systems the available space will be optimized. Thus their cost calculation will include the investment cost in case of LCOT and investment and replacement costs in terms of LCC, regarding the assumed
calculation period for each case. Therefore, the units of LCC or LCOT for solar systems are €/m². Of course, the use of PV energy production has also storage limitations. The option to implement a battery storage onsite influences the percentage of produced energy that can actually be used inside the household. As the battery has a given capacity, when the battery is full, the additional energy or is not taken advantage of or is sold to the grid. Grid selling can be cost beneficial for the owner of renewable onsite production, as it can help to shorten the payback period. However, the program will not consider grid selling options. The decline of grid selling prices over the past years suggests that this option is not permanent. A future energy exchange between district houses seems more likely.

3.8.1.3 Battery for PV systems

Without the storage, most energy is available during the day. As people are working during daytime, the produced energy could be used for the refrigerators or sold to the grid. For the PV battery implementation there are two types of storage layouts available (Figure 3-9). Such systems include the battery, the PV generator, PV inverter, a charge regulator and a battery inverter. In the AC coupled system, the battery is connected to the PV system, while in the DC coupled system the battery is connected to the DC link of the PV inverter. It will be considered the AC coupled layout as suggested by [49]. The considered battery is lithium based.

![Figure 3-9: Storage layouts for PV systems: Left – AC coupled; Right–DC coupled][49]

In order to calculate the value of energy available for the household per square meter in each case, the degree of self sufficiency \( d \) is calculated. This degree gives us the value of the share of the load consumption that is supplied by the PV battery system – equation (3-28).

\[
    d = \frac{E_{DU} + E_{BD}}{E_{demand}} \tag{3-28}
\]

where \( E_{demand} \) is the energy demand of the household, \( E_{DU} \) is the energy used directly from the PV panel and \( E_{BD} \) is the energy discharged from the battery [49].

[49] analysed this parameter and was able to obtain Figure 3-10. Battery capacity values and PV system size are normalized with energy demand values. The values of self sufficiency of this analysis are used for the
program. Notice that with no battery storage, $d$ reaches around 30%. Another interesting observation is that PV systems for the residential area are normally sized around 1kWh/MWh. For these systems, it does not make much sense to install a battery capacity higher than 1.5kWh/MWh as $d$ will not increase higher than 56%.

![Figure 3-10: Degree of self sufficiency in function of normalized battery capacity and PV size](image)

3.8.2 Wind resource

In order to know how much energy can be obtained out of wind energy, equation (3-29) is used.

$$P_{\text{avail}} = \frac{1}{2} \rho A U^3$$  \hspace{1cm} (3-29)

where $P_{\text{avail}}$ is the available power, $\rho$ the air density, $A$ the swept area and $U$ the wind speed. As the wind speed influences the available power most, it is crucial to take a look at the Portugal’s wind atlas (Figure 3-11). As this work is interested in small heights, the atlas shows the average wind speeds for 10m.

One model to estimate the probability of wind speed occurrences is presented.

$$pdf(U) = \frac{k U^{k-1}}{c^k} e^{-\frac{U}{c}}$$

$$c = \frac{\bar{U}}{\Gamma(1 + k^{-1})}$$

Where $pdf(U)$ is the probability of the wind speed $U$, $k$ is the shape parameter and $c$ the scale parameter. From [26] the shape parameter for Lisbon can be considered 1.6. The average wind speed $\bar{U}$ can be taken out of Figure 3-11 with the value of 4.5ms$^{-1}$. Thus 10m will be considered to be the reference height $h_{\text{ref}}$. In order to know how much available energy we can get in function of height, equation (3-30) is first used to estimate wind speed variations with height.
where $z_o$ is the roughness length, which is the height at which the wind speed theoretically becomes zero or mathematically seen the height underneath which the model is not valid anymore.

\[
\bar{U}(h) = \bar{U}(h_{ref}) \frac{\ln \left( \frac{h}{z_0} \right)}{\ln \left( \frac{h_{ref}}{z_0} \right)}
\]

(3-30)

Figure 3-11: Wind atlas for Portugal at 10m height [50]

Thus this parameter depends strongly on the chosen implementation site. The used roughness values are taken from [51] (Table 3-9).

<table>
<thead>
<tr>
<th>Site</th>
<th>Average roughness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside city</td>
<td>1.2</td>
</tr>
<tr>
<td>Green urban areas</td>
<td>0.6</td>
</tr>
<tr>
<td>Land mainly with agriculture and natural vegetation</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 3-9: Roughness lengths for different sites

In order to demonstrate the influences of the roughness factor and different choices of height $pdf(U)$ is displayed in the Figure 3-12 and Figure 3-13.
Height has the biggest influence of the available energy for wind production. For smaller heights, the average wind speed is lower than for higher heights. The distribution also shows that with higher heights, the wind speeds are more disperse. This is favorable as the wind turbines that normally starts producing energy from 3ms$^{-1}$, are able to capture more wind energy. The roughness parameter has a smaller influence, however it will be taken into account in which landscape the house situates.

### 3.8.2.1 Wind energy production

For wind energy production it is chosen a wind turbine available to purchase in Portugal. The three blade `superwind` model seems adequate and has medium investment costs. The power output of the wind turbine in function of wind speed is shown in Figure 3-14.
Figure 3-14: Chosen wind turbine and its power curve in function of wind speed (taken from [48])

The function that describes a power curve is given in equation (3-31). Notice that in this turbine model there is no cut-off wind speed.

\[
P(U) = \begin{cases} 
0 & U < U_{cut-in} \\
\frac{1}{2} \rho \pi R^2 C_p U^3 & U_{cut-in} < U < U_{rated} \\
P_{rated} & U_{rated} < U < U_{cut-off}
\end{cases} \tag{3-31}
\]

In order to obtain the power curve for this specific wind turbine, the data from the manufacturer is considered: the maximum power output \( P_{rated}=350W \) and the radius of the swept area \( R=0.61m \). The air density is assumed to be \( \rho=1.25\text{Kgm}^{-3} \). The power coefficient \( C_p \), which can be interpreted as the turbines efficiency is given by

\[
C_p = \frac{P_{absorbed}}{P_{available}}
\]

and assumed to be \( C_p=0.45 \), which is the practical limit for this coefficient. Given this data it is possible to write equation (3-31) for this special wind turbine in equation (3-32).

\[
P(U) = \begin{cases} 
0 & U < \frac{3.5m}{s} \\
0.1047 \times U^3 & \frac{3.5m}{s} < U < \frac{12.5m}{s} \\
350W & U > \frac{12.5m}{s}
\end{cases} \tag{3-32}
\]

Knowing the power curve, it is possible to estimate annual energy production \( AEP \) in function of wind speed by equation (3-33).

\[
AEP = 8760 \times \int_{U_{cut-in}}^{U_{cut-out}} P(U) \times pdf(U)dU \tag{3-33}
\]
The wind speed increases when increasing the height, which also ultimately raises the annual wind energy production. For the residential analysis, the maximum height of 30m is considered. To calculate the available energy, equation (3-33) can be rewritten as equation (3-34).

\[ AEP = \frac{8760 \times P(U) \times [F(U_1) - F(U_2)]}{1000} \]  

(3-34)

where \( F(U) \) is the cumulative distribution function, which gives the fraction of time for which the hourly mean velocity exceeds \( U \). The definition of \( F(U) \) can be found in equation (3-35).

\[ F(U) = -\int pdf(U) \, dU = \exp \left[ -\left( \frac{U}{c} \right)^k \right] \]  

(3-35)

Thus \( F(U_1) - F(U_2) \) is the probability of the wind speed being between \( U_1 \) and \( U_2 \). The obtained values of the annual energy production were compared to calculated values from the program HOMER. The obtained values of annual energy production for were plotted in function to their corresponding height (Figure 3-15). From this plot, it was possible to obtain a polynomial equation of energy production in function of height for each roughness length. With this equation it is possible for the optimization algorithm to optimize the height of the wind turbine for a given site.

![Figure 3-15: Fit of the annual energy production in function of different heights](image)

The estimated polynomial equations for the three roughness lengths are given in (3-36).

\[ AEP(h) = \begin{cases} 
4 \times 10^{-5} h^6 - 0.0037 h^5 + 0.1539 h^4 - 3.1346 h^3 + 30.466 h^2 - 59.787 h + 26.673 & z_0 = 1.2 m \\
2 \times 10^{-5} h^6 - 0.002 h^5 + 0.0797 h^4 - 1.4686 h^3 + 11.168 h^2 + 33.425 h - 51.035 & z_0 = 0.6 m \\
4 \times 10^{-5} h^6 - 0.004 h^5 + 0.0107 h^4 - 0.0533 h^3 - 3.5532 h^2 + 95.721 h - 80.315 & z_0 = 0.3 m 
\end{cases} \]  

(3-36)
3.8.2.2 Wind costs

To minimize the costs, the cost has to be given in function of height, too. It is possible to divide the costs $ICC_{\text{wind}}$ of the wind turbine into two parts (equation (3-37)). The first part is the cost of the wind turbine itself $ICC_{\text{turbine}}$ and the second part the costs of the tower $ICC_{\text{tower}}$. It was assumed that the wind turbine has a lifetime of 20 years; however the tower (considered to be made out of steel) is an onetime investment (equations (3-38)(3-39)). [51] [52]

$$ICC_{\text{wind}} = ICC_{\text{tower}} + ICC_{\text{turbine}} \tag{3-37}$$

$$ICC_{\text{tower}} = M_{\text{tower}} \times C_{\text{steel}} \tag{3-38}$$

$$M_{\text{tower}} = 0.2694 \times A_{\text{swept}} \times h + 1779 \tag{3-39}$$

Where $M_{\text{tower}}$ is the mass of the tower and $C_{\text{steel}}$ the steel price (assumed to be around 0.5€/kg [53]). With these equations it is possible for the optimization algorithm to optimize the height of the wind turbine for a given site. As wind production is quite low and the wind speed is taken in average, it will be assumed that all produced Energy can be consumed in the household.
4 Optimization approach

In this chapter the two considered optimization approaches, linear programming and genetic algorithm are presented.

4.1 Linear Programming

Linear programming is an algorithm method to solve linear optimization problems with the following form:

\[
\begin{align*}
\text{Optimize} & \quad f(x) \\
\text{Subject to} & \quad Ax \leq b \\
\text{and} & \quad lb \leq x \leq ub
\end{align*}
\]

Where \( f(x) \) is the objective function, \( Ax \leq b \) the constraints expressed in matrix form and \( lb \leq x \leq ub \) the bound within the variable \( x \) is valid. Linear Programming has the big disadvantage to just optimize one objective function. However, it has the advantage of finding always the global optimum. This optimization method will help this work to decrease the number of variables present in the GA problem, by identifying what are the best technologies for each of the individual services. Models in which first the number of GA variables is reduced and then its optimization is performed were already used by [32]. For this, it is minimized total energy consumption and the LCOT of a given household with LP. As this modelling method can just optimize one objective function each time, the results will be not identically. This analysis permits to take out the worst technologies that consume too much energy or are simply too expensive. The MATLAB inbuilt command used to perform LP is \texttt{linprog()}. The function offers three different solving methods, which due to their background approach find the optimum solution with different efficiency (Table 4-1).

<table>
<thead>
<tr>
<th>Method</th>
<th>Iterations needed to find optimal solution</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Scale</td>
<td>Many</td>
<td>LIPSOL (Linear Interior Point Solver)</td>
</tr>
<tr>
<td>Medium Scale - simplex</td>
<td>Few</td>
<td>Simplex method</td>
</tr>
<tr>
<td>Medium Scale – active set</td>
<td>Intermediate</td>
<td>Projection method</td>
</tr>
</tbody>
</table>

Table 4-1: Different solving methods for LP

The large scale method uses the linear interior point solver to find an optimum solution. This solver approximates to the final solution by crossing the feasible region. While iterating, the possible solutions approximate to a vertex of the feasible region. Both medium scale methods use the simplex algorithm to find a feasible solution. The simplex method starts searching for the optimal value on a vertex of the feasible solution region. In the next iteration it moves towards the next vertex testing if it is optimal. To do so, the iteration process searches for the optimal bases; this gives the corresponding optimal vertex and thus the optimal solution. The projection method is a variation of the simplex method, which uses the initial variable values \( x_0 \) as initial starting vertex.

4.1.1 Objective functions

In this section, the mathematical formulation of each energy service optimization is presented.
4.1.1 Water heating

The objective functions for minimizing energy consumption for water heating is given in equation (4-1) and minimizing LCOT in equation (4-2). Notice that water heating includes 25 possible technologies (see Table 3-1 and Table 3-2).

\[
f_{\text{WH}}(x) = \sum_{i=1}^{D} \sum_{j=1}^{B} x_{1ij} - x_{1BB} + \sum_{i=1}^{D} \sum_{j=1}^{B} x_{2ij} + \sum_{i=1}^{D} \sum_{j=1}^{B} y_{1ij} + \sum_{i=1}^{D} \sum_{j=1}^{B} y_{2ij}
\]  

(4-1)

\[
f_{\text{WH}_2}(x) = \sum_{i=1}^{D} \sum_{j=1}^{B} \text{LCOT}(x_{1ij})x_{1ij} - \text{LCOT}(x_{1BB})x_{1BB} + \sum_{i=1}^{D} \sum_{j=1}^{B} \text{LCOT}(x_{2ij})x_{2ij} + \sum_{i=1}^{D} \sum_{j=1}^{B} \text{LCOT}(y_{1ij})y_{1ij} + \sum_{i=1}^{D} \sum_{j=1}^{B} \text{LCOT}(y_{2ij})y_{2ij}
\]  

(4-2)

The corresponding constraints are given in equation (4-3).

\[
\eta_{x1DA}x_{1DA} + \eta_{x1DB}x_{1DB} \leq \%_{\text{SUN}}Q_{\text{WH}}
\]

\[
\eta_{x1BA}x_{1BA} + 0.5194 \times (\eta_{x1CA}x_{1CA} + \eta_{x1CB}x_{1CB}) + \eta_{x1DA}x_{1DA} + \eta_{x1DB}x_{1DB} = \%_{\text{RE}}Q_{\text{WH}}
\]  

(4-3)

Of course not only the renewable options have to fulfil the required energy for a certain %RE, but also the fuel options have to cover the additional energy requirement.

4.1.1.2 Space heating

Space heating has an identical approach to water heating. The objective functions can be found in equations (4-4) and (4-5) and the constraints in equation (4-6). In total, space heating includes 23 technologies, which can be found in Table 3-2 and Table 3-4.

\[
f_{\text{SH}}(x) = \sum_{i=1}^{B} \sum_{j=1}^{C} y_{1ij} + \sum_{i=1}^{B} \sum_{j=1}^{C} y_{2ij} + x_{1DA} + x_{1BA}
\]

\[
+ \sum_{i=1}^{D} \sum_{j=1}^{B} \sum_{k=1}^{C} z_{kij} + \sum_{i=1}^{D} z_{1i} + z_{2D} + z_{3} + z_{4}
\]  

(4-4)
4.1.1.3 Space cooling

Space cooling includes only four technologies as described in Table 3-6. The objective functions for this energy service can be found in equation (4-7) and (4-8) and the constraints in equation (4-9).

\[
f_{\text{SH}_2}(x) = \sum_{i=A}^{B} \sum_{j=A}^{C} \text{LCOT}(y_{i1j})y_{i1j} + \sum_{i=A}^{B} \sum_{j=A}^{C} \text{LCOT}(y_{2ij})y_{2ij} + \text{LCOT}(x_{1DA})x_{1DA} + \sum_{k=1}^{B} \sum_{l=1}^{B} \text{LCOT}(z_{ki})z_{ki} + \sum_{i=B}^{D} \text{LCOT}(z_{1i})z_{1i} + \text{LCOT}(z_3)z_3 + \text{LCOT}(z_4)z_4 + \text{LCOT}(x_{1BA})x_{1BA}
\]

\[
\eta_{1DA}x_{1DA} \leq \eta_{\text{SUN}_{SH}} Q_{\text{SH}}
\]

\[
\eta_{1BA}x_{1BA} + 0.5194 \left( \sum_{k=1}^{B} \sum_{l=1}^{B} \eta_{ki}z_{ki} + z_{1C} + z_{1D} \right) + \eta_{1DA}x_{1DA} + \eta_{E3}z_3 = \eta_{\text{RE}} Q_{\text{SH}}
\]

4.2 Genetic Algorithm

The genetic algorithm as described in section 2.4.2.2 is a biology-based optimization method that was inspired by the process of genetic reproduction. This algorithm type repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects randomly individuals from the current population (parents) and uses their genome to produce a next generation (children). The production of a new child includes crossover and mutation rules. Over various generations, the population evolves towards an optimal solution. The chosen technologies for this optimization method are presented in Table 4-2. These technologies are obtained from the LP results (section 5.1).
<table>
<thead>
<tr>
<th>Energy Service</th>
<th>Technology</th>
<th>Variable for mathematical analysis</th>
<th>Efficiency ($\eta$)</th>
<th>Investment cost (~€)</th>
<th>Fuel costs (~€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water heating</strong></td>
<td>Natural gas Boiler</td>
<td>x(1)</td>
<td>0.98</td>
<td>2295-2750</td>
<td>~0.0746</td>
</tr>
<tr>
<td></td>
<td>Biomass Boiler</td>
<td>x(2)</td>
<td>0.91</td>
<td>6226-7388</td>
<td>~0.0412</td>
</tr>
<tr>
<td></td>
<td>Heat pump</td>
<td>x(3)</td>
<td>4.30</td>
<td>2250</td>
<td>~0.1528</td>
</tr>
<tr>
<td></td>
<td>Resistance water heater</td>
<td>x(4)</td>
<td>1.00</td>
<td>143-650</td>
<td>~0.1528</td>
</tr>
<tr>
<td></td>
<td>Solar Circuit</td>
<td>x(5)</td>
<td>=243 kWh/m$^2$</td>
<td>1990-3243</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Thermosyphon</td>
<td>x(6)</td>
<td>=217 kWh/m$^2$</td>
<td>1515-2370</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>Space heating</strong></td>
<td>Air conditioner</td>
<td>x(7)</td>
<td>3.90</td>
<td>790-1030</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Geothermal heat pump</td>
<td>x(8)</td>
<td>4.66</td>
<td>~15000</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Oil heater</td>
<td>x(9)</td>
<td>1.00</td>
<td>~90</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Wood furnace</td>
<td>x(10)</td>
<td>0.70</td>
<td>~904</td>
<td>0.0049</td>
</tr>
<tr>
<td><strong>Space and water heating</strong></td>
<td>Natural gas Boiler with water radiators</td>
<td>x(11)</td>
<td>0.85</td>
<td>2295-2750</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Natural gas Boiler with floor radiators</td>
<td>x(12)</td>
<td>0.82</td>
<td>6226-7388</td>
<td>0.0746-0.0791</td>
</tr>
<tr>
<td></td>
<td>Biomass Boiler with water radiators</td>
<td>x(13)</td>
<td>0.79×0.87</td>
<td>6226-7388</td>
<td>0.0412</td>
</tr>
<tr>
<td></td>
<td>Biomass Boiler with floor radiator</td>
<td>x(14)</td>
<td>0.79×0.84</td>
<td>6226-7388</td>
<td>0.0412</td>
</tr>
<tr>
<td></td>
<td>Solar Circuit with water radiators</td>
<td>x(15)</td>
<td>=264 kWh/m$^2$</td>
<td>(1990-3243)+50€/room</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Solar Circuit with floor radiators</td>
<td>x(16)</td>
<td>=264 kWh/m$^2$</td>
<td>(1990-3243)+16€/m$^2$</td>
<td>0</td>
</tr>
<tr>
<td><strong>Space cooling</strong></td>
<td>Air conditioner</td>
<td>x(17)</td>
<td>6.00</td>
<td>~790</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Geothermal heat pump</td>
<td>x(18)</td>
<td>4.66</td>
<td>~15000</td>
<td>0.1528</td>
</tr>
<tr>
<td><strong>Space cooling and heating</strong></td>
<td>Air conditioner</td>
<td>x(19)</td>
<td>5.00</td>
<td>~790</td>
<td>0.1528</td>
</tr>
<tr>
<td></td>
<td>Geothermal heat pump</td>
<td>x(20)</td>
<td>4.66</td>
<td>~15000</td>
<td>0.1528</td>
</tr>
<tr>
<td><strong>Supply options</strong></td>
<td>Photovoltaics</td>
<td>x(21)</td>
<td>Depends on PV area and storage</td>
<td>Depends on PV area and storage</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Wind turbine</td>
<td>x(22)</td>
<td>Depends on hub height</td>
<td>Depends on hub height</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4-2: Chosen technologies for GA

Notice that for space heaters an additional value to their efficiency is added, depending on how the heat is delivered. For the water radiators and floor radiators the values are indicated in Table 4-2 and for direct convection the assumed value is 0.94.

For this work, the initial population contains 100 individuals with each 22 chromosomes. Thus an individual (solution) $n$ has 22 technologies which can provide the energy demand (see Figure 4-1).

---

7 Units according to technologies – see technology description for further details
8 RE options also depend also on the consumption and storage - here for a two person household
9 Depends on the required heating area (Single rooms or whole house) – here for one room
Each chromosome presents the choice of a technology option. In order to limit the random initialization, each chromosome has to be within the established limits for its technology. During the crossover and mutation procedure, the algorithm always verifies that the chromosomes do not leave their limits. In Figure 4-2 a schematic of the process is presented. From the initial population pairs are selected randomly for the mating. Then in an arbitrary manner, the crossover process is performed. Chromosomes from both individuals are chosen for the new individual. At the end of this process, mutation occurs eventually and changes one chromosome to another random value. After each iteration, the code rounds the obtained result arbitrary up or down in order to obtain integer values.

Note that because the genetic algorithm performs its search randomly, the optimum solutions in different runs may not be the identically. To run this algorithm in MATLAB, the inbuilt function `gamultiobj()` was used. `gamultiobj()` is not a direct minimization method, as it has more than one objective function. The function searches for non-inferior solutions. These solutions are basically frontier solutions in which the improvement of one objective function is the degradation of the other. Such a frontier constituted out of non-inferior solutions is called Pareto front [54]. The function itself gives the designer the possibility to write its own selection,
crossover and mutation function and to determine several other parameters such as step sizes or initial populations. It is based on the NSGA II method, which is considered one of the best approaches to simulate the GA as it helps to keep diversity large [55] [54]. The function provides the possibility to analyze the results directly in a Pareto front. Another important issue is the constraint formulation for GA problems.

4.2.1 Pareto front

The Pareto front is a very common analyze approach for NZEB multi-objective optimization [10]. It represents the solution front created by the objective functions. This method is especially adequate when the optimization problem contains two to three fitness functions. For this case, a two dimensional analysis will be sufficient (see one NZEB implementation example in Figure 4-3).

![Figure 4-3: Example of a Pareto front (adapted from [56])](image)

The Pareto front presents the border between the region of feasible points, for which all constraints are satisfied and the region of infeasibility. This frontier contains the best solutions between the two objectives. Normally the Pareto front can be classified in two very typical shapes: convex and non-convex form. A convex form indicates more space for trade-off solutions. That means in the NZEB case that there is some decision space where we get closer to net zero, without necessarily increasing the costs. A non-convex form makes the trade-off much harder and would be unfavorable for the NZEB case.

4.2.2 Penalty function

GA has some problems in accepting rigid constraints. The penalty function is a good method to solve constrained optimization problems. The purpose of this method is to transform the constrained optimization problem into an equivalent unconstrained one, which is more adaptive for GA to solve. This is due to the fact that the presence of constraints in a nonlinear problem creates bigger difficulties for the algorithm than finding the minimum to an unconstrained one. This minimum may not be an extreme point of the feasible region and may not even lay on one of the boundaries. Furthermore, the solution may not be the exact best solution, but the penalty approach can get reasonably close [57].
The penalty function penalizes the fitness function $f(x)$ in case that a given constraint is not satisfied. Mathematically this can be represented by [58]

$$f(x) = f(x) + \text{penalty}(x). \quad (4-10)$$

For the overall constraint violation it is possible to assign weights denoted as penalty coefficients $\omega_j$ for each constraint violation $v_j(x)$.

$$\text{penalty}(x) = \sum_{j=1}^{k} \omega_j v_j^2(x), \quad (4-11)$$

being $k$ the number of constraints.

Equation (4-10) penalizes the infeasible solutions by increasing their fitness values with the penalty. As their fitness grows worse the solutions for these cases are infeasible as desired. Penalty functions as defined above can be static, dynamic or adaptive. Dynamic and adaptive penalty functions have some advantages over static ones as the penalty coefficient evolve during the generation progress [59]. However for the case of NZEB often is also used the static method [60]. In this method the penalty coefficient is predefined by the user and does not change during the evolving process. As the NZEB problem is complex, the static penalty function has the advantage of simplifying the problem.

Although gamultiobj() provides an inbuilt function to perform a penalty on the fitness function, it is difficult to follow the evaluation of the penalty weights and it is not used directly to implement constraints. This is the reason why in this work the penalty functions were added manually. Thus it will be used the approach of the static penalty for additional cost or energy parameters and a dynamical method for satisfying energy demand or available space for solar installations. For each constraint it has to be defined a penalty coefficient. Their weights define how strong the fitness function is going to be penalized. Finding a weight for each penalty function is a difficult task and will be analyzed for this work in section 5.2. Low penalty coefficients may converge too quickly to the supposed solution, giving too imprecise values. Higher penalty coefficients give in principle more precise solutions. However, if these coefficients are too big, the solutions will be ill-conditioned, presenting large gradients.

### 4.2.3 Fitness functions and penalty functions

The first objective function minimizes the out of side energy consumption, while the second objective function minimizes the costs in terms of LCOT or LCC. The meaning of all variables in Figure 4-4 not yet presented in Table 4-2 is given in Table 4-3.

<table>
<thead>
<tr>
<th>$\eta_n$</th>
<th>Efficiency for technology $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Number of the technology choice</td>
</tr>
<tr>
<td>$E_n$</td>
<td>kWh/m²</td>
</tr>
<tr>
<td>$a_k$</td>
<td>kWh/m</td>
</tr>
<tr>
<td>$\omega_{area}$</td>
<td>Penalty weight for roof space penalty function</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$\omega_{WH}$</td>
<td>Penalty weight for water heating energy demand penalty function</td>
</tr>
<tr>
<td>$\omega_{SH}$</td>
<td>Penalty weight for space heating energy demand penalty function</td>
</tr>
<tr>
<td>$\omega_{SC}$</td>
<td>Penalty weight for space cooling energy demand penalty function</td>
</tr>
<tr>
<td>$A_{roof}$</td>
<td>Roof space for solar options</td>
</tr>
<tr>
<td>$Q_{wh}$</td>
<td>Water heating energy demand</td>
</tr>
<tr>
<td>$Q_{sh}$</td>
<td>Space heating energy demand</td>
</tr>
<tr>
<td>$Q_{sc}$</td>
<td>Space cooling energy demand</td>
</tr>
<tr>
<td>$C_n$</td>
<td>LCC or LCOT costs of element n</td>
</tr>
</tbody>
</table>

Table 4-3: Variables for GA analysis
Figure 4-4: Fitness functions for GA with penalty functions

Objective Function 1

\[ y(1) = Q_{electricity} + \eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) - E_5 x(5) - E_6 x(6) + \eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \eta_{11} x(11) + \eta_{12} x(12) + \eta_{13} x(13) + \eta_{14} x(14) - E_{15} x(15) - E_{16} x(16) + \eta_{17} x(17) + \eta_{18} x(18) + \eta_{19} x(19) + \eta_{20} x(20) - E_{21} x(21) - (a_1 x(22)^6 + a_2 x(22)^5 + a_3 x(22)^4 + a_4 x(22)^3 + a_5 x(22)^2 + a_6 x(22)) \]

Dynamic Penalties 1

\[ + \omega_{area}(x(5) + x(6) + x(15) + x(16) + x(21) - A_{roof})^2 \]

\[ + \omega_{wh}(\eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) + E_5 x(5) + E_6 x(6) + \%_{wh} \eta_{11} x(11) + \%_{wh} \eta_{12} x(12) + \%_{wh} \eta_{13} x(13) + \%_{wh} \eta_{14} x(14) + \%_{wh} E_{15} x(15) + \%_{wh} E_{16} x(16) - Q_{wh})^2 \]

\[ + \omega_{sh}(\eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \%_{sh} \eta_{11} x(11) + \%_{sh} \eta_{12} x(12) + \%_{sh} \eta_{13} x(13) + \%_{sh} \eta_{14} x(14) + \%_{sh} E_{15} x(15) + \%_{sh} E_{16} x(16) + \%_{sh} Q_{19} x(19) + \%_{sh} Q_{20} x(20) - Q_{sh})^2 \]

\[ + \omega_{sc}(\eta_{17} x(17) + \eta_{18} x(18) + \%_{sc} \eta_{19} x(19) + \%_{sc} Q_{20} x(20) - Q_{sc})^2 \]

Static Penalties 1

\[ \text{if } x(22) > 0 \]

\[ y(1) = y(1) + a_7 \text{ end} \]

Objective Function 2

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

Dynamic Penalties 2

\[ + \omega_{area}(x(5) + x(6) + x(15) + x(16) + x(21) - A_{roof})^2 \]

\[ + \omega_{wh}(\eta_1 x(1) + \eta_2 x(2) + \eta_3 x(3) + \eta_4 x(4) + E_5 x(5) + E_6 x(6) + \%_{wh} \eta_{11} x(11) + \%_{wh} \eta_{12} x(12) + \%_{wh} \eta_{13} x(13) + \%_{wh} \eta_{14} x(14) + \%_{wh} E_{15} x(15) + \%_{wh} E_{16} x(16) - Q_{wh})^2 \]

\[ + \omega_{sh}(\eta_7 x(7) + \eta_8 x(8) + \eta_9 x(9) + \eta_{10} x(10) + \%_{sh} \eta_{11} x(11) + \%_{sh} \eta_{12} x(12) + \%_{sh} \eta_{13} x(13) + \%_{sh} \eta_{14} x(14) + \%_{sh} E_{15} x(15) + \%_{sh} E_{16} x(16) + \%_{sh} Q_{19} x(19) + \%_{sh} Q_{20} x(20) - Q_{sh})^2 \]

\[ + \omega_{sc}(\eta_{17} x(17) + \eta_{18} x(18) + \%_{sc} \eta_{19} x(19) + \%_{sc} Q_{20} x(20) - Q_{sc})^2 \]

Static Penalties 2

\[ \text{if } x(21) > 0 \&\& \text{ storage } == \text{ ON} \]

\[ y(2) = y(2) + C_{storage} \text{ end} \]

\[ \text{if } x(22) > 0 \]

\[ y(2) = y(2) + C_{turbine} + 1775 \text{ end} \]
5 CASE STUDIES AND RESULTS

In this section the results from linear programming and genetic algorithm are presented. The created GUI (see Figure 5-1) first asks the user about its household conditions, as they depend from case to case. It is however assumed that the house was constructed with needed requirements to meet NZEB. That is for instance a good isolation with $U=0.15 \text{ Wm}^{-2}\text{°C}^{-1}$ for an isolated wall and $U =0.50 \text{ Wm}^{-2}\text{°C}^{-1}$ for windows, low water consumption with $f_{eh}=0.9$ or the optimal building orientation. These assumptions and the answers from the user in the questionnaire are essential for the calculation of the energy needs of the house.

To show some possible results for LP and GA, two scenarios are analyzed. For GA, it will be considered also a third scenario which will be presented in section 5.2. Scenario 1 is a two person city apartment, which specifications can be found in Table 5-1.

![Figure 5-1: Questionnaire excerpt from the Energy Service Optimization GUI](image)

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of people</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hot water consumption</td>
<td>36L day$^{-1}$ person$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Heating preferences</td>
<td>1 room</td>
<td>20m$^2$ with 2 contact walls</td>
</tr>
<tr>
<td>Cooling preferences</td>
<td>1 room</td>
<td>20m$^2$ with 2 contact walls</td>
</tr>
<tr>
<td>Lighting</td>
<td>28m$^2$ in average 4h per day</td>
<td></td>
</tr>
<tr>
<td>Kitchen appliances</td>
<td>Only electrical cooker</td>
<td></td>
</tr>
<tr>
<td>Washing appliances</td>
<td>Only washing machine</td>
<td></td>
</tr>
<tr>
<td>Available rooftop area</td>
<td>5m$^2$</td>
<td>No storage</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>1</td>
<td>With maximum hub height of 10m</td>
</tr>
<tr>
<td>Water heating energy demand</td>
<td>1282.6kWh</td>
<td></td>
</tr>
<tr>
<td>Space heating energy demand</td>
<td>52.17kWh</td>
<td></td>
</tr>
<tr>
<td>Space cooling energy demand</td>
<td>29.84kWh</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: Case study scenario 1: a two-person city apartment

Scenario 2 is a four person household, where the considered house type has a garden. The specifications can be found in Table 5-2.

---

58
### Table 5-2: Case study scenario 2: a four-headed family house

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of people</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Hot water consumption</td>
<td>36L day(^{-1}) person(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Heating preferences</td>
<td>2 rooms</td>
<td>30m(^2) with 2 contact walls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15m(^2) with 2 contact walls</td>
</tr>
<tr>
<td>Cooling preferences</td>
<td>2 rooms</td>
<td>30m(^2) with 2 contact walls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15m(^2) with 2 contact walls</td>
</tr>
<tr>
<td>Lighting</td>
<td>45m(^2) in average 5h per day</td>
<td></td>
</tr>
<tr>
<td>Kitchen appliances</td>
<td>Dishwasher, cooker and stove</td>
<td></td>
</tr>
<tr>
<td>Washing</td>
<td>Washing machine and dryer</td>
<td></td>
</tr>
<tr>
<td>Available rooftop area</td>
<td>20m(^2)</td>
<td>With Storage</td>
</tr>
<tr>
<td>Wind turbine height</td>
<td>1</td>
<td>With maximum hub height of 20m</td>
</tr>
<tr>
<td>Water heating energy demand</td>
<td>2565.1kWh</td>
<td></td>
</tr>
<tr>
<td>Space heating energy demand</td>
<td>112.29kWh</td>
<td></td>
</tr>
<tr>
<td>Space cooling energy demand</td>
<td>59.63kWh</td>
<td></td>
</tr>
</tbody>
</table>

#### 5.1 Linear Programming

The purpose of the linear program is to test this optimization method for NZEB optimization until this method is not sufficient anymore. Difficulties arise in this type of optimization with choosing only one objective function, which for the aim of this thesis is not sufficient. However, linear programming showed to be very helpful in function as a hybrid model, selecting relevant technology choices for the GA.

As mentioned in section 4.1, linear programming is tested for two different objective functions. The first objective function minimizes energy consumption for a given energy service and the second objective function minimizes LCOT. Linear optimization is not able to find a feasible solution when trying to optimize all energy services together or when considering electrical renewable onsite supply options. The way the constraints were defined for all technologies is somehow conflicting. In other LP papers, it is normally optimized the system cost in order to fulfil the EU Directive statement of cost optimization. The authors such as [12] define in priori which equipment and technology they are optimizing, which enables LP to solve the required.

The Energy service optimization is solved with the simplex method. Comparing this method to the interior point method, the simplex method needs three iterations to find an adequate solution and the interior point method needs five iterations to get a result. As expected, the obtained results for the technologies are the same.

The number of persons does not affect so much the choice of technology, but just the needed energy that a chosen technology needs to deliver, which increases the associated fuel costs. The chosen objective function however influences most the technology choices. While the first objective function chooses the most efficient technologies, the second objective function chooses the options with the lowest cost impact.

All LP results are presented in a GUI so that every user can obtain them easily (see for example Figure 5-6). For LP it is also crucial to define the desired %RE in the questionnaire. Thus the program will give corresponding solutions to the chosen value.
5.1.1 Water heating

The best technologies for water heating were the heat pump, the solar circuit system, the thermosyphon, the biomass boiler and the natural gas boiler or instant heater. For scenario 1, one can observe these differences in Figure 5-2.

![Figure 5-2: Scenario1: Chosen Technologies for water heating and their corresponding annual costs, minimizing energy consumption (top graph) and minimizing LCOT (bottom graph)](image)

The program determines the needed technologies to fulfil a chosen %RE for an energy service. When considering 50% of RE than the program takes 50% of a renewable resource (solar circuit system or thermosyphon) and a 50% non renewable resource (natural gas boiler or instant heater). When defining a higher %RE, the program implements thermal water systems until the delivered energy is limited due to weather conditions. Between 80% and 90% of %RE, the program implements the heat pump, a choice which for water heating is efficient and cost-effective. This technology presents the available %RE from the grid with circa 52%. For 100% of %RE, the program is forced to implement the biomass boiler which in last instant is the backup system for the thermal water heating devices. The annual costs can also be observed in Figure 5-2.
Clearly does the objective function which minimizes LCOT chose devices which require less annual costs. However, when approximating net zero, the annual costs are for both objective functions similar as there are fewer decision devices. It is also possible to say that the annual costs depend strongly on the investment costs of chosen technologies and that fewer technologies for the same energy service are advantageous. The same analysis is done for scenario 2 and the obtained results can be seen in Figure 5-3.

![Figure 5-3: Scenario2: Chosen Technologies for water heating and their corresponding annual costs, minimizing energy consumption (top graph) and minimizing LCOT (bottom graph)](image)

For scenario 2, the thermal water heating systems are at every %RE value at their maximum performance. The heat pump and natural gas heater are implemented at lower %RE values and the biomass boiler is not just a backup system for the water heating system, but an essential choice to reach 100% of %RE. Annual costs for a four person family house are, as expected, much higher than for a two person apartment. Also is it interesting to notice that the program for scenario 1 suggests mostly two technologies, while for four persons three technologies are suggested.
5.1.2 Space heating

The most promising technologies for space heating are the air conditioner, the geothermal heat pump, the solar circuit system, the biomass boiler, the wood furnace, the natural gas boiler and the propane heater.

The results for scenario 1 can be observed in Figure 5-4.

![Figure 5-4: Scenario1: Chosen Technologies for space heating and their corresponding annual costs, minimizing energy consumption (top graph) and minimizing LCOT (bottom graph)](image)

The space heating technology options are more sensitive to the two different objective function approaches than the other energy services. Not just the technologies vary between them, but also the annual costs. When optimizing the efficiencies of space heating devices, the biomass boiler and solar circuit systems are the chosen technologies to reach net zero. Biomass boilers as well as solar circuit systems are expensive devices due to their high investment costs. When optimizing LCOT, the program suggests instead of the biomass boiler the wood furnace, a relatively cheap option in investment and fuel, but less efficient.

The same conclusion is obtained when analyzing the family house (scenario 2 - Figure 5-5).
Even with higher energy consumption, the technology choices for space heating do not vary. Obviously, the solar circuit system cannot provide as much space heating as in scenario 1. Therefore, the air conditioner is more used.

### 5.1.3 Space cooling

Space cooling has fewer decision devices as water and space heating. Its maximum percentage of renewable supply is given by the renewables present in the grid with a value of 51.94%.

The LCOT analysis prefers the geothermal heat pump, with lower investment budget, which is horizontally installed under the ground. This option may not be possible for all sites, especially in the city. It could however be an option for a block of apartments (district heating and cooling). The most effective option is the vertical installed system of the geothermal heat pump. This option is however the most expensive. Because of their high initial investment and required installation space, geothermal heat pumps are normally just used for houses with garden.

Figure 5-5: Scenario2: Chosen Technologies for space heating and their corresponding annual costs, minimizing energy consumption (top graph) and minimizing LCOT (bottom graph)
Whenever one decides to install a heat pump (geothermal or air conditioner), the service they provide should include space heating and cooling. This lowers not just investment costs, but also LCOT.

5.1.4 Other appliances

The program is able to optimize food cooling, lighting, cooking and washing. It is, however, also possible for the user to choose directly the desired equipment from the available choices. For optimizing the appliances, the program calculates directly from real appliances the LCOT and chooses the option with the lowest value. For scenario 2, the results can be seen in Figure 5-6.

![GUI solutions for food cooling, lighting, washing and cooking](image.png)

Figure 5-6: GUI solutions for food cooling, lighting, washing and cooking

5.2 Genetic Algorithm

As mentioned in section 4.2, after each selection, crossover and mutation process, the solutions are arbitrary rounded. This method was chosen as it is more adequate for the design of the problem to work with integer values given the area of the solar option and hub height. The difference between working with rounded and not rounded values can be seen in the Pareto front displayed in Figure 5-7. These results include the boundary of each technology, that is, the values are between zero and the maximum energy demand for the energy service they perform. As they do not include any constraints, the solutions for energy outside consumption go to $-\infty$. It is obvious that in this case, GA only prefers renewable options. Another important point for not considering just bounded GA iterations is that most of the time the obtained solutions are inconclusive, as the constraints are not properly satisfied.

To evaluate an obtained Pareto front from the GA optimization exist various methods. How to choose one particular solution depends on the decision maker. There are no favorable solutions in the front as they are all equally optimal. To find most adequate solutions, most of decision makers use the similarity of elements in the non-dominated set and groups these elements. A typical element is selected out of the group and represents
this group. The choice of the best group lies within the decision maker and his/her knowledge of the system’s intended usage. Normally, this approach can be divided into two options: considering the group of solutions closest to the required ideal solution or analyzing the objective function values [61].

In this work, the Pareto front will be divided into clusters or regions, which are similar. This means these regions have solutions with same technologies and similar values for delivered energy from these choices. The representative solutions of these groups are analyzed, as the objective function values include technologies that are ultimately not used, altering the real value of outside energy and cost.

In this chapter, the two presented scenarios are optimized. Both are analyzed with LCOT and LCC cost optimization versus outside energy consumption. Then a third scenario is considered in which two persons instead of four are living in the scenario 2 house.

![Pareto front](image)

**Figure 5-7: Difference between rounded solutions and not rounded solutions (scenario 2)**

### 5.2.1 LCC and LCOT

As the Genetic Algorithm includes two options of cost evaluation, it is analyzed the difference between both, using a four person household. The results can be seen in Figure 5-8. As the cost evaluation also depends on the energy that is needed, the values of LCC and LCOT for water heating WH devices are the lowest as it is the largest energy consumer and the associated equipment is cheaper. For the same reason, the LCC and LCOT values for space cooling SC devices are the largest, as this energy service is the one with the lowest energy consumption. The devices for space heating SH values situate between these two. Furthermore, it can be observed from Figure 5-8 that even both differ in their magnitude, the comparison between cost relations between devices is similar. For each scenario LCC and LCOT will be evaluated.
5.2.2 Penalty weights

In order to find penalty coefficients that describe the constraints, some tests are performed, where the coefficients are increased until finding a nonsense solution. Notice that this process is a completely trial error analysis. It is also kept in mind that the orders of magnitude of the penalty coefficients lay within the range of values from the constraint.

Adequate penalty weights were found to be $\omega_{\text{area}}=60$, $\omega_{\text{water}}=50 \times 10^8$, $\omega_{\text{heat}}=50 \times 10^5$ and $\omega_{\text{cool}}=50 \times 10^7$.

Observing the penalty function values for the four cases in Figure 5-9 while the iteration proceeds, it is possible to see that they are becoming closer to the desired value of zero. It is also possible to verify that diversity stays high as the algorithm always try to find other penalty values, resulting in the protruding peaks. In addition, the penalty value may not reach exactly zero. The reason for this is the trade-off between technological variety and precision.
Figure 5-9: Evolution of the penalty function values during 50 generations
5.2.3 Scenario 1 – LCC analysis versus out of site energy consumption

The obtained Pareto front for scenario 1 analyzed with LCC costs is presented in Figure 5-10.

In region A it is possible to achieve 69% of renewable energy production. The chosen technologies are the solar circuit system, mono-split air conditioner, natural gas boiler and as an onsite supply system the wind turbine. In this region all available roof space for solar energy production was used for the solar thermal circuit system, which is suggested to be implemented as hot water supply and also as space heating system. The natural gas boiler provides these both energy services, too. The chosen heating system is floor heating. If the natural gas boiler would be substituted for a biomass boiler, it would be possible to increase the 69% of renewable energy production to 85%. However, the annual LCC costs would increase about 250€. This is why the algorithm determined this option as infeasible given the trade-off between outside energy consumption and costs. Space cooling is performed with a mono-split air conditioner. For the onsite production the wind turbine was accepted, with an optimal hub height of 4m. When considering region B, the percentage of renewable energy present in the energy consumption maintains with a value of 68%. The technologies are the same of both regions; however in region B the solar thermal system uses only 4m² of its available area. As this 1m² is substituted with the natural gas boiler in space heating, the change has little influence in %RE. In region C, only 59% of the energy consumption comes from renewable choices. It is easy to verify the energy decrease within the renewable onsite options, as the thermal options are shrunk to an area of 3m². The available space is filled with PV option. However, PV is small space is not as efficient as solar thermal options. The electrical oil heater
is substituting the solar thermal circuit for space heating, while the natural gas boiler system cares about the water heating demand. The natural gas boiler seems a good trade-off option between efficiency and LCC as it is always present. The same is valid for the mono-split air conditioner for the energy service of space cooling. Region D only presents 30% of renewables, considering only the PV option.

Region D only presents 30% of renewables, considering only the PV option.

In Figure 5-11 the results in terms of annual LCC are shown. The option with 69% of the households energy coming from renewables, is 267€/year more expensive than the 30% of renewables. Notice that space cooling requires a lot of money for less energy production, which results in a high LCC. An alternative option for space cooling for a NZEB is in this case with 30kWh/year, could be an improved ventilation system. The analysis of this case scenario is consistent with scenario 1 in the LP methodology, observing that between 60% and 70% of renewable energy sources, the suggested technologies were the solar thermal options and natural gas boilers. As best group for a trade-off solution was chosen region C, as these technology choices are in middle of the Pareto front, not giving much advantage to the costs or energy out of side consumption. Which technology provides how much of the household is represented in Figure 5-12. The electrical grid for other appliances is always present once PV and wind are not able to satisfy on their own the required.

Figure 5-11: Annual LCC and chosen technologies for scenario 1

In Figure 5-11 the results in terms of annual LCC are shown. The option with 69% of the households energy coming from renewables, is 267€/year more expensive than the 30% of renewables. Notice that space cooling requires a lot of money for less energy production, which results in a high LCC. An alternative option for space cooling for a NZEB is in this case with 30kWh/year, could be an improved ventilation system. The analysis of this case scenario is consistent with scenario 1 in the LP methodology, observing that between 60% and 70% of renewable energy sources, the suggested technologies were the solar thermal options and natural gas boilers. As best group for a trade-off solution was chosen region C, as these technology choices are in middle of the Pareto front, not giving much advantage to the costs or energy out of side consumption. Which technology provides how much of the household is represented in Figure 5-12. The electrical grid for other appliances is always present once PV and wind are not able to satisfy on their own the required.

Figure 5-12: Provided energy by sources for C with 59% of the household’s energy coming from renewables
5.2.4 Scenario 1 – LCOT analysis versus out of site energy consumption

Analyzing the Pareto front from scenario 1 with LCOT analysis (see Figure 5-13), the highest percentage of renewable energies present in the total consumption does not vary much to the LCC analysis and assumes a value of 72%. Also the chosen technologies are in general the same, however there are some differences. For region A, the wood furnace is considered for space heating, which increases the %RE for this region. Again, all roof area was used for solar thermal circuit systems. In region B, value of %RE maintains, however, the wood furnace is substituted with an electrical oil heater and 2m² of the roof area is for PV. Regions B, C and D use the same technologies; however the delivered energy from each technology differs. Thus region C can present 63% of %RE and region D 59%. The region with the lowest %RE of 34% is E. This region does not consider any solar thermal options and uses the water heat pump and natural gas boiler for water heating. The biggest difference is certainly in the energy onsite supply.

<table>
<thead>
<tr>
<th>Region</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Solar circuit, Air conditioner, Wind turbine, Natural gas boiler, Wood furnace</td>
</tr>
<tr>
<td>B,C,D</td>
<td>Solar circuit, Air conditioner, Wind turbine, Natural gas boiler, Electrical oil heater, PV</td>
</tr>
<tr>
<td>E</td>
<td>Water HP, Natural gas boiler, Electrical oil heater, PV, Air conditioner</td>
</tr>
</tbody>
</table>

Figure 5-13: Obtained Pareto front from a two person apartment with LCOT analysis

After knowing which technologies are considered, it is recalculated their LCOT (see Figure 5-14). Notice that technologies with little energy delivery have higher LCOT values.
Figure 5-14: LCOT and chosen technologies for scenario 1

Region C with 63% will be considered again the best trade-off between the objective functions, as it is situated in the central region of the Pareto front. The distribution of the technologies in the whole household consumption in this case can be seen in Figure 5-15.

5.2.5 Scenario 2 – LCC analysis versus out of site energy consumption

Analyzing a house with more space for renewable implementations, gives certainly raise to higher %RE values. The maximum achievable value of %RE for scenario 2 is 77% (region A – see Figure 5-16). In region A not just solar thermal option are one of the biggest energy delivers, but also biomass, PV and wind. The available rooftop area is divided into 9m² of PV and 11m² for solar thermal systems. The optimal hub height was estimated between 7 and 8m. Region B presents 74% of renewables, with the big difference of using the air conditioner instead of the wood furnace and lowering the wind turbine hub height to 6m. The chosen technologies are identical in region B and C, however in region C less space from the rooftop area is used. This process decreases the LCC and also %RE to 71%.
In region D, the rooftop area is only used with $8m^2$ for solar thermal and PV systems. The wind turbine is not considered in this region anymore. The %RE for this region is 64%. In the last region E the %RE drops to 57%. Less renewable technologies are considered and option such as the natural gas boiler systems substitute them. In Figure 5-17 one can see the annual LCC for each region. It is clearer than in scenario 1 that the higher the %RE, the higher the LCC costs.

Figure 5-16: Obtained Pareto front from four person house with LCC analysis

<table>
<thead>
<tr>
<th>Region</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Solar circuit, Wind turbine, Wood furnace, PV, Air conditioner, Water HP</td>
</tr>
<tr>
<td>B, C</td>
<td>Solar circuit, Wind turbine, PV, Air conditioner, Water HP</td>
</tr>
<tr>
<td>D</td>
<td>Solar circuit, PV, Air conditioner, Water HP</td>
</tr>
<tr>
<td>E</td>
<td>Solar circuit, PV, Air conditioner, Water HP, Natural gas boiler</td>
</tr>
</tbody>
</table>

Figure 5-17: Annual LCC and chosen technologies per region for scenario 2
Region C is analyzed in more detail as it considered the best trade-off solution (see Figure 5-18). It is possible to verify that most of the energy is for water heating.

![Figure 5-18: Provided energy by sources for C with 71% of the household’s energy coming from renewables](image)

5.2.6 Scenario 2 - LCOT analysis versus out of site energy consumption

In the analysis of this scenario was included tested the outcome of two GA runs. The results can be seen in Figure 5-19. First, it is possible to see that the Pareto fronts are quite similar and the chosen technologies in both runs are the same. Even the percentage of renewables present in the household consumption is identical. Thus regions A and B from the first run present 84% and 83% of %RE, respectively and regions C and D present 58% and 56%, respectively. In the second run, the %RE for region A, B and C presents 86%, 85%, 84%, respectively and region D presents 53% of %RE. Taken a closer look at the objective function values, it is possible to confirm that the two runs provide the same solutions, even when not completely identical.

![Chart showing LCOT(€) against Annual outside energy consumption (kWh)](chart)
Second, both runs gave a total of 25 solutions with 6m² of solar circuit system and 7m² of PV. The wind turbine height was optimized to 6m. Once again, the LCOT of the chosen technologies is calculated and presented in Figure 5-20. Technologies which are used for little energy delivery have a much higher LCOT and their acquisition has to be thought through.

Ultimately, region B from the first run, or region C from the second run is considered as the best solution group for the household. Which technologies provide most of the household's energy needs is shown in Figure 5-21.
5.2.7 Scenario 3 – Two persons in a house with garden

This additional scenario was chosen in order to check for net zero maximum values. The house remains the one from scenario 2; however there are now just two persons. The analysis is performed as previously, presenting the LCC results and then the LCOT results. From Figure 5-23 it is possible to see that for two persons in a house fewer technology options are considered as the chosen ones are able to satisfy the lower demand. This is advantageous for net zero as %RE becomes 89% in region A. Regions B, C and D present values of 79%, 78% and 75% of %RE, respectively. The annual LCC related to these options is shown in Figure 5-22. Again, an higher %RE results in higher annual costs.
This time, it was decided to analyze not the best trade-off option, but the region with the highest %RE. Thermal solar options satisfy 37% of the whole energy household.

The LCOT analysis for this scenario (see Figure 5-25) gives the highest %RE obtained in all analysis with 91% for region A. Instead of the thermosyphon the LCOT analysis chooses the natural gas boiler for the regions B to D. These regions present none the less a high %RE with 83%, 82% and 79%, respectively.
The LCOT for the chosen technologies can be seen in Figure 5-26. The air conditioner is merely used for the energy service of space cooling, which increases its LCOT.

For region A, it is demonstrated in Figure 5-27 that a big usage of grid energy and a solar circuit supply seem to be the best approach to reach net zero.
5.2.8 Comparison of the results

All the analysis done can be found resumed in Table 5-3. When calculating annual costs, the LCOT analysis presents higher values than the LCC analysis. However, the LCOT technologies provide always a higher value of %RE and include also expensive options such as the geothermal heat pump.

![Figure 5-27: Provided energy by sources for 91% of the household’s energy coming from renewables](image)

<table>
<thead>
<tr>
<th>Nº of persons</th>
<th>House type</th>
<th>Cost analysis</th>
<th>Annual costs (€)</th>
<th>Highest %RE</th>
<th>Considered %RE</th>
<th>Considered technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Apartment</td>
<td>LCC</td>
<td>400.81</td>
<td>69%</td>
<td>59%</td>
<td>Solar circuit, Air conditioner, Natural gas boiler, Electrical oil heater, PV and Wind turbine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LCOT</td>
<td>839.99</td>
<td>73%</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>House with garden</td>
<td>LCC</td>
<td>535.77</td>
<td>77%</td>
<td>71%</td>
<td>Solar circuit, Air conditioner, Water heat pump, PV and Wind turbine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LCOT</td>
<td>3947.03</td>
<td>86%</td>
<td>83%</td>
<td>Solar circuit, Geothermal heat pump, Biomass boiler, Wood furnace, PV and Wind turbine</td>
</tr>
<tr>
<td>2</td>
<td>House with garden</td>
<td>LCC</td>
<td>779.09</td>
<td>89%</td>
<td>89%</td>
<td>Solar circuit, Air conditioner, PV and Wind turbine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LCOT</td>
<td>1901.52</td>
<td>91%</td>
<td>91%</td>
<td>Solar circuit, Air conditioner and Wind turbine</td>
</tr>
</tbody>
</table>

Table 5-3: Comparison between the analysis
6 CONCLUSIONS

From Table 5-3 it is possible to suggest values for renewables present in the energy consumption of a nearly NZEBs in Portugal. This value depends on the house type and on the number of person present in the household. Furthermore, the value can be influenced by the behavioural aspects of energy demand. This work suggests the value of 60-65% of %RE for smaller installations such as apartments and town houses. For houses with more available space for onsite renewables, the suggested value ranges from 75-80%. Dividing houses into classes and determine the mandatory %RE value seems the right regulatory approach.
Continuing implementing renewables for the grid system is also a right approach. For this, electrical appliances in the household should be chosen over gas systems. It has been showed that fewer technologies for the same energy service are cost favourable. A technology which has been very successful in this work for thermal comfort is the air conditioner. Additionally, solar thermal systems should be a must in Portugal once they were included in every simulated case. From the two available options the best trade-off between costs and efficiency is done by the forced circulation circuit. Solar PV systems compensate when more space is available.
Water heating was the energy service with the biggest influence in energy consumption. Space heating and cooling needs are able to decrease, taken the right isolation for the NZEB. As the isolation values were assumed very optimistically, one should not forget that these may not correspond completely to reality.
LCOT and LCC are both cost comparison method, but give different results. It depends on the required optimization approach in order to choose. While LCC has the advantage of obtaining real cost values, LCOT is able to compare the technologies directly to each other and to eliminate options in case of doubt.
The practical implementation of certain case studies performed in this work may not be as simple as shown as it depends from case to case. Furthermore in practice, technologies with a high LCOT that in this work were chosen should be recalculated with care if installed for only one energy service.
Other assumptions for this work could have additional interesting outcomes such as grid selling or implementation of a combined heat power plant onsite. Choosing a different NZEB balance could result in different solutions and may be conclusive about which method is economically seen better for Portugal. A combined program such as GenOpt could help to optimize with more precision the energy services. Considering other renewables as solar ovens, solar thermal tubes and thin film PV technologies is a future point of investigation.
REFERENCES


APPENDICES

Appendix A – Code structure

Questionnaire

START.m

housetype.m

personhouse.m

Water heating

$Q_{wh}, f_{wh}$

housecond.m

centralheating.m

room.m

roomn.m (nE[1,5])

cool.m

coolroomn.m (nE[1,5])

foodcool.m

foodcooling.m

coolroom.m (nE[1,5])

centralcooling.m

lighting.m

lighting.m

media.m

media1.m

media.m

media1.m

Linear Programming

Genetic Algorithm

General variables

$z_0, N_{persons}, \Delta_{limit}$

Space heating

$Q_{sh}, A_h, N_{contactwait}$

Supply options

$Use_{PV}, Use_{wind}, Storage$

Kitchen & washing

$Q_{media}$

Choose method

%RE

Linear Programming

Genetic Algorithm
Linear Programming

Choose energy service to optimize

Get data
- technologydata.xlsx
- sunlimit.m
- variables.m

LCOT calculation
- \( WH_{personk}.m \) (\( k \in [1,6] \))
- \( SH_{personk}.m \) (\( k \in [1,6] \))
- \( SC_{personk}.m \) (\( k \in [1,6] \))

Linear optimization
- Other.m
- WH_linprog.m
- SH_linprog.m
- SC_linprog.m
- FC_linprog.m
- LIGHT_linprog.m

Display solution in GUI
- MEDIA_solutions.m
- WH_solutions.m
- SH_solutions.m
- SC_solutions.m
- FC_solutions.m
- LIGHT_solutions.m
Genetic Algorithm

Data input
Start \texttt{gamultiobj()}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Calculate Costs and evaluate RE

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}

Initial population
\texttt{CreationFcn}

Mutation
\texttt{MutationFcn}

Crossover
\texttt{CrossoverFcn}

Fitness function
\texttt{Evaluation}
Appendix B – Objective function code

Linear programming

Excerpt from WH_linprog.m:

%%%%%%%%%%%%%%%%%%%%%%%%%OPTIMIZATION%%%%%%%%%%%%%%%%%%%%%%%%%

%optimization parameters
f=[lcoewhng lcoewhpro lcoewhbio lcoewhdsd lcoewhhsd lcoewhngat...
   lcoewhngvt lcoewhngst lcoewhproat lcoewhprost...
lcoewhngcond lcoewhngamb lcoewhngseab lcoewhngcondt lcoewhngseabt...
lcoewhprocond lcoewhproamb lcoewhproseab lcoewhproambt lcoewhproseabt]
A=[0 0 0 nwhsd nwhsd 0 0 0 0 0 0 ... 0 0 0 0 0 0 0 0 0 0 0 0]
b=[ pRERsun*QyearallWH]
Aeq=[nwhng nwhpro 0 (1-pRERwheg)*nwheg 0 0 (1-pRERwhhp)*nwhhp ...
nwhngat nwhngvt nwhngst nwhproat nwhprost nwhprost ...
nwhngcond nwhngamb nwhngseab nwhngcondt nwhngseabt nwhngseabt ...
nwhprocond nwhproamb nwhproseab nwhproambt nwhproambt];
Aeq=[nwhng nwhpro 0 (1-pRERwheg)*nwheg 0 0 (1-pRERwhhp)*nwhhp ...
nwhngat nwhngvt nwhngst nwhproat nwhprost nwhprost ...
nwhngcond nwhngamb nwhngseab nwhngcondt nwhngseabt nwhngseabt ...
nwhprocond nwhproamb nwhproseab nwhproambt nwhproambt];
beq=[pRERnon*QyearallWH;pRERd*QyearallWH;pRERsun*QyearallWH]
lb=zeros(25,1)
up=(Inf(25,1))'
x0=(zeros(25,1))'

options=optimset('LargeScale', 'off', 'Simplex', 'on', 'Diagnostics', 'on', 'Display', 'iter', 'MaxIter', 10000, 'TolFun', 10e-8)

%execute linprog
[solution,funcvalue]=linprog(f,A,b,Aeq,beq,lb,up,x0,options)
solution=linprog(f,A,b,Aeq,beq,lb,up,x0,options)

%store solution for GUI
setappdata(0,'solution',solution);

%recalculate actual LCOT
WH_reallcoecalc();
WH_RERcost();

%present solutions
run('C:/Users/Ulrike/MEOCloud/Uli/Dokumente_tese/Codes - teste/solutions/WH_solutions.m');
Excerpt from \texttt{gamultiobj.m}:

```matlab
%% Problem setup
fitnessFunction = @multiobjective;  % Function handle to the fitness function
numberOfVariables = 22;   % Number of decision variables
populationSize = 100;
stallGenLimit = 200;
generations = 50;

% Bound Constraints
lb = zeros(1,22);       % Lower bound
ub = [Qwh/nbng, Qwh/nbbm, Qwh/nhwp, Qwh/nhws, Arearoof, Arearoof, ...
    Qsh/(nhpeg*ndirect), Qsh/(nhpgeo*ndirect), Qsh/(neh*ndirect), Qsh/(nwf*ndirect),...
    (Qsh+Qwh)/(nbng*pWH+pSH*nbng*nwaterrad),
    (Qsh+Qwh)/(nbng*pWH+pSH*nbng*nwaterfloor),...
    (Qsh+Qwh)/(nbbm*pWH+pSH*nbbm*nwaterfloor),...
    Arearoof, Arearoof, ...
    (Qsc+Qsh)/(nhpeg*pSHsc*ndirect+nhpegsc*pSC*ndirect), (Qsc+Qsh)/(nhpgeo*ndirect),
    Qsc/(nhpegsc*ndirect), Qsc/(nhpgeo*ndirect),...
    Arearoof, hlimit];         % Upper bound
Bound = [lb; ub];

%% Solve the problem with integer constraints
options = gaoptimset('PopulationSize',populationSize,...
    'CreationFcn', @int_pop,...
    'MutationFcn', @int_mutation,...
    'CrossoverFcn',@int_crossoverarithmetic,...
    'PopulationSize',populationSize,...
    'StallGenLimit', stallGenLimit,...
    'Generations', generations,...
    'PopInitRange', Bound, ...
    'ParetoFraction',0.5,...
    'PlotFcns',@gaplotpareto);

[x1, f1, exitflag1, output1, population1, score1] = gamultiobj(fitnessFunction,...
    numberOfVariables, [], [], [], [], lb, ub, options);

fprintf('The number of points on the Pareto front was: %d\n', size(x1,1));
fprintf('The number of generations was : %d\n', generations);

%% Plot the results

% Ploy Pareto front
fh1 = figure;
scatter(f1(:, 1), f1(:, 2), 'fill');
xlabel('f_1');
ylabel('f_2');
legend({'round values'});
title('Pareto front');
```

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