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A MULTI-OBJECTIVE DECISION SUPPORT METHODOLOGY FOR DEVELOPING NATIONAL ENERGY EFFICIENCY PLANS

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ABSTRACT

This research aims to aid the decision process of designing and selecting national energy efficiency (EE) plans based on formalizing the problem as a multiple objective problem, on disaggregating the energy demand to the level of end-uses, where the impacts of the energy efficiency measures can be estimated, and on multi-objective optimization methods to overcome the problem of searching the decision space delimited by the objectives and the constraints attributed.

The research started by identifying the objectives and how to make them operational. For that, three key decision makers were interviewed following the value-focused thinking approach, along with a review of the bibliography on the subject. From this process six fundamental objectives were identified formalizing the problem as a multi-objective one. These objectives are: i) to minimize the influence of energy use on climate change; ii) to minimize the financial risk from the investment; iii) to maximize the security of energy supply; iv) to minimize investment costs; v) to minimize the impacts of building new power plants and transmission infrastructures; vi) to maximize of the local air quality.

The second stage concerned the development of a methodology for the disaggregation of the demand energy use into end-uses. This enabled the application and the quantification of the final energy savings, and the estimation of the attributes translating the objectives identified for the problem. Also, such disaggregation enabled the construction of a database of energy efficiency measures containing nearly 1600 measures.

Finally, a hybrid multi-objective MCDA model is proposed to search for the possible energy efficiency plans (combinations of measures) in order to cope with the decision makers' preferences during the search process. This hybrid model was applied to Portugal to search for the most fitted Energy Efficiency plans according to the country's energy context and five different decision perspectives. The combined analysis of the potential Energy Efficiency plans according to different perspectives offers an additional contribution to decision support.

This work intends to contribute to a more systematic analysis of the potential Energy Efficiency plans that can be applied to a country, allowing the consideration of multiple objectives, fulfilling constraints, and the preferences from decision makers, actually focusing the final decision on the alternatives that best correspond to the fundamental objectives behind the purpose of improving the energy efficiency of a country.

RESUMO

Esta dissertação tem como objetivo auxiliar o processo de decisão de construção de planos nacionais de eficiência energética (EE). Tem como base a formalização do problema como um problema envolvendo múltiplos objetivos, a desagregação do sistema de procura energética ao nível dos usos finais, sobre a qual podem ser estimados os impactos das medidas de eficiência energéticas, e em métodos de otimização multi-objetivo para superar o problema de procurar num espaço de decisão de dimensão extremamente grande, delimitado pelos objetivos e pelas restrições consideradas.

A investigação começou por identificar os objetivos e desenvolver uma forma de os tornar operacionais. Para isso, três decisores relevantes com ação na área da eficiência energética foram entrevistados seguindo a abordagem da técnica “value-focused thinking”, processo depois complementado pela identificação de objetivos através da revisão bibliográfica de planos de eficiência energética e similares. A partir deste processo, foram identificados seis objetivos fundamentais, formalizando assim o problema como um problema multi-objetivo. Estes objetivos são: i) minimizar a influência do uso de energia nas alterações climáticas; ii) minimizar o risco financeiro em relação investimento em planos de EE; iii) maximizar a segurança do abastecimento energético; iv) minimizar os custos de investimento; v) minimizar os impactos da construção de novas centrais elétricas e infraestruturas de transmissão; vi) maximizar a qualidade do ar.

A segunda etapa correspondeu ao desenvolvimento de uma metodologia para a desagregação da procura de energia ao nível dos usos finais. Isto permitiu a aplicação e quantificação da energia final poupada, e a quantificação dos atributos adotados para traduzir os objetivos identificados para o problema principal. Além disso, a construção desta desagregação permitiu a criação de um banco de dados de medidas de eficiência energética que contém quase 1600 medidas.

Por fim, um modelo híbrido multi-objetivo e MCDA foi proposto para procurar os planos de eficiência energética possíveis (combinações de medidas), a fim de lidar com as preferências dos decisores. Este modelo híbrido foi aplicado a Portugal para procurar os potenciais planos de eficiência energética mais adequados ao contexto energético do país, em cinco perspectivas de decisão diferentes. A análise combinada dos potenciais planos de eficiência energética de acordo com diferentes perspetivas oferece uma contribuição adicional para o apoio à decisão.

CONTENTS

List of Abbreviations

BAU - Business as Usual

DSM – Demand-side Management

EE – Energy Efficiency

ESD - E.U. Energy end-use efficiency and energy Services Directive

IEA - International Energy Agency

IPCC - Intergovernmental Panel on Climate Change

IPMVP - International Performance Measurement and Verification Protocol

LPG - Liquefied Petroleum Gas

MCDA - Multi-Criteria Decision Aid

MOOP - Multi-Objective Optimization

NEEAP - National Energy Efficiency Action Plan

NGL - Natural Gas Liquids

TSP - Total Suspended Particles

UNFCCC - United Nations Framework Convention on Climate Change

1. Introduction

The worldwide energy use has been growing since the industrial revolution in close relation with the increase of welfare. Fossil fuels were the main resources used to provide energy, and despite the efforts to increase the use of renewable resources in the energy mix, fossil fuels seems to continue being one of the key resources used to provide energy for the near future according to the estimations from the International Energy Agency [1]. The recent world economic crises have slowed down the energy markets, but some local recoveries show that this lower energy use trend may not to stay [1]. Besides the energy demand growth due to long-term economic growth, the energy market is also facing a new challenge. The Fukushima disaster brought additional uncertainty on having nuclear power plants to contribute to the energy mix. This new problem is affecting the energy markets, putting in risk the security of supply of several economies and in special is putting doubts on climate related agreements. However, even if before the recent nuclear crisis, serious concerns about the security of supplies, environmental problems related to climate change and sustainability were present at the world leaders' agenda, leading to rethink the problem: How to balance the demand for energy and its supply in a more sustainable way? To answer this question, a lot of possibilities have been pointed out, like increasing the renewables penetration in the energy mix, energy storage for electricity use (to be stored at cheapest and cleanest hours and to be used at the expensive and "dirtiest" hours), energy efficiency (EE), among others.

Energy efficiency plays a key role to help the global community on the way to a more sustainable energy future according to the Intergovernmental Panel on Climate Change (IPCC) [2] and the McKinsey & Company [3]. Although, the challenge is not only at the energy conversion technologies, but also at the energy management and at urban and building infrastructures that avoid intensive energy needs. The Green Paper on Energy Efficiency [4] shows that one way to direct and improve energy efficiency is through policy instruments, as energy efficiency plans. In general, energy efficiency plans give guidelines to the process of achieving energy savings and reaching desired targets [5][6][7]. When more than guidelines are provided, in the case of having an action plan, energy efficiency measures are selected to represent a plan and to enable the quantification of savings and targets. However, the process of choosing among energy efficiency measures is generally neither clearly structured nor transparent (e.g., several plans in Europe following the Directive 2006/32 [5]).

Besides the problem of selecting energy efficiency measures, another issue is observed in relation to the choice problem, that despite an energy efficiency plan aims to reach one main target, which can be energy savings or greenhouse gas emissions reductions, the plan will affect the economy, the society and the environment in several different ways, helping to achieve other indirect, but also important, objectives. Therefore, the problem must not be seen as a single objective decision making problem which aims reach the defined target restricted to some constraints (as budget), but a process of making decisions in the presence of multiple, and maybe conflicting objectives, such as reinforcing environmental agreements and improving the security of the economies [8] for countries with endogenous fossil resources.

In order to fill the gap found between selecting energy efficiency measures and building transparent energy efficiency plans appears the need to build a methodology to give more guidance and confidence to the process of building energy efficiency plans. This methodology requires the description of energy end-uses and trends for energy demand, including a method to quantify the impacts from the energy efficiency plans and their measures and using a multi-objective decision making approach to evaluate those same plans and measures according to the objectives indicated by the decision makers involved in the problem.

1.1. Review on the problem

1.1.1. Evolution of energy efficiency initiatives

Programs related to energy efficiency appeared in the power sector in the 1960s as load management programs aiming to influence consumers' electricity use in order to obtain improvements in the load shape, namely peak clipping, valley filling and/or load shift to off-peak periods. It was used by electricity suppliers to mitigate both the rising cost of peak power and the difficulty of adding new capacity [9]. Despite having started in Europe and New Zealand [9], it was in the United States that the energy management programs or demand-side management (DSM) programs had a boost as a consequence of the 1973 energy crisis when oil, the main resource used in the energy industry, once abundant and cheap, had its price dramatically increased [10]. Demand-side management therefore came as an opportunity for the utilities to adapt their business to the new context of energy costs, and in some cases even to survive in business [10].

Although its practical appearance dates back to the 1960's, it was only in the 1980s that the concept of energy Demand-side Management began to be systematized and established. Clark W. Gellings proposed what became its most adopted definition: "*The planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load. Utility programs falling under the umbrella of DSM include: load management, new uses, strategic conservation, electrification, customer generation, and adjustments in market share*" [9]. After the consolidation of the concept an advanced use of DSM appeared: to integrate demand-side management with traditional supply-side planning and operation [11]. From this time on, DSM was not just away to influence customers' electricity use for an already existing infrastructure, but a viable resource option to be used in energy planning to postpone or even to avoid investments in new infrastructures and to mitigate the increasing use of resources (mostly fossil and exogenous) and their impacts on the security of the economies and on the environment.

Gellings stated that the fundamental concept of DSM is based on the fact that customers do not purchase energy for the sake of consuming it per se, but instead are interested in the services it provides. That services include warmth, cooling, artificial illumination, motive power, and/or other conveniences [12]. This statement opened a door for a broader approach, where Nilsson “upgraded” the original definition by Gellings replacing the word “utility” with other entities, such as “Government/country”, “Municipality/community” or “Company”, and electricity with “energy,” thus including, gas, oil, heat, etc [13]. The new definition thus became: “*The planning and implementation of those (utility) activities designed to influence the customer use of electricity/energy in ways that will produce desired changes in the (utility's) load shape - i.e. changes in the pattern and magnitude of a (utility's) load*” [13].

Under the later definition, it became possible to use the expression “Demand-Side Management” beyond the strict context of electricity and to deal with all carriers of energy. Furthermore, it opened the floor for other entities, like natural gas suppliers, government organizations and energy service companies (ESCOs), to become actors of energy demand-side management. In line with this broadening of the concept, the International Energy Agency (IEA) in 2008 stated that: “*The basic objective remains, to balance energy demand to energy supply thereby enabling the least cost resources, normally on the demand side, being used first... DSM nowadays looks not only at least cost in selecting resources, but also at enhanced energy security, improved diversification of resources and at environmental sustainability*” [14].

The promotion of energy efficiency programs therefore started as way to reduce costs and to decrease the impacts of the energy crisis, but it gained space as an important resource option to mitigate energy security and environmental problems. Energy efficiency initiatives can now be seen more and more organized as plans, and they are now often promoted by greater players as cities, regions and countries; they aim to reach challenging targets and they have financial support never seen for traditional energy efficiency initiatives and programs, such as the European movement Covenant of Mayors [15].

1.1.2. An overview of practices to develop energy efficiency plans

Energy related policies in Europe have been evolving towards a strategy in which security of energy supply, environmental sustainability and competitiveness are the main concerns. In this context, policies to promote energy efficiency play a key role to contribute to these three main goals [2][3]. The Green Paper on energy efficiency [4] shows that one key way to put in place energy efficiency initiatives is through policy instruments, such as energy efficiency plans.

In 2006 the European Union adopted the Directive 2006/32 from the European Commission, also known as the energy end-use efficiency and energy services Directive [5]. This directive establishes that each country is obliged to develop National Energy Efficiency Action Plan (NEEAP) to promote energy services or any other energy efficiency improvement measures in order to achieve formal final energy savings targets.

According to the ESD [5], the NEEAP is intended to set out the national strategy of a Member State towards the overall national indicative final energy savings target of 9% or higher (for 2015-2016) and also to set intermediate targets. For that, each Member State should use, as a baseline for comparison (i.e., for calculating the energy efficiency improvements and for measuring the targets), the average of the annual final inland energy distributed (or, alternatively, the final energy sold to final customers) during the most recent five-year period previous to the implementation of the Directive. This final energy use should be provided by official available data and not be adjusted for climatic degree days, structural changes or production changes. The national indicative energy savings target for each Member State consist of 9% of the annual average amount of consumption, to be “measured” after the ninth year of application of the Directive, as the result of cumulative annual energy savings achieved throughout the nine-year application period of the Directive.

The 9% savings target in the Directive does not regard total energy savings, but only the extra savings beyond a business as usual trend compared to the eligible baseline. The equation 1-1 shows how the final energy savings are calculated.

$$Energy\ savings\ (\%) = \frac{BAU\ trend\ [ktoe] - Efficiency\ projection\ [ktoe]}{baseline\ [ktoe]} \times 100 \qquad \text{eq.1.1}$$

The ESD does not provide a method to build a BAU trend. The only explicit requirement in this regard is that the amount of energy savings should be either inferred by top down-methods using energy efficiency indicators, or calculated through bottom-up methods.

The Directive [5][5] states that one of the objectives of the NEEAP is to stimulate the translation of energy saving objectives into concrete and coherent measures and actions at the level of each Member State [5]. According to an analysis done by the European Commission in 2008 to the available NEEAPs, many demonstrate coherent and comprehensive strategies towards the intermediate and overall targets, backed by institutional and financial provisions [16].

Analyzing several European NEEAP [17][18][19][20][21][22][7] more in deep, it is easily identified a wide range of policies and measures targeting different sectors of the economy. Some identify their priority end-use sectors or policy tools (e.g., plans from Austria [17] and Hungary [20]). However, some other plans, as the plan from Denmark [19] and Portugal [7], just described some measures with almost no detail or indications of how the impacts were calculated.

The absence, or sporadic indication of savings estimates, from the whole plan, and also individually from each measure, in the majority of NEEAP, along with the mostly limited degree of detail about assumptions made in estimating savings from different measures, have impeded the quantitative assessment of the NEEAPs and therefore of how realistic they are [16].

Complimentarily, it was verified that most of the NEEAPs were built based on "early action" [16] (measures that already existed before the implementation of the plan) but, in contrast, the NEEAP of some Member States such as Poland [22] rely extensively on new measures. Besides the difference between maintaining previous measures and using new ones, it is very difficult to assess whether it is realistic that the Member States will be able to reach their targets, due to too brief descriptions of measures and the absence of detailed saving estimates and calculation methods.

However, some countries have developed specific energy end-use models to give confidence to their savings estimations. The UK Department of Energy and Climate Change generated economy-wide energy projections, which are based on econometric analysis of historic data and which also provide for linear optimization of energy resources [23]. On the other hand, many of the NEEAPs incorporate simply the policy measures along with their expected impacts, without any background calculation [24].

As an exception from what was done for the majority of the EE plans in Europe, Hull [24] modeled the Irish energy context for the implementation of the ESD using the MEDEE bottom-up energy end-use model from Enerdata [25]. This choice was made because the model has a ready to use structure to disaggregate the energy end-use, which can be sub-divided by type of end-user, technology or fuel. The structure provided by the model can be fine-tuned to take into account of the data available for the country being modeled. This approach seems to be the more appropriate for assessing the immediate and direct impacts of specific energy-efficiency measures, as indicated by Thomas [26]. However, the model shows no guidance on how this process should be done and needs to be to be backed-up by a theoretical model built in order to have the end-uses and their possible quantification.

Assessing the measures included in the plans and the quantity of measures dedicated to each sector, it was found that the buildings sector, with focus on the residential or domestic buildings, has been the main choice of most NEEAP. In particular, there are consistently several measures targeting refurbishment of existing buildings. All NEEAP also included measures in the services, transport and industrial sectors as required in the ESD [5]. Most Member States have introduced a variety of information measures, aimed at altering general public awareness through campaigns, public training and education. However, besides the difficulty of assessing the outcomes from such actions, no additional information was provided to demonstrate their consequences on saving energy.

Another very important observation from the analysis of the plans was that it was never clear why and how on which policy and technical grounds the measures belonging to each plan were selected, besides the fact that they can be found at the indicative list of examples of eligible energy efficiency improvement measures and follow (for those Member States that explained their measures) the general framework for measurement and verification of energy savings defined by the ESD. For example, no comparative analysis on the possible outcomes from several measures was performed to find the possible more adequate ones. Besides the problem observed on proving a solid methodological support to estimate the energy savings of the energy efficiency measures and how they were chosen to belong to the plans, it was also observed that despite having a strategy regarding security of energy supply, environmental sustainability and competitiveness, clearly described at the ESD, those objectives were never actually taken into consideration, just the “hope” that if energy is saved, those objectives will be indirectly achieved.

Besides the energy efficiency plans found in Europe, other countries around the world are also building energy efficiency plans aiming at improving the energy efficiency of the country and establishing energy savings targets, such as Brazil [27] and the USA [28]. However, they both suffer from the same shortcomings found in the European plans, such as lack of methodological support to estimate the savings, clear description of measures, and no justifications on how the EE measures were chosen.

The verified context of the Energy Efficiency energy planning practices thus reveals three main opportunities or even needs for improvement from the methodological point of view:

1) To include a clear, objective and transparent identification of the real objectives for the EE plans. As observed from the ESD, it is clear that energy savings are only a means to achieve fundamental objectives, such as the improvement of the energy security.

2) To develop methods that perform an integrated analysis of the EE measures, accounting for the possible quantitative cross-effects between different measures when applied at the same time.

3) The consideration of a very large group of EE measures to be potentially chosen, in order to compare their combined effects when put together in many different possible plans. These many different potential plans would then be evaluated in terms of the objectives identified in 1), and then allow a confident identification of the most adequate possible one(s).

1.1.3. Energy planning in a multiple criteria decision aid context

The previous section argued that the problem of building energy efficiency plans can be a problem considering multiple objectives instead of just a fixed target in energy savings. This section now presents how this problem may fit into the multiple criteria decision aid context. The starting point for this discussion will be previous works using MCDA in the energy planning area.

Multi-criteria decision analysis or aid (MCDA) is a generic term for all approaches that exist for helping people making decisions according to their preferences, in cases where there is more than one conflicting criterion [29–31].

Energy planning using MCDA has attracted the attention of decision makers since late 1970's and beginning of 1980's [29] since these methods provide support to decision makers in making better decisions to the increasing complex energy management problems. When making decisions, DMs tend to choose the optimal solution, but, unfortunately, the optimal solution only exists when considering a single criterion. In most real decision situations several conflicting and often non-commensurable objectives are intrinsic to the problem and considering a decision based only on one criterion can be either insufficient or misguided [8] [31]. Traditional single criteria decision making problems in energy planning aimed at exploring the relationship between energy and economy through the maximization of benefits or the minimization of costs. One of the most popular problems was to identify the most efficient supply options at the lowest cost [8]. The growing environmental awareness and the need for social considerations since the 1980s played a key role for the increasing use of multi-criteria approaches, since the previous simplification of the decision problems into a single criterion was not as well accepted as before.

Changes in the economy and the energy context such as consequences from the oil crisis of 1973 modified the decision making process in the energy planning introducing options such as energy conservation and energy substitution. The energy substitution of fossil fuels for renewable energy sources and the promotion of energy efficiency have several benefits that are more difficult to account using traditional single criterion decision approaches. It was felt that, along with the necessary policy measures to force the market to valorize non-economical criteria, the wide exploitation of sustainable energy and energy efficiency options should be based on a holistic conception of energy planning process.

Chattopadhyay [32] integrated energy efficiency initiatives under the umbrella of DSM options in a multi-objective framework to perform an integrated resource planning claiming that the associated benefits of DSM options, such as cost reduction, emissions reduction and improvement of supply system reliability would be evaluated and valorized, and this approach would also consider various types of DSM options and their characteristics. A compromise programming approach based on the minimization of a distance to the ideal solution was used to compute solutions considering as objective functions the annual system cost, CO2 emissions and loss-of-load expectation (LOLE) of the generating system. DSM options are characterized as supply-side resources following the concept from Gellings [11] in order to compete with traditional supply-side options such as a power plant. The main idea from the work was to assist decision makers and planners in selecting a compromise solution for the integrated resource planning evaluating and finding trade-offs between costs and other important criteria using both supply and demand options.

Kablan [33] defined that an effective energy efficiency policy should encourage the different agents in a country to employ energy-efficient processes, technologies, equipment and materials, and also should take into consideration important aspects such as economic growth and sustainable energy sector development, environmental pollution, and more utilization of the available renewable energy resources, turning the process of choosing among energy efficiency policies into a multi-criteria problem. However, his work uses one of several MCDA approaches, the analytic hierarchy process (AHP), not to choose among policies, but to prioritize the use of the available implementation mechanisms, such as pricing policy, regulation and legislation and training and education to promote energy efficiency.

Following Kablan [33] that defined the choice of energy efficiency policies as a multi-criteria problem, Neves [34] proposed a multi-criteria decision approach for sorting energy-efficiency initiatives related to the power sector to overcome the limitations and drawbacks of cost-benefit analysis. The approach was based on the ELECTRE-TRI multi-criteria method, which by the nature of the method avoids the difficult measurements, unit conversions and compensations between criteria, allows the consideration of different kinds of impacts and lets the incorporation the actual preferences of decision makers in the analysis. Neves claims as advantages of his approach that it deals with enabling the decision maker to base the decision on the natural values from the criteria, instead of using conversion rules to currency, providing more confidence in the decision process; another advantage is the fact that a good performance in one criterion does not hide a poor performance in another since no compensation is performed; and to the possibility of conducting an analysis to assess the robustness of the decisions regarding the uncertainty of the input data. The outcome from this work was the performance evaluation and further classification for 24 energy efficiency initiatives according to different criteria and decision maker perspectives.

Taking into consideration that energy efficiency plans are supposed be a part of a strategy to, at least, improve security of energy supply, environmental sustainability and competitiveness, the process of choosing energy efficiency initiatives to be present in a plan can be seen as multi-criteria problem and is in line with the proposed approaches by Chattopadhyay [32] regarding searching the multi-objective space in order to find the most fitted solutions and by Neves [34] on the perspective of screening the more fitted energy efficiency initiatives to be promoted in accordance to the decision maker's perspective.

As a conclusion, this sections has shown that using a multi-objective approach to search for the more adequate combination of EE measures to build energy efficiency plans has the potentiality to answer to the methodological challenges indentified in the previous section, i.e., to support and provide confidence for the decision process of such a complex problem.

1.2. Research questions, scope and main assumptions

The research has as general goal of developing a methodology to aid the decision process when building energy efficiency plans at the geographic scale of countries, and it is oriented to be used by energy analysts and decision makers. However, since the methodology intends to assess the impacts of energy efficiency measures at the main sectors and their respective end-uses, its application can be further used to different geographic scales, such as groups of countries, country regions, or even municipalities.

To guide this work, research questions were identified from the main problem and are addressed along the work.

The principal research questions for this study can be stated as follows:

- How can fundamental objectives be identified and made operational for the construction of national energy efficiency plans?

According to Keeney [35], decisions are often characterized by multiple objectives and each objective represents something that someone wants to achieve in a specific decision context. Keeney also claims that the most obvious way to identify objectives is to engage in a discussion of the decision situation with the decision makers. The results from such discussions provide a list of potential objectives and a basis for further questioning. Chapter 2 shows how this process was dealt and its outcomes.

- How to systemically identify the potential EE measures and soundly quantify the energy savings that they enable?

The quantification of the results from energy efficiency measures is one of the main challenges found when building energy efficiency plans [16][36]. In order to overcome this issue, a methodology to model the energy system was developed at the level of end-uses and energy carriers, following [26]. This approach shows how the energy is transformed into end-uses and eases the process of calculating changes due to technological-based improvements and by other drivers which are the physical representation of EE measure. Complementarily, the model developed also enables a systemic identification of the potential EE measures. This research question is addressed in chapter 3 and chapter 4.

- How can EE measures be combined into EE plans, and how can these be evaluated considering the objectives identified and the preferences of the decision makers?

After addressing the first and second research questions, it is possible to identify the objectives that can be used to evaluate plans and also EE measures that can be used to build plans. Having the measures and the objectives it is proposed to search the multi-objective space in order to find the solutions (EE plans) that best correspond to the perspectives from the decision makers, attending the restrictions imposed by the problem. A method to answer to this question is addressed in chapter 5, and an example of its application using Portugal as a case study is presented in chapter 6.

This research is developed under a specific scope and based on several main assumptions that are described below.

Energy efficiency measures can be seen as an activity or set of activities designed to increase the energy efficiency of a system, and it may also conserve energy without changing efficiency by operational changes. Such changes are performed via physical changes of systems and equipments (e.g., changing a motor at an industry for a more efficient one) or based on behavioral and educational enhancement (e.g., turning the equipments off while they are not in use). However, just knowing what to do does not make the measure operational. In order to make EE measures operational it is necessary to rely on the implementation processes, or mechanisms. Such processes formalize how to encourage, or even force, the society to accept and implement the expected changes. Typical implementation mechanisms are the distribution of more efficient equipments, the creation of a new regulation to make mandatory minimum efficiency standards and information campaigns.

Since most measures can be implemented through many different mechanisms, and since those mechanisms depend on volatile political issues and interests, the scope of this work will not consider this issue, limiting to develop a pre-analysis tool to guarantee that measures can be implemented through physical changes of systems, and such changes can be implemented up to a maximum applicable size in a specific context (country).

In order to deliver a quantitative assessment of the EE plans and how realistic they can be, the scope of this work limits the EE measures to technical-based measures (measures designed to deal with physical changes of systems and equipments), with an exception to the behavioral measures involving modal shift. This position was taken to reduce the uncertainties that are intrinsically associated with behavioral and educational measures. However, the use of such measures is open for future research, since the methodology developed in chapter 3 is open to cope with drivers that reflect behavioral and educational changes.

Energy efficiency plans can be seen by several different perspectives. Some countries, such as Brazil [27] and the USA [28] organized their EE plans as guidelines and group of intentions that can be used to improve energy efficiency in a country. However, other countries, such as those belonging to the European Union [5], try to be more concrete and specific in the formulation of their plans, intending to put together energy efficiency measures and the expected results from such measures. Therefore, for the scope of this research energy efficiency plans are represented as combinations of energy efficiency measures and the respective degree of implementation of each one. Besides differences in the definition of EE plans around the world, one detail is transversal to all plans: that there is always a predefined target that they intend to achieve. Therefore, for the scope of this research, EE plans have at least one target and such target is associated with energy savings.

The scope of this research is limited to the demand-side, considering no interactive effect between the demand and the supply-side. The results from the plans will not affect decisions made on the supply-side, and despite the interactions between the electricity supply and its demand, the values associated to the electricity use, such as CO_2 emissions and energy imports, are treated as external inputs.

In what concerns the case study, it is assumed that all the information about the electricity supply-side is based on the “Roteiro Nacional das Energias Renováveis Aplicação da Directiva 2009/28/CE” [37] and the “Plano Nacional das Energias Renováveis” [38]. It is also assumed that the preferences for the decision process are obtained from decision makers involved in the problem and experts.

1.3. Thesis structure

The research started by understanding the problem of building energy efficiency plans. This was formalized by a review of the context of the problem and the identification of the principal research questions, the scope of the research and the main assumptions, as reported in section 1.2. After this, a general methodology was assembled to guide the research process. Chapter 1 organizes the approach to the problem.

The research proposes a methodology to identify the relevant criteria that represent the general interests from decision makers when building an energy efficiency plan. For this, a process involving interviews with decision makers and a literature review is proposed to obtain the ends objectives. After identifying the objectives, the process follows to quantify the objectives (obtain their respective attributes) to further evaluate energy efficiency plans. The methodology is used to guide the interviews with decision makers from Portugal and Brazil in order to obtain a broad and generic view of the problem. Both the methodology and its application are described in chapter 2.

Knowing the objectives of a plan, the research was directed to the development of a methodology to perform a breakdown of national energy systems into the most representative end-uses (e.g. domestic hot water, space heating and individual transportation) within the domestic, services, industry and transport sectors. The methodology allows the creation of a model where the energy can be associated to the drivers that influence the energy use in each end-use. Also, the way in which energy use is modeled facilitates the later quantification of the effects from the implementation of energy efficiency measures. Since energy efficiency plans tend to obtain results in a near future, a time-evolution methodology, based on trends on energy use, macro-economical factors and the ownership of equipments, is applied in order to project the energy demand into the future for the evaluation of the objectives of the plans. The end-use and the time-evolution methodologies are explained and illustrated using data from Portugal for the year 2006 in chapter 3. The end-use methodology made possible the identification of approximately 1600 EE measures to be used in plans. Both the identification of measures and their final energy calculation are explained in chapter 4.

Assuming the main problem of building energy efficiency plans as a multi-objective problem and understanding the natural restrictions of the problem, as a target for final energy savings at the last year of the application of the EE plan, the next stage was to search the potential solutions space (the groups of energy efficiency measures and their degree of implementation) in order to find the non-constrained ones that would reflect the preferences from the decision makers. The preferences of the DMs is illustrated for Portugal with five profiles, developed based on the results from the interviews and based on preferences that the research group presented to test other possible groups of DMs, such as an environmentalist group. In order to overcome the problem of searching for a solution using the preferences from the DMs, a hybrid multi-objective genetic algorithm combined with multi-criteria decision algorithm was proposed. All the multi-criteria decision aid is described in chapter 5 and their outcomes can be observed in chapter 6, which has a case study application of the overall methodology for Portugal.

The general key findings of the research, as a discussion over the results for Portugal and future steps for this research, are presented in chapter 7.

2. Identifying objectives for energy efficiency plans

Generally, decision makers start their decision process thinking of possible alternatives or comparing alternatives that are already shaped to solve their problems, and only afterwards they address objectives and criteria to help to evaluate and/or choose among them, turning this process of thinking on the objectives a reactive process in relation to the alternatives. Keeney [35] refers to this standard problem-solving approach as alternative-focused thinking and defends that focusing on alternatives is a limited way to think through decision situations because it “solves” decision problems, but does not identify desirable decision opportunities (does not create new (better) alternatives beyond the pre-identified ones). Decision opportunities can be only reached if the decision maker starts by thinking on what he values. According to Keeney, values are the representation of what one desires to achieve in a specific decision process, therefore they are fundamental and should be the driving force for the decision making process, while alternatives are only relevant because they are means to achieve values. Keeney names this process of thinking as “value-focused thinking”, and it is based on having significant effort to make values explicit by applying logical and systematic concepts to qualitatively identify and structure the values that best fit a decision situation.

Decisions are often characterized by multiple objectives, which, in turn, are the desires that values represent. Consequently, as the problem of choosing energy efficiency plans can be characterized as being a multi-objective problem and shaped around few defined key-questions, thus leaving enough space for creative thinking and for inventing potential courses of actions. The value-focused thinking approach matches perfectly this context, and therefore it was decided to use it to structure the processes of identifying objectives, their respective attributes, and the construction of alternatives (plans).

2.1. Value-focused thinking procedures to obtain objectives

Following the Value-focused thinking approach, four procedures must be done to guide the way of thinking in order to obtain the objectives and later the alternatives. First, one must compile an initial list of objectives. Second, these objectives must be categorized as means or ends objectives and then be logically structured. Ends objectives concern the ends that decision makers value in a specific decision context, and means objectives are objectives that will lead the way to achieve the ends. After, the objectives must be used to create alternatives and the same objectives should be examined to identify worthwhile decision opportunities [35].

The most obvious way to identify objectives is to engage in a discussion with the decision makers about the decision situation [39]. The process requires creativity and hard thinking and it can begin by asking the decision maker, "What would you like to achieve in this situation?" The responses provide a list of potential objectives and a basis for further questioning. When asking a decision maker to express objectives, it is very important to make it clear that what is needed is a list of objectives without ranking or priorities, to facilitate the process and bring more objectives [39]. This is because if the decision maker starts the process by introducing any value judgment, he could exclude important objectives that seemed less important, or apparently could not reach targets. This could have the undesirable effect of biasing the list, limiting the process of thinking. To expand the list, one may ask, "If you had no limitations at all, what would your objectives be?" Similarly, one may ask what elements constitute the bottom line for the decision situation and for the decision maker. Many words, such as tradeoffs, consequences, impacts, concerns, fair, and balance, should trigger questions to make implicit objectives explicit. If a decision maker says "tradeoffs are necessary", one should ask “tradeoffs between what and what?” in order to explicit the situation. If a decision maker says "the consequences should be fair", one should ask “fair to whom?”, and “what characterizes “fair”?”. If the decision maker seems to stop and think, one should ask what the thoughts are. Answers to these questions may lead to other questions and, in the end, to a more realistic and reliable identification of the objectives [39].

2.1.1. Structuring objectives

According to Keeney an initial list of objectives contains many items that are not really objectives [39]. It instead includes a mix of alternatives, constraints, guidelines, and attributes to evaluate alternatives. In order to get the most of the initial list, each possible item from the list is analyzed to lead to the objectives that can be behind it.

When alternatives appear in the wish list, they generally do not appear alone, coming at least in pairs, which enable the comparison among them to find which is “better”. The articulation of features that distinguish existing alternatives provides a basis for identifying some objectives for the decision problem. This can be easily done by asking what the objectives are. To push further, one should ask what a “perfect” and a “terrible” alternative would be. These extreme cases could highlight important objectives.

Constraints and goals are responsible for setting a level or standard with respect to a specific measure of an objective. Both are meant to be achieved and what differs one from the other is the fact that goals are used to motivate achievements, while constraints work as a screening process to limit minimum requirements for alternatives. Both goals and constraints can suggest objectives. Generally, the standard involved is an objective that one wants to minimize or maximize.

Quoting Keeney, “guidelines are less definitive than goals, or constraints.” [39]. They indicate objectives or alternatives that should or should not be pondered. They generally cover broad issues, but they can be very helpful in identifying important general objectives. They come from several sources, as strategic plans, policies or incentive systems.

Attributes are the degree to which an objective is measured. Therefore, knowing how an objective is measured, it is just a question away from knowing the objective. Consequently, one should ask “what is important, to minimize or maximize this attribute?”

After filtering the objectives from a wish list, the second step should be tracing ends objectives from specific means objectives in order to find at least one fundamental objective in a given decision situation. For each objective, one should ask "Why is this objective important in the decision context?" For this question, two types of answers are possible. One is that the objective is one of the main interests in the situation. Therefore, this objective is a fundamental objective. The other response is that the objective is important because of its implications for achieving some other objective. In this case it may be a means objective. The "Why is it important?" test should now be applied to this objective to ascertain whether it is a means objective or a fundamental objective.

Having the objectives identified and structured allows understanding the problem faced by the decision maker, and it also is the first step to identify future alternatives to help solving the problem and transforming the objectives into attributes to evaluate the proposed alternatives.

2.2. Value-focused thinking procedures to obtain attributes

Attributes measure the degree to which an objective is achieved [39] and they can be seen as a representation of criteria. In turn, criteria are, in Roy’s definition [30], “tools” that allow the comparison of alternatives according to a particular “significant axis” or a “point of view”. Both definitions converge in measuring how good alternatives are according to each objective.

According to Keeney [39], there are essentially three types of attributes, which can be defined as natural, constructed or proxy attributes. The distinction between attributes as one of these types is not always obvious, but this trichotomy is useful to clarify differences between the attributes and how they are constructed.

2.2.1. Defining types of attributes

Natural attributes are those that have a common interpretation from the objective. Having an objective to minimize costs, the attribute cost, in a desired currency, is a natural attribute. Often the selection of a natural attribute may not be that simple and frequently involves value judgment, as is the case of using the length of paved roads as an attribute to evaluate the objective of maximizing road conditions. In this case, there is a value judgment that all roads are “equal” and the width of the roads or the number of tracks does not matter. For this situation, another “better” natural attribute can be used, as the area of paved roads. If natural attributes do not exist or if they have inappropriate built-in value judgment, two other possibilities can be used: constructing an attribute to measure the associate effects of the objective, or measuring the achievements in an indirect way by the use of proxies.

When the objective is not clear, the attributes assume an important role to define what is meant by the objective. In those cases, the development of a constructed attribute may be a very satisfactory approach. Differently from natural attributes, which are transversal to several decision contexts, a constructed attribute is developed specifically for a certain decision context. With time and use, some constructed attributes tend to be seen as natural attributes, as their levels of understanding become more uniform by many individuals [39]. Examples of constructed attributes are the GDP (gross domestic product) and the Richter scale.

There are some cases where the identification of a natural or a constructed attribute is very difficult or even impossible. In these cases, a solution is to use a proxy (or indirect) attribute. In general, proxy attributes are natural attributes for a means objective. It is important to have in mind that these attributes are valued by their perceived relationship to the achievement of the fundamental objective. An example of this can be “reducing CO_2 emissions” as a proxy to “minimizing climate change effects”.

Keeney states that attributes must embrace desirable properties, such as being measurable, operational and understandable, in order to clarify the related objectives and facilitate the value-focused thinking [39]. An attribute that is measurable is capable of defining the associated objective in more detail than the provided objective itself. To do this, the attribute should embody appropriate value judgments and exclude the ones that are inappropriate. The fact that value judgment is appropriate or not will depend on each context. For example, using GDP as an attribute for defining the objective of maximizing the economic well-being of a country will depend on each country. If GDP does not reflect the distribution of the purchasing power, it would be better to decompose the objective or change to an attribute that could really reflect the achievement. On the other hand, an operational attribute, is one that describes the consequences with the respective objective and provides a sound basis for value judgment about the degrees to which the objective might be achieved. Also, an attribute is operational when there is data to measure the attribute, or there is a reasonable way to find such information. Using the previous example, when the GDP does reflect the distribution of the purchasing power and does not leave room for doubts on the consequences of the values achieved, it can be considered operational. Finally, attributes are understandable when there is no ambiguity in describing and interpreting the consequences in terms of the attributes. This means that there should be no loss of information when one person assigns an attribute level to describe the achievements of an objective and another person interprets that level of accomplishment.

2.2.2. Selecting attributes

Selecting attributes is an important part of the decision process, due to its influence in improving communication and in quantifying a value model and evaluating alternatives to solve decision problems. One should choose between a natural, a constructed or a proxy attribute depending on the context of the problem and the objectives. If a natural attribute is available for a specific objective, this should be automatically chosen. In case natural attributes are not available, the situation becomes more complex and the objective should be decomposed into less complex components or a constructed or proxy attribute should be used [39].

Constructed attributes measure exactly what objectives are meant to address. Since constructed attributes are a complete description of their respective objectives, it is easier to separate judgments about consequences from value judgment when compared to proxy attributes or decompositions from objectives. The potential shortcoming of these attributes is that they are not necessarily understandable and operational. As they are specific for a context they do not necessarily have a common interpretation of attribute levels, making it more difficult to communicate the consequences of using these attributes.

Decomposition can be seen as a special procedure to construct an attribute from an objective. Here, the objective is specified into component objectives and then attributes are found for those components and are integrated through the use of value judgment. At the limit, decomposition is a way to build constructed attributes. The advantage of using decomposition is that it enables the identification of natural attributes for the lower-level objectives created; the drawbacks are that there will be more attributes to manage and more data to collect and also there is a possibility that the decomposed attributes may miss some detail about the original one, especially if the objective is a little vague or too broad.

The proxy attributes generally reduce the number of attributes in a decision process and simplify the description of consequences. The disadvantage is the likelihood of redundancy in evaluation, because it is like having a means objective among fundamental objectives and this means objective is related to more than one fundamental objective.

Consequently, selecting or defining the attributes to measure the objectives from the decision process is always a complex task. This task should be taken with care, having the aim to leave the decision makers involved in the process comfortable with the future effort to collect all the data needed, and not forgetting that the selected attributes should be measurable, operational and understandable.

2.3. Applying value-focused thinking to obtain objectives

Throughout the previous sections, the problem of building energy efficiency plans was characterized as a problem involving multiple objectives. In order to identify what are the potential objectives involved in this problem (taking into consideration that the objectives should describe the desires from the respective decision makers), an effort was made to find the most transversal ones, which could be used as reference objectives when building EE plans. This process was performed by interviewing key decision makers involved in building EE plans in two different countries, and also by performing a bibliographic review on the subject to identify “missing” objectives that might be relevant.

In the first stage, following the procedures described in section 2.1, three decision makers were interviewed in order to identify the fundamental objectives for energy efficiency plans. Since energy efficiency plans are constituted from measures, the same process was applied to find specific objectives for measures, for the case that there appears a need to individually evaluate and select measures.

The interviewees were selected according to their position as decision makers responsible for the promotion of local and national energy efficiency. The selected interviewees were Professor Eduardo Oliveira Fernandes (1) President of the Porto Energy Agency in Portugal (AdEPorto), Engineer Paulo Calau (2) Director of energy audits in industry area in the Portuguese Energy Agency (ADENE), which is the institution responsible for the National Energy Efficiency Action Plan for Portugal under the context of the ESD, and Engineer Raymundo Aragão (3), from the department of Economy and Energy Studies at the Brazilian enterprise for research and energy (EPE) and also as one of the responsible persons in the development of the Brazilian National Energy Efficiency Action Plan (PNEf).

From the interviews with the decision makers, it was possible to list six fundamental objectives for the energy efficiency plans: to minimize the influence of energy use on climate change, to minimize the financial risk from the investment, to maximize the security of energy supply, to minimize the risk of failure, to minimize the investment costs and to minimize time until the plan starts to make effect. From the same interviews, seven fundamental objectives were listed for the energy efficiency measures: the same six for the plans plus the objective of maximizing the duration of the effect of measures. Table 1 shows the objectives that the decision makers found relevant to the process.

Table 1 – List of fundamental objectives from interviewed decision makers

Objectives	Decision Makers
Minimize the influence of energy use on climate change	1,2
Minimize the financial risk from the investment	2,3
Maximize the security of energy supply	1,2,3
Minimize the risk of failure	3
Minimize time until the effect of the plan	1,3
Minimize investment costs	1,3
Maximize the duration of the effect of measures*	3

*Only applicable to measures

Key:1 Eduardo Oliveira Fernandes; 2 Paulo Calau; 3 Raymundo Aragão

During the process of listing the objectives, all the decision makers realized that increasing (maximizing) the final energy savings was not a fundamental objective, but a means objective to make the fundamental objectives possible or, as in the specific case of the ESD, a restriction that should be achieved.

Evaluating the list resulting from the decision makers, two objectives lost relevance to this research because they were strongly linked to the implementation mechanisms (e.g. regulation, finance incentives), which is outside of the scope of the current research, as justified in chapter 1. The non-relevant objectives of this research are i) the minimization of the risk of failure, intended to give priority to measures that are less difficult or complicated to be implemented and also to measures which the expected results are more reliable; and ii) the objective related to minimize time until effect of the plan, that reflects the time that one must wait to observe the results from measures. Continuing the process of evaluating the list, the objective that is only applicable to the measures could be also applied to plans. However, discussing the problem with the decision makers and the research group a consensus was not reached on if it would be really relevant to have a plan that would last for a long time (as long as possible), nor on what would be the best way to group this information. Therefore this objective also did not enter the list for plans.

In the second stage, in order to confirm that the selected objectives from the interviews were complete, reflecting all of the important consequences from the energy efficiency plans in a decision process, and also that they are adequately described in terms of the set of fundamental objectives, the objectives interpreted from the ESD were listed in order to complement the objectives resulted from the interviews. Also the works from Neves [40] and

Brown [41] were revised to collect more perspectives of objectives applied to evaluate EE policies and measures.

The objectives found in the ESD [5] were: i) to mitigate (minimize) greenhouse gas emissions to prevent climate change; ii) to exploit potential cost-effective energy savings in an economically efficient way; iii) to help the Community to reduce its dependence on energy imports; iv)to boost the Community's innovativeness and competitiveness as underlined in the Lisbon strategy; and v) that the public sector in each Member State should set a good example on energy-using equipment, energy services and other energy efficiency improvement measures. Since this work addresses only the energy efficiency measures of technical nature, and is not considering the specifications of the implementation process (promotion mechanism), as focusing the application of measures to a sector not because of its impacts, but due to political objectives, and considering the energy reduction per se as a proxy to increase competitiveness, the list from the interviews seems to be in line with the objectives found in the Directive.

Analyzing the work from Brown on energy efficiency and renewable energy policies at state level in the Unites States [41], seven objectives were identified: three for economic development, two related to energy security and two environmental. The economic development ones were: the value of Industry, measured in the dollar value of the industry relative to overall industry in the state; gross state product impact, related to the value of a growing industry as the result of the policy; and job impact, reflecting state policymaker interest in increasing job creation in the state. The two objectives for energy security were: fuel import offset, intended to reduce energy imports from both international locations and other states; and fuel diversity, measured relative to the overall energy mix in order to obtain a more diversified and shared energy mix. The environmental ones were: local air quality impacts, measured in particulate emissions reductions; and greenhouse gas emissions reductions, measured in carbon and carbon equivalent gas emissions reductions. From the objectives suggested, it is considered that the three economic ones were essentially related to how the measures are implemented and not directly to the technical nature of measures, which is the main focus of this work. The decrease of fuel (energy) imports and the greenhouse gas emissions reductions were already found in list resulting from the interviews (Table 1). The two new elements were therefore the local air quality impacts and the fuel diversity. The local air quality impact was added to the list as an objective due to its consistency with the problem (tackling local pollution). The fuel diversity was not considered because during the discussions with the decision makers it was clear that, as far the resources are endogenous and the sources reliable, the diversification was not relevant.

Regarding the thesis from Neves [40], thirteen objectives could be pointed out: i) to minimize the impacts from energy use; ii) to minimize the impacts from the peak load; iii) to minimize the use from other resources (e.g., water and space); iv) to maximize wellbeing; v) to minimize the rise in unemployment or to maximize number of jobs; vi) to minimize implementation costs; vii) to minimize the impact on budgets; viii) to allow the evaluation of alternatives; ix) to create market transformation; x) to maximize compatibility with strategic targets; xi) to minimize impacts on tariffs; xii) to maximize reductions on energy bills; and xiii) to minimize non-funded costs to consumers. From the objectives listed above, the ones that can be directly linked to measures of technical nature are the objectives of minimizing the impacts from energy use, of minimizing the impacts from peak load, minimizing the costs in general terms, and the possibility to evaluate alternatives. Besides the minimization of the peak load to avoid building new power plants and accounting their impact, and taking into consideration that all technical-based EE alternatives can be evaluated, the objectives are in line to those found in the interviews. The minimization from the peak load was observed as a means objective and included in the form of a fundamental objective: minimizing the impacts of building new power plants and transmission infrastructures.

Having selected the relevant objectives from the interviews and included another two from the bibliographic review, the resulting group appears to be complete, non-redundant, concise, specific and understandable, pertaining collectively to the set of fundamental objectives as specified by Eduard [42] and Keeney [39]. This indicates that a satisfactory group of objectives was obtained to evaluate the energy efficiency plans and, moreover, that these findings also changed the problem of building energy efficiency plans to a decision opportunity where efforts can be directed to find alternatives that will bring more outcomes than just specific final energy savings as defined at the ESD. Table 2 lists the fundamental objectives presented by the interviewees and raised from the bibliographic review that fit in the boundaries of the problem. Table 2 references the objectives found at the ESD as 4, those from the research from Neves as 5 and those from the work from Brown as 6.

Table 2 – Fundamental objectives resulting from the interviews and bibliographic review

Fundamental objectives	Decision Makers and reviews
Minimize the influence of energy use on climate change	1,2,4,5,6
Minimize the financial risk from the investment	2,3,4,5
Maximize the security of energy supply	1,2,3,4,5,6
Minimize investment costs	1,3,5
Minimize the impacts of building new power plants and transmission infrastructures	5
Maximization of the local air quality	6
Maximize the duration of measures*	3

*Only applicable to measures
Key:1 Eduardo Oliveira Fernandes; 2 Paulo Calau; 3 Raymundo Aragão; 4 ESD; 5 Neves; 6 Brown.

The nature of the objectives identified seems to be quite general and not particular of the Portuguese or Brazilian specific contexts, and therefore very likely applicable to other geographical contexts. Nevertheless, it is worth reminding that the good practices of value-focused thinking do recommend performing the whole process described in section 2.1 again with the respective decision makers in a case of applying this research to another country.

2.4. Applying value-focused thinking to obtain attributes

Once the fundamental objectives were identified (section 2.3), it becomes necessary to measure them in order to use the objectives to evaluate alternatives. For that purpose, attributes were defined to indicate the degree to which an objective is measured. Following the process described in section 2.2, all fundamental objectives were translated into attributes, and this translation received the agreement from the decision makers interviewed. The next sections describe all the attributes related to the fundamental objectives.

2.4.1. CO_2 emissions savings

After identifying the fundamental objective of minimizing the influence of energy use on climate change, the decision makers were asked how they would be able to verify the achievement of this objective. All the decision makers asked were unanimous in expressing that their preferred way to measure the objective was through the CO_2 emissions saved or avoided. Due to the fact that CO_2 emission is widely identified as the most important agent of the climate change process [2], and also due to the understanding and operability expressed by the decision makers, the CO_2 emission savings was chosen as the attribute to represent the minimization of the influence of energy use on climate change.

Considering the premise that the outcomes from energy efficiency plans are reductions or savings on final energy, it was proposed to quantify the CO_2 emission savings from plans as:

$$CO_{2savings} = \sum_{y=1}^{m} \sum_{i=1}^{n} \left(Q_{fiy} \times CO_{2EFiy} - Q_{fiplany} \times CO_{2EFiy} \right) \ [tCO_2] \qquad \text{eq.2.1}$$

Where:

Q_{fiy}: Original final energy use for energy carrier i in the BAU scenario at year y (i.e., without EE plan) [MWh]

$Q_{fiplany}$: Yearly final energy for energy carrier i from the application of an EE plan at year y [MWh]

CO_{2EFiy}: CO_2 emission factor for energy carrier i at year y [tCO_2/MWh] n: total (number of) energy carriers

m: total number of years analyzed

Following the methodology and data from the IPCC Guidelines for National Greenhouse Gas Inventories [43], it was possible to determine the CO_2 emission factors for the main energy carriers used in a country. The CO_2 emissions from use of bio-energy were not accounted as emissions in the energy sector, since they are considered stock losses in the land use sector following the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol [2]. Table 3 presents the CO_2 emission factors for all energy carriers, with the exception of electricity that was treated separately.

Table 3 - CO_2 emission factors for energy carriers

Energy Carriers	CO_2 emission factor (t/MWh)
Bio Gas	0
Biodiesel	0
Biomass	0
Coal (Anthracite)	0.354
Diesel	0.267
Diesel for Heating	0.267
Ethanol	0
Fuel Oil	0.279
Gasoline	0.249
Hydro	0
Industrial Wastes	0.515
Jet	0.252
Liquors (Other Liquid Biofuels)	0
LPG	0.227
Methanol	0
Municipal Wastes	0.330
Natural Gas	0.202
Oil for lighting	0.264
Other	0.264
Solar	0
Wind	0

Considering fact that electricity is generated from the conversion of several different energy sources, through several different conversion processes, the CO_2 emission factor of electricity was accounted as a yearly weighted sum of the CO_2 emission factors from all sources that contributed for the electricity conversion, whose several contributions can be seen at the national energy balance of countries [44]. Equation 2.2 formalizes the calculations for the CO_2 emission factor of electricity.

$$CO_{2EFelectricity} = \sum_{i=1}^{n} \frac{CO_{2EFi} \times Yearly\ share_i}{\eta_i} \ [tCO_2/\mathrm{MWh}] \qquad \text{eq.2.2}$$

Where:

Yearly $share_i$: Yearly contribution share of the electricity converted from carrier i [-]

η_i: Average efficiency of the conversion process from carrier i to electricity [-]

CO_{2EFi}: CO_2 emission factor for energy carrier i [tCO_2/MWh]

n: total (number of) energy carriers used for producing electricity

To illustrate the calculations to find the CO_2 emission factor for electricity, data from the energy balances for Portugal between 2006 and 2008 were used [45]. The average conversion efficiency for each conversion process to generate electricity was calculated following equation 2.3.

$$\eta_i = \frac{Yearly\ share_i \times Q_{felectricity}}{Q_{si}} \ [-] \qquad \text{eq.2.3}$$

Where:

Yearly $share_i$: Contribution share of the electricity converted from carrier i [-]

$Q_{felectricity}$: Total electricity converted by the electric system, including losses, pumping and the electricity used by power plants [MWh]

Q_{si}: Energy source used from process i [MWh]

Table 4 presents the reference average efficiency of the conversion processes to electricity for Portugal.

Table 4 - Average conversion efficiency to electricity by process

Conversion process	η
Bio Gas - Thermal process	0.31
Biomass - Thermal process	0.25
Coal - Thermal process	0.39
Cogeneration (all carriers)	0.79
Diesel - Thermal process	0.30
Fuel Oil - Thermal process	0.39
Hydro, Wind, Geothermal and Solar	1.00
Imports	1.00
Municipal Wastes - Thermal process	0.25
Natural Gas - Thermal process	0.51

Using the energy contributions for electricity generation in 2008 [45] and the projected energy contributions for electricity from 2009 to 2020 [37], applying the conversion efficiencies presented in Table 4 and using equation 2.2, it was possible to find the reference values for the CO_2 emission factor from the Portuguese power generation system and thus quantify the attribute. Table 5 presents the computed CO_2 emission factors of the Portuguese power generation system from 2008 to 2020. Although, obtained in a totally independent manner, these results are in line with the projections published by REN in its document “Relatório sobre Segurança de Abastecimento ao nível da Produção de Electricidade Análise intercalar Período 2009-2020” [46].

Table 5 - CO_2 emission factors of electricity in Portugal by year (verified for 2008, and projected until 2020)

Year	CO_2 emission factor for electricity (t/MWh)
2008	0.336
2009	0.275
2010	0.169
2011	0.182
2012	0.173
2013	0.165
2014	0.157
2015	0.141
2016	0.135
2017	0.135
2018	0.124
2019	0.124
2020	0.122

2.4.2. Investment cost

Considering the fundamental objective of minimizing investment costs, the attribute suggested by the interviewed decision makers was the natural attribute of costs, measured in currency. In order to make this attribute operational, it was proposed that all costs involving the purchase of equipments and the respective installation costs, would compose this attribute, and that it would be seen as the total investment cost in the perspective of the society. The calculation of the monetary value was generally a straightforward process with the exception of alternatives that would involve infrastructure change or operational modifications, such as alternatives involving changes in the public transport system in order to cope with modal shift. For those cases, the investment cost was assumed to be the increase of the maintenance and operational costs to keep the system functional.

Regarding the option to consider the total costs it reflects the fact that even when there are subsidy schemes or other incentives, they in one way or another generally end up being costs transferred to the society as a whole. This option is however neutral in what regards the policy mechanisms that may be chosen later to implement the measures. Equation 2.4 formalizes the calculation for the investment cost.

$$Investment\ cost = P + Int + Imp\ [€] \qquad \text{eq.2.4}$$

Where:

P: Purchase cost of any item representing an EE measure (e.g. motor or wall insulation) [€]

Int: Installation cost [€]

Imp: Management costs associated with the implementation of the measure [€]

For the specific case of improving structures to attend changes in their use, the respective operational and maintenance costs will represent the purchase cost in equation 2.4. In order to illustrate this specific case of investment costs, the case of the passenger modal shift to trains in Portugal is presented. Considering a linear increment per passenger utilization (measured in passenger-kilometer or pkm), the investment costs for the modal shift to trains in Portugal, using data from 2009, would be considered as the total yearly operational and maintenance cost (298,969,000€) minus total fuel expenses (2,990,121) divided by the total usage of the system (3,822,258,000 pkm) [47], accounting for 0.08€/pkm.

2.4.3. Lifetime

The attribute lifetime is the measurement, in years, of the fundamental objective of maximizing the duration of measures. This attribute, as referred and justified in section 2.3, is only applicable to evaluate measures and it is not valid in the process of building or evaluating plans. This attribute is a natural attribute referring to the lifetime of the equipment behind the energy efficiency measure. The lifetime was unanimously considered operational and understandable. Examples of lifetime can be 50 years for wall insulation [48] and 16 years for an air source heat pump [49].

2.4.4. Payback

To translate the desire to minimize the financial risk from the investment to a measurable attribute, two options were suggested by the decision makers: one was to perform a cost-benefit analysis, and the other was to use the payback time. The payback was chosen because it provides an assessment of the duration of the period during which the investor's capital is at risk [50], and despite being a composed attribute, it can be considered a natural one due to its wide use and understanding of the meaning. It is also operational, because it is simple to calculate and it has a relatively easy acquisition of data. Another motive why the payback was preferred was the fact that the cost-benefit is a method to evaluate alternatives that depends on the value of some benefits that can be considered to be other fundamental objectives.

The payback is the number of years necessary to recover the financial investments. The way of computing the payback time or period is presented in equation 2.5.

$$Payback = \frac{\sum_m^n Investment\ costs_m}{\sum_i^p Q_{fi} \times E_{Ci} - \sum_j^p Q_{fjplan} \times E_{Cj} + \sum_i^p OM_{ci} - \sum_j^p OM_{cj}} \qquad \text{eq.2.5}$$

Where:

Investment $costs_m$: The non-discounted investment costs (equation 2.4) for each applied measure [€]

Q_{fi}: Original final energy use (without plan) for energy carrier i at the first year [MWh]

Q_{fjplan}: Final energy for energy carrier j with the application of an EE plan at the first year [MWh]

E_{ci}: Energy costs for energy carrier i at the first year [€/MWh]

E_{cj}: Energy costs for energy carrier j at the first year [€/MWh]

OM_{ci}: Operational and maintenance cost from carrier i at the first year [€]

OM_{cj}: Operational and maintenance cost from carrier j at the first year [€]

n: Total number of measures applied

p: Total number of energy carriers

2.4.5. Electricity savings

The impacts related with reduction of needs to build new power plants and transmission infrastructures are very difficult to calculate, and it is even more difficult to calculate the implications of energy efficiency initiatives at this level. According to Neves [40], it is safe to assert that these impacts will be reduced depending on the peak load avoided. Thus, the peak load prevented is an indirect measure, or a proxy, for these benefits, as well as of the improvements in system reliability and capacity avoided costs. However, it may be not possible to account the load in power units. Since hourly time-profile or load curves for all the possible EE measures are not available. Therefore, it was considered that reductions in electricity use would very likely attenuate the peak load and, consequently, affect the impacts related with building new power plants and transmission infrastructures. Equation 2.6 presents how to calculate this attribute.

$$Electriciy\ savings = \sum_{y=1}^{m} Q_{felectricityy} - Q_{felectricityplany}\ [MWh] \qquad \text{eq.2.6}$$

Where:

$Q_{felectricityy}$: Original final electricity energy use for year y (without plan) [MWh]

$Q_{felectricityplany}$: Final electricity energy use with the application of an EE plan for year y [MWh]

m: total number of years analyzed

2.4.6. Imported energy savings

The maximization of the security of energy supply was the only objective mentioned by all interviewees and it was present in all works analyzed for this specific review. All the decision makers were concerned about the importance of the energy availability to sustain their countries and their respective economies, and the fact that it was directly related to the energy dependency from energy supplier countries. Consequently, it was proposed to quantify the security of energy supply in terms of imported energy savings, following [51-53]. The proposed quantification of the imported energy savings is expressed in equation 2.7.

$$Imported\ energy\ savings = \sum_{y=1}^{m}\left(\sum_{i=1}^{n} Q_{fiy} \times \eta_{pif} \times \eta_{Iip} - \sum_{j=1}^{n} Q_{fjplany} \times \eta_{pjf} \times \eta_{Ijp}\right)[MWh] \qquad \text{eq.2.7}$$

Where:

Q_{fiy}: Original final energy use (without plan) for energy carrier i for year y [MWh]

η_{pif}: Final to primary energy factor for energy carrier i

η_{Iip}: Primary to imported energy factor for energy carrier i

$Q_{fjplany}$: Final energy for energy carrier j from the application of an EE plan for year y [MWh]

η_{pjf}: Final to primary energy factor for energy carrier j

η_{Ijp}: Primary to imported energy factor for energy carrier j

n: total (number of) energy carriers used

m: total number of years analyzed

The final to primary energy factor accounts how much primary energy is used for each unit of final energy and it is applicable only when the transformation process from the primary energy to final is performed inside the country. In all other cases it is assumed as one. For example, when oil is imported to be refined to further be sold as gasoline or diesel, the primary energy factor should be applied. The primary energy factor is also considered to be one when local electricity is accounted, because the imported energy factor for electricity already accounts the primary energy conversion as is demonstrated in equation 2.8. The primary energy factor follows the methodology proposed by the IEA and the Eurostat [54]. Table 6 shows some applicable values for the primary energy factor that can be used for Portugal, estimated based on energy balances from 2006 to 2008 [45].

Table 6 - Estimated primary energy factor for energy carriers in Portugal (2006-2008)

Energy Carriers	Primary energy factor
Diesel	1.02
Diesel for Heating	1.02
Fuel Oil	1.02
Gasoline	1.02
Jet	1.02
LPG	1.02
Oil for lighting	1.02

The imported energy factor is the ratio that express how much of an energy carrier is imported. Table 7 illustrates the imported energy factors for Portugal, based on energy balances from 2006 to 2008 [45].

Table 7 – Imported energy factor for energy carriers (2006-2008)

Energy Carriers	Imported energy factor
Bio Gas	0
Biodiesel	0
Biomass	0
Coal (Anthracite)	1
Diesel	1
Diesel for Heating	1
Electricity (imported)	1
Ethanol	1
Fuel Oil	1
Gasoline	1
Hydro	0
Industrial Wastes	0
Jet	1
Liquors (Other Liquid Biofuels)	0
LPG	1
Methanol	1
Municipal Wastes	0
Natural Gas	1
Oil for lighting	1
Other	1
Solar	0
Wind	0

Like in the case of the attribute CO_2 emissions savings, the electricity is treated apart due to the contributions of several energy carriers to its conversion. The imported energy factor for electricity was accounted as a yearly weighted sum of the imported energy factors from all energy carriers that contributed for the electricity conversion. Equation 2.8 formalizes the calculations.

$$Q_{Ielectricityf} = \sum_{i=1}^{n} \frac{Q_{pif} \times \eta_{Iip} \times Yearly\ share_i}{\eta_i} \quad [-] \qquad \text{eq.2.8}$$

Where:

Yearly $share_i$: Yearly contribution share of the electricity converted from carrier i [-]

η_i: Average efficiency of the conversion process from carrier i to electricity [-]

η_{Iip}: Imported energy factor for energy carrier i

η_{pif}: Final to primary energy factor for energy carrier i

n: total (number of) energy carriers used

Applying the conversion efficiencies presented in Table 4 and using equation 2-8, it was possible to find the reference values for the imported energy factor for the Portuguese power generation system and to present the attribute with values. Table 8 presents the imported energy factors for the electricity converted in Portugal from 2008 to 2020 based on data from [45] for 2008 and from [37] for the electricity from 2009 to 2020.

Table 8 - Imported energy factors for electricity in Portugal: Historical for 2008 and forecasted until 2020

Year	Imported energy factor for electricity
2008	1.43
2009	1.24
2010	0.87
2011	1.05
2012	0.97
2013	0.90
2014	0.82
2015	0.70
2016	0.66
2017	0.68
2018	0.60
2019	0.61
2020	0.59

2.4.7. Total suspended particles emissions savings

The possible improvements on the local air quality are a fundamental objective that was not mentioned by any decision maker during the interviews, but which was recovered from the bibliographic review [41]. In order cope with the need to quantify the improvements on local air quality, Brown [41] proposed in her work to use the suspended particles emitted by energy use as a proxy. The total suspended particles (TSP) are widely associated with respiratory health problems and local air pollution [2,55] and due to these facts it is relatively easy to find data related to energy use for this type of emissions, making this choice operational and transparent.

Considering the premise that the outcomes from energy efficiency plans are reductions or savings on final energy, it was proposed to quantify the TSP emission savings from plans as:

$$TSP_{savings} = \sum_{y=1}^{m}\sum_{s=1}^{o}\sum_{i=1}^{n}\left(Q_{fiy} \times TSP_{EFis} - Q_{fisplany} \times TSP_{EFis}\right)\ [t] \qquad \text{eq.2.9}$$

Where:

Q_{fisy}: Original final energy use (without plan) for energy carrier i, sector s and year y [MWh]

$Q_{fisplany}$: Yearly final energy for energy carrier i, sector s and year y from the application of an EE plan [MWh]

TSP_{EFis}: TSP emission factor for energy carrier i and sector s [t/MWh] n: total (number of) energy carriers used

m: total number of years analyzed

o: total (number of) sectors analyzed

Following the methodology and data from the EMEP/EEA air pollutant emission inventory guidebook [56], it was possible to calculate the TSP emission factors for the main energy carriers used in a country by sector. For TSP emissions the sector is of relatively importance since some sectors as industry and transports have to follow several environmental laws forcing their TSP emissions to a maximum allowed level, while others as the domestic sector do not. Table 9 presents the TSP emission factors from all energy carriers by sector assumed as a reference for Portugal, with the exception of electricity and heat that were treated separately. However, Table 9 presents the TSP emission factor for the imported electricity considered as 0, since the burning process is not made at the country and would not influence the local air quality. The data on Table 9 assumes default tier 1 emission factors for industry, services and transports, and uncontrolled emissions for the domestic sector [56].

Table 9 - TSP emission factors for energy carriers

Energy Carriers	Sector	TSP emission factor (t/MWh)
Bio Gas	All	0.0000180
Biodiesel	Domestic	0.0000090
	Industry, Services, Transports	0.0000054
Biomass	Domestic	0.0005760
	Industry, Services, Transports	0.0001836
Coal (Anthracite)	Domestic	0.0018000
	Industry, Services, Transports	0.0001080
Diesel Diesel for Heating	Domestic	0.0000180
	Industry, Services, Transports	0.0000108
Electricity (imported)	All	0
Ethanol Methanol	Domestic	0.0000119
	Industry, Services, Transports	0.0000071
Fuel Oil	Domestic	0.0002160
	Industry, Services, Transports	0.0000900
Gasoline	Domestic	0.0000180
	Industry, Services, Transports	0.0000108
Hydro, Geothermal, Solar, Wind	All	0
Industrial Wastes	All	0.0003600
Jet	All	0
Liquors (Other Liquid Biofuels)	All	0.0005760
LPG	Domestic	0.0000180
	Industry, Services, Transports	0.0000108
Municipal Wastes	All	0.0003600
Natural Gas	All	0.0000032
Oil for lighting Other	Domestic	0.0002160
	Industry, Services, Transports	0.0000900

The TSP emission factor from electricity was accounted as a yearly weighted sum of the TSP emission factors from all energy carriers that contributed for the electricity conversion. Equation 2-10 formalizes the calculations for TSP emission factor from electricity in year y.

$$TSP_{EFelectricity(y)} = \sum_{i=1}^{n} \frac{TSP_{EFi} \times share_{iy}}{\eta_i} \; [t] \qquad \text{eq.2.10}$$

Where:

$share_{iy}$: Contribution share of the electricity converted from carrier i for a specific year (y) [-]

η_i: Average efficiency of the conversion process from carrier i to electricity [-]

TSP_{EFi}: TSP emission factor for energy carrier i [t/MWh]

n: total (number of) energy carriers used

Using the energy contributions for electricity in 2008 [45] and the projected energy contributions for electricity from 2009 to 2020 [37], applying the conversion efficiencies presented in Table 4 and using equation 2.10, it was possible to find the reference values for the TSP emission factors from the Portuguese power generation system and to present the attribute with values. Table 10 presents the TSP emission factors from the Portuguese power generation system from 2008 to 2020.

Table 10 - TSP emission factors for electricity by year: Historical for 2008 and forecasted until 2020

Year	TSP Emission factor for electricity (t/MWh)
2008	0.000320
2009	0.000104
2010	0.000079
2011	0.000073
2012	0.000072
2013	0.000071
2014	0.000072
2015	0.000069
2016	0.000067
2017	0.000066
2018	0.000073
2019	0.000073
2020	0.000072

The guidelines indicated by Keeney [35,39] under the "value-focused thinking" were crucial to filter and organize the values, resulting in fundamental objectives that were converted into attributes for the use of any multi-objective or multi-criteria approach to aid decision makers with this complicated problem. Next chapter proposes a demand model to provide the necessary information about energy use which will be fundamental to estimate energy savings.

3. Modeling the energy system of a country

The main objective of this research is to aid the decision process in building and selecting the most fitted energy efficiency plans for a country. However, to build such plans it is first necessary to estimate the impacts of the EE measures in a country. This process can best be made operational if an energy end-use model of a country is available to account the original energy uses and the possible reflects on energy use due to the application of EE measures. This chapter describes a generic methodology create an end-use energy model for a country, along with a suggested manner to project the energy use in time (to also enable the estimation of the impacts of EE plans in the future).

In a general sense, models are a representation of systems. They are used to help to understand the subject matter they represent. Many models use mathematical concepts to formalize their systems. Mathematical models are used in the natural sciences (such as physics, biology, earth science or meteorology), engineering disciplines (e.g. computer science, artificial intelligence), and also in the social sciences (such as economics, psychology, sociology or political science). All models are a simplification of reality and include only the aspects that their developers regarded as important at that time [57]. Models trying to describe the energy use in a region or country are no different from other abstract models. They vary from simple models to very complex ones depending on the range of options available and the degree of specification needed or of interest of the developer [58].

The necessity to build a model for the energy system of a country derives from the need to quantify the energy efficiency measures. Such estimation would only be possible with reasonable and transparent characterization of the demand system to support the potential changes in this system as reflection of the application of EE measures [26]. Furthermore, it must be reminded that some energy-efficiency measures have cross-effects between them (e.g., the result of simultaneously installing daylight controls for electric lighting and changing to more efficient lamps is less than the sum of the results of taking each measure separately). The best way of dealing with such issues is to have an integrated model of the energy system, where these cross-effects would systemically be accounted.

3.1. Characterization of existing energy models

There are many ways of characterizing the different energy models. Hourcane [59] identified three ways to distinguish energy models: 1) the purpose of the models; 2) the structure; and 3) external or input assumptions. On the other hand, the EEA [60] classifies models also in three main dimensions and seven minor characteristics. The main dimensions are: 1) thematic focus (in this case energy); 2) geographical scale; and 3) analytical technique. The minor characteristics are: 1) input/output; 2) temporal coverage; 3) quality assurance; 4) uncertainty analysis; 5) level of integration; 6) accessibility; and 7) model context. Beside those two, Grubb [58] uses six categories to classify the energy models, being: 1) top-down vs. bottom-up; 2) time horizon; 3) sectoral coverage; 4) optimization vs. simulation techniques; 5) level of aggregation; and 6) geographic coverage, trade, and leakage. Finally, Beeck [57] divides the energy models according to nine characteristics, as: 1) general and specific purposes of energy models; 2) the model structure (internal assumptions & external assumptions); 3) the analytical approach (top-down vs. bottom-up); 4) the underlying methodology; 5) the mathematical approach; 6) geographical coverage (global, regional, national, local, or project); 7) sectoral coverage; 8) the time horizon (short, mid, and long-term), and 9) data requirements.

From the above model classifications it becomes clear that no harmonization or standard exists for them, although there are some similarities and even common “classifications” found in literature. The classification proposed by Beeck [57] seems to be the most comprehensive among all, but there are still some redundancies, such as found in the mathematical approach, analytical approach and the underlying approach. Furthermore, since all models in the previous classifications are all energy models, energy, or the considered energy carriers, should represent a category itself. Therefore, observing the classifications, a new one could be proposed including:

1. Energy Carriers Considered
2. Model Focus
3. Aggregation Level
4. Underlying Methodology
5. Geographical Scale
6. Sectors Considered
7. Time Horizon
8. Time-scale of energy balance

3.1.1. Energy Carriers Considered

The energy covered is a dimension describing how energy is characterized in a model. In general, energy models cover a single carrier, several carriers or treat energy as one single thing (i.e., all carriers are represented as one). Models that address energy as one single entity cannot distinguish different energy carriers and thus do not deal with the fact that not all energy carriers are suited for the same purposes (e.g., it's not possible to “fuel” a TV directly with natural gas). Therefore, knowing beforehand the energy carriers considered in each model could facilitate choosing the energy model to reflect the characterization needed. For the specific case of enabling the quantification of energy efficiency measures, and following [26], it would be necessary to account at least the main energy carriers used in a country, therefore, the energy covered consists of several energy carriers.

3.1.2. Model Focus

Energy models generally have a focus on the demand or the supply side, building futures and/or options to fulfill their needs according to predefined constraints. Beeck [57] includes two more focus for the energy models, the impact and the appraisal focus. The most recent models generally have a more comprehensive approach in the sense that they combine more than one focus. Examples of integrated models are the demand-supply balance models and impact-appraisal models [55]. General types of model focus:

I. Energy Demand: These models have their focus on the demand for energy, and this demand can be for the entire economy, for some sectors or even only one sector of the economy (e.g., industries, services, etc.). Generally, demand is described as a function of changes in population, income, and energy prices or a trend based on the behavior from the last observed periods.

II. Energy Supply: These models are mainly focused on the technical aspects of energy systems and whether supply can meet a given demand. Generally, in this approach, the demand is treated as a historical trend or an exogenous value to the model. This focus may also include financial aspects using a least-cost approach for the supply options.

III. Impact: These models try to assess the consequences of selecting certain options caused by using a certain energy system or putting a policy into work. Generally, the impacts are more comprehensive than the demand or the supply focus and may include changes in the financial/economic situation, changes in the social situation (e.g., distribution of wealth and employment), and changes in the environment (e.g., pollutant emissions and bio-diversity) [57].

IV. Appraisal: If a decision maker has the chance to choose among several energy options, they need to be compared and appraised in order to select the most suited one(s), even if the selected option is not choosing any. The possible outcomes from each option are generally compared and appraised according to one or more criteria of which monetary efficiency is the most commonly used [57].

Observing the descriptions of model focus, the specific case of building and selecting energy efficiency plans would better fit the appraisal focus in relation to the demand.

3.1.3. The Aggregation Level (Top-Down vs. Bottom-Up)

The top-down approach typically represents technology (and the economy in general) using relatively aggregated production functions [61]. These production functions rely on inputs such as capital, income, population, etc. (e.g., electricity production may be treated as a single sector with capital, labor, material, and fuel as inputs). Continuous substitution among inputs (e.g., between natural gas and coal) represents the shift from one technology to another in such aggregation level. The data is generally aggregated relying on statistical indicators defined by sector and/or type of end-use from national averages [62], going down to more disaggregated data when (if) necessary.

In the other hand, the bottom-up approach generally uses highly disaggregated data to describe energy end-uses and technological options. It represents a handful set of energy supply and demand technology options at a high level of detail. The technologies are typically described as a set of linear activity models based on engineering data of life cycle costs and thermodynamic efficiencies [61]. This approach generally considers energy prices, costs, capital and preferences as exogenous, sometimes not reflecting a “reliable” prediction on the market and the future. Hourcane [59] defines this most common bottom-up approach as prescriptive, providing an estimate for the technological potential by examining the effects of acquiring only the most efficient existing technologies. Hourcane [59] also describes another bottom-up approach as descriptive, seen as an attempt to bridge the gap between common used bottom-up approach (also called “the engineering paradigm”) and the economic paradigm. Descriptive bottom-up approaches try to describe the demand and the supply for energy still in detail, but based on factors such as complex preferences, intangible costs, capital constraints, attitudes to risk, uncertainty, and market barriers.

According to the EMEEES project “Evaluation and Monitoring for the EU Directive on Energy End-Use Efficiency and Energy Services” [63], the major advantage of using bottom-up approaches when compared to top-down is the fact that they allow a direct monitoring of the energy savings that are due to energy efficiency measures and can thus achieve greater accuracy. But a potential drawback of bottom-up approaches is the potentially high costs of data collection.

The top-down and bottom-up approaches basically rely on what degree of aggregation the data must have to feed the model and on the way energy technologies (demand and supply) are represented. Therefore, to model an energy system where energy efficiency measures can be applied, the aggregation level would ideally be bottom-up. However, due to the difficulties in acquiring specific data, it is also possible the obtain results with a top-down approach disaggregated at the end-use level.

3.1.4. The Underlying Methodology

The underlying methodology can be considered as the essence of the model, representing what kind of data are needed and the approach to process the inputs in order to obtain results and projections of the future. The methodology is generally selected according to the desired focus and (usually) available information. The underlying methodology is suggested be divided in seven categories:

I. Economic methodologies [57] are designed to illustrate the market interactions between the demand and the supply in the different sectors of the economy, aiming to predict and/or explore the behaviors in the economy. They can be divided in 2 groups:

    i. Economic equilibrium methodologies [57] (also referred to as resource allocation methodologies) use actual economic data to estimate how an economy might react to changes in policy, technology or other external factors. Economic equilibrium methodologies aim to find an optimal allocation of resources under a given set of constraints and they rely on (neo-classical) perfect market equilibrium assumptions. They can generally be subdivided in partial and general equilibrium methodologies. Partial equilibrium methodologies (also referred to as sectoral methodologies or models) only focus on balancing parts of the economy, generally one specific sector, such as the equilibrium between energy demand and supply. On the other hand, general equilibrium methodologies are intended to allocate the resources efficiently, allowing simultaneous equilibrium in the whole economy. According to Beeck [57], economic equilibrium methodologies are used to simulate very long-term growth paths and do not systematically rely on econometric relationships but are instead benchmarked on a given year in order to guarantee consistency of parameters.

    ii. Empirical-statistical methodologies [57] apply statistical methods to extrapolate past market behavior into the future (often derived by multiple linear regression analysis) and explore the interactions in the sectors of the economy (e.g., to analyze energy-economy interactions). The parameters of the equations of the models are commonly estimated by econometric methodologies or associated with indexes (e.g., statistical decomposition methods). Therefore, the purpose of the empirical-statistical methodologies is to forecast the future as accurately as possible using past information.

II. Trend analysis methodologies [57] are very similar to empirical-statistical methodologies. They also extrapolate past trends of energy-economic activities and energy ratios. They generally do not take into consideration the interactions in the economy (e.g., electricity use in the industry sector can be a trend only from the electricity use from the sector from the past years). Trend analysis is commonly used in engineering models. They have a drawback of not reflecting the energy-economy feedbacks, they cannot capture structural changes and do not explain determinants of energy demand [57].

III. Optimization methodologies [57] are usually used to optimize energy investment decisions. The outcome represents the "best" solution while meeting given constraints. Optimization is often used by utilities to build their investment strategies (e.g., expansion of transmission lines meeting a maximum budget and minimum values of reliability). According to Beeck [57], the underlying assumption of optimization methodologies is that all acting agents behave optimally under given constraints. Optimization methodologies may use linear and non-linear programming techniques, evolutionary and genetic algorithms, among other techniques.

IV. Dynamic system methodologies [57] (also known as system theory or systems models) rely on equations based on causality. However the causality sometimes may come from an empirical analysis of data. This causality comes from the fact that all phenomena can be seen as a web of relationships between elements (or systems) and all elements have patterns, behaviors, and properties that can be understood and used to explore futures. Usually the set of equations are used to express levels of stock variables and rates as a measure of change in the stock variables.

V. Simulation methodologies (models). The European Environment Agency (EEA) defines simulation-based models as mathematical representations or computer simulations that attempt to describe the characteristics or relationships of physical events or socio-economic developments, usually in a quantitative manner [60]. A simulation model is generally referred to as static or dynamic. If the model represents the operation of the system in a single time period, it is considered as static, however if the output of the current period is affected (dependent) by the evolution or expansion from the previous periods, it is considered as dynamic. Simulation models are mostly used in engineering processes where it is impossible or extremely costly to do experiments on the system itself (e.g., calculating the power flow from a transmission system when a new generator is introduced, or observing the effects of a flywheel on the frequency of an electric system).

VI. Backcasting methodologies [57] are based on interviewing field experts aiming to build desirable visions of futures, finding which trends should be followed and which should be broken to accomplish the desired futures. According to Beeck [57], this approach is often used in alternative energy studies.

VII. Hybrid methodology [57] (tool boxes or spreadsheet models) models combine the above types of methodologies. However, while most models apply, in different degrees, a combination of different methodologies, the label "hybrid" is reserved for models that cannot be clearly framed in the above methodologies. The classification spreadsheet comes from highly flexible model which is more similar to a software package to generate models or a tool box which often can be easily modified according to the user needs. For example, The LEAP (Long-range Energy Alternatives Planning).

The most fitted underlying methodology to be applied to a model to find the desired plans that are able to fulfill targets and satisfy the decision makers involved would be the optimization methodology. However, trend analysis could also be used to deal with a necessary base case future projection in order to obtain a future to compare with the "optimized" future and present the possible advantages.

3.1.5. Geographical Scale

The geographical coverage reflects the geographical level of analysis. Beeck [57] divides the geographical coverage in global, regional, national, local, or project. The global coverage describes the world (economic) situation. Beeck [57] tries to solve a common problem related to the clarity of the "regional" coverage concept. It can be found applied to international regions, such as Europe, and also to a group of regions inside a country, such as north region or central region. Using the term "local" for regions inside the countries, Beeck tries to formalize the use of regions for groups of countries. However, "solving" one problem, a new one is created, since the name "local" can be used for municipalities or cities. Therefore, in the scope of this research, it is considered "international regions" referring to group of countries, "regional" referring to a group of regions inside a country and local referring to municipalities and cities. National coverage is responsible up to all sectors found inside the boundaries of a country. The “project level” refers to something even smaller than local and much more specific, like an engineering project, as a Dam, or even a simple house.

Since the main idea in this research is to build national energy efficiency plans, the energy model should work, at most, at the national level.

3.1.6. Sectors Considered

The economy is traditionally divided into several sectors (e.g., primary, secondary, tertiary, etc. or their subcategories as services, transports, industry, etc.), and a model can cover a single sector or several. Multi-sectoral models enable interactions among sectors, while single-sectoral models describe only a sector in particular and do not take into account the interactions of that sector with the rest of the economy, and when the rest of the economy is represented, it is highly simplified.

The choice of a single-sector energy model or a multi-sector will depend on the objectives of the final user. For example, if the final user is a utility, a single (energy) sector will probably meet its needs, but if the final user is a policy maker, he/she would need to assess the effects of the policy across the economy and not only on the (energy) sector where he would act. Therefore, for the specific case of this research the sectoral coverage of the energy model should be multi-sectoral.

3.1.7. The Time Horizon

Energy models vary according to the time horizons, some are fit for short-term while others are better fit for long-term, and generally a model designed for the short run should not be used for the long run and vice-versa. The time horizon plays an important rule since different processes are important at different time scales. For example, most long-term models have a base assumption that the model is in equilibrium, therefore there will not be any disturbance in the energy system, while for a short-term model, the effect of the disturbance is, in general, what it is intended to be analyzed.

There is no common accordance in the definition of the time horizon (short, mid and long-term). However, Grubb [58] formalizes a period of 5 years or less as short-term, between 3 and 15 years for the mid-term, and 10 years or more for the long-term. However, even the proposed definition is flexible due to the intersections between periods.

Since energy efficiency plans intend to improve the energy system along several years, it is possible to use models with a mid-term or a long-term time-horizon.

3.1.8. Time-scale of energy balance

The energy balance time-frame can be a very useful classification, since most of the models have different balance time-frames between the demand and supply, varying by the minute (or several minutes, 10 to 20) to a yearly average. The way the balance is seen may be used for different approaches and may bring different results, such as assessing the peak and the valley demand hours to introduce a new policy, or a better representation from the fluctuations from the renewable resources.

Ideally, in order to get the maximum from energy efficiency measures, an energy model would have a balance time-frame in an hourly basis. However, for this case, the balance could be also left apart, assuming that there would be energy to fulfill the demand and focusing only at the demand-side.

3.2. Energy system models

After the identification of the decision attributes that need to be quantified, done in chapter 2, and the review of energy models characteristics, done in the previous chapter, it is possible to conclude that a model that fits the need to quantify energy efficiency measures and would be able to help the decision process to build and select energy efficiency plans should have cumulatively the following characteristics:

- account several energy carriers;
- fit the appraisal focus in relation to the demand;
- be a bottom-up model or have a top-down approach disaggregated at the end-use level;
- use an optimization methodology and a trend analysis;
- be at the national level;
- be multi-sectoral;
- use a mid-term or a long-term time-horizon;
- use any balance method.

The next stage was to investigate if there are already developed models that comply with all these requirements or if it is needed to develop a new one.

Connolly [64] performed a review of 37 different computer tools that can be used to analyze the integration of renewable energy. Despite the focus on the integration of renewable energy, his paper provides the information necessary to compare and identify the possible use from all the energy tools under assessment. The assessment of the typical applications for the 37 tools reviewed combines numerous factors such as the energy-sectors considered, technologies accounted for, time parameters used, tool availability, and previous studies, which made it possible to verify if a tool can fit the requirements of this research. Among the analyzed tools in Connolly's work there can be found some of the most used ones, such as IKARUS, a dynamic bottom-up linear cost-optimization scenario tool for national energy-systems; HOMER, a user-friendly micro-power optimization model intended to support the design of off-grid and grid-connected power systems; EnergyPLAN, a user-friendly tool to assist the design of national or regional energy planning strategies by simulating the entire energy-system; ENPEP-BALANCE, which uses a market-based simulation approach to determine the response of various segments of the energy-system to changes in energy prices and demand levels; LEAP (Long-range Energy Alternatives Planning), a tool used to account energy consumption, production, and resource extraction in all sectors of the economy; and the TIMES-MARKAL, a tool used to estimate energy dynamics of all energy carriers in local, national or multi-regional energy systems over a long-term time horizon.

Comparing the results of this review with the needed characteristics outlined in the beginning of this section, it is concluded that it was not possible to find a model that could fulfill all the needs of the problem. Even if tools like LEAP and IKARUS could be used to model the energy system of a country as requested, they are not able to access a database of EE measures, nor to automatically join them to build many EE plans, nor to evaluate and compare plans in order to indicate the most fitted by their own. Therefore, it was decided to create a model that could be implemented by anyone using the support of existing tools for the parts that they may fit, and implementing the rest or the totality of the model in any computer language, like C or Matlab®.

3.3. Breakdown of energy demand

Energy demand is usually divided in broad sectors, such as residential or domestic, services, industry, transports, and "others", with the latter usually accounting less than 5% of the energy demand in developed countries [44]. This highly aggregated approach is very useful for observing trends in energy use of each sector over time, for building indicators or for giving guidance to overall energy policies. However, it does not provide any information on the role of technological components that effectively convert energy into services (e.g., water heaters, pumps and lighting systems) and where energy efficiency gains can be obtained.

It is important to note that energy Efficiency gains as considered in this work can be obtained mainly in two ways: through technological or through behavioral measures - even if authors like Nakicenovic prefer to include only the technological measures and exclude the behavioral ones, which in their point of view imply a certain degree of austerity or loss of service [65].

Gellings [12] stated that "*customers do not purchase energy for the sake of consuming it per se, but instead are interested in the service it provides. That service brings warmth, cooling, artificial illumination, motive power and other conveniences*". When he wrote "customers", he was thinking on a utility perspective, but instead of customers one could use "society" and apply his concept in a broad manner. Using Gellings' perspective and looking at the energy used in a highly aggregated perspective, it becomes clear that those analyses fail to breakdown the demand through the several systems that convert energy into services, therefore hiding clues to energy efficiency potentials. Besides orienting direct energy measures (i.e., measures to improve efficiency due to technological upgrade), the breakdown to energy systems and their services would help finding also measures regarding shifting from one energy carrier to other that could provide the same service without losing quality, based on any objective defined, such as imported energy used or even on CO_2 emissions.

The United States Department of Energy (DoE) [66] developed an energy footprint map to show the flow of energy supply, demand, and losses in U.S. manufacturing industries with the objective to identify the energy sources and end-uses, helping to pinpoint most energy intensive areas, giving guidance to saving opportunities and providing a baseline to estimate the benefits of improving energy efficiency. Also, at the US, the Energy Information Administration (EIA) [67] tries to provide data about the major sectors of the economy in an extremely disaggregated manner, showing the main conversion technologies (from energy to service) divided by energy carrier and end-use. Those data can be used as a reference to build a map of the energy system, where opportunities to save energy can be shown and energy efficiency measures can be estimated.

The challenge is to find a breakdown from the energy supply to the energy service in a way that energy efficiency measures can be estimated and evaluated, taking into consideration the lack of appropriate data and having a manageable number of technologies. Therefore, following [26] in a perspective that the end-uses and their respective energy carriers can be seen as the natural application of EE measures, this work tries to focus on the highest energy end-users and the greatest potential for efficiency improvement.

Several authors base their identification of the energy system on previous studies or statistic data [68] due to reliability of the information, but sometimes the level of desegregation is not specific enough to estimate savings or even identifying the real efficiency measures. In this research, the , a breakdown adopted for the end-uses of the domestic, services, industry and transports sectors is based on statistic data [69][67] and several studies [68][70][65], aiming at improving the actual characterization found in literature. Therefore, this work considers a set of end-uses and technologies that account for the majority of demand in the main sectors of the economy and are not limited to particular regions.

In order to represent the energy system in a way that it can allow the direct application of energy efficiency measures, the chains from energy to services must be addressed, focusing on the technological appliances and the services where "active" (conversion technologies) and "passive" (techniques to lessen the needs, e.g., insulation for houses) gains can be obtained. Each sector must be disaggregated in order to represent the technologies and the services (end-uses) in a way that it becomes easier to compare energy efficiency options for the services and to identify the most intensive end-uses. At the same time the disaggregation must be in a manageable size, where the assumptions made due to lack of specific data to build the energy system must not compromise the future outcomes.

The characterization proposed intends to guide the construction of energy systems in a straightforward way, relying on essential parameters to model the demand and the efficiency of many end-uses belonging to the four main sectors of the economy (i.e., domestic, services, industry and transports). The characterization intends to be modular and generic, but at the same time, rigid enough to assure harmonization and that the main demand areas are included.

It is proposed to describe the end-uses with three general parameters:

i) The useful energy need, being the quantification of the service provided by an end-use in its specific units, for instance the lighting demand in lumens. Useful energy is sometimes also called energy service [68];

ii) the efficiency of the technology providing the useful energy needed, such as the COP of an air heat pump;

iii) the activity level, translated in ownership rate or the share of usage (e.g., 100% of the households have lighting systems) and the respective total market size where the need is inserted (e.g., households, total area from the services sector).

The process of defining those parameters for each end-use and technology relies on the analysis of many diverse sources. Although the details may differ significantly, the structure of the demand calculation is the same across regions, sectors and end-uses. This allows a straightforward inquiry of model parameters and variables. In addition, the generic nature from the inputs allows for an easy revision of output values when non-existing and referenced data is replaced with more precise data.

The proposed demand model has the following levels: 1) the sectors from the economy where the end-uses belong; 2) the end-uses, representing the main services needed by the society (e.g., ambient heating and cooling); 3) the useful energy need required by the end-use, being an attempt to show how far the actual energy uses are from the real energy needs; 4) the "competing" end-use technologies inside each end-use (e.g., gasoline car and methanol car); 5) the efficiency of each technology or the reference energy use, if efficiency is not applicable or more difficult to characterize (e.g., annual energy use from fridges or energy use per passenger-kilometer); and 6) the activity level, as the ownership rate or the share from the total market size where the need is inserted in order to aggregate and calibrate the energy used.

Observing the final energy used by the main sectors of the economy in the world (excluding non-energy uses), presented in Figure 1, it is clear that the principal contributors to the use of final energy are the domestic sector, the industry sector, the services sector and the transport sector [71]. Therefore, the work was shaped to model in detail these sectors.

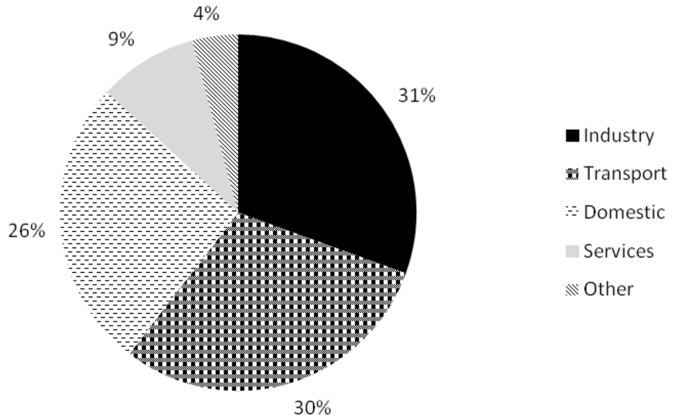


Figure 1 – Share of final energy use in the world in 2008 by sectors [71]

3.3.1. Modeling of the domestic sector

Energy use in the domestic, or residential, sector is generally defined as the energy used by households excluding the transportation outside the residential boundaries (i.e., transportation by lifts and escalators are considered as energy used in the domestic sector) and was responsible for 26 percent of world delivered final energy in 2008 [72]. That use in the domestic sector can be refined according to needs of the members of the household, as domestic hot water, ambient heating and cooling, lighting, cooking, entertainment, etc. The sizes of a household (physical size and number of members) are key indicators of the amount of energy use, because, in general, larger residences require more energy to provide basic needs as lighting and heating and cooling (more space to be heated or cooled and more heat transfer with the outdoor environment), and they tend to include more energy-using appliances, such as televisions and laundry machines.

Observing the literature [68][73][74], the domestic sector is commonly disaggregated by locale (urban or rural), by electrification status and by the type of the dwellings (i.e., single family house or multi-family house). However, the structure is not rigidly formatted in this methodology, and the vertical structure of choice can defined according to the data available or provided. For example, to model Portugal it was chosen to use just a global representation of the households for the whole country as a consequence of relative homogeneity across the country and, mainly, lack of data to feed with reasonable accuracy a more disaggregated model.

The main end-uses that characterize the domestic sector in the world were defined based on [68][73][74] as: i) domestic hot water; ii) ambient heating; iii) ambient cooling; iv) refrigeration; v) freezing; vi) cloth washing; vii) cloth drying; viii) dish washing; ix) entertainment; x) computers; xi) lighting; xii) cooking; xiii) lifting and others. The characterization proposed intends to be useable across the countries, because despite the differences that can appear in the penetration, in the energy carries and in the share of each use according to specific conditions, such as income levels, natural resources, climate, energy infrastructure and comfort conditions, the characterization is still able to point the main energy uses and needs. The calculation of each energy use is explained in more detail in the next subsections.

3.3.1.1. Domestic Hot Water

Hot water for domestic purposes is one of the largest heat demands in the domestic sector, and depending on the climate of a country this can represent the most important heat demand (in the more temperate countries),. To quantify the useful energy needs for hot water, it is proposed to use an estimation based on the following equation from [75]:

$$Q_u = \frac{N_{HW} \times SH_W \times \Delta T \times 365}{3600000} [kWh/hh \times yr] \qquad \text{eq.3.1}$$

Where:

N_{HW}: Needs of hot water per day per household [l/day*hh]

ΔT: Temperature difference between the cold water and desired hot water [°C]

SH_W: Water Specific Heat = 4187 [W/(ρ*l* °C)]

Households (hh) is a unit that represents a family unit, but can be changed according to the needs and data. If it is interesting and there is data available about different uses in urban and rural areas, this household can be subdivided into those levels of convenience.

Surveys including information of hot water consumption are not so common, and what is generally found is information related to design conditions for hot water systems. The needs from hot water may vary from region to region, and from study to study. EVA [76] defines the average need for hot water as 36 liters per person per day as the average for Europe, but other values can be found as an average of 50 liters per person per day, in Ecoheatcool [77], and a smaller value of 24 liters per person per day found in [78]. For Portugal the reference value is 40 liters per person per day found in the directive 80/2006 [75]. For the temperature difference, all studies [76] [77] [78] agree with an average of 50ºC (10ºC for cold water and 60ºC for hot water). In Portugal [75] the difference is considered as 45ºC (15ºC for cold water and 60ºC for hot water).

In order to represent the technologies and quantify the final energy needs (the energy that is available as data, e.g., in energy balances or market sales figures) a conversion factor must be used to translate the useful needs to the final energy use by technology. Since there is no data about all technologies available by each end-use, an average efficiency must be estimated to evaluate the actual stock of each end-use and to make possible to compare several technological options. To estimate the average conversion efficiency from each end-use, at least, two variables must exist or must be assumed: The final energy used by end-use by technology (generally not available) or the final energy used by end-use by energy carrier (or the share of the energy carrier by end-use and the total final energy used by carrier), and the ownership of the technology or the ownership of the end-use by energy carrier. The following equation can be used for this purpose:

$$\eta = \frac{Own \times hh \times Q_u \times 100}{Q_f} [\%] \qquad \text{eq.3.2}$$

Where:

Own: Ownership of the technology or the end-use by energy carrier [-].

hh: Total number of households [hh]

Q_f: Total final energy by technology or by energy carrier for the end-use [kWh/yr]

Some technologies have contribution from renewable resources, as the solar contributions from solar systems. Those systems are generally not autonomous and need some backup by the traditional systems. In case there is no data about the energy used by solar systems, the previous calculation must be adapted to estimate this contribution to the efficiency of the system and the final energy for solar systems must be calculated.

$$Q_f = \frac{Own \times hh \times (Q_u - Q_s)}{\eta_{bkp}} [kWh/yr] \qquad \text{eq.3.3}$$

And

$$Q_{s=}\eta_s \times \eta_0 \times G \times 365 - a_1(T_m - T_a) - a_2(T_m - T_a)^2 [kWh/m^2 \times yr] \qquad \text{eq.3.4}$$

Where:

Q_f: Total final energy by technology or by energy carrier for the end-use [kWh/yr]

η_{bkp}: Efficiency from the backup system [-]

η_s: Solar system efficiency (it considers pipe losses and tank losses)

η_0: Zero-loss efficiency

G: Solar irradiation [kWh/m2*day]

T_a: Ambient air temperature

T_m: Collector's mean temperature

a_1 = 1st order heat loss coefficient

a_2 = 2nd order heat loss coefficient

Table 11 summarizes the data needed to calculate the energy needs, the overall efficiency and the solar contributions. Note that the energy needs and the solar contribution can be calculated according to the suggested methodology or can be directly used if those data are available.

Table 11 - Data for hot water energy needs

Data needed	Proxy values (Portugal - 2006)	Corresponding data sources
Needs of hot water per day per household (N_{HW})	111 l	[75][69]
Temperature difference between the cold water and desired hot water (ΔT)	45°C	[75]
Ownership of the technology or the end-use by energy carrier (Own) in relation to all households	Electricity 1.2%	[79]
	Natural Gas 1.2%	[79]
Total number of households (hh)	3,829,464	[69]
Total final energy by technology or by energy carrier for the end-use (Q_f)	Electricity 32,539 MWh	[45], calculations
	Natural Gas 39,770 MWh	[45], calculations
Solar system efficiency (η_s)	0.86	[79]
Zero-loss efficiency (η_0)	0.70	[79]
Solar irradiation – optimal angle (G)	4.86 kWh/m2*day	[80]
Ambient air temperature (T_a)	15°C	[75]
Collector's mean temperature (T_m)	60°C	[75]
1st order heat loss coefficient (a_1)	5	[75]
2nd order heat loss coefficient (a_2)	0.05	[75]

Table 12 shows a description for the hot water energy system for the domestic sector in Portugal in 2006. This description is divided into the end-use, the useful energy needs, ownership, the end-use technologies and the reference efficiency for those technologies. The end-use is a general end-use or a description of the energy need, in this case domestic hot water. The useful energy needs represent a reference value of the needs that must be fulfilled by the technologies after the conversion from final to useful energy. The end-use technologies are related to the technology used to convert energy into service and the reference efficiencies represent an estimated or known value of efficiency for each technology.

Table 12 – Energy system description for the Portuguese domestic hot water in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference efficiency
Domestic Hot Water	2,115	5.0%	Biomass Storage Water Heaters	60%
		55.0%	Gas Storage Water Heaters	72%
			Gas Tankless Water Heaters	50%
		0%	Fuel Oil Storage Water Heaters	80%
		15.8%	Electric Storage Water Heaters	88%
			Electric Tankless Water Heaters	99%
			Electric Heat pump water heaters	220%
		2.4%	Solar water heaters + Gas Storage	72%*
			Solar water heaters + Electric Storage	88%*
			Solar water heaters + electric heat pump	220%*
		0%	Heat Distribution Systems	100%

Sources: [75][73][69], *Backup efficiency

3.3.1.2. Ambient Heating

The colder the climate, the higher is the heat demand for space heating. Generally, differences in climate justify higher demand for heating, since heating systems must compensate the heat transmission losses through walls and roofs and for heating the supplied air by mechanical or natural ventilation systems. However, countries nowadays with more severe climate have more severe regulation concerning insulation and heat demands which brings an evaluation not only by the severance of the climate, but on the maximum heat load allowed and the heating loads from the existing stock. Therefore, here the average stock values for heating demand are considered as the useful energy. However, the heating demand is the maximum heat that would be needed to put the whole dwelling in a temperature of comfort, although, the behavior and the cost of energy are much relevant here, diminishing the energy use because not all the dwelling is used at the same time or because the costs would be too high to have the comfort conditions (fuel poverty). The useful energy needs are generally measured in kWh/m^2 (calculated according to a thermal balance of a dwelling) and this value can be attributed for a country or region according to the average value of the stock, according to local regulations or even targets. Assuming the useful energy need as known for a region, if not it can be calculated according to the RCCTE [75], the average efficiency of the actual stock can be estimated as:

$$\eta = \frac{Own \times hh \times Q_u \times A_{hf} \times 100}{Q_f} [\%] \qquad \text{eq.3.5}$$

Where:

Q_f: Total final energy by technology or by energy carrier for the end-use [kWh/yr]

η: Efficiency system [-]

Own: Ownership of the technology or the end-use by energy carrier [-].

hh: Total number of households [hh]

A_{hf}: Area heating factor [-]

The area heating factor (A_{hf}) can be seen as the average fraction of the area used to be heated. This value can be obtained from surveys or calculated using reference heating values from studies or even measured values using the formula above. The heating area factor can be an average for all energy carriers or can be calculated or estimated for each one.

Table 13 shows a description for the ambient heating energy system for the domestic sector in Portugal in 2006. This description is divided in the same way as Table 12.

Table 13 - Energy system description for the Portuguese domestic ambient heating in 2006

End-use	Useful energy needs (kWh/m^2)	Ownership (% of hh)	End-use technologies	Reference efficiency
Ambient Heating	139	20.9%	Gas Heating	87%
		30.9%	Wood and Pellet-Fuel Heating	60%
		46.6%	Electric Resistance Heating	100%
			Electric Heat Pump Systems	400%
		0%	Heat Distribution Systems	100%
		1.7%	Diesel Heating	80%

Useful energy needs calculated based on [75]; data from [75][73][69], distribution systems assumed as 100%.

3.3.1.3. Ambient Cooling

Space cooling can represent one of the highest shares in energy use in countries with tropical and arid climates, and it is becoming more and more common, even in regions such as Western Europe due to higher comfort conditions and affordable energy and cooling systems prices. Space cooling is a high-intensity end-use, and evidence suggests that space cooling could be quite an important end-use in developing countries in the future as the comfort conditions rise [74]. The behavior in space cooling is a very important fact, since generally not all the dwelling is cooled to the comfort conditions, but only the rooms that are occupied. Another important factor is the energy price, which influences the use of cooling systems in the domestic sector, reducing the energy used to a level inferior than the useful needs. The useful energy needs are generally measured in kWh/m^2 and this value can be attributed for a country or region according to the average value of the stock or according to local regulations. Assuming the useful energy need is known for a region the average efficiency of the actual stock can be estimated in the same way as for ambient heating:

$$\eta = \frac{Own \times hh \times Q_u \times A_{cf} \times 100}{Q_f} [\%] \qquad \text{eq.3.6}$$

Where:

Q_f: Total final energy by technology or by energy carrier for the end-use [kWh/yr]

η: Efficiency system [-]

Own: Ownership of the technology or the end-use by energy carrier [-].

hh: Total number of households [hh]

A_{cf}: Area cooling factor [-]

The area cooling factor (A_{cf}) can be seen as the average fraction of the area used to be cooled when cooled systems are used. This value can be obtained from surveys or calculated using reference cooling values from studies or even measured values using the formula above. Almeida [81] found in his research average values for 11 European countries, varying from 15% of the area used for ambient cooling (Portugal) to 66% (Norway).

Table 14 shows a description for the ambient cooling energy system in the domestic sector. This description is divided in the same way as Table 12, by end-use, useful energy needs, ownership, end-use technologies and their reference efficiency.

Table 14 - Energy system description for the Portuguese domestic ambient cooling in 2006

End-use	Useful energy needs (kWh/m2)	Ownership (% of hh)	End-use technologies	Reference efficiency
Ambient Cooling	38	0%	Heat Pump Systems	300%
		16.9%	Air Conditioning	184% (calculations)
		0%	Cooling Distribution Systems	100%

Source: [82][73][69]

3.3.1.4. Refrigeration and freezing

Refrigerators and freezers are responsible for a high share of the household electricity use, in Portugal that share reached 24% according to a study from Quercus [83]. There are multiple types of refrigerators, varying in size and the presence of freezer compartments. Due to the many types of fridges and freezers, this methodology groups both of them in two groups, refrigerators and freezers, where distinction in each group is done by the efficiency of the categories labeled in order to make the evaluation easier and due to the fact that those products are the one of the most regulated product around the world. The useful energy needs are based here on the average of the best available technology. Here only the final energy use can be calculated based on the average final energy use per equipment, and vice-versa depending on the available data.

$$Q_f = Own \times hh \times Q_{feq}[kWh/yr] \qquad \text{eq.3.7}$$

Where:

Q_{feq}: Final energy by technology or by energy carrier for the end-use [kWh/yr]

Own: Ownership of the technology or the end-use by energy carrier [-].

hh: Total number of households [hh]

Table 15 shows a description for the refrigeration and freezing energy systems in the domestic sector for Portugal in 2006.

Table 15 - Energy system description for the Portuguese domestic refrigeration and freezing in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference efficiency (kWh/yr)
Refrigerators	219	109%	Refrigerators	495
Freezers	217	63.1%	Freezers	555

Source: [81][83][69]

3.3.1.5. Cloth Washing

Cloth washing is basically characterized by washing machines, for which the energy use varies by product class, by the number of loads used and the temperature chosen for the loads. The temperature for the load may represent the major energy use driver for the washing machines in each washing cycle. According to Almeida [81], a reference number of washes per household per year can be considered as around 272 for Europe, and a typical load can be considered as 4 kg (assumed value based on model calibration). Therefore, using a typical load and the average number of washes one can calculate the useful energy and the actual final energy used as below:

$$Q_u = Q_{feq} = N_W \times Load \times E_c[kWh/hh \times yr] \qquad \text{eq.3.8}$$

Where:

N_W: Number of washes per year per household [washes/hh x yr]

Load: Load per wash [kg]

E_c: Energy per kg per wash [kWh/wash*kg], this number can be assumed as the value for the best technology available. This number can be under the recommendations from labeling systems or can be used according to the temperatures used to wash cloths. E_c for class A equipments are less or equal to 0.19 kWh per kilogram on a program using a cotton cycle at 60°C with a maximum declared load [84]. However, there exist washing machines that can work with both hot and cold water, being much less energy intensive and allowing other conversion technologies to be responsible for hot water, as solar water systems. If when applying the methodology the user sees that using those washing machines would be a better approach, the only difference would be that the E_c used would be for the specific machine and all the hot water needed must be allocated to domestic hot water in order to have a precise use of the energy and to avoid double counting.

Besides the useful energy, the average final energy or the total final energy can also be calculated using equation 3.7. Table 16 summarizes the data needed to calculate the energy needs for the cloth washing system.

Table 16 – Data for cloth washing energy needs

Data needed	Proxy values	Corresponding data sources
Number of washes per year per household (N_W)	272 washes/hh*yr (Europe)	[81]
Load per wash (Load)	4 kg	[81]
Energy per kg per wash (E_c)	0.31 kWh/wash*kg (PT)	calculations based on eq.3.7 and 3.8

Table 17 shows a description for the cloth washing energy system for the Portuguese domestic sector in 2006.

Table 17 – Energy system description for the Portuguese domestic cloth washing in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference efficiency (kWh/hh*yr)
Cloth washing	207	92.1%	Washing machine	342

Source: [81][83][69]

3.3.1.6. Clothes Drying

Clothes drying are basically characterized by tumble dryers, for which the energy use varies by type (i.e., condensed and vented), energy carrier (i.e., electricity and gas), energy class, and by the number of loads. A typical load for tumble dryers can be considered 5 kg (assumed value based on model calibration) and, according to Almeida [81], the average number of dryings per household per year is related to the number of washes per year, and this share is around 30% for Portugal. Using a typical load and an average number of dryings, one can calculate the useful energy and the actual final energy used as below:

$$Q_u = Q_{feq} = N_D \times Load \times E_c [kWh/hh \times yr] \qquad \text{eq.3.9}$$

Where:

N_D: Number of dryings per household per year [dryings/hh x yr]

Load: Load per drying [kg]

E_c: Energy per kg per drying [kWh/drying*kg]. To calculate the useful energy needs this value can be assumed as the value for the best technology available.

Besides the useful energy, the average final energy or the total final energy can also be calculated using equation 3.7. Table 18 summarizes the data needed to calculate the energy needs for the cloth drying system.

Table 18 - Data for the energy needs for clothes drying

Data needed	Proxy values	Corresponding data sources
Number of dryings per year per household (N_D)	82 dryings/hh*yr (PT)	[81]
Load per wash (Load)	5 kg	assumed based on [81]
Energy per kg per drying (E_c)	0.9 kWh/wash*kg (PT)	calculated using eq.3.9

Table 19 shows a description for the cloth drying energy system in the domestic sector for Portugal in 2006.

Table 19 - Energy system description for the Portuguese domestic cloth drying in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference efficiency (kWh/hh*yr)
Clothes drying	224	19.1	Tumble dryer	367

Source: [81][83][69]

3.3.1.7. Dishwashing

The dishwasher has seen a rapid growth in their rate of market penetration, and in Portugal it is present in about 35% of households [69]. This equipment uses water and electricity. Electricity is mainly used by the electrical resistance that allows water heating (in the power equipment with cold water) and drying the dishes. These cycles may represent more than 80% of total energy use. The choice of the temperature is an important factor in the energy use of this appliance. The useful energy needs can be measured in kWh per year. According to Almeida [81], the average number of washes using dishwashers per household per year is around 207 in Europe. Therefore, using the average number of washes, one can calculate the useful energy and the actual final energy used as below:

$$Q_u = Q_{feq} = N_W \times E_c[kWh/hh \times yr] \qquad \text{eq.3.10}$$

Where:

N_W: Number of washes per household per year [wash/hh x yr]

E_c: Energy per kg per wash [kWh/wash], this number can be assumed as the value for the best technology available.

Besides the useful energy, the average final energy or the total final energy can also be calculated using equation 3.7. Table 20 shows a description for the dishwashing energy system in the domestic sector in Portugal in 2006.

Table 20 – Energy system description for the Portuguese domestic dishwashing in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference efficiency (kWh/hh*yr)
Dishwashing	219	34.7%	Dishwasher	303

Source: [81][83][69]

3.3.1.8. Entertainment

This is the fastest growing electricity end-use in the residential sector [85]. It includes equipments such as TVs, audio systems, signal receivers (i.e., cable and satellite), video-games, VCRs and DVDs and several other entertainment devices (here together as a group called others). TVs are, until the present, the largest electricity user in this group [85], therefore they are generally modeled with more detail than other devices belonging to entertainment. The energy use of a TV is mainly dependent on the size and the image technology. Televisions can be generally characterized by their image technology as CRT, LCD and Plasma. Reference values for power can be seen as 70, 180 and 300W, respectively [74]. Another factor that influences the energy use is the amount of time that TVs are used per day. Bertoldi [85] found an average value of 232 minutes per person per day in Europe, 260 in the US, 240 in Japan and 150 in South Korea. But more rounded values can be used as 4 hours of use per day per TV [74] or 6.5 hours per TV per day [86]. Another important factor in TVs and other entertainment systems is the stand-by mode. Most appliances have a stand-by mode and, in general, are not completely turned off during times when they are not in use. Despite of some low stand-by values, especially due to the efforts of international labeling systems, the stand-by mode must be used in the calculation of the useful and the actual final energy use. The calculation is showed below and can be used for any entertainment system.

$$Q_u = Q_{feq} = \frac{h_u \times P_c + (8760 - h_u) \times P_{sb}}{1000} [kWh/hh \times yr] \qquad \text{eq.3.11}$$

Where:

h_u: Number hours of equipment use per household per year [h/hh x yr]

P_c: Equipment power [W]

P_{sb}: Equipment power on stand-by mode [W]

Besides the useful energy, the average final energy or the total final energy can also be calculated using equation 3.7. Table 21 shows a description for the entertainment energy system in the Portuguese domestic sector.

Table 21 - Energy system description for entertainment in 2006 in Portugal

End-use	Useful energy needs (kWh/yr)	Ownership (% of hh)	End-use technologies	Reference efficiency per equipment (kWh/yr)
Entertainment	107	98.9%	CRT Tv	96
			LCD Tv	144
			Plasma Tv	400
	57	42.1%	TV Receiver	75
	7	90.4%	Audio Systems	46
	8	49.2%	VCR and DVDs	23

Source: [81][83][69]

3.3.1.9. Computers

The computers are getting more and more representative in homes due to several activities, going from home-working to entertainment and communication via internet. Besides, they are also becoming rather individual equipments, multiplying the energy use by the population. In this category, the most representative energy use comes from computers (personal or portable ones). The energy use is directly associated with the power of the equipments and the time of use. The useful and final energy uses for the equipments belonging to this category can be calculated in the same way as in the entertainment category (equations 3.11 and 3.7).

Table 22 shows a description for the computers energy system in the domestic sector for 2006 in Portugal.

Table 22 – Energy system description for the domestic computers in Portugal in 2006

End-use	Useful energy needs (kWh/yr)	Ownership (% of hh)	End-use technologies	Reference efficiency per equipment (kWh/yr)
Computers	25	77.4	Laptop PC	53
	100	79.0%	Desktop PC + Monitor CRT	276
			Desktop PC + Monitor LCD	211
	17	66.7%	Printers	33

Source: Almeida [81]

3.3.1.10. Lighting

Lighting is one of the most important energy services in a house and it has a representative part in the energy use of a household. Ideally, the useful energy needs for lighting could be measured in lumens, since what is really needed is visual comfort. This value could be converted into energy according to the technologies used. There are several standards defining minimum levels of visual comfort, but in the end, the value is related to the behavior of each person in a household. Therefore, lighting energy use can be seen as a function of number of light points, technologies used to provide light, and the hours of usage of each lighting point [85]. Bertoldi [85] estimated in his research an average value of 2.5 hours a day per light point and 19.5 light points in average for households in the European Union (EU27); their value for Portugal was 11.4 light points per household, although Almeida [81] found 25 as the average number of light points for Portugal, used as a reference for Portugal in this research. Annual lighting energy use (final energy) is given by Q_f and the useful needs by Q_u:

$$Q_{\mathrm{f}} = \frac{h_u \times \sum_{t=1}^{n} N_{lp,t} \times P_{c,t}}{1000} [kWh/hh \times yr] \qquad \text{eq.3.12}$$

$$Q_{\mathrm{f}} = \frac{Q_u \times (1/\eta_t) \times h_u}{1000} [kWh/lp \times yr] \qquad \text{eq.3.13}$$

Where:

Q_u: Useful energy need [lm]

h_u: Number hours of use per light point per household per year [h/lp x hh x yr]

$P_{c,t}$: Nominal power of technology t [W]

$N_{lp,t}$: Number of light points of the technology t [lp]

η_t: "Efficiency" or efficacy of the technology t [lm/W]

hh: number of households [hh]

n: total number of technologies

Table 23 summarizes the data needed to calculate the energy needs for the lighting system and their values for Portugal in 2006.

Table 23 - Data for lighting energy needs

Data needed	Proxy values (Portugal)	Corresponding data sources
Number hours of use per light point per year (h_u)	1710h (Halogen) 2420h (CFL) 3020h (Fluorescent) 2690h (Incandescent)	[83]
Nominal power of technology t ($P_{c,t}$)	59 W (Halogen) 13 W (CFL) 27 W (Fluorescent) 43 W (Incandescent)	[83]
Number of light points of the technology t ($N_{lp,t}$)	5 lp (Halogen) 4 lp (CFL) 3 lp (Fluorescent) 13 lp (Incandescent)	[83]
"Efficiency" of the technology t (η_t)	24 lm/W (Halogen) 60 lm/W (CFL) 60 lm/W (Fluorescent) 8 lm/W (Incandescent)	[81][83][85] calculations (eq.3.12, 3.13)
total number of technologies in use (n)	4	[83]

Table 24 shows a description for the lighting energy system in the domestic sector for Portugal in 2006. The useful energy needs can be calculated using the best available technology for each light point (e.g., 15W CFL, the most used CFL size [74]) or by converting the illuminance (useful needs) into energy using the efficacy of most efficient technology.

Table 24 - Energy system description for the Portuguese domestic lighting in 2006

End-use	Useful energy needs (lm/lp)	Ownership (% of hh)	End-use technologies	Reference energy use (kWh/hh*yr)	Reference energy use (kWh/lp*yr)
Lighting	1416	100.0%	Halogen	86	17
	780	100.0%	CFL	27	7
	1620	100.0%	Fluorescent	69	23
	344	100.0%	Incandescent	98	8
	5345	0.01%	Average (Oil for lighting)	42060	42060

Source:**[45][81][83][85]** calculations (eq.3.12, 3.13)

3.3.1.11. Cooking

The ovens and hobs have different energy needs according to the different processes used in food preparation, considering time spent and how people cook, and the energy carrier used. In terms of final energy, gas ovens are found to be slightly more energy intensive than electric ones in the European Union and the United States. Therefore, here ovens and hobs are distinguished by energy carrier. According to the Carbon footprint [86], the average number of meals prepared using ovens is around 135 and using hobs is around 424 per household per year in UK. The useful energy needs and the final energy use can be calculated according to the pattern of use and the amount of energy spent on each use. The amount of energy used is an averaged value based on [87]. The equation below shows the calculation for final or useful energy use.

$$Q = N_C \times E_c [kWh/hh \times yr] \qquad \text{eq.3.14}$$

Where:

N_C: Number of meals per household per year [meal/yr]

E_c: Energy per meals per technology [kWh/meal], this number can be assumed as the value for the best technology available for the useful needs. Technology means ovens or hobs.

Table 25 shows a description for the cooking energy system in the domestic sector for Portugal in 2006.

Table 25 - Energy system description for the Portuguese domestic cooking in 2006

End-use	Useful energy needs (kWh/hh*yr)	Ownership (% of hh)	End-use technologies	Reference energy use (kWh/meal)
Cooking	301	12%	Electric Hob	0.71
		85%	Gas Hob	0.9
	108	20%	Electric Oven	1.2
		77%	Gas Oven	1.52

Source: [81][83][85]

3.3.1.12. Lifts

Lifts are becoming more and more common in domestic buildings, since cities are growing and more multi-family builds are replacing single family houses. The energy used by lifts is strongly dependent on the type of driving machines used (i.e., hydraulic and tractions), number of people in an elevator, number of travels, standby losses, programming (does the elevator return to ground floor when unattended?). The simplest way to assess energy use for lifts is direct energy measurement and lifts traffic monitoring. The estimation of energy use for lifts can be based on:

$$Q = \frac{N_t \times E_t + h_{sb} \times P_{sb}}{hh_b} [kWh/hh \times yr] \qquad \text{eq.3.15}$$

Where:

N_C: Number of trips per building per year [trips/yr]

E_t: Energy used per trip [kWh/trip]

h_{sb}: Number hours in stand-by per year [h/yr]

P_{sb}: Elevator power on stand-by mode [kW]

hh_b: Number households per building [hh]

The number of trips can be measured or assumed. The energy used per trip will vary according to the elevator, the trip (floors traveled) and the weight, but an average value can be used.

Since no data was found referencing the energy used by lift, it was not modeled for Portugal

3.3.1.13. Others

This category exists to represent all other energy needs that were not specified. The energy use is calculated by subtracting the total energy use of the domestic sector by all the categories above, or can be represented by a share of the total energy, if it is previously known.

Table 26 shows a description for the other energy systems in the domestic sector for Portugal in 2006. This description is divided by end-use (others) and the respective energy use per accounted energy carrier.

Table 26 – Energy system for the others in the domestic sector

End-use	End-use carriers	Ownership (% of hh)	(Reference energy use (kWh/hh*yr)
Others	Electricity	100%	355
	Diesel	100%	7
	Gasoline	100%	0.006

Sources: [45,69]

3.3.2. Modeling of the services sector

The services sector, also referred to as the commerce sector or the tertiary sector, consists of businesses, institutions, and organizations that provide services and encompasses many different types of buildings and a wide range of activities. The services sector is a very heterogeneous sector and it includes facilities such as public and private offices, hotels, restaurants, supermarkets, schools, universities, malls, hospitals and swimming pools. Many types of buildings can be found in the services sector, which vary by size, technical standard, building age, equipment used, etc. Those different types of buildings can be associated to the type of service that they provide, which, despite the different type of building, have different type of energy needs. Most of the services energy use occurs on supplying services such as space heating and cooling, water heating, lighting and cooking. Commonly, the energy used for services such as traffic lights and city water and sewer services, is also categorized as a part of the energy use from the services sector.

The services sector is generally not well defined in many energy statistics because it is often assigned whatever cannot be attributed to households, industry or transports [88]. Also, time series data at the level of the economic activity (e.g., health, education, trade) and end-use (e.g., lighting, heating and cooling, office equipment) for most countries are not available, therefore the energy use for these activities and, especially, the end-uses are very difficult to be examined at the national level except in a few countries as the US [88] [67].

In order to have a better model of the energy system and to apply and evaluate the possible outcomes from energy efficiency measures, it is necessary to have a detailed and reliable energy use characterization and a status of the energy-relevant technologies. Improved data about energy end-uses in the services sector can be a key element to design and select adequate physical efficiency measures on local, national and regional levels.

Economic trends and population growth drive the services sector activities and its resulting energy use. The need for services (health, education, financial, and government) increases as populations increase. Economic growth also determines the increase in activities offered in the services sector. Higher levels of economic activity and disposable income may lead to increased demand for leisure, cultural activities and consumption, influencing the services growth in areas such theatres and malls.

Gross Added Value (or, if not available, Gross Domestic Product), floor area and employment are the three main indicators of activity in the sector [89]. Floor area is the most important indicator of activity in this sector, because energy uses tend to be proportional to area even when GAV or employment fluctuates with economic cycles [88] and especially because of physical relations (e.g., heat demand is directly dependent on the size of a building). A frequent problem is that floor area is not generally measured in all countries.

Analysis of the services sector energy use patterns is very complicated because of the variety of activities in the sector. To model the energy use one has to look into the services subsectors and end-uses. Here what are defined are the end-uses, which despite the heterogeneity of the sector can be found, in higher or lower levels, in most of the subsectors. The end-uses that most characterize the services sector in the world were defined based on [88] [74] [85] [90] as: Hot water, lighting and public lighting, ambient heating and cooling, refrigeration, office equipments, cooking, motors and others.

The services sector is covered in less detail than the residential, due to the lack of detail on equipment type penetration and use patterns [85]. Nevertheless, the general categories covered typically account for the bulk of energy consumption in this sector, and can be generally characterized even in the absence of detailed datasets.

As for the domestic sector, the description proposed below is for the general characterization of the energy system, letting the services sector be subdivided into several activities according to each region, data or desire from the user (e.g., education, food sales and services, health care, private and public buildings). Each activity is intended to share the same general end-uses and technologies.

3.3.2.1. Water Heating

In services sector the amount of hot water used, and consequently the energy for this purpose, can vary significantly depending on the subsector observed. The energy tied up in water heating can represent a significant component of the services total energy use. Observing US data [67], the energy use for heating water in the lodging subsector (e.g., hotels, motels, retirement homes) represented, in 2003, 31% of the total energy use in this subsector, while for offices, it represented only 2% of its total. Other services with heavy hot water demand include food services (e.g., fast food and restaurants) and health care. On the average, the energy for hot water in the US services sector represented 8% of the total energy used for the sector in 2003 [67].

The energy needs for hot water in the services sector depends heavily on the number of users [89]. Thus, according to Krackeler [91], employment is the most appropriate indicator to relate hot water needs to energy use. Although, the statement on the number of users is right, but associating only to employment would not represent a good relationship, since the subsector that uses more quantity of hot water is the lodging subsector and there the use is associated mainly with guests than the number of employees. Ideally, each subsector from the services should be analyzed to find their best dependences between activity and energy use. However, due to the amount of subsectors in the services sector and lack of specific data, the approach used here to normalize all subsectors will be to associate the energy use for heating water with a physical dimension, as floor area, and when not possible to the GAV.

There are several technologies available to heat water, turning almost impossible to know at a high level (e.g., city, country) the exactly technologies used. Therefore in case no such data is available, a reference technology (or reference conversion efficiency) must be assumed. This assumption can be done by interviewing specialists in the field or through surveys. After assuming the average energy conversion technology for each energy carrier, one may calculate the average useful energy needs and then apply other technologies to compare energy savings. The useful energy can be calculated as:

$$Q_u = \frac{\sum_{i=1}^{n} Q_{fi} \times Share_i \times \eta_i}{A} [kWh/m^2 \times yr] \qquad \text{eq.3.16}$$

Where:

Q_u: Useful energy [kWh/m^2 x yr]

Q_{fi}: Total final energy from carrier i [kWh/yr]

$Share_i$: Share from the energy carrier i used for water heating [-]

A: Total area from the sector or subsector [m^2]

η_i: Efficiency from the reference system for the carrier i [-]

n: number representing the energy carriers or technologies for all carriers available

Table 27 shows a description for the hot water energy system for the services sector in Portugal in 2006. For that, it was used a reference value for the total area from the sector in 2006 as 126 million m^2 [82].

Table 27 – Energy system description for services water heating in Portugal in 2006

End-use	Useful energy needs (kWh/yr*m^2)	Ownership (% of m^2)	End-use technologies	Reference efficiency
Hot Water	7.1	0%	Biomass Storage System	60%
		42.6%	Gas Storage System	72%
			Gas Tankless Heaters	50%
		28.3%	Fuel Oil/Diesel Storage System	80%
		28.5%	Electric Storage System	88%
			Electric Tankless Heaters	99%
			Electric Heat Pump	220%
		0%	Solar water heaters + Gas Storage	240%*
			Solar water heaters + Electric Storage	293%*
			Solar water heaters + Heat pumps	733%*
		0.6%	Heat Distribution Systems	100%

Sources: [75][73][69][92], *Total efficiency considering backup efficiency and using 70% solar factor

3.3.2.2. Space Heating

Space heating is found in almost every building in the services sector in Europe, US and Japan, and its energy use can represent around 70% of the total energy needs of a subsector in the services sector (share of space heating from total energy use at education and research subsector in France in 2001 [89]).

The building envelope and the floor area are critical components from the space heating energy use, since they play a major role by defining the flow of energy between the interior and exterior of the building. Since the energy use for space heating depends largely on the area to be heated, the floor area can be best suited for expressing the space heating energy needs in terms of an input from the sector [89]. Although, an important factor besides the area in the services sector is to know the heated area; this factor could impact in the efficiency of the systems if a higher area is used rather than the actual one [78].

Defining an average value for the useful energy use for space heating (thermal demand per unit surface) can be an extremely complicated work, since the building thermal demand depends on building energy codes, type of building, usage patterns and on climate. The patterns and the types of buildings may vary drastically even in the same subsector from the services sector, turning this work even more difficult. Some studies tried to find an average value for the useful energy demand for space heating in the services sector. McNeil [74] defined a value for thermal demand depending on the heating degree days (HDD) of each country as 0.0353 times HDD comparing typical values from several countries. Another study from Kemna [78] made an assessment on building characteristics and tried to calculate an average heat load from the available data from the European Union, reaching a fairly confident average for the EU. The first study, based only on a few typical values and heating degree days, reflects the climate but would overestimate or underestimate the situation of the insulation of the building stock of some countries. Using Portugal as example, the average value found according to the first study is 48 kWh/m^2*yr against 109 kWh/m^2*yr in the second one, more than double in energy need. This difference can be minimized if a area heating factor is applied to the work of Kemna [78], since in his study he calculated the heating needs based on a physical model where only the heated area is accounted, while for McNeil [74], he calculated the heating needs based on general statistics for heating use and area. Due to the well documented and consistent data from the services sector found in [78], it was decided to use them as proxies if no better data is provided. Table 28 shows the useful energy needs for space heating for the European Union and its Member States.

Table 28 - Useful energy needs for space heating for the services sector in the European Union [78]

Member State	Useful energy needs for Space Heating (kWh/m²*yr)
Austria	144
Belgium	142
Cyprus	51
Czech Republic	155
Germany	98
Denmark	127
Estonia	235
Greece	55
Spain	91
Finland	240
France	128
Hungary	154
Ireland	168
Italy	117
Lithuania	239
Luxembourg	75
Latvia	207
Malta	42
Netherlands	102
Poland	134
Portugal	109
Sweden	289
Slovenia	62
Slovakia	139
United Kingdom	100
EU-25	117

However, independently of the useful energy needs, the final energy can be estimated following:

$$Q_{fi} = \frac{Q_{fti} \times Share_i}{A \times Own_i} [kWh/m^2 \times yr] \qquad \text{eq.3.17}$$

Where:

Q_{fi}: Final energy from carrier or technology i [kWh/ m^2 x yr]

Q_{fti}: Total final energy from carrier i [kWh/yr]

$Share_i$: Share from the energy carrier i used for space heating [-]

A: Total area from the sector or subsector [m^2]

Own_i: Ownership or diffusion from the reference system for the carrier i [-]

i: Energy carrier; if data is available, the technologies can also be represented for this index

In order to represent the technologies, a conversion factor must be used to relate the useful energy needs with the final energy use by technology (or at least by energy carrier if no data on technology is available). To estimate the average conversion efficiency for space heating, one must use the final energy use, the useful energy use and the area heating factor as showed in the following equation:

$$\eta_i = \frac{Q_u \times A_{hf} \times 100}{Q_{fi}} [\%] \qquad \text{eq.3.18}$$

Where:

η_i: Efficiency from the reference system for the carrier i or the technology i [%]

Q_u: Useful energy needs for space heating [kWh/m^2 x yr]

Q_{fi}: Final energy from carrier or technology i [kWh/ m^2 x yr]

A_{hf}: Area heating factor [-]

The area heating factor can be surveyed, or can be estimated using the previous equation assuming a reference value for the efficiency. Using the efficiencies from Kyle [93], the area heating factor for Portugal was estimated as 42% of the total area.

In the services sector, the vast majority of the energy for space heating is provided by commercial fuels like natural gas and heating oil [74]. Space heating in services sector started to be the target of efficiency standards recently [85], despite being one of the largest single end-use in non-tropical regions. For this reason, there is not a great wealth of international data with descriptive ratings systems and baseline estimates of equipment efficiency. Table 29 shows a description for the space heating energy system for the services sector for Portugal in 2006.

Table 29 - Energy system description for space heating for services in Portugal in 2006

End-use	Useful energy needs (kWh/yr*m^2)	Ownership (% of m^2)	End-use technologies	Reference efficiency
Space Heating	109	24.5%	Electric Heat Pumps	310%
			Electric Furnaces and Boilers	98%
			Individual Electric Space Heaters	100%
		46%	Fuel Oil/Diesel Furnaces	77%
		1.2%	Heat Distribution Systems	100%
		28.2%	Gas Furnaces and Boilers	76%
		0%	Coal Furnaces and Boilers	60%

Source: [75][78][92][93]

3.3.2.3. Space Cooling

Space cooling is a growing end-use in the services sector, especially in countries in Europe and the US and Japan. Its energy use can represent, on average, 7% of the total electricity use in the services sector at the European Union [90] and an average value of 8% from total final energy use for the US services sector in 2003 [67].

The space cooling, as the space heating, is highly dependent on the building envelope and the floor area. One main difference from cooling compared to heating is the fact that the energy use from other end-uses does not work as gains, but as an increase in the load to be cooled. As for the space heating, the floor area can be best suited for expressing the energy needs for space cooling in terms of an input from the sector [89]. Ideally the floor area could be better accounted if the cooled area is known. Thus, the spacing cooling in final energy could be estimated as:

$$Q_{fi} = \frac{Q_{fti} \times Share_i}{A \times Own_i} [kWh/m^2 \times yr] \qquad \text{eq.3.19}$$

Where:

Q_{fi}: Final energy from carrier or technology i [kWh/ m^2 x yr]

Q_{fti}: Total final energy from carrier i [kWh/yr]

$Share_i$: Share from the energy carrier i used for space cooling [-]

A: Total area from the sector or subsector [m^2]

Own_i: Ownership or diffusion from the reference system for the carrier i [-]

i: Energy carrier; if data is available the technologies can also be represented for this index

An average value for useful energy use for space cooling (cooling demand per unit surface) is as hard to define as for space heating, because they are both influenced by the building energy codes, type of building, usage patterns and on climate. The usage pattern may vary drastically and have huge influences even in the same type of buildings from the services sector. Dalin [82] specified an average value for the useful energy demand for space cooling in the services sector for Europe as 82 kWh/m^2*yr based on the new European Cooling Index (developed in the same work, which takes into consideration outdoor temperature and the building conditions), an average composition of service sector buildings (12% for hotels and restaurants, 13% for health and social buildings, 18% for education and research, 26% for offices and public administration, 22% for commercial purposes and 10% for other purposes) respecting the specific cooling demands and the building areas. The average value of 82 kWh/m^2*yr is the reference value for the European Cooling Index at level 100 (ECI-100), making possible to extrapolate for all countries covered by the index. Table 30 shows the ECI values and the average useful space cooling energy use for the services sector.

Table 30 - European Cooling Index (ECI) and average useful space cooling energy use [82].

Country	ECI	Useful space cooling demand in kWh/m^2*yr
Austria	106	87
Belgium	77	63
Bulgaria	116	95
Croatia	127	104
Cyprus	143	118
Czech Republic	89	73
Denmark	59	48
Estonia	65	54
Finland	72	59
France	95	78
Germany	94	77
Greece	161	132
Hungary	123	101
Iceland	6	5
Ireland	32	26
Italy	133	109
Latvia	79	65
Lithuania	85	70
Luxembourg	81	67
Malta	143	118
Netherlands	65	53
Norway	67	55
Poland	95	78
Portugal	104	85
Romania	137	112
Slovak republic	117	96
Slovenia	127	104
Spain	147	121
Sweden	73	60
Switzerland	85	70
Turkey	135	111
United Kingdom	74	60

In order to represent the technologies, a conversion factor must be addressed to relate the useful energy needs with the final energy use by technology (or at least by energy carrier if no data on technology is available). The following equation can be used to estimate the average conversion efficiency for space cooling.

$$\eta_i = \frac{Q_u \times A_{cf} \times 100}{Q_{fi}} [\%] \qquad \text{eq.3.20}$$

Where:

η_i: Efficiency from the reference system for the carrier i or the technology i [%]

Q_u: Useful energy needs for space cooling [kWh/m^2 x yr]

Q_{fi}: Final energy from carrier or technology i [kWh/ m^2 x yr]

A_{cf}: Area cooling factor [-]

The area cooling factor can be surveyed, or can be estimated using the previous equation assuming a reference value for the efficiency. Using the efficiencies from RCCTE [75], the area cooling factor for Portugal was estimated as 28% of the total area.

The analysis of cooling systems is also a very difficult task due to the technical variety and complexity of the systems. To simplify the methodology, the cooling system is divided into 3 main technologies: systems based on compression cycles (excluding heat pumps), systems based on absorption cycles and heat pumps. This choice of simplification was based on the work from Gruber [90] and on the RCCTE [75]. Table 31 presents a description for the space cooling energy system for the services sector and the reference efficiencies for the three categories of systems chosen for Portugal in 2006.

Table 31 – Energy system description for space cooling for services in Portugal in 2006

End-use	Useful energy needs (kWh/yr*m^2)	Ownership (% of m^2)	End-use technologies	Reference efficiency
Space Cooling	85	100%	Electric Heat Pumps	300%
			Systems Based on Compression Cycles	300%
			Systems Based on Absorption Cycles	80%

Sources: [75][78][92]

3.3.2.4. Motors

Motors at the services sector can be subdivided according to Almeida [94] into pumps, fans, conveyors, refrigeration, air conditioning and other motors. Since in this work air conditioning is covered by space cooling and refrigeration is a specific end-use, motors contemplate pumps, fans, conveyors and other motors.

Almeida [94] in his work defined that electric motors could be grouped according to their output power range, and thus defined 8 power range groups that can be seen in Table 32. Table 32 also presents the share of the total number of motors found in the services sector for Europe, their respective energy use share, their average efficiency values and the average energy use by motor type per year, all based on Almeida's [94] work.

Table 32 - Average characteristics for the electric motors for Europe [94]

Output power ranges, kW	Share of possession of motors	Energy use share	Average η	Average final energy use per motor kWh/yr
0 < 0.75	25.5%	6.3%	66%	741
0.75 < 4	51.2%	29.5%	79%	1729
4 < 10	16.6%	26.2%	85%	4728
10 < 30	5.9%	23.9%	88%	12198
30 < 70	0.5%	5.7%	90%	34653
70 < 130	0.2%	4.7%	93%	92147
130 < 500	0.0%	2.8%	95%	217573
>500	0.0%	0.8%	96%	339367
Total	100%	100%	-	-

Using Table 32 as reference, it is possible to calculate the final energy use and the useful energy use for each output power range.

$$Q_{fi} = Q_f \times Share_m \times Share_i [kWh/yr] \qquad \text{eq.3.21}$$

$$Q_{ui} = Q_{fi} \times \eta_i [kWh/yr] \qquad \text{eq.3.22}$$

Where:

Q_{fi}: Final energy from output power range i [kWh/yr]

Q_{ui}: Useful energy from output power range i [kWh/yr]

Q_f: Total electricity [kWh/yr]

$Share_m$: share of motors electricity [-]

$Share_i$: electricity share of the power range i [-]

η_i: Efficiency from the power range i [-]

i: Power range as in Table 32

The stock from each output power range can be estimated, for the purpose of quantifying the impact of replacing the average equipments for new more efficient ones, using the average energy use per motor and the final energy from output power range.

Table 33 presents a description for the energy system of motors for the services sector. This table shows the 8 output power ranges to describe the motor system, the useful energy needs and the reference efficiencies.

Table 33 – Energy system description for motors for services in Portugal in 2006

End-use	Useful energy needs (kWh/eq*yr)	Stock of motors	End-use Motor Power range (kW)	End-use technologies (Ref. Efficiency)
Motors	489	59	0<0.75	66%
	1,366	210,251	0.75<4	79%
	4,019	421,832	4<10	85%
	10,734	48,438	10<30	88%
	31,188	318	30<70	90%
	85,696	4,032	70<130	93%
	206,695	137,062	130<500	95%
	325,792	1,271	>500	96%

Source:[45][92][94]

3.3.2.5. Lighting and Public Lighting

Lighting is an essential service in any building, especially in the services sector because it provides illumination for tasks and activities, bringing value to the sector. In general, lighting represents the major electricity use in the services sector, responsible, in 2005, for an average of 30% of the electricity share of the sector worldwide [95]. According to Gruber [90], the numbers for the European Union are very similar, rounding 29% as an average share of electricity use in the services sector.

The lighting energy use can be associated with three main factors, the quality of light, the efficacy of the lighting system and patterns of use or occupancy. Defining the quality of light delivered is still challenging and not a fully determinable parameter. It is responsible for the distribution of light, avoidance of glare and the spectral characteristics of the delivered light (light color temperature). However most countries try to define quality through (quantity) illuminance guidelines depending on visual tasks, generally defined in lux or lumens per square meter (lm/m^2) [95]. The lighting requirements are highly dependent on the nature of the visual tasks, according to NBR 5413/1992 [96], the Brazilian lighting standard, the recommended illuminance for a surgery is in a range from 10 000 lux to 20 000 lux, while for office lighting it is recommended a range from 500 lux to 1000 lux. Efficacy is a ratio of light output to the power, measured in lumens per watt (lm/W), and it varies according to the technology used. Patterns of use or occupancy vary from type of building (and subsector) and space, the more operating hours a type of building has, the more will be the energy use from lighting. Different spaces require different lighting demand. Some spaces must be lit throughout the entire day, while others are needed only for certain periods (e.g., corridors are constantly lighted while offices may not be). These three factors define the energy use, but at the same time show how different the activities in the services sector can be and how the energy for lighting can be used.

The useful lighting needs would be represented in lumens based on guidelines for lighting quality [95].The average useful lighting needs (Q_u) can be estimated from the equations below:

$$Q_f = \frac{Q_{ft}}{area} [kWh/m^2 \times yr] \qquad \text{eq.3.23}$$

$$Q_u = \frac{Q_f \times \eta \times 1000}{FO \times FD \times h} [lm/m^2] \qquad \text{eq.3.24}$$

$$\eta = \sum_{i=1}^{n} Share_t \times \eta_t \, [lm/W] \qquad \text{eq.3.25}$$

Where:

Q_{ft}: Total final energy for lighting [kWh/yr]

Q_f: Final energy for lighting [kWh/m^2*yr]

area: Total area from the sector or subsector [m^2]

η_t: Efficacy of the technology t [lm/W]

h: Hours use [h/yr]

n: Number of technologies

$Share_t$: Share of the technology t in the sector [%]

FO = occupancy dependency factor; factor relating the usage of the total installed lighting power to occupancy period in the room or zone; $0 \leq FO \leq 1$

FD = daylight dependency factor; factor relating the usage of the total installed lighting power to daylight availability in the room or zone; $0 \leq FD \leq 1$

The average hours of use of a lighting system can be obtained through surveys or studies, or found in international or national standards. Pindar [97] estimated an average operating hour for the services sector in Europe as 2500 hours per year based on the more conservative value of the sources used. The value considered, despite conservative, seems very low compared with the EN 15193 [98] (also used by Pindar in the study). Therefore, here is considered as proxy the values found at EN 15193 [98], as presented in Table 34.

Table 34 – Annual operating hours by building category in the services sector [98]

Building types	Default annual operating hours		
	Daylight time usage [h]	Non-daylight time usage [h]	Annual operating time [h]
Offices	2250	250	2500
Education buildings	1800	200	2000
Hospitals	3000	2000	5000
Hotels	3000	2000	5000
Restaurants	1250	1250	2500
Sports facilities	2000	2000	4000
Wholesale and retail services	3000	2000	5000
AVERAGE	**2329**	**1386**	**3714**

The lighting technologies or the technology of a lighting system are what defines the efficacy. A lighting system includes lamps, ballasts, luminaries and lighting controls. Lamps are lighting sources, like fluorescent and incandescent light bulbs, and high intensity discharge lamps. Ballasts limit the current of the lamps, transform and control power, and either alone or in combination with a starting device, they provide necessary conditions for starting lamps such as fluorescent lamps. Luminaries are all parts necessary for fixing and protecting the lamps and in some cases have circuits to connect the lamps to the electric supply in accordance with the lamps needs. Lighting controls are devices such as switches, timers and sensors that turn the lights on and off according to the needs or rules from the spaces or the occupants.

The share of each lighting technology in the services sector is an important factor defining the average efficacy. According to the U.S. DoE [99] the share of lamps was, in 2002, 22% of incandescent lamps, 77% of fluorescent and 1% of high intensity discharge lamps in the services sector. This share is very similar to the one provided by IEA [95] for the OECD countries, as 76.5% for fluorescent, and the remaining 23.5% of the delivered light is supplied by a mixture of incandescent, compact fluorescent and HID lamps. This distribution can be more complete knowing that the share of electricity used was 32% of incandescent lamps, 56% of fluorescent and 12% of high intensity discharge lamps.

Table 35 presents a description for the lighting energy system in the services sector for Portugal in 2006. The useful needs can be obtained by estimations as presented above. The technologies used are the most common technologies found in the service sector and organized as: Incandescent lamps, fluorescent tube lamps, compact fluorescent lamps, high intensity discharge lamps, low pressure sodium lamps, solid-state lighting (LEDs) and halogen lamps.

Table 35 – Energy system description for lighting for services in Portugal in 2006

End-use	Useful energy needs (lm/m^2)	Ownership (% of m^2)	End-use technologies	End-use efficacy (lm/W)
Lighting	409	7%	Incandescent Lamps	10-15
		74%	Fluorescent Tube Lamps	60-100
		-	Compact Fluorescent Lamps	35-80
		19%	High Intensity Discharge Lamps	23-120
		-	Low Pressure Sodium Lamps	120-200
		-	Halogen	15-33
		-	LEDs	50-100

Sources: [95]

Lighting is also required for outdoor illumination, such as streets, car parking, stadiums, roadways and tunnel lighting. Since this type of lighting is generally a responsibility attributed to governments and it has some specificity as the quality of light, the type of subspace to be illuminated, economic factors and, in special, are discriminated in energy studies and surveys, it was decided to create an specific end-use named public lighting. The public lighting is based on the same equations as lighting, however for public lighting the ownership is better associated to power installed than area. To estimate values for Portugal for public lighting an average number of operating hours is assumed as 4500 following [100]. Table 36 presents a description for the Portuguese public lighting energy system in 2006.

Table 36 – Energy system description for public lighting in Portugal in 2006

End-use	Useful energy needs (lm)	Ownership (MW)	End-use technologies	End-use Efficacy (lm/W)
Public Lighting	7905117228	220	Low/High-Pressure Sodium	36
	1472064591	107	Mercury Vapor	14
	642428188	21	Metal Halide	30
	49602176	7	Incandescent	7

Sources: [95][45]

3.3.2.6. Office Equipments

Office equipments are one of the fastest-growing uses of electricity in the services sector. In the European Union they account for 1% of the total electricity use for health and social works and up to 18% of the total electricity use for offices, with an average of 9% of the total electricity use in the sector [90].

Office Equipments can aggregate a huge variety of energy-using equipment including computers, servers, copiers, fax machines, cash registers, printers, coffee makers, electric kettles and many more, making it almost impossible to measure the complete energy use of all devices. Actually the group formed by office equipments can be much diversified according to the study or the survey performed. Depending on the surveys, computers can be classified as a new group outside office equipment and other devices like coffee machines can be associated with other uses or miscellaneous appliances. As an example, Schlomann [101] defines office equipments in her study as personal computers (desktops, laptops, PDA), computer monitors, printers, copiers, scanner, multifunctional devices (MFD), modems, phones, fax machines, servers, workstations and networks (wired, wireless), while McNeil [74] defines their office equipment as personal computers, laptops, printers, fax machines, coffee makers, electrical kettles and others.

When considering an indicator to relate office equipments to energy use, Mairet [89] defines the most appropriate one been employment. The number of employees can work as a level of saturation for most of the office equipments, as computers, printers, faxes and cash machines, and for the others can work as value of reference.

Due to the complexity of the group represented by office equipments, a way to represent the useful needs is through the total hours of use. Assuming that the equipments are used during the operation hours from the sector or the subsector (Table 34 can be used as a reference), and having the penetration or ownership of the equipments, a bottom-up approach can be used find the final energy use, as:

$$Q_f = \frac{(h_u \times P_c + h_{sb} \times P_{sb} + h_{off} \times P_{off})}{1000 \times PN \times emp} [kWh/emp \times yr] \qquad \text{eq.3.26}$$

Where:

h_u: Number hours of equipment use per year [h/yr]

h_{sb}: Number hours of equipment on standby per year [h/yr]

h_{off}: Number hours of equipment on off mode per year [h/yr]

P_c: Equipment power [W]

P_{sb}: Equipment power on stand-by mode [W]

P_{off}: Equipment power on off mode [W]

PN: Penetration from the equipment in relation to the number of employees [%]

emp: Number of employees in the sector or subsector [emp]

In case no specific data is available for individual office equipments, a more aggregate indicator can be used to show a reference value for final energy.

$$Q_f = \frac{Q_{ft}}{emp} [kWh/emp \times yr] \quad \text{eq.3.27}$$

Where:

Q_{ft}: Total final energy for office equipments [kWh/yr]

emp: Number of employees in the sector or subsector [emp]

Table 37 shows a description for the office equipment energy system in the services sector. Due to complexity from the office equipment group, here the technologies are organized as computers and other office equipments in order to facilitate the process when comparing technologies and following the study from Rosenquist [102]. For example, when comparing printers the energy is not the only important fact, since some printers have more functions than others, or have the ability to print in color or can print a large number of pages, those fact influence the comparability of printers.

Table 37 - Energy system for the services office equipment in Portugal in 2006

End-use	Useful energy needs (kWh/emp x yr)	Ownership (% of employees)	End-use technologies	Reference efficiency (kWh/emp x yr)
Office Equipment	18	70%	Computers	293
	224	100%	Other office equipments	224

Sources: [101][45][92]

3.3.2.7. Refrigeration

Refrigeration represents a significant share of the electricity use depending on the subsector. It is estimated that refrigeration corresponds to 15% and 19% of the electricity use in trade and hotels and restaurants, respectively, in the European Union [90]. Refrigeration is very representative in those subsectors due to the need for conserving food and beverages.

Despite the direct relation for conserving food, generally, the refrigeration energy needs are directly represented in energy units due to the continuous use of the equipments, allowing an easier approximation from annual energy consumption and the fact that equipments related to refrigeration are commonly labeled worldwide. Due to international label scheme, the useful energy needs can be associated to the best technologies available depending on the refrigeration service. Although, the energy use can also be associated to an indicator in order to forecast trends. The most appropriate indicator is area, despite the relation with GAV for specific technologies found in this activity, as vending machines. Thus, the refrigeration in final energy can be estimated using equation 3.23.

The refrigeration services (in this case, technologies) were divided, according to Westphalen [103], in walk-Ins, beverage merchandisers, reach-in freezers, reach-in refrigerators, refrigerated vending machines, ice machines and others.

The stock from each technology can be estimated, for the purpose of quantifying the impact of replacing the average equipments for new more efficient ones, using the reference energy use for each technology, the share from the energy use for refrigeration for each technology and the total final energy for refrigeration in the services sector. Westphalen [103] estimated the primary energy use from the above technologies where one can calculate the share from the final energy use for refrigeration in the USA as: walk-Ins 18%, beverage merchandisers 5%, reach-in freezers 7%, reach-in refrigerators 5%, refrigerated vending machines 13%, ice machines 10%, supermarkets 33% and others 8%. Therefore, one can estimate the stock of equipments using:

$$Stock_i = \frac{Q_{ft} \times Share_i}{Q_{frefi}} [equipments] \qquad \text{eq.3.28}$$

Where:

Q_{ft}: Total final energy for refrigeration [kWh/yr]

$Share_i$: Share of energy use from each technology i [%]

Q_{frefi}: Final reference energy use for technology i [kWh/yr*equipment]

Table 38 shows a description for the refrigeration energy system in the services sector for Portugal in 2006.

Table 38 – Energy system description for the services refrigeration in Portugal in 2006

End-use	Useful energy needs (kWh/yr)	Ownership (equipments)	End-use technologies	Reference energy use (efficiency) (kWh/yr)
Refrigeration	22600	6992	Walk-Ins	22600
	3900	11704	Beverage Merchandisers	3900
	3687	38490	Reach-In Freezers	5200
	1262	44300	Reach-In Refrigerators	4300
	2057	39210	Refrigerated Vending Machines	3000
	7800	11479	Ice Machines	7800

Sources: [45][92][103]

3.3.2.8. Cooking

Cooking is an important energy use for food services as restaurants and cafeteria, which accounted 25% of the total final energy use for food services in 2003 in the US [67]. Although, the energy used for cooking is nearly non-existent for offices, not accounting even 1% of its total final energy use for the same period.

There are several cooking equipments used for food services, and the most common are the braising pans, broilers, fryers, griddles, ovens, pasta cookers, range (range tops), steam kettles, steamers and microwaves. Despite the existence of several equipments, the most widely used pieces of commercial cooking equipments are still the ovens and the ranges [104], and due to this fact, and for simplification, the technologies for cooking are chosen to be represented as ovens, ranges and others.

When considering an indicator to relate cooking to energy use the most appropriate one appears to be employment. The number of employees can express the cooking needs since employees can both be responsible for preparing the food, as in restaurants, or can be the consumers from the food, as office buildings with kitchens of even restaurants. Thus, a reference value for final energy can be estimated using equation 3.27.

In order to find the final energy per technology or the final energy needs for ranges and ovens (if it is not measured or quantified by any study), a share from the energy carriers must be estimated to apply the following equation:

$$Q_{fi} = Q_{fc} \times Share_{ic}[kWh/emp \times yr] \qquad \text{eq.3.29}$$

Where:

Q_{fc}: Final energy for cooking for carrier c [kWh/emp x yr]

$Share_i$: Share of energy use from each technology i for the carrier c [%]

Table 39 presents a description for the cooking energy system in the services sector for Portugal in 2006.

Table 39 - Energy system description for cooking for services in Portugal in 2006

End-use	Useful energy needs (kWh/emp*yr)	Ownership (% of employess)	End-use technologies	End-use technologies (Ref. efficiency)
Cooking	38	35%	Electric Range	75%
		48%	Gas Range	28%
	13	39%	Electric Oven	65%
		53%	Gas Oven	35%

Sources: [45][86][92][104]

3.3.2.9. Others (Miscellaneous Appliances)

This category exists to represent all other energy needs that were not specified. The energy use is calculated by subtracting the total energy use from the services sector by all the categories above, or can be represented by a share of the total energy, if it is previously known.

Table 40 presents a description for the others energy system in the services sector for Portugal in 2006. This description is divided by energy carriers and their reference energy use in kWh per year and square meter. The square meter was chosen to keep the physical relation from energy to the size of the sector.

Table 40 – Others energy system for the services sector in Portugal in 2006

End-use	End-use carriers	End-use technologies (Ref. Energy use) kWh/m^2*yr
Others	Natural Gas	1.29
	LPG	0.73
	Fuel Oil	0.68
	Diesel for Heating	0.71
	Diesel	18.79
	Gasoline	1.41
	Heat	0.01
	Electricity	22.51

Sources: [45][92]

3.3.3. Modeling of the industry sector

The industry sector is generally defined by mining and quarrying of raw materials, the manufacture of goods and products, and construction (NACE Rev.2 B, C and F respectively, according to Statistical Classification of Economic Activities in the European Community [105]). Power generation, refineries and the distribution of electricity, gas and water are generally excluded.

The most important and most energy intensive part of the industry sector is the manufacture of goods and products, which consists basically on three kinds of productions: raw materials (e.g., steel and paper pulp), intermediate goods (e.g., machines and engines) and final goods used by consumers (e.g., TVs and washing machines). As in the services sector, the energy use and its structure be associated to physical inputs and outputs, physical processes and monetary measures. The physical units that represent those groups are generally the weight for the raw materials and the actual units produced for the other two.

Energy use based on physical units is connected to “technical efficiency” and, hence, can be linked to technology performance and improvement. They can therefore be used to identify the potential for efficiency improvements through new technologies. They are not affected by cyclical variations in the price of industrial commodities, as is the case with indicators that use value added and so tend to be subjected to less “noise” from economic fluctuations. Although, measurements in physical units can be misleading, because even if the goods produced by a sub-sector can be measured in same units like tons, it is not always meaningful to add tons of one product to tons of another, especially if the energy-consuming processes required for their production are very different [106], and because several products and processes from some industries are dependent on the raw material used as input. Using the example of the steel industry, the amount of energy needed to produce one ton of steel will be very different if the steel is made using iron ore or using scrap metal, and depending on the process used (blast furnace, basic oxygen furnace or electric arc furnace). Comparing a route composed by scrap metal with electric arc furnace with a route using iron ore with blast furnace, the first one is much less energy intensive (4 GJ to 6 GJ per ton) than the second route (13 GJ to 14 GJ per ton), because there is no need to reduce iron ore to iron, and it removes the need for the ore preparation, coke-making and iron-making steps [107]. Therefore, the measurement should be analyzed by process, inputs and the nature of the outputs, what would be virtually impossible due to the amount of data to gather, if such data is available, which generally is not.

Physical measures of output are useful when studying a particular product or process, but it is almost impossible to find a single material or product that could represent the whole industry. The use of monetary measures of value solves the aggregation problem by relying on a common unit of output specification. Therefore, this is why most studies rely on monetary measures.

This study proposes a characterization based on monetary units to measure the size, the structure and the growth from the industry sector and based on more general processes that are present in all manufacture industries. The processes and end-uses selected are based on studies developed by [66] [94] [108] [109]. They consist on conventional boiler use, process heating, process cooling and refrigeration, motor-driven processes, electro-chemical processes, facility HVAC, facility lighting, onsite transportation and others.

The energy use at the manufacturing industry is different from other sectors since industrial processes and technologies are not very dependent on the climate, geography, consumer’s behavior and income levels, facilitating a comparison across countries and making it easier to use available data characterizing the industry from a few countries as proxies [110]. Using data from US DoE [66] as proxy, and taking as base the end-use models proposed by Giraldo [108] and Ozalp [109], a generic processes and end-use model is defined using the share of the energy used for each process and end-use for each type of manufacturing industry (defined under the two-digit U.S. Standard Industrial Classification (SIC) system [111]). Figure 2 presents the generic model as a flowchart.

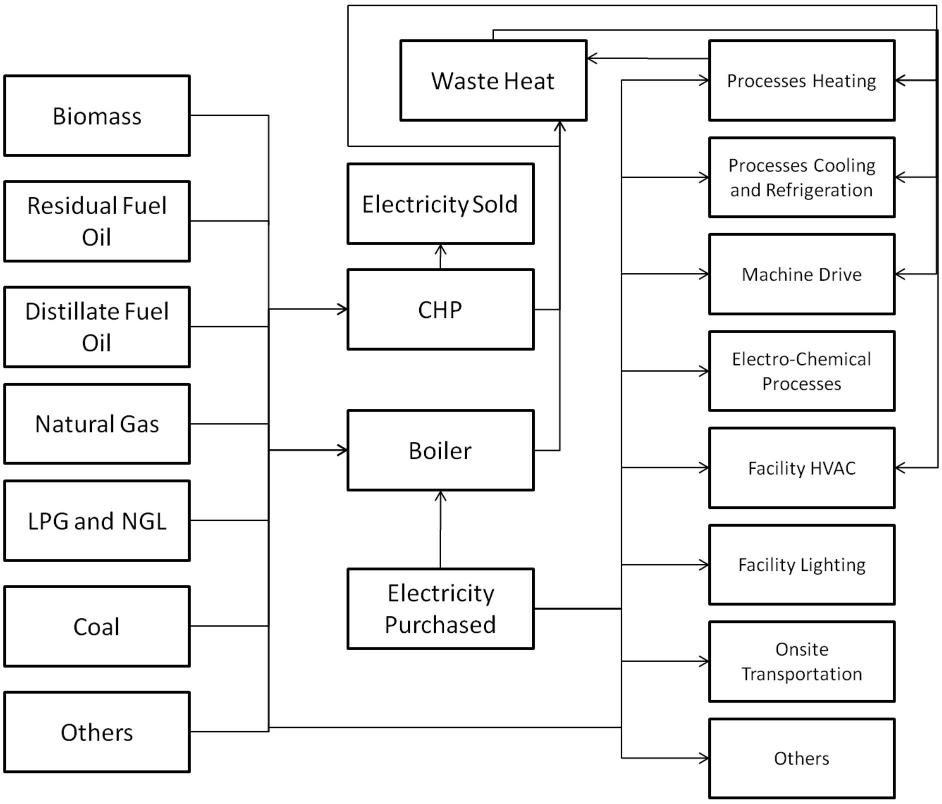


Figure 2 – Generic process and end-use energy model for manufacturing industries

The energy flow from the energy carriers to each process and end-use is explained in detail below.

3.3.3.1. Energy carriers

The data used as proxy from the US DoE [66] only distinguishes the energy carriers used in the manufacturing industry as electricity, residual fuel oil, distillate fuel oil and diesel, natural gas, Liquefied petroleum gas (LPG) and Natural Gas Liquids NGL, coal and a group of other carriers. Those carriers are the more representative in the manufacturing industry, but other carriers can also be important, as biomass, that is largely used at the pulp and paper and wood industries.

The electricity carrier can be seen in Figure 2 as the purchased electricity and the sold electricity. In order to avoid double counting, all electricity converted by systems inside the boundaries of the industries is considered sold and all electricity demanded is considered purchased.

It was used data from [66] to build proxies for the share of the energy used by each end-use and process in each subsector in the industry sector. Table 41 presents the share of each energy carrier for each process and end-use for the pulp and paper industry as an example. The heat energy carrier found in Table 41 represents the assumed share of steam from boilers and CHP (combined heat and power) and the share from the waste heat that can used by the end-uses. This share is the share from the total combustible fuels used by process heating, process cooling and refrigeration, machine drive and HVAC as assumed in [108] [109]. The share of energy use from each carrier for CHP is not considered because it is assumed that data for this process is known and is added in a later process.

Table 41 - Share of energy use for processes and end-uses in the pulp and paper industry [66]

End Use	Electricity	Residual Fuel Oil	Distillate Fuel Oil	Natural Gas	LPG and NGL	Coal	Other	Heat (Steam)
Conventional Boiler Use	1%	49%	33%	43%	0%	70%	56%	-
Process Heating	3%	42%	33%	39%	20%	16%	44%	69%
Process Cooling and Refrigeration	2%	0%	0%	1%	0%	0%	-	1%
Machine Drive	81%	3%	0%	6%	0%	9%	-	11%
Electro-Chemical Processes	2%	0%	0%	0%	0%	0%	-	-
Facility HVAC	4%	0%	0%	6%	0%	2%	-	8%
Facility Lighting	4%	0%	0%	0%	0%	0%	-	-
Onsite Transportation	0%	0%	33%	0%	40%	0%	-	-
Other	5%	5%	0%	5%	40%	2%	-	10%

3.3.3.2. Conventional boiler use and combined heat and power

Industrial boilers use a fuel source to provide heat in several temperatures and forms. The most used fuels are coal, gas (mostly natural gas), oil, and biomass. The steam provided by the boiler systems are used in the manufacturing sector to heat raw materials, to provide heat for buildings, to power equipments and to be converted into electricity. The steam can be generally classified according to a temperature quality depending to each end-use. This temperature quality may vary from 150°C to 540°C for manufacturing uses according to the US DoE [112].

Boiler efficiency depends on many factors such as operating schedules, maintenance, boiler vintage, design and fuel type [108] [109]. Table 42 presents typical efficiency values according to fuel used [108]. The efficiencies for CHP can be divided into heat efficiency and electric efficiency and typical values can round 60% for heat and 20% for electricity [45].

Table 42 – Typical industrial boiler efficiency according to fuel type [108]

Fuel	Efficiency
Oil	83%
Gas	82%
Coal	81%
Biomass	64%
Spent Liquor	65%
Electricity	100%

Most fired boilers have efficiency between 64% and 83%, resulting 17%-36% of waste energy. Some of this waste is unavoidable, but some of it can be recovered, if it is understood how the waste is generated. Due to absence information on the quality of this waste energy, this waste is considered not recovered as defined in [108] [109].

Distribution losses are also very significant for steam systems, occurring in steam traps, valves, and pipes where steam is transported throughout the industry boundaries. Steam distribution losses can vary from 15% to 40% [109] [112]. In the proposed model, it is assumed a conservative average of 20% steam loss during distribution following [109] [112].

The final energy for boilers can be retrieved using Table 41 (or the respective proxy according to the subsector), Table 42 and some energy statistic for the respective manufacturing industry for a country. For CHP, it is assumed that local statistics have data for its final energy.

Data that represent the energy use for boilers is very limited, therefore estimations on useful energy needs were not found, leading to evaluate possible improvements in the system by comparing efficiencies. Efficiencies from boiler systems are assumed as proxy based on [108], as seen in Table 42. After assuming the average energy conversion efficiency one may calculate the average useful energy needs and then apply better systems to compare energy savings. The estimations can be done using:

$$Q_u = \sum_{i=1}^{n} Q_{fi} \times \eta_{refi} [kWh \times yr] \qquad \text{eq.3.30}$$

Where:

Q_{fi}: Final energy for boilers by energy carrier i [kWh * yr]

Q_u: Useful energy [kWh * yr]

η_{refi}: Reference Efficiency for carrier i [-]

The efficiency for CHP can be assumed or calculated. Generally energy data for CHP enable the calculation of the electric and heat efficiencies by energy carrier or at least the average efficiencies for all carriers as:

$$\eta_{el} = \frac{\sum_{i=1}^{n} Q_{feli}}{Q_f} \; or \; \frac{Q_{feli}}{Q_{fi}} \; [-] \qquad \text{eq.3.31}$$

$$\eta_{heat} = \frac{\sum_{i=1}^{n} Q_{fheati}}{Q_f} \; or \; \frac{Q_{heati}}{Q_{fi}} \; [-] \qquad \text{eq.3.32}$$

Where:

η_{el}: Electric conversion efficiency [-]

η_{heat}: Heat conversion efficiency [-]

Q_{fi}: Final energy used for CHP by energy carrier i [kWh * yr]

Q_f: Final energy used for CHP [kWh * yr]

Q_{feli}: Final electric energy delivered by the CHP by energy carrier i [kWh * yr]

Q_{fel}: Final electric energy delivered by the CHP [kWh * yr]

Q_{fheati}: Final heat energy delivered by the CHP by energy carrier i [kWh * yr]

Q_{fheat}: Final heat energy delivered by the CHP [kWh * yr]

Using equations 3.31 and 3.32 it was possible to estimate the CHP efficiencies for the Portuguese industries in 2006 using the yearly balance as source for energy use [45]. Such estimations are presented in Table 43.

Table 43 - CHP efficiencies for the Portuguese industries in 2006

Type of industry	η_{heat}	η_{el}
Paper	68%	16%
Food and beverage	51%	26%
Textile	23%	39%
Chemicals, plastic and rubber	66%	22%
Ceramics	45%	34%
Glass	2%	39%
Apparel and footwear	22%	40%
Wood	35%	33%
Metal machines and electro products	5%	40%

Source: [45]

3.3.3.3. Process heating

Process heating is one of the most important and most energy consuming end-use in the industry sector. It is responsible for a variety of processes as fluid heating, distillation, drying, curing and forming, metal or nonmetal heating, heat treating, metal and nonmetal melting, calcining, smelting and agglomeration. The temperature quality for process heating varies according to each process, as from 60°C for fluid heating to more than 1600°C for metal melting. Depending on the temperature quality the energy used for process heating can come from the use of steam from boilers and CHP, fired heaters (e.g., furnaces), and several heating devices.

The wasted energy from process heating can have a large range in temperature quality. Therefore it is assumed that 30% of the total energy used by process heating is recovered to be used by other processes and by other end-uses as defined in the energy carriers section above.

Process heating is a group of many types of processes. This fact makes this group of hard simplification as done for several end-uses in the services sector or the domestic sector, therefore this group is just considered as an end-use which uses energy end provide waste heat, with no room for improvements due to efficiency measures.

3.3.3.4. Machine drive (motors), Facility Heating, Ventilation, and Air Conditioning (HVAC) and Process cooling and refrigeration

Process cooling and refrigeration and HVAC are processes where energy is used to lower the temperature of substances involved in the manufacturing process and for space cooling for storage and work spaces [113]. Examples include, lowering the temperature of chemical feedstocks to be used in reactions in the chemical industries, and freezing food to be sold by the food industry. The process cooling and HVAC consist of a refrigeration cycle, where the most common types of cooling and refrigeration systems use the reverse-Rankine vapor-compression refrigeration cycle. Those refrigeration cycles can be fueled by several energy carriers, including heat from boilers and recovered waste heat.

Motors are found in almost every process in manufacturing industries and they are responsible for converting thermal and electrical energy into mechanical energy. Therefore, when motors are found in equipment that belongs to another end-use such as process cooling and refrigeration, the energy should be classified there rather than in machine drive. The methodology proposed splits the energy used for process cooling and refrigeration, HVAC and machine drive letting who uses it to perform an individual analysis of the energy use.

However most of their energy is used by motor systems, therefore regrouping the three of them in one bigger group could facilitate some energy analysis.

Electric motors are by far the most important electric load at the manufacturing sector. Motor systems (including cooling and refrigeration) are responsible for about 69% of the electricity used in the industrial sector in the European Union (EU) [94]. Disregarding the compressors for cooling and refrigeration, motor systems can be further subdivided into pumps, fans, conveyors and other motors [94].

The useful energy use from motor system can be measured accounting the efficiency of the motors, the number of hours of use, the load factor and the electric power from the motors. In case none of the needed data is available, reference values and references shares can be used.

Table 44 and Table 45 present the average share of electricity use and the average efficiency of electric motors by range of output power for the European Union for 6 specific manufacturing industries and an average value from those 6 to be used for the others not listed [94]. The range of power output is used because greater outputs tend to have higher efficiency and almost no room from improvements, while the lower outputs can offer a better room for efficiency improvements. If an average value was used here, the potential for improvements could be even more distorted than will probably be using the average proxy values.

Table 44 – Reference share of electricity used for motor by output and type of industry [94]

Motor output, kW	non-metallic mineral	paper, pulp and print	food, beverage and tobacco	chemicals	machinery and metal	iron and steel	Average
0 < 0.75	1%	0%	3%	-	2%	-	1%
0.75 < 4	6%	3%	16%	2%	13%	4%	7%
4 < 10	6%	5%	12%	5%	16%	5%	8%
10 < 30	9%	12%	9%	6%	46%	7%	13%
30 < 70	20%	20%	34%	13%	23%	14%	20%
70 < 130	22%	19%	5%	12%	-	10%	12%
130 < 500	11%	33%	20%	30%	-	34%	23%
> 500	25%	8%	-	33%	-	26%	17%

Table 45 – Average motor efficiency by output and type of industry [94]

Motor output, kW	non-metallic mineral	paper, pulp and print	food, beverage and tobacco	chemicals	machinery and metal	iron and steel	Average
0 < 0.75	65%	65%	67%	-	57%	-	64%
0.75 < 4	67%	67%	79%	75%	77%	75%	75%
4 < 10	82%	82%	87%	85%	85%	85%	85%
10 < 30	88%	88%	91%	88%	90%	88%	89%
30 < 70	91%	91%	92%	91%	92%	91%	91%
70 < 130	92%	92%	92%	92%	-	92%	92%
130 < 500	92%	92%	93%	93%	-	93%	93%
> 500	93%	93%	-	94%	-	94%	94%

In order to find the useful energy per motor output and the opportunities for efficiency improvements, the share from electricity must be used, as the efficiency for each range. Table 44 and Table 45 can be used to further apply the following equation to obtain the useful energy by output range:

$$Q_{ur} = Q_f \times Share_r [kWh/yr] \qquad \text{eq.3.33}$$

Where:

Q_f: Final energy for motors (electricity) [kWh/yr]

$Share_r$: Share of energy use from each output range r [%]

The stock from each output power range can be estimated, for the purpose of quantifying the impact of replacing the average equipments for new more efficient ones, using the average energy use per motor and the final energy from output power range found in Table 41, Table 44 and Table 45 and [45] for the specific case of Portugal.

3.3.3.5. Electrochemical Process

Electrochemical Processes are processes where electricity is used to cause a chemical reaction. Major uses of electrochemical process occur in the aluminum industry in which alumina is reduced to molten aluminum metal and oxygen, and in the alkalies and chlorine industry, in which brine is separated into caustic soda, chlorine, and hydrogen [113].

As for process heating this group is not considered in more detail. This group will not be used for efficiency opportunities at this level, but will only be considered as a group where energy is allocated due to the specificities found in each subsector.

3.3.3.6. Facility Lighting

Facility lighting is an end-use that provides illumination for tasks and activities in the industry sector. Different from the services sector where lighting is the major electricity user, lighting in industry represented only over 8.7% of total electricity use in the industrial sector worldwide in 2005 [95].

The useful lighting needs would be represented in lumens, since the industry sector is not modeled only by its energy use. The average useful lighting needs (U_n) can be estimated from the equations below:

$$U_n = \frac{Q_f \times Effc}{FD \times h_d + h_n} [lm] \qquad \text{eq.3.34}$$

$$Effc = \sum_{i=1}^{n} Share_t \times Effc_t \, [lm/W] \qquad \text{eq.3.35}$$

Where:

Q_f: Final energy for lighting [kWh*yr]

$Effc_t$: Efficacy of the technology t [lm/W]

h_d: Hours of day use [h/yr]

h_n: Hours of night use [h/yr]

n: Number of technologies

$Share_t$: Share of the technology t in the sector [%]

FD = daylight dependency factor; factor relating the usage of the total installed lighting power to daylight availability in the room or zone; $0 \leq FD \leq 1$

The average hours of use of a lighting system can be obtained on surveys, by studies or found in international or national standards. Therefore, here is considered as proxy, the values found at EN 15193 [98] and presented in Table 46.

Table 46 - Annual operating hours in the industry sector [98]

Building types	Default annual operating hours		
	Daylight time usage [h]	Non-daylight time usage [h]	Annual operating time [h]
Manufacturing factories	2500	1500	4000

The lighting technologies or the technology of a lighting system are what defines the efficacy. The most common technologies can be found in Table 35 and their respective efficacy. The share of each lighting technology in the industry sector is an important factor defining the average efficacy. According to the U.S. DoE [99] the share of lamps was, in 2002, 2% of incandescent lamps, 93% of fluorescent and 5% of high intensity discharge lamps in the services sector. This distribution can be more complete knowing that the share of electricity used was 2% of incandescent lamps, 67% of fluorescent and 31% of high intensity discharge lamps. Based on proxy values, it was possible to estimate the energy use from lighting in each type of industry in Portugal in 2006, as presented in Table 47.

Table 47 – Energy use by type of lighting and type of industry in Portugal in 2006

Type of industry	Energy use in MWh		
	Fluorescent	HID	Incandescent
Apparel and Footwear	37,687	17,437	1,125
Cement	20,195	9,344	603
Ceramics	22,494	10,408	671
Chemicals Plastic and Rubber	87,862	40,653	2,623
Food and Beverage	80,053	37,039	2,390
Glass	16,006	7,406	478
Metal Machinery and Electro	146,406	67,740	4,370
Metals	29,816	13,795	890
Other	77,996	36,087	2,328
Paper	59,273	27,425	1,769
Textile	100,276	46,396	2,993
Wood	22,610	10,461	675

Source: [45][99]

Using the operating hours in Table 46 and the energy used in Table 47, it is possible to estimate a reference possession of lighting systems referenced by the installed capacity (MW), and use it to apply changes from energy efficiency measures.

3.3.3.7. Onsite transportation

Onsite transportation is the end-use responsible for the energy used in vehicles and transportation equipment within the boundaries of the manufacturing industry. As for process heating, this group is not considered in more detail due absence of more specific data. This group will not be used for efficiency opportunities at this level, but will only be considered as a group where energy is allocated. Table 41 can be used as a proxy to find the respective energy use from this end-use.

3.3.3.8. Others

Others are an end-use that allocates all the energy used by minor process and end-uses belonging to the manufacturing industry. Due to almost no information about this group, no detailed description is done, just an account of the energy not used by the main process and end-uses to be able to allocate all the energy used in the manufacturing industry. Table 41 can be used as a proxy to find the respective energy use from this end-use.

3.3.4. Modeling of the transport sector

Energy use in the transport sector includes the energy used in moving people and goods by road, rail, air, water, and pipelines. The road transport includes light-duty vehicles, such as automobiles, small trucks, and motorbikes, and heavy-duty vehicles, such as trucks used for moving freight and buses for passenger travel. Here, the transport sector is divided into two major groups as passenger travel and freight transport.

The increase at the economic activity and the population are the main driving factors for the increasing energy demand in the transportation sector. Economic growth encourages the increase in the industrial goods, requiring the movement of raw materials to the industry and the manufactured goods to end-users. The Economic growth is also responsible for the higher displacement of people for work and leisure.

3.3.4.1. Passenger travel

Passenger travel can be generally seen as individual road transportation, mass transportation by road, rail, water and air and non-motorized modes, as cycling and walking. According to IEA [88], the non-motorized modes account for as many as one-third of all trips, but less than 10% of the distance traveled. Individual road transportation is characterized by the most used mean of transportation, the automobile, as cars. Cars include personal light trucks and small vans. The cars can be distinguished between them according to the fuel technology, represented here by 14 technologies: diesel, gasoline, hybrid diesel, hybrid gasoline, ethanol, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, biodiesel, diesel fuel cell, gasoline fuel cell, methanol fuel cell, plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV). Mass transportation are also divided by fuel technology as buses using diesel, gasoline, hybrid diesel, methanol, LPG, CNG, hydrogen, diesel fuel cell and electric buses for road transportation, rail transportation by diesel and electricity, water transports by diesel and fuel oil and air transportation by jet fuel.

Measuring the energy use in passenger travel requires examination of components such as the characteristics of vehicles, their utilization, travel patterns and the actual energy use by mode of transportation.

To relate vehicle utilization into mobility, the distance traveled by each vehicle must be multiplied by a respective load factor representing the number of passengers or, the share occupied and the number of places offered by the vehicle. The mobility is generally measured in passenger-kilometer (p-km) or passenger-mile (p-mile). Mobility is a very important indicator for transportation, because the energy used by a vehicle can be associated to mobility, in other words, associating vehicle energy intensity to modal energy intensity, enabling comparison among different modes of transportation where their individual energy use can be several times higher than others and even though, more efficient at the mobility perspective.

Energy use per passenger-kilometer is the most important indicator of energy intensity for comparing modes of transportation [88]. Vehicle (mode) utilization and load factor explain part of the mobility differences among modes and individual fuel efficiency explains differences among technologies using same fuel and among different fuels. Fuel efficiency is still used to refer to the energy efficiency of transports because most of the transports and travels are powered by fossil fuels. Since electricity is also used at the transport sector, a more appropriate term for fuel efficiency would be energy efficiency, but this work will still use the usual nomenclature. Table 48 presents the values for the mobility of people found for Portugal in 2006.

Table 48 – Mobility of people by means of transportation and energy carrier in Portugal in 2006

Means of transportation	Energy Carrier	Mobility (p-km)
Cars	Gasoline	3.96E+10
	Diesel	1.09E+11
	LPG	6.08E+08
Bus	Diesel	9.84E+09
	Gasoline	3.54E+07
	CNG	6.85E+08
Rail	Diesel	6.35E+08
	Electricity	3.24E+09
Metro	Electricity	9.88E+08
Air	Jet	2.40E+09
Water	Diesel	5.92E+08
	Fuel Oil	1.01E+09

Source: [69,114]

All individual and mass transportation have a different load factor and this load factor can vary from region to region and according to the purpose of each travel, as urban travel or long distance travel. According to IEA [88], the European average load factor for cars was considered 1.6 persons per car. Other works have very similar values, as 1.57 persons per car for US [93], 1.58 persons per car for Portugal [115] and 1.6 persons per car for Netherlands [116]. On the other hand, mass transportation have always a higher load factor than individual transportation, considering the average load factor of buses, it may vary from 14 passengers per bus from [116] to 17 from [117], around 10 times more passengers than cars. For Portugal, the load factor found for the year of 2006 was converted to a ratio from the maximum load and presented in Table 49.

Table 49 – Load factor for passenger transportation in Portugal for 2006

Means of transportation	Load factor
Cars	32%
Truck	34%
Bus	19%
Rail	34%
Metro	19%
Air	69%

Sources:[47,69,115,118]

The fuel efficiency is the other factor of the energy intensity indicator for transports. Each mode and each fuel (energy) technology used has its own intensity. The fleet's age and energy technologies of each type of transportation mode dictate the fuel efficiency in a region. Fuel efficiency is generally measured in liters per 100 kilometers, MJ per kilometer or kilometers per liter. According to PNAC [115], the average fuel efficiency for diesel cars in Portugal was 6.9 liters per 100 km or 2.5 MJ/km in 2005 and the average fuel efficiency for diesel buses were 36.5 liters per 100 km or 13 MJ/km.

Using the fuel efficiency and the load factor, or the energy used by a mode of transportation and its mobility, it is possible to estimate the energy use per passenger-kilometer, being able to compare modes of transportation and even indicate ways to improve overall mobility efficiency. Comparing the diesel car and the diesel bus for Portugal using the information given above, it is clear that comparing actual uses, buses (0.88 MJ/p-km) are more efficient than cars (1.56 MJ/p-km) in a mobility context. Table 50 shows a range of energy intensity values according to the respective fleet end-use and fuel / technology for passenger transport found in literature and some reference values for Portugal [69] [93] [115] [116] [117] [119] [120] [121] [122] [123] [124] [125]. The values found in Table 50 must be seen with care, because they show a typical range of intensities, but values outside this range can be also acceptable since they depend on the fleet and the load factor. Countries with a more renewed fleet may have even better values, and worse values can be found if load factors are inferior to those typical ones. Actually, there is a tendency in decreasing the load factor for all means of transportation, except the air, due to higher motorization level (higher car ownership) [88].

Table 50 – Range of energy intensity values found in literature for passenger transportation and reference values for Portugal.

End-uses	Fuel / Technology	MJ/p-km		
		Min	Max	PT
Individual Transport by Road	Diesel	0.53	2.20	1.56
	Gasoline	0.53	2.20	1.83
	Hybrid Diesel	0.89	1.63	
	Hybrid Gasoline	0.59	1.63	
	Ethanol	1.20	2.20	
	LPG	1.53	2.20	1.53
	CNG	0.47	2.20	
	Hydrogen	0.50	1.06	
	Biodiesel	1.09	2.20	
	Fuel Cell Diesel	1.03	1.03	
	Fuel Cell Gasoline	1.03	1.13	
	Fuel Cell Methanol	0.93	0.93	
	PHEV	0.42	0.42	
	BEV	0.23	0.34	
Mass Transport by Road	Diesel	0.21	1.57	0.58
	Gasoline	0.78	1.16	1.56
	Hybrid Diesel	0.69	1.02	
	Methanol	1.07	1.73	
	LPG	0.67	1.03	
	CNG	0.81	2.01	1.00
	Hydrogen	0.86	1.43	
	Fuel Cell Diesel	0.84	0.84	
	Electric Motors	0.10	0.36	
Mass Transport – Rail	Diesel	0.24	1.50	0.81
	Coal	1.39	1.39	
	Electricity	0.12	0.69	0.30
Mass Transport – Metro	Electricity	0.27	0.27	0.27
Mass Transport by Water	Diesel	1.59	1.59	1.59
Mass Transport by Air	Jet Kerosene	1.55	8.78	8.78

Sources: [69] [93] [115] [116] [117] [119] [120] [121] [122] [123] [124] [125]

Modal shares are important to total energy use for travel because modal energy intensities may vary considerably among modes, since land mass transportation is in general less energy intensive than individual transportation. Because all modes do not feature the same convenience, comfort, time, or speed, comparisons of travel or trips among modes must be made with care. This is especially important for situations involving circuitry, where trips by bus or rail must incorporate detours to make connections between lines [88]. Table 50 can be used as a reference for comparisons among modes and fuel/technologies.

In order to apply energy efficiency measures, it is necessary to obtain the stock of vehicles in a country. The best way to obtain such stock is using surveys or regional statistics. In case no such information is found or it is not complete, it is possible to estimate the stock using the average mobility performed by a type of vehicle. Table 51 presents the average mobility by means of transportation in Portugal in 2006.

Table 51 – Mobility by means of transportation in Portugal in 2006

Means of transportation	p-km/vehicle
Cars	34684
Buses	703800
Metro	2409268
Trains	4264026

Sources: [47,69,115,118]

3.3.4.2. Freight transport

Freight transport can be grouped as land freight by road and rail, water freight by rivers and sea, and air freight. Land freight can be characterized by trucks and trains, where each of them can work with a variety of fuels and technologies. However, they mainly run on diesel, gasoline and electricity. Land freights are used to transport piece goods (e.g., packages) and bulk goods (e.g., oil and ore). In general trains are more suited to transport bulk goods than trucks due to its higher haulage capacity, but in the other hand, trucks are more flexible to transport and delivery goods. Water freights mainly run on diesel and fuel oil and are mostly used to transport piece goods and bulk goods, especially bulk goods due to its intrinsic high load capacity, through long and very long distances. Air freights mostly run on jet fuel and are more used to transport piece goods due their relative low weight in relation to its aggregated value.

In this work road freight is represented by diesel, gasoline, ethanol, LPG, CNG, hydrogen and electricity (BEV). Rail freight is characterized by diesel, coal and electricity. Freight by waterways is represented by diesel and fuel oil technologies. And air freight is represented by jet kerosene.

The structure of the freight subsector is made up by some elements as the stock of vehicles, the distance traveled, the characteristics of freight and its quantity, and the utilization, usually measured in tones-kilometers. Utilization is one of the main indicators composing the energy intensity, showing the weight carried and the distance moved, representing an equivalent of the mobility indicator for freights. The energy intensity also rely on the modal choice, the fuel choice and the fuel intensity, which along with utilization, serve to explain and compare freight energy use among modes and over time. The modal choice is generally related to costs, availability, length of roads, waterways and rail lines, and, getting even more important, time requirements (“just in time”). The fuel efficiency is the other factor of the energy intensity indicator for freight transports. Each mode and each fuel technology has its own intensity. As for passengers’ transportation, the fleet’s age and energy technologies of each type of transportation mode dictate the fuel efficiency in a region. Fuel efficiency is generally measured in liters per 100 kilometers, MJ per kilometer or kilometers per liter. According to ANTRAM [126], the average fuel efficiency for diesel trucks in Portugal was 38.5

liters per 100 km or 13.7 MJ/km in 2009. Table 52 presents the utilization values found for Portugal in 2006.

Table 52 – Utilization by freight mode and energy carrier for Portugal in 2006

Freight mode	Energy carrier	utilization (t-km)
Truck	Diesel	4.38E+10
	Gasoline	6.58E+08
	LPG	4.99E+07
	CNG	8.37E+04
	Fuel oil	3.38E+08
Rail	Diesel	9.01E+08
	Electricity	1.53E+09
Water	Diesel	6.78E+09
	Fuel Oil	1.15E+10
Air	Jet	1.33E+04

Source: [69,114][126]

Freight transport, as passenger transport, can also use a load factor to represent the average weight of freight moved, although, this value can be very easy to find for trucks, but very hard to find a general value for trains and boats due to their characteristics as tons offered per wagon for trains. Therefore it is more common to apply the energy used by each freight mode (and by fuel) and its respective utilization to calculate the energy intensity of each mode. For Portugal, a reference load factor of 50% of the offered load was found for trucks and for rails [47,69,115,118] [126].

Table 53 presents a range of energy intensity values according to the respective fleet end-use and fuel / technology found in literature for freight transports and some reference values for Portugal [115][69][45][126][116][124][93][127][125]. The values found in Table 53, as the ones found in Table 50, must be seen with care, they show a typical range of intensities, but values outside this range can be also acceptable. Based on IEA [88], three factors seems to have a large impact on the energy intensity for freights, the 1) stock of vehicles, accounting utilization and respective fuel intensity; 2) regulatory conditions that can vary from country to country and region to region, affecting modal mix and modal energy intensity, as the restriction to heavy trucks inside the São Paulo municipal area [128], which increased the number of less efficient light trucks; and 3) traffic conditions.

Table 53 - Range of energy intensity values found in literature for freight transportation and reference values for Portugal

End-uses	Fuel / Technology	MJ/t-km Min	 Max	 PT
Freight Transport by Road	Diesel	1.25	3.79	1.25
	Gasoline	1.83	1.83	1.83
	Ethanol (E85)	1.67	1.67	
	LPG	1.84	1.84	1.84
	CNG	1.90	1.90	1.90
	Hydrogen	-	-	
	Electricity	0.44	0.44	
Freight Transport by Rail	Diesel	0.22	0.87	0.56
	Coal	1.62	1.62	
	Electricity	0.11	0.87	0.47
Freight Transport by Water	Diesel	0.14	0.14	0.14
	Fuel Oil	0.14	0.14	0.14
Freight Transport by Air	Jet Kerosene	14.39	62.73	62.73

Source: [115][69][45][126][116][124][93][127][125]

In order to apply energy efficiency measures, it is necessary to obtain the stock of vehicles used to transport goods in a country. The best way to obtain such stock is using surveys or regional statistics. In case no such information is found or it is not complete, it is possible to estimate the stock using the average utilization performed by the type of vehicle. The average utilization for trucks in Portugal in 2006 was 660066 t-km per truck and for trains it was 5388027 t-km per train. No such data was found for water and air transportation.

3.4. Developing a reference time-evolution

Energy efficiency plans are, in general, designed to guide or expected to achieve energy savings in the future. This future may vary from small periods to a considerable future like 20 years from the start of the plan. In Europe, the ESD determines that each plan should present measures that are able to reduce an equivalent of 9% of the final energy expected in the ninth year of the application of the plan [5]. Such target is very specific. However, the fact that it is estimated in relation to a projection of the energy use of a country is transversal to many plans. Since there is a need to project the energy use in the future, here is specified a simple and transparent way to perform those projections.

When comparing the savings alternatives, each of them should be compared first with the reference energy system, or to the reference energy system trend (also known as business as usual or baseline trend). The reference energy system is the original system over which any savings from some efficiency improvements will be assessed.

In the case of a complex system, the reference system is generally considered as a trend. This trend can be a market trend, such as in the case of the stock of fridges used by the household sector due to new acquisitions [129]. Another possibility is to define a historic energy use (average or not) and use this historical data to project the future [130]. Therefore, here is proposed to use two methods to make the projections: the frozen efficiency method and the vintage stock method. The availability of data and the fact that the ESD [5] “supports” the use from the frozen efficiency method were also taken into consideration to choose the methods.

The frozen technology or frozen efficiency method is referred to as frozen efficiency because the energy efficiency is frozen at the level of the base year (first year before the projections) while the demand drivers are evolving according to a trend. In such a method, the realized energy savings are savings obtained by the difference between the energy needs using the frozen efficiency values and the needs using the values expected from the energy efficiency measures. This method is more often used in models with low aggregation level, and generally demands a detailed description of the total energy system, where every technology has its place.

The vintage stock method is used to estimate the future energy needs of a stock of goods (e.g., fridges, motors, cars and buildings) under natural market trends and under the effect of policy options. Vintage stock models divide the total stock of goods into groups, or vintages, based on their year of sale [129]. Each vintage of goods demands energy according to the technology, the usage pattern, and/or the ownership. Generally, each vintage energy demand is calculated according to an average energy demand of all similar goods of each vintage. For each year projected in the future, a rate of retirement is applied to all goods and new goods are added as new vintages according to the expected ownership. The total energy demand in a determined year is calculated according to the total stock of goods present in that year. Policies can be applied to build alternative futures, their effects can be modeled as different ownerships, usages and technologies than the ones from natural market trends (e.g., increasing the selling of A++ fridges by financial incentives). In opposition to the frozen technology method, the vintage method accomplishes for the natural market trends, therefore giving a more reliable comparison between a future with no intervention and a future with energy efficiency policies and measures.

From the methods to determine energy savings, the most appropriated to use is the vintage stock model, because it reflects with more precision the real situation from the energy system and can easily quantify technological and behavioral measures. The problem with this method is the data required. According to Boonekamp [131], reliable data to disaggregate energy use to the lowest aggregation level and to find appropriate variables to construct reference demand trends are generally difficult to obtain. Therefore, the use of each method is adapted to the available data.

The methods are adapted to data available and the specificities found in each sector as detailed in the next sections.

3.4.1. Projections at the domestic sector

The energy used in this sector can be basically quantified by the energy used by the specific end-uses, the ownership of these end-uses by the households and the total number of households (specified in section 3.3.1). Considering the ownership and the number of households and the size of a household as the main demand drivers, frozen efficiency method can be applied to build a future for the energy use. Such application can be estimated using the generic equation presented:

$$Q_{fend-use} = Q_{fi} \times \mathrm{Own_{iy}} \times \mathrm{hh_y} \qquad \text{eq.3.36}$$

Where:

$Q_{fend-use}$: Total final energy use by a specific end-use for a specific year [kWh]

Q_{fi}: Final (frozen) energy use from technology i or energy carrier i from a specific end-use [kWh/hh]

$\mathrm{Own_{iy}}$: Ownership of the technology i or energy carrier i for the year y [-]

$\mathrm{hh_y}$: Number of households in year y [hh]

When data is available, the ownership can be described as an S-shaped curve, since growth in appliance ownership tends to follow such behavior [129]. For such cases the ownership can be modeled using a Gompertz curve (equation 3.37).

$$\mathrm{Own_{iy}} = \mathrm{Se^{-ae^{-b(y-h0)}}} \qquad \text{eq.3.37}$$

Where:

S: Saturation of ownership at last year of projection

a and b: Variables that should be fitted according to data

y: Desired projection year

h0: Initial year of data of introduction of the product in the market

In case data is not available, two options may be used, assumed ownership as frozen also, or find a possible proxy to associate ownership, as energy use.

For the specific case of Portugal, the Gompertz curve was applied to clothes drying, freezers, washing machines, dish washers, TVs, audio systems, desktops, laptops and TV Receivers due to available data and a fit superior to 0.9 when performing the regression for the respective Gompertz curve. Table 54 presents the respective ownership along the years.

Table 54 – Projected ownerships from Gompertz curve for domestic appliances for Portugal

Year	Ownership								
	Clothes drying	Freezers	Washing machines	Dish washer	TV	Audio	desktop	laptop	TV Receiver
2007	20%	62%	94%	38%	100%	90%	51%	54%	52%
2008	21%	63%	95%	40%	100%	90%	54%	59%	57%
2009	22%	64%	96%	42%	100%	90%	58%	65%	62%
2010	23%	64%	96%	45%	101%	90%	61%	70%	66%
2011	24%	65%	97%	47%	101%	91%	64%	76%	70%
2012	25%	66%	97%	49%	101%	91%	67%	82%	75%
2013	25%	66%	98%	51%	102%	91%	70%	88%	78%
2014	26%	67%	98%	53%	102%	91%	72%	94%	82%
2015	26%	67%	98%	54%	102%	91%	75%	100%	86%
2016	27%	68%	98%	56%	103%	91%	77%	106%	89%

Source: [69]

The future ownerships of the technologies responsible for ambient heating, domestic hot water, hobs and ovens fuelled by LPG and natural gas were based on a linear regression of the calculated equivalent ownership using a frozen technology (based on values from 2006) and the energy use from 2000 to 2006, since there is a trend in leaving LPG and another increasing the use from natural gas. Both trends on the energy use in the sector for LPG and natural gas had a correlation of 0.94 using the year from 2000 to 2006 and data from [45]. The Ownership from solar domestic hot water was based on a linear regression using data from 2006 to 2008 [79]. This linear regression had a correlation of 0.95. The ownership trend for lighting fuelled by oil was assumed as a decrease of 15% per year as observed at the energy use from 2005 to 2006. This was considered a safe assumption, compared to a much higher decreasing trend between 2000 and 2005. The ownership of fridges and lighting systems are assumed constant due to a present “saturated” value for the base year. For the other technologies the values for ownership were maintained the same through the years.

3.4.2. Projections at the services sector

The energy used in this sector can be basically quantified by the energy used by the specific end-uses, the ownership of these end-uses by the sector and the total size of the sector (specified in section 3.3.2). Depending on the energy end-use, different factors may better represent the ownership from the sector. For more structural end-uses as ambient heating and cooling, hot water, lighting, other uses and some technologies of refrigeration the most fitted physical factor that would better represent ownership is the area, or the share of the total service’s area. For office equipment and cooking, the factor that better represents size is the number of employees, or the share of employees in the sector with access to those uses. Motors and mostly of the refrigeration are represented by the number of equipments due to the availability of data. Finally, for public lighting the ownership is measured in MW of lighting installed. This was a solution due to lack of data availability and no or small relation to other factors from the sector.

Considering the number of employees, the area and the Gross Added Value (GAV) from the sector as the main demand drivers, the frozen technology method was applied to build future energy uses in line to what was done for the domestic sector. Equations 3.38 and 3.39 generalize the processes to estimate the future energy use.

$$Q_{fend-use-y} = Q_{fi} \times \mathrm{Own_{iy}} \times \mathrm{driver_y} \tag{eq.3.38}$$

Where:

$Q_{fend-use-y}$: Total final energy use by a specific end-use for a year y [kWh]

Q_{fi}: Final (frozen) energy use from technology i or energy carrier i from a specific end-use [kWh/driver]

$\mathrm{Own_{iy}}$: Ownership of the technology i or energy carrier i for the year y [-]

$\mathrm{driver_y}$: Associated driver value in year y (e.g. area, employees)

Equation 3.38 is better fitted for end-uses where the ownership can be assumed constant in relation to the physical driver. For Portugal, the case study, this was used for all end-uses described in section 3.3.2, but for commercial refrigeration, motors and public lighting. The application of equation 3.38 is illustrated using lighting as an example.

Due the absence of data for the size of the services sector in Portugal, it was necessary to project the area of the sector in function of a known driver, the GAV. The number of employees in the sector were also associated to the GAV in order to harmonize the main driver of the sector, and also to a more conservative projection obtained from such association in comparison to the direct projection from the employees based on in the years and the respective number of employees. For the regression for the employees it was used data from employees and GAV from the sector from 1998 to 2006. For the regression for the area it was used the only available year that was 2006. For the regression for the GAV it was used data from the GAV from the sector from 1998 to 2006. Table 55 presents the results from the regressions.

Table 55 - Regressions for demand drivers in the service sector

	Function fit		
Linear functions	**Slope**	**Intercept**	**R2**
Employees (million) in function of GAV (M€)	12.1508	1871285	0.9925
Area (million) in function of GAV (M€)	0.0012	0	-
GAV (M€) in function of year	225.3200	-432531	0.9502

Source: [69,82]

Considering the final energy use for services' lighting in Portugal in 2006 estimated in 25 kWh/m^2*yr (calculations performed based on section 3.3.2.5), the ownership of 74% of the total area (Table 35) and a total projected area for the Portuguese services sector as 184 million m^2 in 2016, it is possible to apply equation 3.38 an obtain the projected final energy use in 2016 for fluorescent lighting in the sector as 3.4 TWh.

In some cases, ownerships are not directly associated to the energy drivers, such as for motors, where the ownership is estimated in the equivalent stock of motors. For these cases, the variation on the driver must be reflected in the future ownership in order to estimate the future stock of equipments and the future final energy use. Table 56 presents the linear functions associating the stock of the equipments used for refrigeration, the stock of motors to and the stock of public lighting to the GAV of the sector for Portugal. Due the absence of data, the ownership found for the base year (section 3.3.2) was used to relate de number of equipments to the GAV from the same year and make the projections. The same procedure was applied to the public lighting ownership. However, it was found data for final energy use from public lighting from 2000 to 2006 [45], which were used to associate the ownership to the GAV. It is possible to still apply equation 3.38 to find the final energy use for these cases. However, the driver influence should be removed since the new ownership reflects its influence.

Table 56 - Linear regressions for refrigeration, motors and public lighting in function of GAV (M€)

End-use / end-use technology	Slope	Intercept	R2
Beverage Merchandisers (units)	0.1206	0	-
Ice Machines (units)	0.1183	0	-
Reach-In Freezers (units)	0.3967	0	-
Reach-In Refrigerators (units)	0.4566	0	-
Refrigerated Vending Machines (units)	0.4041	0	-
Walk-Ins (units)	0.0720	0	-
Motors >500 kW (units)	0.0006	0	-
Motors 0 <0.75 kW (units)	2.1673	0	-
Motors 0.75<4 kW (units)	4.3484	0	-
Motors 10<30 kW (units)	0.4993	0	-
Motors 130<500 kW (units)	0.0032	0	-
Motors 30<70 kW (units)	0.0415	0	-
Motors 4<10 kW (units)	1.4129	0	-
Motors 70<130 kW (units)	0.0131	0	-
Public lighting (MW)	0.0042	-57.8407	0.9631

3.4.3. Projections at the Industry sector

The energy used in the industry sector is quantified by the energy used by the main end-uses that characterize the sector. This energy use is a translation of the ownership of these end-uses (estimated here in installed power (MW), with the exception of motors that were estimated by number of equipments found in the sector) and the average operating hours per year. This generic approach for the ownership was a solution found to harmonize the estimation of the ownership of equipments in the sector and due to the common lack of data characterizing the industry sector over the world.

Considering the Gross Added Value (GAV) from the sector as the main demand driver, the frozen technology method can be applied to build future energy uses in line to what was done for the domestic and the services sectors. The final energy use and the respective ownership at the projected year can be estimated using equation 3.39. For the specific case of motors, where the ownership was defined using the stock of motors, the equation 3.40 must be used instead to find projected ownership and final energy use.

$$Q_{fend-use-y} = \mathrm{h} \times \mathrm{Own_{ib}} \times \Delta\mathrm{driver_y}\ [\mathrm{kWh}] \qquad \text{eq.3.39}$$

$$Q_{fend-use-y} = Q_{fi} \times \mathrm{Own_{ib}} \times \Delta\mathrm{driver_y} [\mathrm{kWh}] \qquad \text{eq.3.40}$$

Where:

$Q_{fend-use-y}$: Total final energy use by a specific end-use for a year y [kWh]

h: Average operating hours for the sector or subsector [h]

Q_{fi}: Final (frozen) energy use from technology i or energy carrier i from a specific end-use [kWh]

$\mathrm{Own_{ib}}$: Ownership of the technology i or energy carrier i for the base year b

$\Delta\mathrm{driver_y}$: Variation of the demand driver at year y in relation to its value in the base year

The trend behind the GAV for industry in Portugal was based in a linear regression from the values from the sector between 1998 and 2006 from INE [69]. The correlation from such regression was 0.95 confirming the trend observed. From the trend it was possible to define general energy growths of 1.63% per year from 2006 to 2010 and 1.06% from 2011 and 2020.

3.4.4. Projections at the transports sector

The transports sector uses energy to provide mobility of people and goods. This mobility can be divided by several types of end-uses (section 3.3.4). The energy use for the sector can be obtained by the combination of the displacement of people or goods by the fleet (estimated in people-km or ton-km) and energy intensity of the vehicles (section 3.3.4). Consequently, if estimation on the future displacement is defined and the actual energy intensity is used, following the frozen efficiency method, the projected energy use and ownership of the vehicles can be estimated.

$$Q_{fi-y} = \mathrm{EI_{ib}} \times \mathrm{D_{ib}} \times \Delta\mathrm{D_{iyb}} \qquad \text{eq.3.41}$$

$$\mathrm{Own_{iy}} = \frac{Q_{fi-y}}{\mathrm{DV_{ib}}} \qquad \text{eq.3.42}$$

Where:

Q_{fi-y}: Total final energy use by a specific end-use technology or energy carrier for a year y [kWh]

$\mathrm{EI_{ib}}$: Energy intensity of the technology or energy carrier I at the base year b [kWh/p-km or kWh/t-km]

$\mathrm{D_{ib}}$: Displacement or mobility related to the technology or energy carrier I at the base year b [p-km or t-km]

$\Delta\mathrm{D_{iyb}}$: Variation of the displacement related to technology I between base year b and year y

$\mathrm{Own_{iy}}$: Stock of vehicles from technology I at year y

$\mathrm{DV_{ib}}$: Average displacement or mobility of a vehicle of technology I at the base year b [p-km/vehicle or t-km/vehicle]

Data for the projections of the mobility of people and goods for each end-use proposed in section 3.3.4 can be found for Europe in [118] until the year of 2030. This source was used for the projections made to the transportation sector for Portugal.

3.4.5. Projections at the other sectors

The other sectors are not characterized by end-uses, but by their main energy carriers and are present at the research to account all the final energy used. Therefore, they can use the same evolution approach used for the industry sector where, for the reference evolution, the energy demand is indexed to the variation to the projected GAV. Equation 3.40 can be used for such purpose.

4. Identifying energy efficiency measures

Energy efficiency measures are the basis of an energy efficiency plan, since a plan, in the perspective of this research and in line with the ESD [5], is a group of energy efficiency measures that applied together are able to fulfill the desires of the decision makers involved and respect restrictions, such as total energy savings targets [6].

The Efficiency Valuation Organization (EVO) [132] defines energy conservation measure (ECM) as an activity or set of activities designed to increase the energy efficiency of a facility, system or piece of equipment, and it may also conserve energy without changing efficiency. An ECM may involve physical changes to equipments, revisions to operating and maintenance procedures, software changes, or new means of training and education. An ECM may be applied as a retrofit to an existing system or facility, or as a modification to a design before construction of a new system or facility. In this research, due to its intangibility, generally the measures of purely behavioral nature were not considered - with the exception of modal shift in the transports sector.

One of the objectives of this research is to build and compare energy efficiency plans in order to find the most fitted ones to a country respecting the involved decision maker's preference. To make such process operational, it is necessary to: 1) to indentify the measures that can potentially be used in plans; 2) organize the measures in a way that final energy savings and the attributes identified in chapter 2 from plans can be estimated; and 3) Obtain the data needed to inputs into the equations of chapter 3 and actually estimate the final energy savings.

In order to obtain a reasonable list of EE measures, the methodology applied in section 3.3 to map the energy system was reviewed under the perspective of the "value-focused thinking" [39], therefore not just collecting measures from the bibliography, but also trying to identify new energy opportunities of efficiency measures. Following the principle that end-uses are the natural level to apply EE measures [26], it was observed that all end-uses defined in section 3.3 are subjects of potential EE measures, or more specifically, each technology representing an end-use would represent a potential EE measure. The main advantage of this approach is the fact that it would automatically make the EE measures operational for further evaluations, since it was based on a methodology to characterize the energy system which estimates its final energy use and the respective penetration of the end-use equipments.

With the intention of estimating the physical changes and the respective final energy savings, the EE measures were specified according to the sector and subsector that they are inserted, according to the end-use, the technology and the energy carrier that they represent and intend to replace or to improve (the end-uses, technologies and carriers to be affected by the measures are represented by “target”), the respective new efficiency to apply and the size of the measure. Table 57 presents some measures to exemplify the specifications.

Table 57 presents several EE measures for the domestic, industry, services and transports sector, and how they can be specified and used. The cells referring to the efficiency are the respective efficiency of the new equipment that will be introduced. The values for the efficiencies are filled in accordance to how efficiency is associated with the respective end-use (section 3). Those values can represent the efficiency ratio between the final and the useful energy, such as for the air source heating pumps. They can also represent the lowest final energy use for the most efficient equipment (kWh/yr), such as for the refrigerators. And they can also represent the energy intensity of a technology, such as for the mobility energy intensity for cars running on ethanol (kWh/p-km). The measure size represents how much of a measure can be applied, depending on the units behind the ownership of each end-use (section 3). For example, for equipments such as motors at the services and industry sector, air conditioners and lamps at the domestic sector, and car at the transports sector, the measure size is measured in units of equipments. For boilers and public lighting, the measure size is measured in MW installed. And for the modal shift related measures, it is measured in p-km or t-km.

Table 57 - Specifications of the proposed energy efficiency measures

Sector	Subsector	End-Use	Target End-Use	Technology	Target Technology	Energy Carrier	Target Energy Carrier	Energy Carrier2	Target Energy Carrier2	Efficiency	Efficiency2	Measure Size
Domestic	All Households	Ambient Cooling	Ambient Cooling	Air conditioning	Average	Electricity	Electricity	-	-	4	0	
Domestic	All Households	Ambient Heating	Ambient Heating	Air source heat pump	Average	Electricity	Natural Gas	-	-	4	0	
Domestic	All Households	Domestic Hot Water	Domestic Hot Water	Solar Hot Water + Electric bkp	Average	Solar	Electricity	Electricity	-	1	0.95	
Domestic	All Households	Lighting	Lighting	LED	Halogen	Electricity	Electricity	-	-	46*	0	
Domestic	All Households	Refrigeration	Refrigeration	Refrigerators	Average	Electricity	Electricity	-	-	272**	0	
Industry	Apparel and Footwear	Boiler Use	Boiler Use	Average	Average	Natural Gas	Fuel Oil	-	-	0.82	0	
Industry	Apparel and Footwear	CHP	Boiler Use	Average	Average	Biomass	Diesel	Electricity	-	0.54	0.26	
Industry	Apparel and Footwear	Lighting	Lighting	HID	Fluorescent	Electricity	Electricity	-	-	119*	0	
Industry	Apparel and Footwear	Motors	Motors	10 < 30 kW	10 < 30 kW	Electricity	Electricity	-	-	0.92	0	
Services	All Services	Ambient Cooling	Ambient Cooling	Air source heat pump	Average	Electricity	Electricity	-	-	3.3	0	
Services	All Services	Commercial Refrigeration	Commercial Refrigeration	Reach-In Refrigerators	Reach-In Refrigerators	Electricity	Electricity	-	-	1262**	0	
Services	All Services	Hot Water	Hot Water	Biomass storage water heaters	Average	Biomass	Electricity	-	-	0.6	0	
Services	All Services	Public Lighting	Public Lighting	HID	Mercury Vapor	Electricity	Electricity	-	-	39*	0	
Transports	Freight	Rail	Truck	Average	Average	Electricity	Diesel	-	Biodiesel	0.13***	0	
Transports	Passengers	Bus	Bus	CNG	Average	Natural Gas	Diesel	-	Biodiesel	0.17****	0	
Transports	Passengers	Bus	Cars	Average	Average	Gasoline	Diesel	-	-	0.32****	0	
Transports	Passengers	Cars	Cars	BEV	Average	Electricity	Diesel	-	-	0.08****	0	
Transports	Passengers	Cars	Cars	Ethanol	Average	Ethanol	Gasoline	-	-	0.33****	0	

Efficiency is also indirectly expressed in: *lm/W; **kWh/yr for most efficient technology available; ***kWh/t-km; ****kWh/p-km (as explained in chapter 3)

Using the energy system description from section 3 and considering that all technologies currently in use for each end-use described can be replaced for another available technology, it was considered that each replacement represents a technical-based energy efficiency measure. Besides the technological change, in the transportation sector it is also possible to perform modal shift. Accounting the technical-based measures and the modal shift ones, it was possible to find 1598 quantifiable EE measures that can be used for energy efficiency plans (presented at the annexed excel file “measures.xlsx”).

In order to verify if the proposed measures reflect the most common used energy efficiency measures, the EE measures found at the “National Residential Efficiency Measures Database” from NREL [49] were compared to those found at the research. All the measures in their database that were related to physical changes on the system and could be represented by the end-uses found in section 3 had an equivalent measure among the 1598 measures found. It was not possible to find a list of physical measures for the other sectors. However, observing the EE plans applied in Europe, it was possible to find similar descriptions of EE measures to those found here for the services, industry and transports sectors.

With the EE measures identified and operational according to the methodology proposed on section 3.3, it is necessary to formalize the estimations of the final energy savings from the application of the measures. The next section is dedicated to this subject.

4.1. Calculating final energy savings resulting from measures

Energy savings mean energy not used when comparing options. Those options either: 1) coexist, and can be physically measured and can be compared; 2) cannot coexist, but can be physically measured and also can be compared; 3) or cannot coexist, but can be estimated and then be compared [131,132]. The first and the second ones are applied to straightforward energy use processes, where savings are calculated from improvements of the ratio between physically measured outputs and inputs, such as changing an incandescent lamp for a CFL. Both processes are based on measuring past performances (ex-post) and can only be used to verify if energy savings actually occurred. The third process is generally related to situations which energy savings cannot be physically measured (i.e., in a very large system, like an industry or a city) or when the results from energy savings are to be estimated before the occurrence of the event (ex-ante). Figure 3 presents a graphical representation of the ex-ante process considering a hypothetical BAU energy evolution compared to a hypothetical projection with the expected results from an EE plan. Therefore, energy savings, according to [129,130], are the difference between the both projections, reflection the EE measures applied.

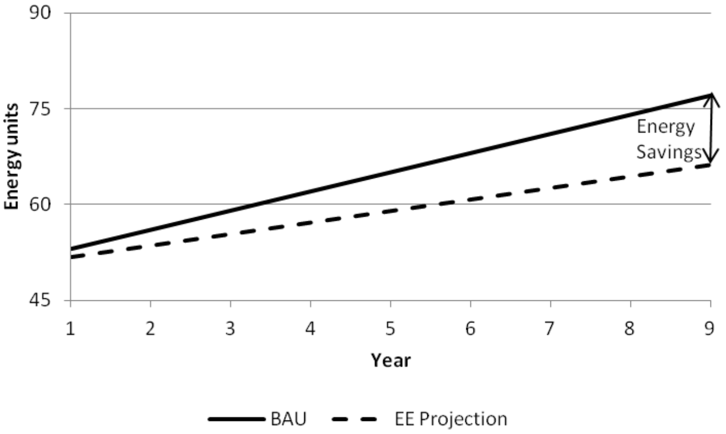


Figure 3 – Graphical demonstration of projected energy savings

Another important issue is the quantification and communication of the percent savings (e.g., target). According to Boonekamp [129] and the International Performance Measurement and Verification Protocol (IPMVP) [132], a protocol referred by the ESD to be used as guideline for the measurement and verification of the results from the NEEAPs, targets should be assigned in relation to the BAU evolution, as exemplified in Figure 3. However the approach suggested at the ESD (vide equation 1.1), calculates the percent value having in the denominator a baseline value previous to the first application year of the plan, and not to the actual last projected year as formalized in equation 4.1. Since the percent target estimated by equation 4.1 is more transparent and really reflects the proportional savings, this is the approach used in this research.

$$Energy\ savings\ (\%) = \frac{BAU\ trend(y)\ -\ Efficiency\ projection(y)}{BAU\ trend\ (\mathrm{y})} \times 100 \qquad \text{eq.4.1}$$

Where:

BAU trend: Is the Business as usual energy use trend for year y [energy unit]

Efficiency projection: Is the energy use projection considering EE measures for year y [energy unit]

y: is the year in the future

Boonekamp [131] divided the determination of the energy savings in three evaluation levels according to how straightforward are the relations between the inputs and the outputs of the systems, and nature (also size) of the systems. These are:

1) The micro-level, which is represented by stand-alone energy-using systems, where savings can be easily defined to straightforward relations between energy inputs and achievements. For example, if a motor-pump system that uses a throttle to decrease its

water flux is replaced for a less powerful motor-pump system, which does not need the throttle to provide the same water flux, the savings will be equal to the decrease in electricity used.

2) The meso-level energy-using systems, which are composed of a (large) number of 'micro' systems. For instance, the industry system encompasses not only motor-pump systems, but lighting devices, boilers and other equipments and machinery, but also how those systems are used (operational processes). Total energy savings at meso-level are not only the result of straightforward relations mentioned, but is also influenced by other factors of influence as well, such as changing operational schedules.

3) The macro-level systems are systems of an abstract nature, such as the industry sector or the services sector. In that case achievements can be easier defined in non-material quantities, such as value added for services, but also by the aggregating of meso-level savings that match. Total energy needs at this level are also influenced by various structure-effects, as sub-sector shifts or modal shifts, but mostly by growth in activities. Therefore, using the approaches proposed by Boonekamp to quantify energy savings, it is proposed to use the meso-level approach, where the micro influences of each physical based EE measure can be added to estimate the total final energy savings.

Quantification is an essential component of any compliance process, and it plays a key role in helping to determine whether something will meet or have met its goals. It is also important to evaluate and compare alternatives. Quantification can be done at three time frames: i) before the decision and implementation processes (ex-ante); ii) during the processes; and iii) after to evaluate the results (ex-post). Ex-ante analysis of energy efficiency options can help to ensure that the most appropriate measures are selected and observe future alternative scenarios. The evaluation during the implementation process allows decision makers to address problems along the way and update measures to meet new or unpredicted situations. The ex-post quantification allows an assessment of whether a measure has achieved its intended objectives or not, how and why, and thus can enhance learning from the effectiveness of the methodologies and the measures applied. Also quantification is essential for verifying tradable units of energy conservation, such as greenhouse gas emissions and costs. Since the main objective of this research in to support the decision process when building and selecting energy efficiency plans, all the quantification of the final energy savings and the objectives proposed by the decision makers are performed ex-ante to make the decision process operational.

In order to enable the quantification, or the estimation, of the final energy savings from the application of EE measures, the measures were divided into 5 major groups of application where they share whole or part of the estimation method. The calculations are described in the next subsections.

4.1.1. Thermal insulation

Thermal insulation measures are measures related to the improvement of the thermal insulation of a house. This measure is only applied to the domestic sector due to the possibility to model the sector with such detail. It relates improvements on the insulation of walls and the possibility to change windows. The first approach to apply such measures is to estimate the new thermal balance as the consequence of the application of the EE measure in one house. The thermal balances is calculated as follows and based on the Portuguese RCCTE [75].

$$Q_i = q_i \times HDM \times A_h \times 0.72 \,[kWh] \qquad \text{eq.4.2}$$

$$Q_v = 0.024 \times \left(0.34 \times R_{ph} \times A_h \times h_c\right) \times HDD \times (1 - \eta_v) \ [kWh] \qquad \text{eq.4.3}$$

$$Q_{ext} = 0.024 \times (U_{wall} \times A_{wall} + U_{window} \times A_{window}) \times HDD \ [kWh] \qquad \text{eq.4.4}$$

$$Q_u = Q_v + Q_{ext} - Q_i - Q_s \,[kWh] \qquad \text{eq.4.5}$$

Where:

Q_i: Internal gains [kWh]

Q_v: Ventilation losses [kWh]

Q_{ext}: Heat losses through the external envelope [kWh]

Q_u: Heating needs (useful energy) [kWh]

q_i: desnity of internal gains [W/m^2]

HDM: heating duration [months]A_h: heated floor area [m^2]

R_{ph}: Air renovation per hour [-]

h_c : ceiling height [m]

HDD: Heating degree day [days]

η_v: vetilation heat recovery efficiency [-]

U: heat transmission coefficient [W/m2 °C]

A_{wall}: wall area [m^2]

A_{window}: window area [m^2]

Q_s: solar gains [kWh]

Using the results from equation 4.5 it is possible to estimate the final energy use after the implementation of a measure to one house:

$$Q_{fmeasure} = \frac{Q_u \times A_{hf}}{\eta} [kWh] \qquad \text{eq.4.6}$$

Where:

η: Efficiency from the system [-]

A_{hf}: Area heating factor [-] (vide section 3.3.1.2)

Finally, the final energy savings can be estimated by finding the difference between the energy used with and without the measure, and multiplying it by the amount of households affected, as presented in equation 4.7:

$$Q_{fsavings} = \left(Q_f - Q_{fmeasure}\right) \times \, measureSize \ [kWh] \qquad \text{eq.4.7}$$

Where:

measureSize: number of households affected by the measure [hh]

Q_f: Original final energy use per household [kWh] (This can be calculated using equation 4.4 or as defined in section 3.3.1.2)

4.1.2. Lighting

The measures in lighting are related to improvements in lighting systems at the domestic, industry and services sector. In order to estimate final energy savings from the applications of such measures, it is necessary to subdivide the group into two subgroups. The lighting measures related to the domestic and services sector, and the lighting measures related to the industry sector and public lighting. This differentiation must be done because of the way how the ownership of the equipments was modeled in section 3. Since the ownership for the lighting is measured in relation to power installed for the industry sector and for the public lighting, it was required a different approach to estimate the final energy savings for the two groups. The final energy savings for lighting systems improvements at the services and domestic sector can be estimated using equations 4.8 and 4.9.

First it is necessary to estimate the final energy use for the new lighting system corresponding to the EE.

$$Q_{fmeasure} = \frac{Q_u \times h}{\eta} [Wh] \qquad \text{eq.4.8}$$

Where:

Q_u: useful energy needs [lm]

h: hours of use per year [h]

η: system efficacy [lm/W]

Knowing the final energy use from the new system, it is possible to find the difference between the old system and the new, and multiply this by the number of systems affected by the measure. For that, equation 4.7 can be used, with a difference that the measure size is defined by the number of lighting systems affected by the measure, or the referenced area affected by the measure.

To estimate the final energy savings for the lighting systems at the industry sector and for the public lighting, first it is necessary to calculate the equivalent installed capacity that will be replaced by new and more efficient lighting system. Equation 4.9 formalizes this calculation.

$$Own_{equiv} = \frac{Own_{new} \times \eta_{new}}{\eta_{old}} [MW] \qquad \text{eq.4.9}$$

Where:

Own_{new}: Ownership of the new technology [MW]

η_{new}: light efficacy of the new system [lm/W]

η_{old}: light efficacy of the old system [lm/W]

Finally, the final energy savings can be estimated as presented by the equation 4.10:

$$Q_{fsavings} = (Own_{equiv} - Own_{new}) \times h \qquad \text{eq.4.10}$$

Where

Own_{new}: Ownership of the new technology [MW]

Own_{equiv}: Equation 4.9 [MW]

h: hours of use in a year [h]

4.1.3. Output-input ratio

The EE measures attributed to the output- input ratio group are those for which the efficiency of the technology behind the measure is expressed by a ratio, or a coefficient, representing the conversion from the (input) final energy into the (output) useful energy or needs. Examples of such technologies are ambient heating systems, water heating systems, motors and vehicles in general.

The first step to estimate the final energy savings is to find the final energy use for the new system corresponding to the EE, as presented by equation 4.11.

$$Q_{fmeasure} = \frac{Q_u}{\eta}[kWh] \qquad \text{eq.4.11}$$

Where:

Q_u: useful energy needs [kWh or, for transports, p-km or t-km]

η: system's efficiency [-, p-km/kWh, t-km/kWh]

Knowing the final energy use from the new system, it is possible to find the difference between the old system and the new, and multiply this by the number of systems affected by the measure. For that, equation 4.7 can be used. In this case, the measure size is defined by the respective sector, but, in general, it is measured in number of systems affected by the measure.

4.1.4. Reference final energy use

The measures addressed in this group are any measures related to end-uses described in section 3.3 for which it is not usual, or it is difficult, to define the useful energy need and, consequently, the respective efficiency between the final energy and the useful needs. For such cases, the efficiency and the useful needs are established according to the lowest final energy use found for the end-uses (best available technologies). Examples for this group are refrigerators, televisions and equipments for the commercial refrigeration.

Since the final energy use for single new equipments are defined at the measure (e.g., new fridges will use on average 220 kWh/year), it is possible to find the difference between the old and the new final energy uses, and multiply this by the number of systems affected by the measure. For that, equation 4.7 can be used. In this case, the measure size is defined by the respective sector, but, in general, it is measured in number systems affected by the measure.

4.1.5. Modal shift

The modal shift measures address measures at the transport sector reflect the final energy savings as a result from the change in means of transportation used to provide any type of mobility. Typical measures are the shift from cars to different types of mass transports. The final energy savings from such measures are estimated by equation 4.12.

$$Q_{fsavings} = \frac{Q_{ushift}}{\eta} - \frac{Q_{ushift}}{\eta_{shift}} \qquad \text{eq.4.12}$$

Where:

Q_{ushift}: The mobility transferred to another mean [p-km or t-km]

η: Energy intensity of the of the affected system [p-km/kWh or t-km/kWh]

η_{shift}: Energy intensity of the of the transferred system [p-km/kWh or t-km/kWh]

Using equations 4.2 to 4.12, it is possible to estimate the final energy savings from all the potential 1598 measures available for energy efficiency plans and, consequently, the final energy savings from plans. Besides the obvious operability achieved by estimating the final energy savings, it is now possible to estimate the objectives of a plan, since most of the objectives are referenced to final energy savings (section 2.4). The only objectives that cannot be estimated by the final energy savings are the investment costs, the payback, and the lifetime, which require specific data for each technology in each measure. For these, all the reference data for the “efficiencies” of the measures, the costs and the lifetime are presented in annex I.

5. Decision Aid

The aim of MCDA methods is to help decision makers (DMs) to organize and synthesize the information they have collected, in order to feel comfortable and confident in their decisions [31]. By using MCDA methods, DMs should feel that all important criteria have been properly accounted and they are complete, nonredundant, concise, specific and understandable [42]. These methods provide better understanding of the decision problem, promote the role of participants in decision making processes, facilitate compromise and collective decisions, help to improve quality of decisions by making them more explicit and rational and avoid making important decisions out of habit [8] [31].

MCDA is divided into two broad multi-criteria methodologies, the also called multi-criteria or multi-attribute decision methods (MADM) and the multi-objective decision methods (MODM) [29] [133]. The MADM have a finite number of the potential alternatives and they are explicitly known before the analysis, while for the MODM, the potential solutions are implicitly defined by a set of constraints. MODM are “natural” evolutions of the single criterion optimization methods.

Along this work, it was identified that the problem of building and evaluating energy efficiency plans is a multi-objective problem because the general targets involving energy savings represent a means to achieve major objectives such as improvements in the energy security and the minimization of environmental loads while using the budget wisely and lowering the risk of the investment. This is a multi-objective problem, since there are several objectives to be minimized or maximized to find the most fitted plans. It can be better specified as a multi-objective optimization (MOOP) problem, because the potential solutions (the energy efficiency plans) are combinations of energy efficiency initiatives and the degree of implementation of each one, and are subjected to a set of constraints, as those stipulated by the ESD [5] for European plans. The set of potential solutions is defined implicitly by these constraints.

This set of potential EE plans available (to be at least evaluated) consists of the combination between the number of available EE measures (M), and their respective degree of implementation (DI), reaching DI^M possible plans. Despite the fact that the problem is naturally framed in the MOOP concept, it would be virtually impossible to find the most fitted plans in another way, i.e., comparing each possible plan to one another, since there are 1598 EE measures available, therefore about DI^{1598} potential different plans.

In order to aid the decision process of selecting the most fitted energy efficiency plans, a MOOP technique was chosen to be used in this research as explained in the next section.

5.1. Some concepts

5.1.1. Dominance

Most multi-objective techniques use the concept of domination. When two solutions are compared, it is said that solution p dominates q if the solution p is no worse than q in all objectives and solution p is strictly better than q in at least one objective [134,135].

5.1.2. Pareto-optimal set or front

When all pair-wise comparisons are performed for a given finite set of solutions in order to find the non-dominated solutions, the resulting sub-set of non-dominated solutions is called the non-nominated set. This set has the property that any solution outside this set is dominated by some solution inside. Some authors consider that inside the non-dominated set of solution there are also some unfeasible solutions [135]. Therefore, when the non-dominated set of solutions has only feasible solutions, this set is known as the Pareto-optimal set.

5.1.3. Problem types (Problematics)

The most common problem types, or problematics, [136] in decision aid are choice, ranking, and sorting.

In the choice problematic the purpose of decision aid is to select a small number (as small as possible) of fitted alternatives in a way that a single alternative may be chosen in the end. However, this does not mean that selection is necessarily focused only on finding a single solution. It can be oriented to find a subset of optimal solutions, from the original set, where such subset contains all the most satisfying alternatives, which remain non-comparable between each other [136].

In the ranking problematic the purpose of decision aid is to find a complete or partial preorder of a set of alternatives. This preorder is a result from a comparison between all the alternatives in the set. The preorder allows to “judge” the alternatives in order to find a rank. The rank can be attributed to each alternative or to a subset of alternatives where each one inside is indifferent to each other [136].

In the sorting problematic, the purpose of decision aid is to assign each alternative from a set of alternatives to a category in a set of pre-defined categories. In such cases, the alternatives are evaluated in order to fulfill the (minimum) requirements to belong to a category [136].

It is also possible to define a description problematic, in which the purpose of decision aid is simply to find an appropriate set of potential alternatives, to build a suitable set of criteria, and establish their performance [136] in each criterion (but not comparing the alternatives at a global level).

5.2. Choosing a MOOP technique

Most practical problems require the simultaneous optimization of multiple, often competing, objectives. In applications of optimization techniques involving multiple objectives, it is important to find several solutions in order to provide the decision maker with insight into the characteristics of the problem before a final solution (or a subset of solutions) is chosen. Those insights are often provided by finding the Pareto-optimal set of solutions. Therefore, the main goal of many multi-objective optimization techniques is to find as many as possible solutions as close as possible to the Pareto-optimal front, where those solutions are as diverse as possible [135].

There exist innumerous techniques or methods used for multi-objective optimization. Deb [135] separates the commonly used methods in two groups, the classical methods and the evolutionary methods.

The classical methods are algorithms based on the existence or non-existence of preferences about the objectives that try to find the Pareto-optimal solutions. Some of the most well-known methods are the weighted sum, the Benson’s method, and the goal programming methods [135]. The main drawbacks of the classical methods are that most algorithms convert MOOP into a single optimization problem by using some user-defined procedure, only one Pareto-optimal solution can be expected to be found in one simulation run and they sometimes use a deterministic procedure for approaching the optimal solution which depends on the chosen initial values and tend to get “stuck” in suboptimal solutions [135]. However, they have the advantage of being widely used and generally have proofs of convergence. Furthermore, they can be used interactively to explore the set of Pareto optimal solutions.

The evolutionary methods simulate the natural evolutionary principles to constitute search and optimization procedures. They work by creating a random population of solutions, instead of a single solution. Then, each solution is evaluated according to the objectives and restrictions, and a fitness score is assigned to each solution according to its relative merit. By the end of each iteration, a termination condition is checked, and if it is not satisfied, a process of reproduction, crossover and mutation of existing solutions is performed to find new (and hopefully better) solutions that will be evaluated closing the loop of the process. Figure 4 presents the flowchart of the process. The main differences between the classical methods and the evolutionary ones are that a population of solutions is processed in each iteration of the method, being an advantage when the main goal of the multi-objective optimization is to find as many as possible solutions belonging to the Pareto-optimal front. Evolutionary methods do not use gradient information for the search process and the operators used are based on stochastic principles, therefore not assuming any particular structure of a problem to be solved.

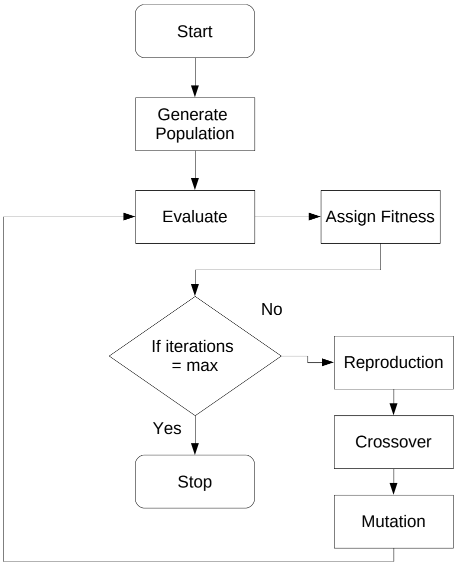


Figure 4 – Flowchart of the working principle of evolutionary methods [135]

There are several well-known multi-objective algorithms that could be applied to the problem of building, evaluating and selecting energy efficiency plans. The Multi-Objective Genetic Algorithm (MOGA) [137] is based on classical genetic algorithms (Figure 4). It implements a rank-based fitness assignment to each solution of the population that made it be the first multi-objective genetic algorithm that explicitly emphasized the non-dominated solutions and at the same time maintained diversity in the non-dominated set of solutions. The Strength Pareto Evolutionary Algorithm (SPEA) [138] is characterized by introducing elitism by storing non-dominated solutions externally in a second, continuously updated population that preserves the resulting new non-dominated solutions using a Pareto dominance relation, and by incorporating a clustering procedure in order to reduce the non-dominated set without destroying its characteristics. The Thermodynamical Genetic Algorithm (TDGA) is a genetic algorithm that uses the concepts of the entropy and the temperature in the selection operation for multi-objective optimization [139]. The Non-dominated Sorting Genetic Algorithm (NSGA) performs a ranking classification according to the non-dominance of the individuals in a population for fitness and distributes the non-dominated points found using a niche formation technique to guarantee diversity [140]. The NSGA, more specifically, the NSGA-II was chosen to be used in this research due to its popularity, the diversity encountered among non-dominated solutions (due to crowding comparison procedure), the possibility to apply constraints, the use of tournament selection to apply elitism, the possibility to work with real parameters values instead of converting to a binary genetic code, and the ability to find spread solutions and good convergence near the true Pareto-optimal front [135,141,142]. The NSGA-II algorithm is explained in the next section in accordance to how it was used in this research.

5.3. NSGA-II

Deb [141] suggested an elitist non-dominated sorting genetic algorithm (NSGA-II) in order to overcome the main criticisms of the NSGA approach. The criticisms where the high computational complexity of non-dominated sorting, in the order of MN^3 (where M is the number of objectives and N is the population size), that makes NSGA computationally expensive for large population sizes; the lack of elitism that helps preventing the loss of good solutions and, in general, improve the results of the algorithm; and the need for specifying the sharing parameter that was used for ensuring diversity. Besides the improvements to overcome the issues found on the previous NSGA, the concept of constrained multi-objective optimization was also introduced since it is important from the point of view of practical problem solving.

5.3.1. General description of the NSGA-II algorithm

First, a randomly created population is initialized. Once the population has been assigned, the solutions are evaluated according to the objectives values and constraints. Then, the population is sorted based on fronts with non-dominated solutions and the crowding distance on the last front. The crowding distance is a measure of how close a solution is to its neighbors. The first front is the completely non-dominated set in the current population and the following fronts are solutions that are non-dominated among each other in the set, but are dominated by the previous fronts. This non-domination rank works as a fitness value, which is assigned to each solution. Solutions in the first front are given a fitness value of 1, solutions in the second front are assigned fitness value as 2 and so on for all fronts. Later, parents are selected from the population by using binary tournament selection based on the rank and the crowding distance. The selected parents generate offspring using crossover and mutation operators. Then, a new population (size 2N) composed by the current population and current offspring is sorted again and only the best N individuals are selected, where N is the original population size. Figure 5 presents a flowchart of the processes used by the NSGA-II algorithm. Alternatively to the elitist sorting to assign the new population, a controlled elitism can also be used in order to guarantee more diversity in the solutions by allowing a restricted number of dominated solutions to be preserved to be further combined to other solutions. The crowding distance, the binary tournament, the crossover and mutation operators and the sorting process are better explained in the following sections.

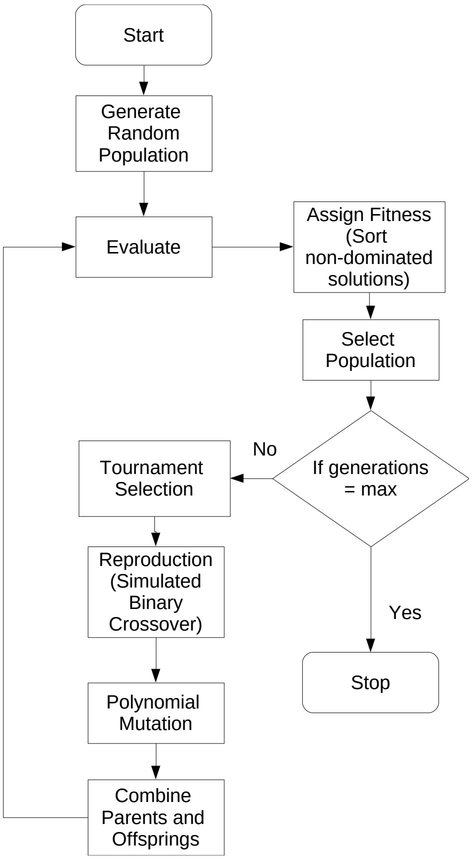


Figure 5 – NSGA-II flowchart [135,141,142]

5.3.2. Fast constrained non-dominated sort

The fast constrained non-dominated sort is a procedure of sorting a population into different non-domination levels. The procedure consists in calculating two entities for each solution p found by the pairwise comparison between all solutions. The entities are: 1) domination count (n_p), representing the number of solutions which dominate the solution p, and 2) S_p, a set of solutions that the solution p dominates [141]. Having those entities determined for each solution, it is possible to split the fronts. All solutions in the first non-dominated front will have a domination count of zero. For each solution with $n_p = 0$, each member (q) of its set S_p is visited and its domination count is reduced by one. In doing so, any member q for which the domination count becomes zero is put in a separate list Q, being the second non-dominated front. After that, the procedure is continued until all fronts are identified. The algorithm below presents the whole process.

```
$FastConstrained-Non-DominatedSort(P)$
for each $p \in P$
  $S_p = 0$
  $n_p = 0$
  for each $q \in P$
    if $(p_{violation} = 0 \land q_{violation} = 0)$ then         If both solutions are feasible and…
      if $(p \, dominates \, q)$ then                             …If p dominates q
        $S_p = S_p \cup \{q\}$
      elseif $(q \, dominates \, p)$ then                         …If q dominates p
        $n_p = n_p + 1$
    elseif $(p_{violation} = 0 \land q_{violation} > 0)$ then     If only p is feasible
      $S_p = S_p \cup \{q\}$
    elseif $(q_{violation} = 0 \land p_{violation} > 0)$ then     If only q is feasible
      $n_p = n_p + 1$
    elseif $(p_{violation} < q_{violation})$ then                 If both solutions are infeasible, but solution
      $S_p = S_p \cup \{q\}$                                      …p has smaller overall constraint violation
    elseif $(q_{violation} < p_{violation})$ then                 If both solutions are infeasible, but solution
      $n_p = n_p + 1$                                             …q has smaller overall constraint violation
  if $n_p = 0$ then
    $p_{rank} = 1$
    $F_1 = F_1 \cup \{p\}$

$i = 1$
while $F_i \neq 0$
  $Q = 0$
  for each $p \in F_i$
    for each $q \in S_p$
      $n_q = n_q - 1$
      if $n_q = 0$ then
        $q_{rank} = i + 1$
        $Q = Q \cup \{q\}$
  $i = i + 1$
  $F_i = Q$
```

The algorithm uses: the population P; a domination counter (n_p) that counts the number of solutions which dominate the solution p; a set of solutions that the solution p dominates (S_p); the violation of the constraints value ($p_{violation}$ or $q_{violation}$), if the value is higher than zero it represents that at least one of the constraints of the problem was violated and it should be proportional to the violation; the set of solutions belonging to a front (F); the rank (or the front) of the solution p (p_{rank}); and the auxiliary variables Q and i.

5.3.3. Crowding distance

The crowding distance is an estimate of the density of the solutions surrounding a particular solution i in the current population. It is calculated by the estimation of the cuboid formed using the nearest neighbors as the vertices. The crowing distance is calculated as below [135]:

Call the number of solutions in the front F_i as $l = |F_i|$. For each front F_i assign the respective crowding distance $d_i = 0$

For each objective function m = 1,2,…,M, sort the set in worse order of f_m, or find the sorted indices vector: $I^m = sort(f_m, >)$.

For m = 1,2,…,M, assign a large distance (infinite) to boundary solutions. For all other solutions j = 2 to (l-1), assign:

$$d_i = \sum_{m=1}^{M} d_i + \frac{f_m^{I_{j+1}^m} - f_m^{I_{j-1}^m}}{f_m^{max} - f_m^{min}} \qquad \text{eq. 5.1}$$

Where:

f_m^{max}: The highest objective from set m

f_m^{min}: The lowest objective from set m

j: Is the position of solution i at the sorted indices vector

5.3.4. Selection

Once the individuals from a generation are sorted based on non-domination, and have the crowding distance assigned, the selection is carried out by allowing the individuals in the first fronts to continue to the next generation until the limit of individuals allowed. In case the last front selected has more individuals than the number missing to complete the new generation, a crowded comparison is carried out to bring the most dispersed ones to fill the missing spots. The procedure is performed as:

Select the solutions at the front i=1. Call the number of solutions in the front F_i as $l = |F_i|$. If l < individuals in generation (N), allow all the front elements to survive to the next generation. Repeat this procedure until complete N or find a front bigger than the missing spots to complete N.

In case the last chosen front is bigger than the number of remaining spots for next generation, sort last front F_i in relation to the crowding distances from the highest to the lowest and get the first solutions that fill the missing spots. This last process is the crowding comparison.

5.3.5. Selection using controlled elitism

The controlled elitism works in similar manner as the regular selection, the difference is that it uses a geometric distribution to limit the number of individuals in each front that will survive to the next generation. Therefore the number of individuals in each front can be calculated as [135]:

$$N_i = N\frac{1-r}{1-r^k}r^{i-1} \qquad \text{eq. 5.2}$$

Where:

N_i is the number of allowed individuals in the ith front

r(<1) is the reduction rate

k is the number of the last front found among the individuals.

Since there is a limit to the number of individuals to survive in each front, the crowding comparison should be performed at each front to select the N_i individuals to the next generation.

5.3.6. Simulated binary crossover

The simulated binary crossover (SBX) simulates the binary crossover observed in nature. It works with two parent solutions and creates two offspring [135]. The procedure of building the offspring $x_i^{(1,t+1)}$ and $x_i^{(2,t+1)}$ from the parent solutions $x_i^{(1,t)}$ and $x_i^{(2,t)}$ is presented by:

$$x_i^{(1,t+1)} = 0.5\left[\left(1+\beta_{qi}\right)x_i^{(1,t)} + \left(1-\beta_{qi}\right)x_i^{(2,t)}\right] \qquad \text{eq. 5.3}$$

$$x_i^{(2,t+1)} = 0.5\left[\left(1-\beta_{qi}\right)x_i^{(1,t)} + \left(1+\beta_{qi}\right)x_i^{(2,t)}\right] \qquad \text{eq. 5.4}$$

Where

$$\beta_{qi} = \begin{cases} (2u_i)^{\frac{1}{\eta_c+1}}, & if\ u_i \le 0.5 \\ \left(\frac{1}{2(1-u_i)}\right)^{\frac{1}{\eta_c+1}}, & otherwise \end{cases} \qquad \text{eq. 5.5}$$

u_i: Random number between 0 and 1

η_c: Distribution index [0,∞[

The distribution index influences the distance between the offspring solutions and their parents, where large values increase the probability for creating “near-parent” solutions and small values allow distant solutions to be chosen as offspring.

5.3.7. Polynomial mutation

The polynomial mutation is an operator created to reproduce the mutation phenomenon occurring in nature as a consequence of the evolution. Deb [135] describes application of the polynomial mutation as:

$$y_i^{(1,t+1)} = x_i^{(1,t+1)} + (x_i^{(U)} - x_i^{(L)})\bar{\delta_i} \qquad \text{eq. 5.6}$$

Where:

$$\bar{\delta_i} = \begin{cases} (2r_i)^{\frac{1}{\eta_m+1}} - 1, & if\ r_i < 0.5 \\ 1 - (2(1-r_i))^{\frac{1}{\eta_m+1}}, & otherwise \end{cases} \qquad \text{eq. 5.7}$$

$y_i^{(1,t+1)}$: Is the mutated individual in relation to the objective i

$x_i^{(1,t+1)}$: Is the original individual in relation to the objective i

$x_i^{(U)}$: Is the upper value for the objective i among the solutions

$x_i^{(L)}$: Is the lower value for the objective i among the solutions

η_m: Polynomial mutation perturbation [0,∞[

r_i: Random number between 0 and 1

The polynomial mutation perturbation sets how different the solution will be from its original. The greater the value, the lower is the perturbation in the variable.

5.4. Merging MCDA with MOOP

The selected MOOP method, NSGA-II, as any other MOOP method, was designed to find the Pareto-optimal front for a constrained multi-objective problem. However, the Pareto-optimal front is not obtained reflecting any type of preference on the process to find the front. It “simply” brings the dominating set of feasible non-dominated solutions. Observing such fact and understanding that decision makers are interested in evaluating and choosing only the solutions that are, at their perspective, most fitted to problem, it was decided to include inside the sorting process of the NSGA-II a method that could reflect such preferences.

Therefore, bringing at the end a set of solutions where all the solutions would reflect the decision makers' desires.

In order to perform such change on the NSGA-II's algorithm, several multi-criteria decision methods were analyzed in order to find the most suited. The next sections present this evaluation, the characteristics of the selected method and the changes on the algorithm of the NSGA-II to handle the selected method.

5.4.1. MCDA methods

Multi-criteria decision aid methods are tools designed to formalize the decision process in order to clarify the decisions and towards recommending, or simply favoring, an alternative or a group or alternatives that reflect the decision makers' preferences [30,133,136]. There are several tools for aiding a decision process and the selection of an appropriate tool is not an easy task and depends on each decision problem and on the objectives and expected support defined by the decision makers.

Greco et al [136] divide the MCDA methods in two groups, the classical and the non-classical approaches. The classical approaches are further subdivided into multi-attribute utility and value theories and the outranking methods.

The multi-attribute utility and value theories approach tries to assign a utility value to each alternative in order to "measure" the preference for an alternative. This utility value is very often the sum of the marginal utilities that are assigned to each criterion. Those preference measurements are used to choose, to rank or to sort the alternatives. This method does not support incomparability between alternatives (given two alternatives, they either have the same utility or one has higher utility than the other one), and, due to the common additive process to produce the utility value, it allows compensation of the loss on a given criterion by a gain on another one. Among the most used tools to aggregate multi-criteria performances into a single synthetic score are the AHP (Analytic Hierarchy Process) and the Simple multi-attribute rating technique (SMART) [133,136,143].

The outranking methods are methods based on, crisp or fuzzy, pairwise comparisons of alternatives in order to decide if one alternative in a pair is preferred, indifferent or incomparable to the other alternative in the pair, according to the decision maker's preferences. In such comparisons, a disadvantage in one criterion sometimes cannot be compensated by advantages in other criteria.

The outrank methods seem to be the most appropriate methods to be used inside the MOOP to reflect the decision makers' preferences, since their concept is similar to the already used dominance concept, and because it is possible to use such methods to find all the alternatives that are “as good as the others” to be an equivalent of the Pareto-optimal front including preferences.

From the main methods using the definition of outranking relation, the ELECTRE family seems to suit better the problem of aiding the decision process on building and selecting EE plans because it uses non-compensatory aggregation procedures, eliminating the possibility to bias the alternatives by one much better objective, and because it uses discrimination thresholds (indifference and preference), which lead to a preference structure where small differences of evaluations are not significant in terms of preferences, while the accumulation of several small differences may become significant, and large differences can be used to define preference. This added value is particularly important because the data behind the decision process is far from perfect, and such approach increases confidence on the selected alternatives.

5.4.2. ELECTRE Family

ELECTRE stands for “ELimination Et Choix Traduisant la REalité” (ELimination and Choice Expressing the REality), and was initially developed by Bernard Roy and his colleagues at SEMA consultancy company [30]. The objective of the method consisted in aiding decision makers in selecting a subset of alternatives, as small as possible, in such a way that a single alternative may finally be chosen.

The ELECTRE methods are based on pairwise comparisons. Given an ordered pair of alternatives (a, b), the method seeks to find whether there are sufficient arguments to assert that “a outranks b”. This assertion is performed comparing the two alternatives criterion by criterion to build (crisp, fuzzy or embedded) preference relations. The outranking relation, S, whose meaning is “at least as good as” is the basis to find the preference relations that are used by the method. When comparing two alternatives, four situations may occur, defining three preference relations:

- a S b and not b S a, i.e., a P b (a is strictly preferred to b)
- b S a and not a S b, i.e., b P a (b is strictly preferred to a)
- a S b and b S a, i.e., a I b (a is indifferent to b)
- Not a S b and not b S a, i.e., a R b (a is incomparable to b)

For an outranking assertion to be validated, two conditions should be true: i) a sufficient majority of criteria should be in favor of this assertion, and ii) none of the criteria in the minority should oppose too strongly to the assertion. The first condition is named concordance and the second is the non-discordance.

To determine concordance, each criterion must be attributed an importance coefficient. Such coefficient is the weight of each criterion and reflects its voting power to contribute to the majority which is in favor of an outranking. The weights used in the ELECTRE methods are independent to the ranges or the encoding of the scales, and they cannot be seen as substitution rates as in compensatory aggregation procedures, since despite the sum of the votes (weights) to find a majority to define concordance, no compensation is performed by any criterion.

The non-discordance is based on the veto threshold, that expresses the power attributed to a given criterion to be against the assertion “a outranks b”, when the difference of the evaluation of the respective criterion between a and b (favorable to b) is greater than this threshold.

The processes of building outranking relations and exploiting these relations vary according to the ELECTRE method.

The ELECTRE I [30][136] was the first ELECTRE method developed and it is devoted to the problem of choosing the best alternative among the available ones. The outrank relations are determined by a crisp (yes/no) verification of the concordance and the non-discordance coefficients. This method exploits the outranking relations in order to identify a small as possible subset of alternatives according to the defined preferences. It does not necessarily lead directly to the best single alternative, due to the possible incomparability between alternatives.

The ELECTRE IS [30][136] is an extension of the ELECTRE I taking into account the use of a fuzzy logic applied at the concordance and the non-discordance coefficients in order to make possible to take into account the imperfect knowledge about real-world decision-making situations. This method also exploits the outranking relations in order to identify a small as possible subset of alternatives according to the defined preferences.

The ELECTRE II method [30][136] was the first of the ELECTRE methods designed to deal with ranking problems. ELECTRE II is based on the same concepts as the ELECTRE I, however, the concordance condition is modified in order to take into account the notion of embedded outranking relations. There are two embedded relations, a strong outranking relation and a weak outranking relation. The exploitation of such embedded relations allows obtaining two pre-orders that lead to a final ranking of the alternatives. The advantage in using two pre-orders to find the final one is the fact that joining both is possible to detect the degree of incomparability of the alternatives.

The method ELECTRE III [30][136] was designed to improve ELECTRE II in order to deal with inaccurate, imprecise, uncertain or ill-determination of data. This was achieved by introducing fuzzy logic to the outranking relations, and it was made operational by incorporating the indifference and preference thresholds. A third threshold, the veto threshold, is used to implement the notion of discordance. The exploitation of the outranking relations can be expressed in the form of two pre-orders, or in the form of a partial pre-order based on an intersection of the complete pre-order.

The ELECTRE IV method [30][136] was developed to overcome the difficulty to define the relative importance of the weights of criteria. It works under the same pairwise comparison concepts of the ELECTRE III method and it exploits the outrank relations also in the same way as the ELECTRE III.

ELECTRE TRI [136] was designed for the sorting problematic. It was based on the ELECTRE III method, however, the exploitation of the outrank relations aims to assign the alternatives to predefined categories. In ELECTRE TRI the categories are ordered from the worst to the best and each category must be characterized by a lower and an upper limit for each criterion involved in the problem.

From all the methods at the ELECTRE family, it was decided to use the outranking relation of ELECTRE III (also used in ELECTRE TRI), because it deals with inaccurate, imprecise, uncertain or ill-determination of data. Another option was to use the ELECTRE IS, however, since no exploitation processes is used, just the outranking relation, it was decided to continue using the method that first handle imprecision in the ELECTRE family.

5.4.3. ELECTRE III outranking relations

In ELECTRE III the outranking relation can be seen as a fuzzy relation. The construction of this relation requires the definition of a credibility index, $\sigma(a,b)$, and the calculation of the concordance, the discordance and the global concordance indices with respect to the assertion “a outranks b”. Considering a and b as any pair of ordered alternatives, n the number of criteria and the j-th criterion (j = 1,...,n), an indifference threshold q_j (representing a value for a criterion j beneath which the decision maker is indifferent to the alternatives a and b for such criteria), a preference threshold p_j (a value defined for a criterion j above which the decision maker shows a clear strict preference of one alternative over the other), and a veto threshold v_j (representing a value where a difference in favor of one alternative for a criterion j greater than this value will require the decision maker to deny any possible outranking relationship indicated by the other criterion), it is possible to find the ELECTRE indices using [144,145]:

$$\Delta_j = \begin{cases} g_j(a) - g_j(b), \text{if the j}^{\text{th}} \text{ criterion is to maximize} \\ g_j(b) - g_j(a), \text{if the j}^{\text{th}} \text{ criterion is to minimize} \end{cases} \qquad \text{eq. 5.8}$$

Where:

$g_j(a)$: Denotes the performance on the j$^{\text{th}}$ criterion of the alternative a

$g_j(b)$: Denotes the performance on the j^{th} criterion of the alternative b

Δ_j: represents the advantage of a over b on the j^{th} criterion

For each criterion (j = 1,...,n), the concordance index is:

$$\mathrm{c}_j(a,b) = \begin{cases} 0 \quad , \quad if\ \Delta_j < -p_j \\ \dfrac{p_j + \Delta_j}{p_j - q_j} \ , if\ \ -p_j \le \Delta_j < -q_j \\ 1 \quad , \quad if\ \Delta_j \ge -q_j \end{cases} \qquad \text{eq. 5.9}$$

The global concordance index is obtained by aggregating the n single-criterion indices:

$$C(a,b) = \frac{\sum_{j=1}^{n} k_j\, c_j(a,b)}{\sum_{j=1}^{n} k_j} \qquad \text{eq. 5.10}$$

Where:

k_j: Is the importance coefficient or weight (which is non-negative)

For each criterion (j = 1,...,n), the discordance index is:

$$\mathrm{d}_j(a,b) = \begin{cases} 1 \quad , \quad if\ \Delta_j < -v_j \\ \dfrac{-p_j - \Delta_j}{v_j - p_j} \ , if\ \ -v_j \le \Delta_j < -p_j \\ 1 \quad , \quad if\ \Delta_j \ge -p_j \end{cases} \qquad \text{eq. 5.11}$$

Finally, the discordance indices and the global concordance index are combined to obtain the credibility index for a S b:

$$\sigma(a,b) = \mathrm{C(a,b)} \prod_{\substack{\mathrm{j} \in \{1,\ldots,\mathrm{n}\}: \\ \mathrm{d}_j(a,b) < C(a,b)}} \frac{1 - \mathrm{d}_j(a,b)}{1 - \mathrm{C(a,b)}} \qquad \text{eq. 5.12}$$

It is finally possible to establish the outranking relations, as soon as a cut threshold λ is defined:

$$\sigma(a,b) \ \ge \lambda\ and\ \sigma(b,a) < \lambda \Leftrightarrow aPb$$

$$\sigma(a,b) \ \ge \lambda\ and\ \sigma(b,a) \ge \lambda \Leftrightarrow aIb$$

$$\sigma(a,b) < \lambda\ and\ \sigma(b,a) < \lambda \Leftrightarrow aRb$$

5.4.4. The MOOP-MCDA model

The NSGA-II was originally conceived to find the Pareto-optimal frontier in a multi-objective problem. After some time, the author of the algorithm adapted it to cope with constrained multi-objective problems with the inclusion of the algorithm called "Fast Constrained-Non-Dominated Sort" (section 5.3.2). However, this algorithm does not take into account preferences among objectives, not reflecting real problems where decision makers' care about the objectives involved in the problem, but, for any reason, give more importance to some objectives then to others.

Since the influence of the decision makers' preferences is part of the problem of building and selecting energy efficiency plans, it was decided to alter the NSGA-II algorithm to include this functionality. For this purpose, the outranking relations from the ELECTRE III method were included inside the "Fast Constrained-Non-Dominated Sort" substituting the original dominance. This implementation allowed the NSGA-II to cope with possible preference, indifference, and veto thresholds, and the use of weights and a cut threshold to better define the decision maker's preference. Such improvement allows not only the possibility to search the multi-objective space in order to find a frontier of solutions representing the preferences of any decision maker, but it also permits to select the solutions in such a frontier considering the imprecision of the data behind each objective and, also, considering differences in objectives when comparing solutions where such differences are not big enough to formalize preference for the eyes of the decision maker (e.g. something costing €1.99 compared to other costing €2.00 may be seen as having the same price, and this may not be used as an advantage to select one for the other).

The adapted algorithm uses: the population P; a domination counter (n_p) that counts the number of solutions which dominate the solution p; a set of solutions that the solution p dominates (S_p); the violation of the constraints value ($p_{violation}$ or $q_{violation}$), if the value is higher than zero it represents that at least one of the constraints of the problem was violated and it should be proportional to the violation; the ELECTRE III credibility index from the comparison of the solutions ($\sigma(p,q)$ equation 5.10); the cut threshold from the ELECTRE III method (λ); the set of solutions belonging to a front (F); the rank (or the front) of the solution p (p_{rank}); and the auxiliary variables Q and i.

```
$FastConstrained-Non-DominatedSortElectre(P)$
for each $p \in P$
 $S_p = 0$
 $n_p = 0$
 for each $q \in P$
  if $(p_{violation} = 0 \wedge q_{violation} = 0)$ then          If both solutions are feasible and…
   if $(\sigma(p,q) \geq \lambda \wedge \sigma(q,p) < \lambda)$ then          …If p outranks q and not the opposite
    $S_p = S_p \cup \{q\}$
   elseif $(\sigma(q,p) \geq \lambda \wedge \sigma(p,q) < \lambda)$ then          …If q outranks p and not the opposite
    $n_p = n_p + 1$
  elseif $(p_{violation} = 0 \wedge q_{violation} > 0)$ then          If only p is feasible
   $S_p = S_p \cup \{q\}$
  elseif $(q_{violation} = 0 \wedge p_{violation} > 0)$ then          If only q is feasible
   $n_p = n_p + 1$
  elseif $(p_{violation} < q_{violation})$ then          If both solutions are infeasible, but solution
   $S_p = S_p \cup \{q\}$                                 …p has smaller overall constraint violation
  elseif $(q_{violation} < p_{violation})$ then          If both solutions are infeasible, but solution
   $n_p = n_p + 1$                                        …q has smaller overall constraint violation
 end for
 if $n_p = 0$ then
  $p_{rank} = 1$
  $F_1 = F_1 \cup \{p\}$
end for

$i = 1$
while $F_i \neq 0$
 $Q = 0$
 for each $p \in F_i$
  for each $q \in S_p$
   $n_q = n_q - 1$
   if $n_q = 0$ then
    $q_{rank} = i + 1$
    $Q = Q \cup \{q\}$
 $i = i + 1$
 $F_i = Q$
end while
```

6. Case study: Portugal

In order to test and observe the outcomes from the methodology developed to aid the decision process of building and selecting energy efficiency plans, it was decided to use Portugal as a case study. Portugal was chosen due to three main reasons: i) Being a Member State of the European Union, Portugal was obliged to build a national energy efficiency plan respecting the targets defined at the ESD [5]; ii) Portugal has a high level of energy dependency and energy efficiency can contribute to mitigate such problem; and iii) the research group is familiar with how energy is used in the country, and has knowledge about the data sources to feed the model. Despite the choice for Portugal, the methodology can be applied to any other country in the world. In fact, the methodology can be used in any geographical scale from a city to a group of countries.

Portugal is situated on the southwest extreme of Europe. Besides the mainland territory the country has two autonomous regions, Madeira and Azores, both archipelagos in the Atlantic Ocean. The country has an area of 92,207 km^2, including the archipelagos of Azores (2,322 km^2) and Madeira (801 km^2) [69]. Portugal has (in 2011) a resident population of 10,555,853 people representing 4,079,577 households [69]. In 2010 Portugal presented a Gross Domestic Product of approximately 162 Billion Euros, equivalent to 15,232 Euros per capita [69].

Portugal is a country with almost no known endogenous fossil energy resources, namely oil, coal and gas. However, it has an important amount of renewable resources as hydro, wind, solar and biomass. In the last decade there was a renewed effort to increase the use of endogenous renewable resources, especially wind power, which has brought a contribution from the renewables to the production of electricity in 2009 to 38.5% [146]. Portugal has a high external energy dependence (80% in 2009 [45]), being totally dependent from the primary resources from fossil origin.

6.1. Model of the energy demand in Portugal

The Portuguese demand for energy was modeled for the year of 2006, and from there projected to the year 2016 in order to assess the energy use at the end-use level. This allowed individually applying and quantifying energy efficiency measures to be joined in energy efficiency plans. The Portuguese energy system was modeled according to the methodology described in chapter 3, divided by the main energy use sectors: domestic, industry, services, transports, and “other sectors”. Each sector was further divided into their respective end-uses, with exception of the other sectors that was modeled by energy carriers.

In a global view, in 2006, the base year for this research, the total final energy use in Portugal corresponded to 249.5 TWh [45]. The final energy use for each sector and the equivalent energy use per inhabitant are presented in Figure 6 [45]. Such energy use corresponds to a shared among the sectors of: 37% for transports, 34% for industry, 15% for domestic, 10% for services and 4% for the other sectors. The transport sector was the major contributor for energy use, followed by industry and the domestic sector.

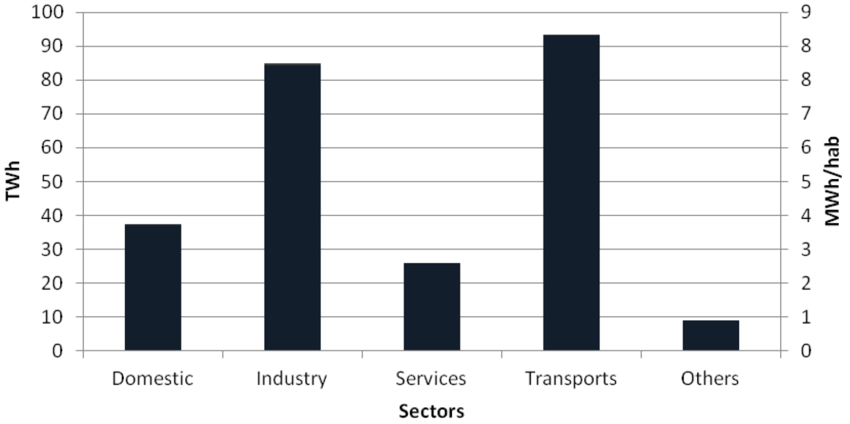


Figure 6 – Portuguese final energy use by sector in 2006

The distribution shown in Figure 6 gives a first indication of prioritary sectors in term of potential energy savings, although it is not more than that, since, theoretically, a sector could have high demand but not opportunities for energy efficiency improvements. A complementary way to improve perception on the final energy use is to observe which the most important energy carriers are. Figure 7 shows the share of final energy use among the main energy carriers. It demonstrates that uses of diesel are a prioritary target in searching for major energy reductions in Portugal, followed by electricity and biomass.

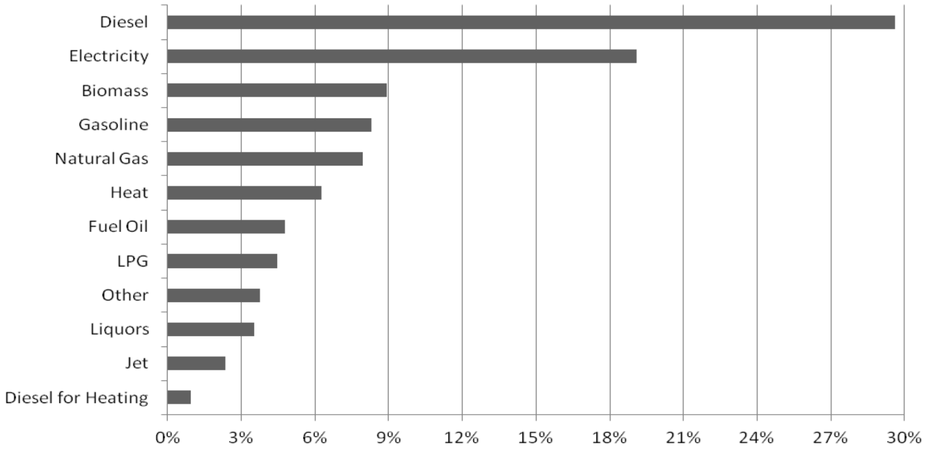


Figure 7 - Portuguese final energy use share by energy carrier in 2006

Since energy efficiency plans generally expect to fulfill targets on energy use reductions in relation to a defined time-frame or a defined future year, projections on the final energy use for Portugal were performed (following the method presented in section3.3). It is then possible to express trends in the energy use and to have values to base the expected results and make possible to calculate the minimum energy savings at the last application year of a plan, as indicated at the ESD [5]. Figure 8 presents the energy projections from 2006, the base year, to 2016. These were used as reference to apply the energy efficiency plans and assess their results. The projections were performed according to the methods presented in section 3.4 and are explained for each sector in the subsequent sections.

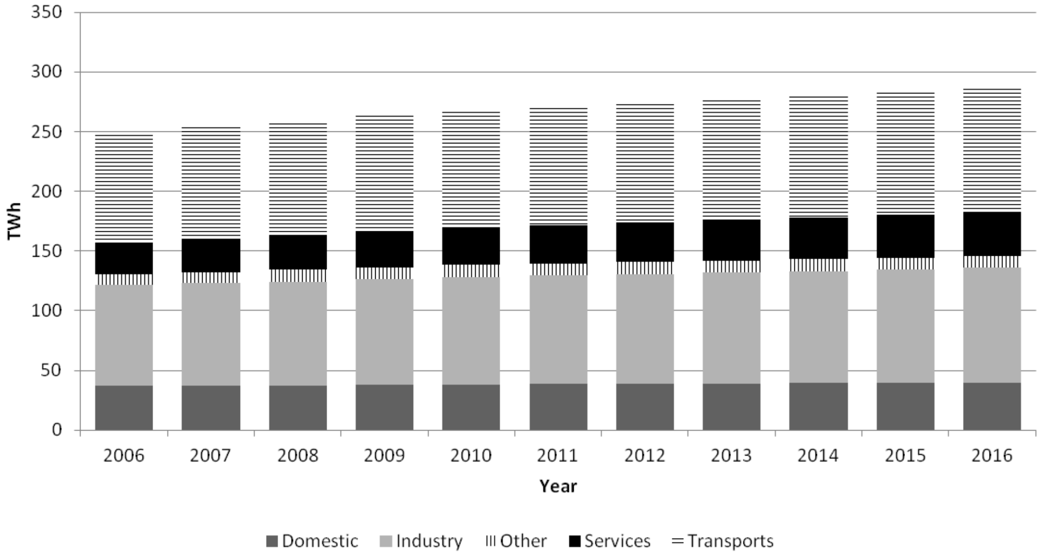


Figure 8 – Final energy use projection for the reference evolution by sector and year

Since global analysis by sector and energy carrier is insufficient to provide a perception of the real use of energy, each sector is desegregated by end-use and described in the next sections.

6.1.1. Domestic sector

The energy used in this sector can be basically quantified by the energy used by 12 main end-uses and “others” (representing all end-uses not mentioned). The end-uses are: i) domestic hot water; ii) ambient heating; iii) ambient cooling, iv) refrigeration, v)freezing, vi) clothes washing, vii) clothes drying, viii) dishwashing, ix) entertainment, x) computers, xi) lighting, xii)cooking. Figure 9 presents the estimated weight of each end-use in the domestic sector according to the final energy used in 2006 [45]. It shows that the major final energy users are the ambient heating and the domestic hot water, which are also the end-uses that have the highest potential to save energy.

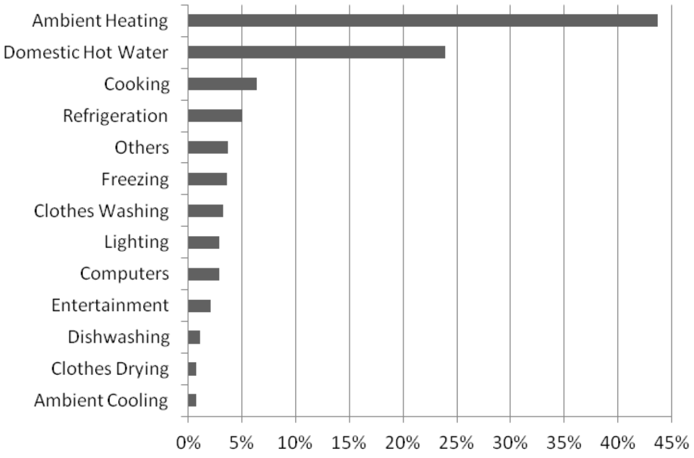


Figure 9 – Estimated Portuguese final energy share for the domestic sector by end-use in 2006

For each end-use, at least one technology was identified to represent it at the base year according to the available data. In the case of lack of specific data, as for the ambient heating or the domestic hot water, an average technology was assigned for each energy carrier, to reflect the average efficiency of the technologies in use. Table 58 presents the end-uses and their respective technologies found for the base year of 2006 [45,48,69,83].

Table 58 – End-uses and their technologies in the domestic sector

End-use	Technology
Ambient Cooling	Average by energy carrier
Ambient Heating	Average by energy carrier
Clothes Drying	Average by energy carrier
Clothes Washing	Average by energy carrier
Computers	Desktop + Monitor
	Laptop
	Printers
Cooking	Hobs
	Ovens
Dishwashing	Average by energy carrier
Domestic Hot Water	Average by energy carrier
Entertainment	Audio Systems
	TV
	TV Receiver
	VCRs and DVDs
Freezing	Average by energy carrier
Lighting	Oil lamp
	CFL
	Fluorescent
	Halogen
	Incandescent
Refrigeration	Average by energy carrier
Others	Average by energy carrier

Each end-use has its energy drivers, which somehow associate the energy use with the services that they provide, such as indoor temperature, use of water or even persons in a house. It is such association that allows the projection of the demand for useful energy in the future. For this purpose, the possession or the ownership of each technology representing an end-use (accounted using one household as a reference), the number of households and the size of a household (persons) can be identified as the common drivers. The ownership of equipments is presented in Figure 10 to illustrate the possession of equipments at the base year (2006) [45,48,69,83] and the projected possession, both following the process presented in chapter 3.

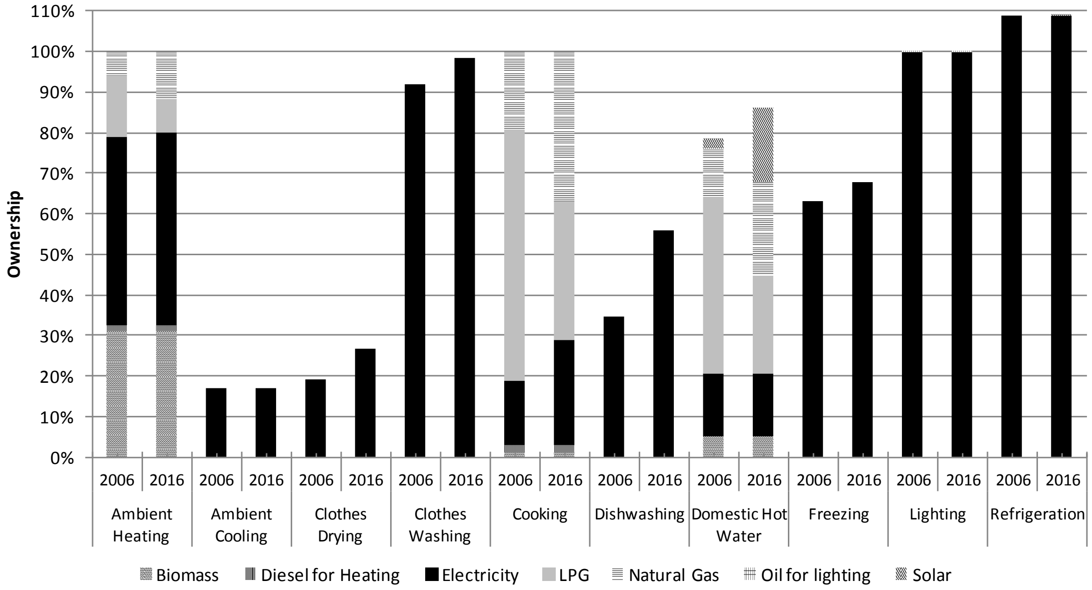


Figure 10 –Ownership of equipments by energy carrier for 2006 and estimated for 2016

The trend behind the household's change was obtained from INE using their base projections for the population from 2008 to 2060 [147], and their historical size of a household and number of households in relation to the population [69]. These trends are presented in Figure 11.

Figure 11 – Population, households and household size in time

The consequences of the changes in the demand drivers in final energy use through time for the domestic sector are presented in Figure 12.

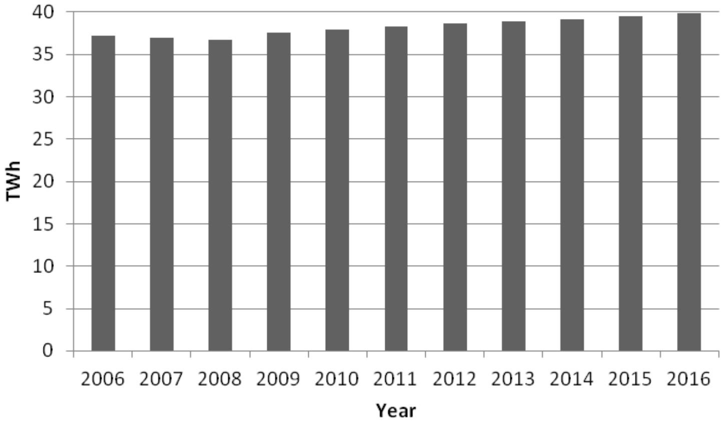


Figure 12 – Resulting projection of Final energy use for the domestic sector

6.1.2. Services sector

The energy used in this sector can be basically quantified through the energy used by the specific end-uses, the ownership of these end-uses and the total size of the sector (very similar to the domestic sector). Figure 13 presents the estimated weight of each end-use in the services sector according to the final energy used in 2006 [45] and shows that the major final energy users are the ambient heating and the other uses followed by lighting and motors. The other uses have a representative amount of the total energy used by the sector. However it represents the almost uncountable number of minor end-uses that are spread in the different services subsectors.

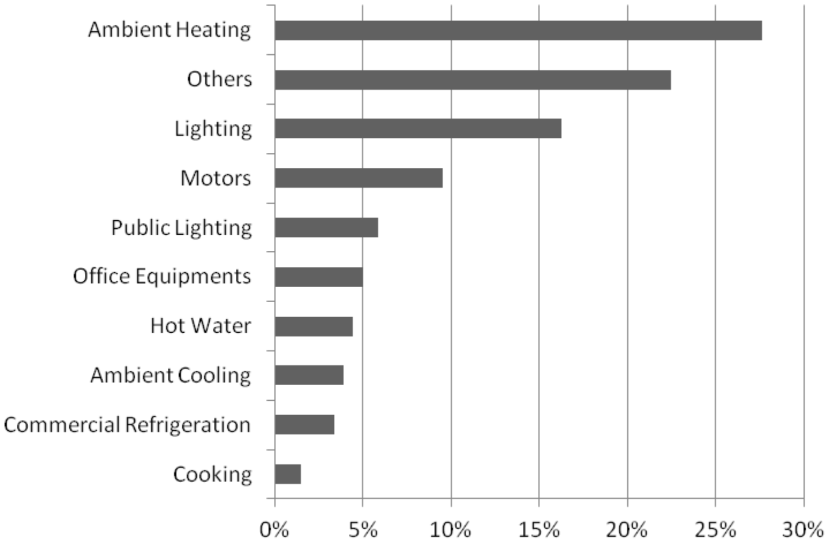


Figure 13 – Estimated Portuguese final energy share for the services sector by end-use in 2006

For each end-use at least one technology was identified to represent it at the base year according to the available data. In the case of lack of specific data an average technology was assigned for each energy carrier to reflect the average efficiency of the technologies in use. For examples are the case of the ambient heating and cooling, and the hot water. Despite the technologies defined for cooking, the ovens and the ranges represent an average efficiency for each energy carrier in use, such as electricity or natural gas (presented and characterized for Portugal in chapter 3). Table 59 presents the end-uses and their respective technologies found for the base year of 2006 (vide section 3.3 for data sources).

Table 59 – End-uses and their technologies in the services sector

End-use	Technology
Ambient Cooling	Average by energy carrier
Ambient Heating	Average by energy carrier
Commercial Refrigeration	Beverage Merchandisers
	Ice Machines
	Other
	Reach-In Freezers
	Reach-In Refrigerators
	Refrigerated Vending Machines
	Walk-Ins
Cooking	Oven
	Range
Hot Water	Average by energy carrier
Lighting	Average Oil technology
	Fluorescent
	HID
	Incandescent
Motors	0 < 0.75 kW
	0.75 < 4 kW
	10 < 30 kW
	130 < 500 kW
	30 < 70 kW
	4 < 10 kW
	70 < 130 kW
	> 500 kW
Office Equipments	Computers
	Other
Public Lighting	Incandescent
	Low/High-Pressure Sodium
	Mercury Vapor
	Metal Halide
Others	Average by energy carrier

Following the same reasoning used for the domestic sector, here the end-uses were also associated with their respective energy drivers. The main drivers considered for the projection were the ownership of the equipments, directly or indirectly connected to the number of employees, the area of the sector, and the Gross Added Value (GAV) from the sector as the main demand drivers. Depending on the energy end-use, different factors may better represent the ownership from the sector. For more structural end-uses as ambient heating and cooling, hot water, lighting, other uses and the non-identified refrigeration technologies (other refrigeration technologies), the physical factor to index the demand of useful energy is the area, or the share of the total service’s area. For office and cooking equipments, the factor that better represents size is the number of employees, or the share of employees in the sector with access to those uses. Motors and most of the refrigeration equipments are indexed to the number of equipments due to the availability of data. Finally, for public lighting the ownership is measured in MW of lighting installed. This was a solution due to lack of data available and due to no or small relation to the other energy drivers from the sector.

Due to general lack of data in relation to the stock of equipments, the total area from the sector and even the number of employees, there was a need to relate all the drivers to the GAV from the sector so that a reasonable projection of the future energy use would be obtained. Figure 14 presents the evolution of the GAV from the sector from 1998 to 2006 [69] and projections for their values until 2016 using a linear regression based on the GAV also from 1998 to 2006. The R2 correlation index for such projection was 0.99.

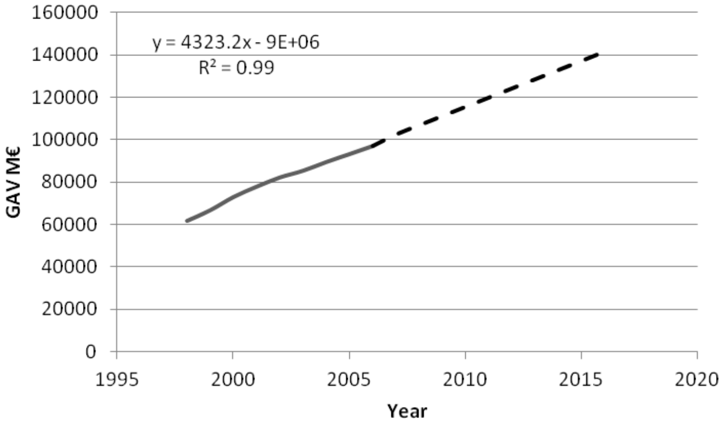


Figure 14 – Services' Gross Added Value from 1998 until 2006 [69] and projections until 2016

Using the projections from the GAV, it was possible to project the associated final energy use through time for the services sector. The final energy projections are presented in Figure 15.

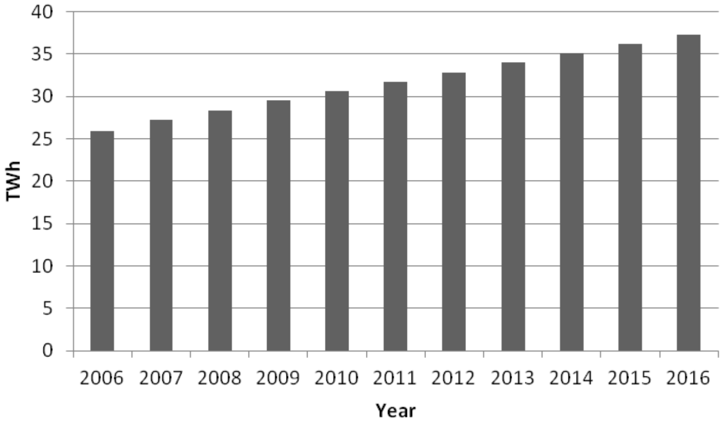


Figure 15 – Resulting projection of final energy use for the services sector by year

6.1.3. Industry sector

The energy used in the industry sector is quantified by the energy used by the main end-uses that characterize the sector, as defined in section 3.3. The main end-uses are process heating, electric motors, facility HVAC, machine drive, lighting, electro-chemical processes, onsite transportation, process cooling, CHPs, boilers, and other to represent all other end-uses not mentioned. Despite boilers and CHP are not exactly end-uses, but a mean to achieve heat to be further used and also have electricity, they are considered end-uses since they are the most relevant equipments that can be changed in the industry sector as a consequence of an EE measure. Figure 16 presents the estimated weight of each end-use in the industry sector according to the final energy used in 2006 [45] and shows that the major final energy users are the process heating, followed by CHP and electric motors.

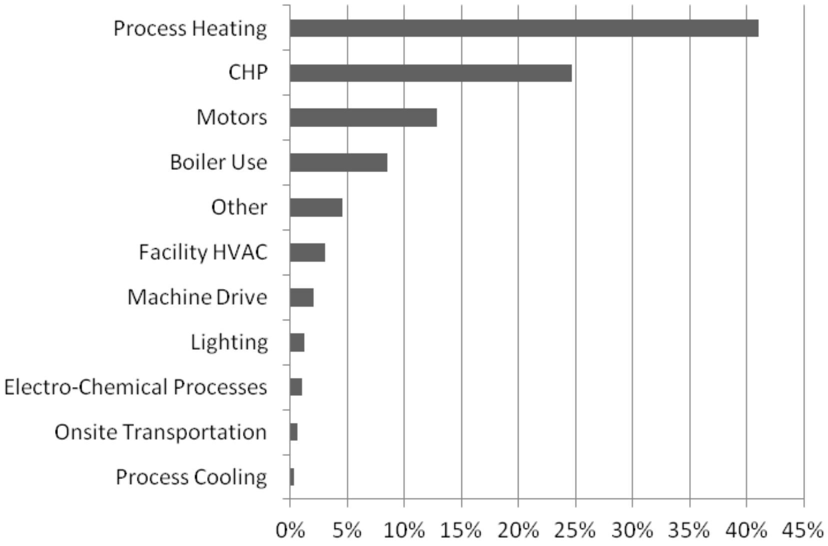


Figure 16 – Estimated Portuguese final energy share for the industry sector by end-use in 2006

For each end-use at least one technology was identified to represent it at the base year according to the available data. In the case of lack of specific data, an average technology was assigned for each energy carrier to reflect the average efficiency of the technologies in use (presented and characterized for Portugal in chapter 3). Table 60 presents the end-uses and their respective technologies found for the base year of 2006 (vide section 3.3 for data sources).

Table 60 – End-uses and their technologies in the industry sector

End-use	Technology
Boiler Use	Average by carrier
CHP	Average by carrier
Electro-Chemical Processes	Average
Facility HVAC	Average by carrier
Lighting	Fluorescent
	HID
	Incandescent
Machine Drive	Average by carrier
Motors	0 < 0.75 kW
	0.75 < 4 kW
	10 < 30 kW
	130 < 500 kW
	30 < 70 kW
	4 < 10 kW
	70 < 130 kW
	> 500 kW
Onsite Transportation	Average by carrier
Process Cooling	Average
Process Heating	Average
Other	Average by carrier

Following the same reasoning used for the services sector, the end-uses were also associated with their respective energy drivers. The final energy use is a translation of the ownership of the end-uses (measured here in installed power (MW), with the exception of motors, which were measured by number of equipments found in the sector) and the average operating hours per year. This generic approach to associate the ownership with the power installed of equipment was a solution found to harmonize and to quantify the possession of equipments due to the common lack of data characterizing the industry sector in Portugal.

Considering the Gross Added Value (GAV) from the sector as the main demand driver to influence the possession of equipments and the industry production, the frozen technology method was applied to build future energy uses (following section 3.3). The trend behind the GAV was based in a linear regression from the values from the sector between 1998 and 2006 from INE [69]. From the trend it was possible to define general energy growths of 1.63% per year from 2006 to 2010 and 1.06% from 2011 to 2020. Figure 17 presents the evolution of the GAV from the sector from 1998 to 2006 [69] and projections for their values until 2016 using a linear regression based on the GAV also from 1998 to 2006. The R2 correlation for such projection was 0.95.

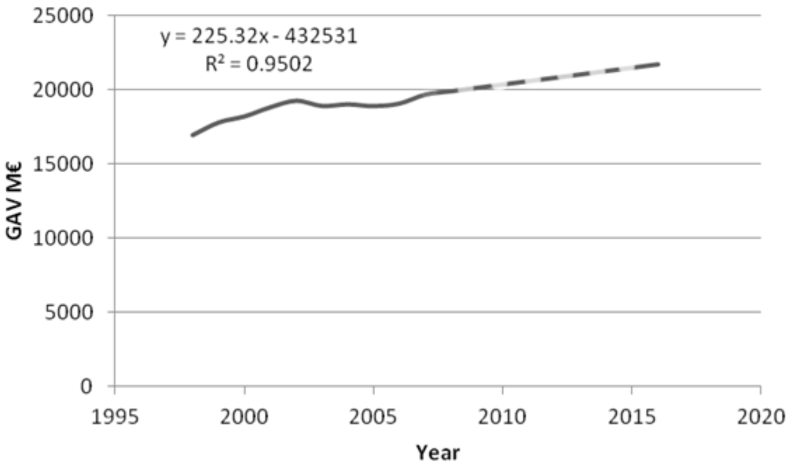


Figure 17 – Industries' Gross Added Value from 1998 until 2006 [69] and projections until 2016

Using the projections from the GAV, it was possible to project the associated final energy use through time for the industry sector. The final energy projections are presented in Figure 18.

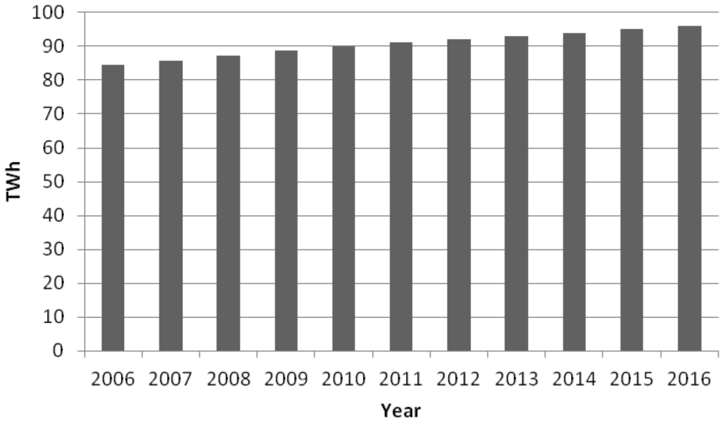


Figure 18 - Resulting projection of final energy use for the industry sector by year

6.1.4. Transport sector

The transport sector uses energy to provide mobility of people and goods. This mobility can be divided by several types or end-uses. Those end-uses can be generally organized as mobility of people and mobility of goods. The mobility of people can be sub-divided into private car transportation, mass transportation by road, rail, air and water. For the mobility of goods, freights by rail, road, air and water are the most common characterizations. The energy use for the sector can be obtained by the combination of factors that characterizes the end-uses. The main factors are the displacement of people or goods (measured in people.km or ton.km), the load factor of the end-use (as the average number of passengers in a car), and the efficiency of the vehicle, all presented in section 3.3.

Figure 19 presents the estimated weight of each end-use in the transports sector according to the final energy used in 2006 [45,114] and shows that the major final energy users are the private transportation by car followed by freight transportation on trucks and airplanes.

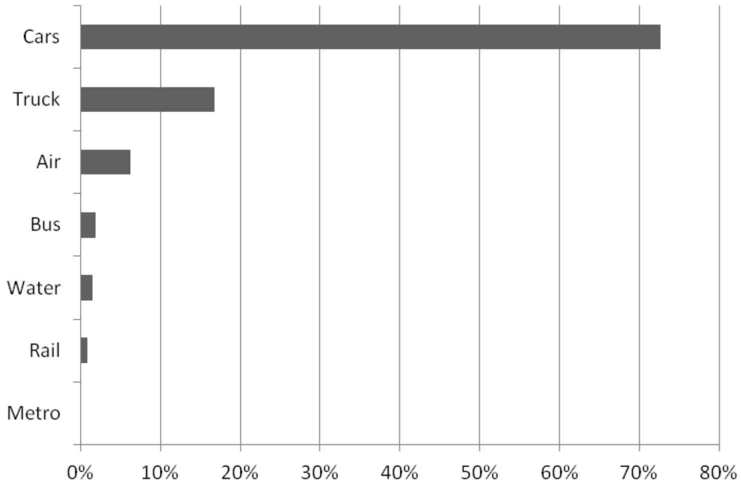


Figure 19 – Estimated Portuguese final energy share for the transports sector by end-use in 2006

For each end-use at least one technology was identified to represent it at the base year according to the available data. Due to the lack of specific data, an average technology was assigned for each end-use / energy carrier pair to reflect the average efficiency of the technologies in use (presented and characterized for Portugal in chapter 3). Table 61 presents the end-uses and their respective technologies found for the base year of 2006 (vide section 3.3 for data sources).

Table 61 - End-uses and their technologies in the transports sector

End-use	Energy Carrier	Technology
Air	Jet	Average
Bus	Diesel	Average
	Gasoline	Average
	Natural Gas	Average
Cars	Diesel	Average
	Gasoline	Average
	LPG	Average
Metro	Electricity	Average
Rail	Diesel	Average
	Electricity	Average
Truck	Diesel	Average
	Fuel Oil	Average
	Gasoline	Average
	LPG	Average
	Natural Gas	Average
Water	Diesel	Average
	Fuel Oil	Average

In order to project the energy use in the future, growths in mobility for each end-use was used according to trends found in [118] and presented in Table 62 and Table 63. Also efficiency gains were considered in each year: -0.99% until 2010 and -1.22% after 2010 for the mobility of people and -0.59% until 2010 and -0.81% after 2010 for the mobility of goods [118]. The change in mobility and the efficiency gains were converted into final energy use following the methodology presented in section 3.3.

Table 62 - Annual mobility growth for passengers [118]

	Annual mobility growth	
Passengers	2006-2010	2010-2020
Cars	3.0%	1.8%
Bus	-0.5%	0.5%
Metro	0.4%	1.6%
Rail	0.4%	1.6%
Air	2.8%	3.5%
Water	2.3%	1.4%

Table 63 - Annual mobility growth for freights [118]

	Annual mobility growth	
Freight	2006-2010	2010-2020
Truck	2.1%	2.1%
Rail	2.2%	2.1%
Water	2.8%	2.4%
Air	2.8%	3.5%

Using the mobility trends presented in Table 62 and Table 63 and the methodology presented in sections 3.3 and 3.4, it was possible to project the associated final energy use through time for the transports sector. The final energy projections are presented in Figure 20.

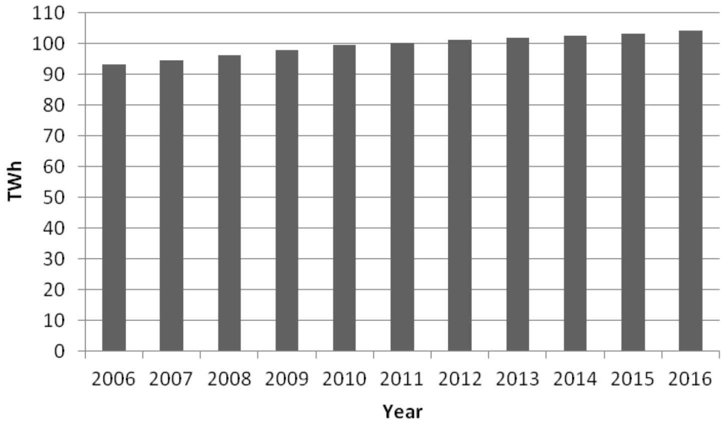


Figure 20 - Resulting projection of final energy for the transports sector by year

6.1.5. Other sectors

The other sectors are agriculture and fishery, mining and quarrying, and construction and public work. Those sectors are classified as other sectors because they can be considered less relevant in terms of final energy use (less than 5% of the total final energy use in 2006). Because of this and also because their diversity would imply a considerable modeling effort with little overall reward to offer, they were not considered to be significantly affected by any energy efficiency or conservation measure. The final energy used in agriculture and fishery, mining and quarrying and construction and public work is accounted by their main energy carriers only and are not characterized by end-uses. They are presented because there is a need to have the whole energy picture in order to calculate targets for energy efficiency plans.

Using the same evolution approach for the industry sector, the main demand driver considered were the respective Gross Added Value (GAV) from the agriculture and fishery, mining and quarrying and construction and public work. The trend behind the GAV was based in a linear regression from the values from the sectors between 2001 and 2006 from INE [69], with exception to mining and quarrying, for which the regression was made based on 1995 to 2005 due to a better, but still not good, fit. The R2 correlation indexes for the fit were 0.83 for agriculture and fishery, 0.43 for mining and quarrying and 0.63 for construction and public work. Figure 21 presents the evolution of the GAV from the sector from 1995 to 2006 [69] and projections for their values until 2016.

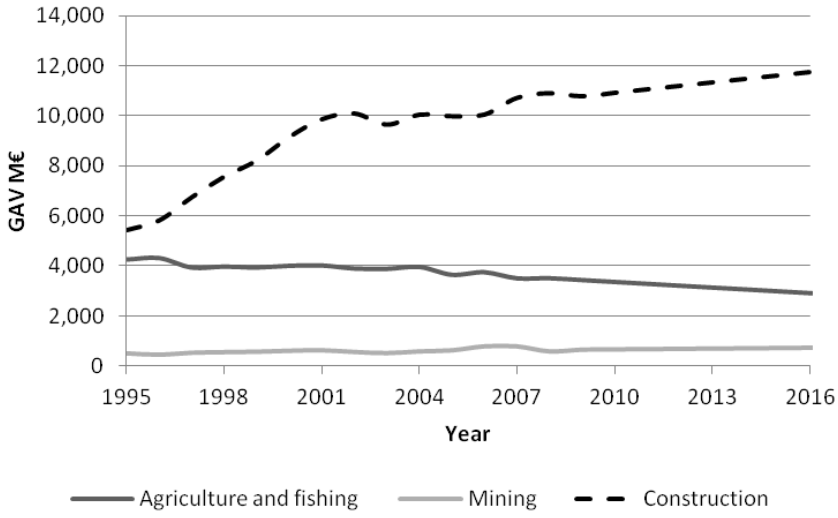


Figure 21 – Other sector's Gross Added Value from 1995 until 2006 [69] and projections until 2016

The year of 2006 was used as the base year for all the sectors in this category in accordance to the year used for the domestic, industry, services and transports sectors. The variation in energy use was applied annually starting at the base year as a top-down approach. From the trend, it was possible to define energy growths for each main energy carrier (LPG, gasoline, diesel, fuel oil, natural gas, electricity, heat, biogas, biodiesel and others) belonging to each sector. The final energy projections are presented in Figure 22.

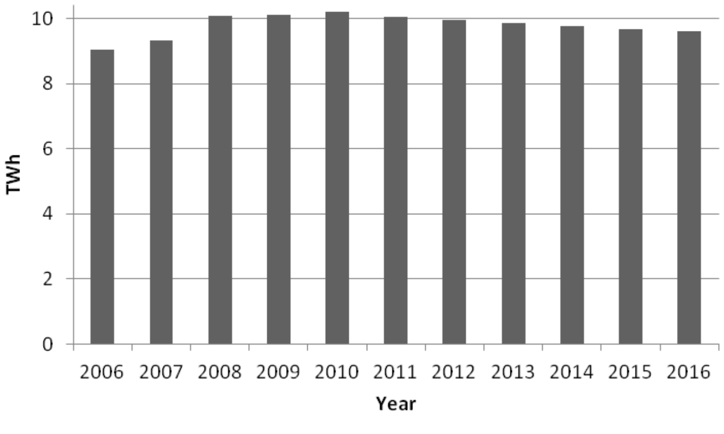


Figure 22 - Resulting projection of final energy use for the other sector by year

6.2. Selecting decision preferences

As described in section 5.4, the MOOP method NSGA-II used in this research was altered to cope with decision preferences while searching for the best alternatives in order to bring to the decision makers the set of alternatives better adapted to their preferences, "discarding" alternatives that would be present in the Pareto-optimal set but are of no relevance for them.

In order to make comparisons between decision perspectives, five decision perspectives were chosen to be used to find the corresponding preferred energy efficiency plans. The decision perspectives were built internally by the research group, to generate diversity and to allow assessing the impact of different decision makers' preferences in the output results. These perspectives are, in alphabetic order:

1. **Economic Balanced** - A perspective based on overweighting both investment costs and the risk of the investment. Here, all other objectives are considered secondary benefits with same importance.
2. **Energy Agencies** – This is the main perspective in this research. It was obtained counting the number of times that each objective was mentioned at the interviews with decision makers. Each mention found at the interviews and, also, each mention at the bibliographic review was considered as a vote.
3. **Environmentalist** – It is based on overweighting all possible emissions savings (CO_2 and TSP). All other objectives are considered secondary benefits with same importance.
4. **Equal Weights** – It is a classic approach, where no preference is given for any objective. This perspective was mainly used to find the dispersion of the alternatives in the search space.
5. **First Cost** – This perspective overweights mostly the investment costs, having all the other objectives as secondary benefits with same importance.

The outranking relations used at the ELECTRE III method was chosen to perform the preference based comparison among alternatives, and as any other multi-criteria evaluation model, it requires a set of parameters to make the preference of the decision makers operational and to allow rationalizing the comparison between alternatives. The definitions of those parameters are presented below.

The first parameters that need to be specified are the weights of each objective (or criterion). Unlike other methods, in which weights are used to express performance in a common value scale, the weights defined in ELECTRE III are not influenced by the scale on which performances are measured, making its definition much simpler because they must only reflect the abstract importance of each objective to the decision maker. Table 64 presents the weights assumed for each decision maker's perspective.

Table 64 – Weights according to decision makers' perspectives to evaluate plans

Perspective	CO2 Savings	TSP Savings	Imported Energy Savings	Electricity Savings	Investment Cost	Payback
Economic Balanced	0.05	0.05	0.05	0.05	0.40	0.40
Energy Agencies	0.12	0.09	0.48	0.09	0.11	0.11
Environmentalist	0.40	0.40	0.05	0.05	0.05	0.05
Equal Weights	1.00	1.00	1.00	1.00	1.00	1.00
First Cost	0.10	0.10	0.10	0.10	0.50	0.10

The second key parameter is the cut threshold. This threshold corresponds to the value that defines when an alternative outranks another. Given two alternatives (a and b), when the sum of the weights of the objectives in which *a* is not worse than *b* exceeds the cut threshold then it is considered that *a* outranks *b* (*a S b).* If *b* does not outrank *a* at the same time, then *a* is considered to be preferred to *b* (*a P b*). The cut threshold is important to reflect the degree of preference among options, or how flexible those preferences are. The cut thresholds were defined trying to reflect stronger preferences that could be reached by each decision maker's perspective. The cut thresholds identified were:

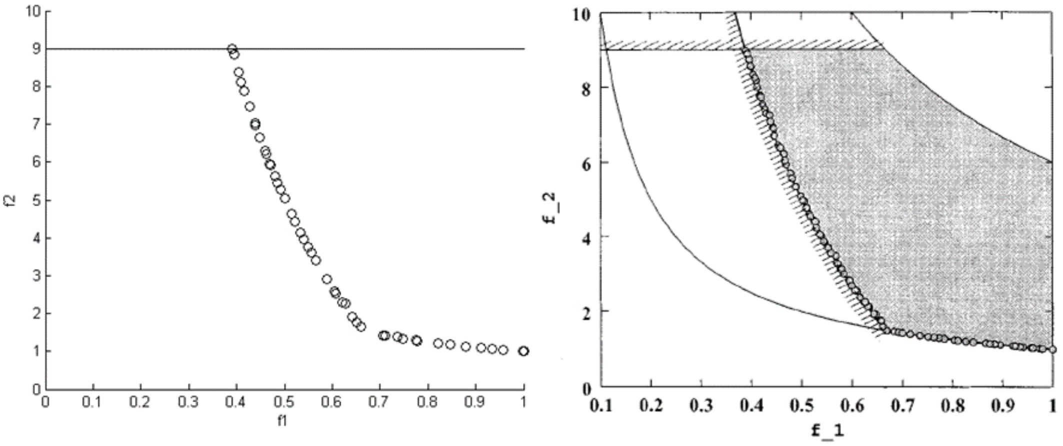
- λ=0.85 for the economic balanced and for the environmentalist perspectives, thereby requiring at least the agreement of the two objectives with weight 0.40 and one of the objectives with weight 0.05 to support an outranking assertion;
- λ=0.80 for the energy agencies, thereby requiring at least the agreement of four objectives, including mandatorily imported energy savings, CO2 savings, and one of the criteria with weight 0.11, to support an outranking assertion;
- λ=0.70 for the first cost, thereby requiring the agreement of Investment Cost plus at least two more objectives, to support an outranking assertion;
- λ=1 for the equal weights perspective, this value was attributed to have a decision perspective where the dominance relation could be observed.

The third parameter is based on the use of "pseudo-criteria" for the calculation of indices of credibility. It is necessary to determine, for each objective considered, the degree of differences that the decision makers would consider sufficiently large in order to assure, or at least best guarantee, that one alternative is really superior to another in an objective. For that, ELECTRE III uses the indifference threshold and the preference threshold. The indifference threshold for an objective represents a difference at which the decision maker cannot actually say that an alternative is really better than another according to that objective. The preference threshold reflects a difference which the decision maker is comfortable to express his preference for one alternative in a comparison to another in the respective objective. For the case of indifference it was assumed a difference of 5% between the alternatives in an objective, and 10% difference for the preference threshold. Both values were assumed based on the fact that the range of the values are not known (there is a need to search the feasible alternatives first), that fact that the data behind the model used to provide the objective values is not perfect and to try to reflect the indecision from the decision makers when two similar values are presented.

At last, the ELECTRE III outranking relations allows defining a veto threshold, corresponding to the difference between alternatives in an objective, that a decision maker considers sufficiently serious for not allowing an alternative to outrank another even if all other objectives would agree with the outranking assertion. However, despite the possibility to use such threshold, its use was discarded.

6.3. Implementing and calibrating NSGA-II for the problem

The NSGA-II algorithm was implemented in MATLAB according to the specifications presented at section 5.3. The basis of the algorithm consists in creating a random population of solutions for the problem, evaluating the population to calculate the objectives' values and restriction violations, performing the "Fast Constrained-Non-Dominated Sort" [141] [135], assigning the "Crowding Distance" [135], performing the "Crowded Tournament Selection" [135], executing the "Simulated Binary Crossover" [135], implementing the "Polynomial Mutation" [135] and selecting the best solutions to survive to the next generation. The algorithm was tested using the "CONSTR" function found at [141] and compared with the results from the same source. This comparison can be graphically seen on Figure 23 where the left plot shows the results from the implementation of the algorithm and the right figure shows the results found at the article [141]. The results were very similar with same limits and values along the Pareto-optimal front giving confidence to the implementation of the algorithm.



Results from implementation

Results from article

Figure 23 – Validation of the use of the NSGA-II algorithm: Results of the implementation in this thesis (left) vs. original source [141] (right)

Having the NSGA-II tested and working, the algorithm was adapted to find solutions for the problem of searching for the feasible energy efficiency plans. An outline of the mathematical formulation of the problem, including its restrictions, is described by the following equations.

$$Min\sum_{m=1}^{n} InvestmentCost(m) \times measureSize(m) \qquad \text{Eq. 6.1}$$

$$Max\sum_{m=1}^{n} CO_2EmissionsSavings(m) \times measureSize(m) \qquad \text{Eq. 6.2}$$

$$Max\sum_{m=1}^{n} ImportedEnergySavings(m) \times measureSize(m) \qquad \text{Eq. 6.3}$$

$$Max\sum_{m=1}^{n} TSPEmissoinsSavings(m) \times measureSize(m) \qquad \text{Eq. 6.4}$$

$$Max\sum_{m=1}^{n} ElectricitySavings(m) \times measureSize(m) \qquad \text{Eq. 6.5}$$

$$Min\ \frac{\sum_{m=1}^{n} InvestmentCost(m) \times measureSize(m)}{\sum_{m=1}^{n} MonetaryBenefits(m) \times measureSize(m)} \qquad \text{Eq. 6.6}$$

Subjected to equations 6.7 to 6.9:

$$g1(plan) = \frac{\sum_{m=1}^{n} FES(m,y) \times measureSize(m)}{TFE(y)} \times 100 \geq 9\% \qquad \text{Eq. 6.7}$$

$$g2(plan) = \begin{cases} \sum\limits_{\substack{m\in\{1..n\}:\\ m\epsilon group}} measureSize(m) \leq \frac{MSLY(m)}{MSA(m)} \times 100, if\ MSA(m) \geq MSLY(m) \\ \sum\limits_{\substack{m\in\{1..n\}:\\ m\epsilon group}} measureSize(m) \leq MSA(m) \times 100, if\ MSA(m) < MSLY(m) \end{cases} \qquad \text{Eq. 6.8}$$

$$g3(plan) = \sum_{m\epsilon\{1..n\}} \begin{matrix} 1, if\ measureSize(m) > 0 \\ 0, if\ measureSize(m) = 0 \end{matrix} \leq MAM\ ; g3\ \epsilon\ \mathbb{Z} \qquad \text{Eq. 6.9}$$

Where:

$n: Total\ number\ of\ measures$

$group: Group\ of\ measures\ that\ affects\ the\ same\ end - use\ and\ energy\ carrier$

$measureSize(m)\ \epsilon\ [0{,}100]$

$InvestmentCost(m)$: *The cost of investing in a measure* m (*chapter* 2)

$CO_2EmissionsSavings(m)$: *The savings of* CO_2*Emissions from a measure* m (*chapter* 2)

$ImportedEnergySavings(m)$: *The reduction in imported energy due to measure* m (*chapter* 2)

$TSPEmissoinsSavings(m)$: *The reductins in TSP emissions due to measure* m (*chapter* 2)

$ElectricitySavings(m)$: *The reductins in electricuty due to measure* m (*chapter* 2)

$MonetaryBenefits(m)$: *The monetary benefits from a measure* m (*chapter* 2)

$FES(m, y)$: *Final energy savings for measure* m *at the result year* y (*last on from the plan*)
(*this follows chapters* 3 *and* 4)

$TFE(y)$: *Total final energy use at year* y

$MSA(m)$: *Maximum size that a measure* m *can be physically applied*

$MSLY(m)$: *Maximum size that a measure* m *can have at the last year of the plan*

MAM: *Maximum number of measures allowed to be in one plan* ($MAM \in \mathbb{Z}$)

In this simplified outline of the mathematical formulation, the decision variables are the sizes of the measures potentially included (*measureSize(1), …, measureSize(n)*). From this simplification it is not possible to realize that the interactions between the measures are accounted for. However, they are accounted for because behind the final energy savings, and therefore, behind all the objectives, all the processes explained in chapters 3 and 4 are performed.

The minimizations and maximizations above represent the desired objectives values. The first restriction (equation 6.7) represents the minimum 9% final energy savings target in relation to the last year of the application of the plan, in this case 2016 assuming the starting year being 2008. Both the 9% savings and the definition of the last year of the application of the plan, as the ninth year after the start of the plan, are based on the ESD [5]. The second restriction (equation 6.8) limits the size of the measures affecting each end-use and energy carrier, which shall not be higher than the projected size of the respective usage indicator (e.g. ownership). In other words, it must not possible to apply more measures than what is physically acceptable by the country.

The third constraint (equation 6.9) was introduced because the plans need to have a concise size of measures to be manageable and also to reduce the search space to try to ease the converging process of the algorithm. For this, a tentative value of 100 measures was assumed.

After having the mathematical definition of the problem implemented at the algorithm, there was only one issue left to be taken into consideration: the size of the problem. Since it is beneficial to reduce the search space to the smallest size possible, in order to ease the process of finding the optimal set of solutions, and, in special, to facilitate the process of communicating the results to the decision makers, it was decided to apply the energy efficiency measures in a discrete manner, varying the application of each measure steps of 10%, regarding their maximum applicability, ranging from 0% to 100%. E.g. replacing 0%,10%, 20%...100% of the fridges stock. The next step was to apply a filter on the energy efficiency measure to exclude measures that, a priori, have negative impacts on energy savings or have an infinite payback. After filtering the measures, the algorithm was fed with 678 measures, from the initial total of 1598 available.

6.3.1. Defining parameters

Like any other genetic algorithm, the NSGA-II needs to be set to “best” suit the problem. The parameter setting is performed by attributing values to the size of the population, the number of generations, the mutation probability, the crossover probability, the distribution index and the polynomial mutation perturbation. In order to find well fitted values for those external parameters, several runs from the algorithm were performed and compared using the energy agencies perspective and are described below.

The first attempt was to find the “best” values for the distribution index and the polynomial mutation perturbation. The distribution index influences the distance between the offspring solutions and their parents, where large values increase the probability for creating “near-parent” solutions and small values allow distant solutions to be chosen as offspring. The polynomial mutation perturbation sets how different the solution will be from its original. The greater the value, the lower is the perturbation in the variable. In this attempt, both values varied on the range [0.002; 0.02; 0.2; 2; 20]. The other parameters were set to: population of 100 individuals; 500 generations; mutation probability of 0.1 and crossover probability of 0.9. In each run only one of the parameters varied leading to 25 different combinations of both parameters. The best choices for the parameter values were defined by the combination that found solutions that could be preferred to the solutions found for the other combinations (*a P b*). The preference process was performed using the ELECTRE III outranking relations considering the preference parameters described in section 5.4 for the energy agencies perspective.

The combination in which the distribution index and the polynomial mutation perturbation of 0.02 and 0.02 yielded a solution set preferred to all the solutions from the other combinations and, therefore, these values were chosen to be used.

The next test was to change the mutation probability to 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40 in order to find more dispersed and better objectives values for the solutions. For this, the same comparison was applied as before considering the other parameters set as a population of 100 individuals, 500 generations, crossover probability of 0.9 and distribution index and polynomial mutation perturbation set to 0.02. The best set of solutions came from a mutation probability of 0.10 that was preferred to all the solutions found using the other values, showing that for this problem the increase in the mutation probability did not improve the search space. The mutation probability of 0.10 was chosen to be used in the next tests.

To continue searching for better and more dispersed solutions, five population sizes were compared. The populations tested were of 100, 150, 200, 250 and 300 individuals in size. From those populations, the solution set that was preferred to all the others were still the solutions from the set having a population of 100 individuals.

Elitism raises an important issue, namely the concept of exploitation versus exploration [148]. To increase exploration and improve the chances of finding the Pareto-optimal front a controlled elitism was applied to the NSGA-II algorithm following [135] (as presented in section 5.3.5). The controlled elitism allows preserving sub-optimal fronts, providing lateral diversity on the solutions that helps the exploration of the search space and helps preventing the algorithm to converge to a sub-optimal Pareto front.

In order to compare the controlled elitism with the elitism already used, five sets of solutions were generated using the controlled elitism with the same parameters used before (distribution index and polynomial mutation perturbation of 0.02 and 0.02, mutation probability of 0.1, crossover probability of 0.9 and 500 generations) with the addition of a reduction rate set to 0.8 that is required by the controlled elitism (presented in section 5.3.5). The five sets of solutions were represented by a variation in the population size from 100 to 300 individuals, as performed before. Comparing the solutions found for the five sets using controlled elitism and the solutions found using the best set of parameters for the elitism (distribution index and polynomial mutation perturbation of 0.02 and 0.02, mutation probability of 0.1, crossover probability of 0.9, 500 generations and a population of 100 individuals), it was found that using controlled elitism with a population of 250 individuals shows general best values for the objectives and its set of solutions was preferred to all the other solutions from the other sets, except for one single solution from the elitism that remained indifferent to the set. The differences in values of the objectives and dispersion between sets can be visualized in Figure 24 and Figure 25. In both figures the dots in gray are the inferior feasible solutions (plans) found during the search, and the black dots are the preferred solutions[1] belonging to a set (as near as found) of the Pareto-optimal front representing the decision maker's preferences. From the comparison of both figures, it is possible to visualize that the solution set found using the controlled elitism reached better values in all objectives, with exception to the electricity savings, and the solutions are more dispersed in the search space. The "worse" values found for the electricity savings objective using the controlled elitism can be justified by the lower weight given to this objective and

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[1] In this work the expression "preferred solutions" is used to designate solutions such that no other solution is preferred to them.

the fact that using more electricity (in this specific case for Portugal) allows better results in emissions savings and energy import savings.

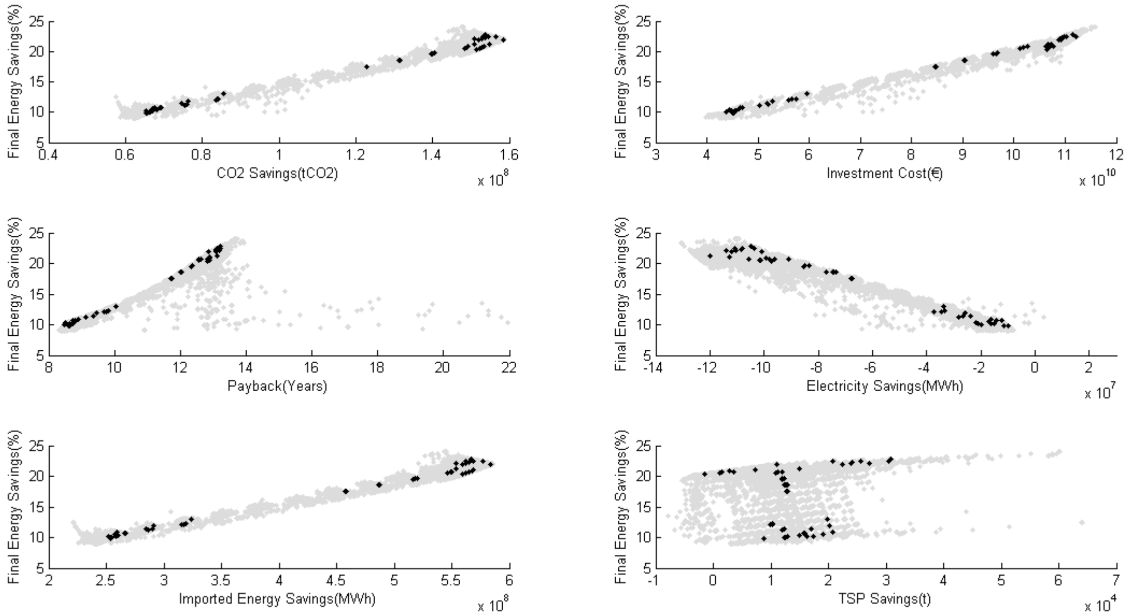

Figure 24 – Results from controlled elitism with a population of 250 individuals (best set using controlled elitism); grey dots are inferior solutions and black dots are preferred solutions

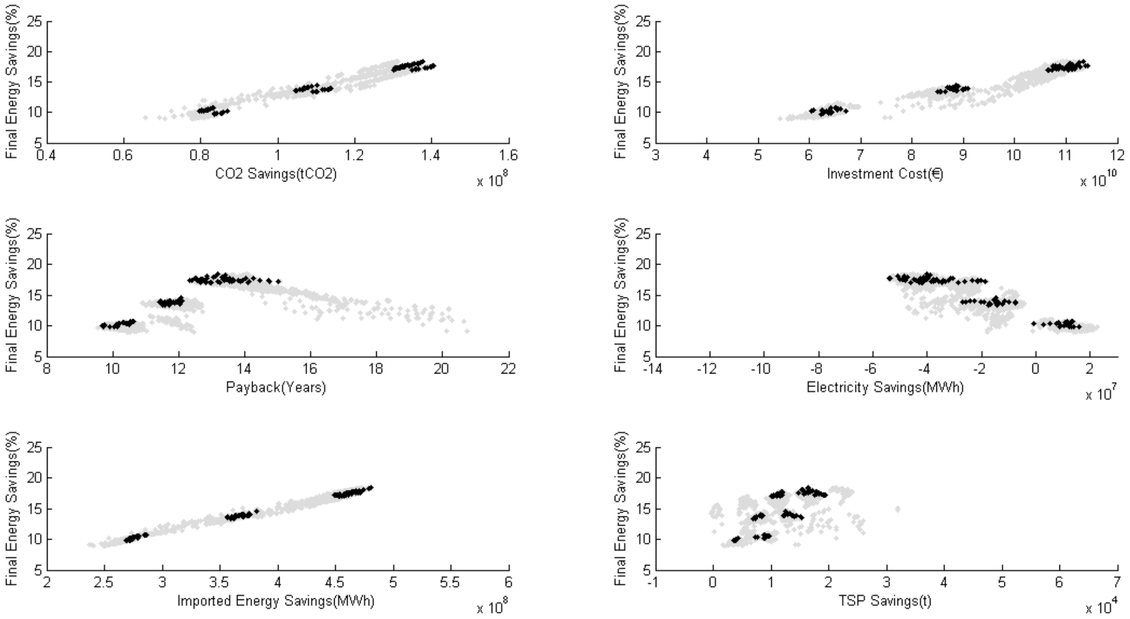

Figure 25 – Results from elitism with a population of 100 individuals (best set from all sets using elitism); grey dots are inferior solutions and black dots are preferred solutions

After choosing the controlled elitism as the process to select the individuals that will pass from one generation to the next, there was need to confirm the value of the parameter reduction rate that would be the most adequate for the problem. The reduction rate is responsible for the distribution of solution among the fronts. The higher the value, the higher is the distribution of the solutions among the fronts. To set this value, the algorithm was tested varying the reduction rate from 0.4 to 0.9 by 0.1 increments and using the already calibrated parameters plus a crossover probability of 0.9 and 500 generations. From these runs, the reduction rate that showed more diverse values and also the preferred set of solutions was the value of 0.8. This value is from now on used as a default value for the reduction rate.

The crossover probability was also tested for values between 0.8 and 1 and using the previous calibrated parameters, however the result for this parameter was not as conclusive as before, since all groups had several preferred solutions. Since the solutions with a crossover with 0.9 represented the higher number of preferred solutions, it was decided to keep this value as default.

Considering the algorithm calibrated, it was time to verify its search consistency in the path for the Pareto-optimal frontier. To perform this test 10 runs were executed using the calibrated set of parameters and the controlled elitism considering twice the number of generations (1000). Each run brings around 100 preferred solutions (the number of solution varies according to the distribution over the fronts and the actual solutions found in each front). All the results came from randomly created first populations and are presented by Figure 26.

The results show a lack of consistency in the objective values along the runs. Besides the range of the objectives, Figure 26 also presents a comparison between all solutions in all runs in order to find where the preferred solutions are. The preferred solutions can be only found in run 6 (marked).

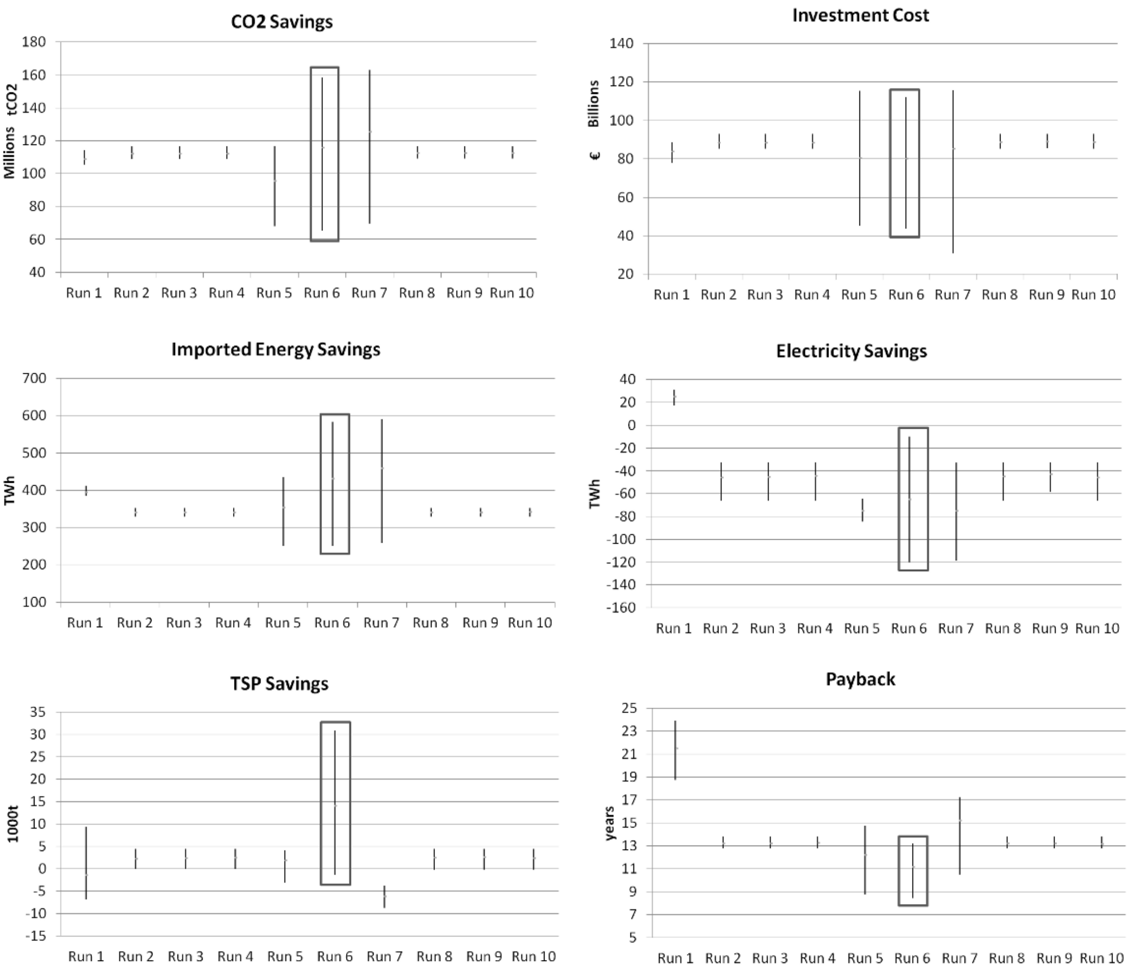

Figure 26 – Range of objectives by run, energy agencies perspective using 678 EE measures

This lack of consistency in the results would difficult the analysis of the results and compromise conclusions of this work. Therefore, to overcome this problem, it was decided to test the use of a screening of measures according to the decision makers' perspectives. The screening process was performed using the outranking relations from the ELECTRE III model to select only the preferred measures for each end-use. This allowed decreasing the dimension of the problem for the energy agencies perspective from $1x10^{706}$ to $3x10^{88}$, improving the chances to find better solutions. Next section describes how this stage was implemented.

6.4. Screening of measures and initial results

The problem of lack of consistency in the alternatives was found in the previous section and is a consequence of the size of the search space. Consequently, it is proposed to reduce the search space by reducing the available EE measures to compose plans. This reduction, or the screening process, is performed using the outranking relation of ELECTRE III to select the most fitted measures according to a decision maker's perspective. Therefore five decision perspectives were considered to evaluate the measures individually, i.e. before evaluating them as groups of measures (economic balanced, energy agencies, environmentalist, equal weights and first cost). However, since individual measures are being evaluated (and not entire plans), two other criteria were added to better evaluate them. The first criterion was the lifetime, and it was added because it was mentioned by the interviewed decision makers that it represents the objective of maximizing the benefits from the measures throughout time. The second criterion was the potential final energy savings in the last application year of the measure, being the energy savings of a measure applied at its maximum at the last application year of the measure. It was added to somehow transpose the restriction of reaching final energy savings to the evaluation of measures, since some measures with high individual final energy savings, but low total energy savings due to its scale of application, could be preferred to measures with high total final energy savings, leading to not being possible to reaching the energy saving targets. Due to the importance of satisfying the constraints of the problem, it was decided to give more weight to the potential final energy savings independently the decision maker's perspective.

Table 65 presents the weights according to the decision makers' perspectives in order to evaluate measures. Beside the weights, to perform the screening process using the ELECTRE III it was also needed to define the cut, the indifference and the preference thresholds. For the indifference and the preference thresholds it was assumed the same values as assumed for the plans, 5% and 10% difference, respectively, between the alternatives for the same criterion. The cut thresholds that were able to reflect stronger preferences were defined as 0.8 for all perspectives but the equal weights that used a value of 1.

Table 65 - Weights according to decision makers' perspectives to evaluate measures

Perspective	Potential Final Energy Savings	CO2 Savings	TSP Savings	Imported Energy Savings	Electricity Savings	Investment Cost	Payback	Lifetime
Economic Balanced	0.25	0.05	0.05	0.05	0.05	0.25	0.25	0.05
Energy Agencies	0.24	0.20	0.03	0.23	0.03	0.12	0.12	0.03
Environmentalist	0.25	0.25	0.25	0.05	0.05	0.05	0.05	0.05
Equal Weights	1	1	1	1	1	1	1	1
First Cost	0.46	0.05	0.05	0.05	0.05	0.24	0.05	0.05

The outranking relation of ELECTRE III was used for screening the preferred EE measures in groups defined by the sector, sub-sector and end-use. This approach was chosen to guarantee that there would be measures available in all sectors and to avoid the problem of incomparability between end-uses (e.g. comparing a CHP in the industry sector to a CFL lamp in the domestic sector), which would require the normalization of values or the creation of indicators to solve such problem.

That screening process allowed to find the most fitted measures for each decision maker perspective and to reduce the available measures, and consequently, the search space when building plans. Each perspective had now a set of EE measures varying from 80 measures available for the first cost perspective to 244 for the equal weights perspectives. Concerning the other perspectives there were now found 85 measures for the energy agencies, 92 measures for the environmentalist and 98 measures for the economic balanced perspective. Each set of measures is presented at the annex I.

After screening the measures, the search for the feasible alternatives was performed for the energy agencies perspective using only the selected measures with the default parameters, with the exception of the reduction rate that was changed to 0.6 due to a better performance, and using 1000 generations in a total of 10 runs. Figure 27 presents the results from 10 runs starting from randomly created populations. It is possible to observe that the results show consistency on the range of the objectives for almost all runs, excluding run 2 that had very particular results. Results now show much more consistency when compared with the results without the screening of the EE measures as presented in Figure 26. Figure 27 also presents a comparison between all solutions in all runs in order to find where the preferred solutions are. The preferred solutions can be found in runs 5, 7 and 9 (marked) totalizing 88 solutions from almost 1000 in all 10 runs. The fact that preferred solutions were found in more runs than just one also shows a good consistency in the results.

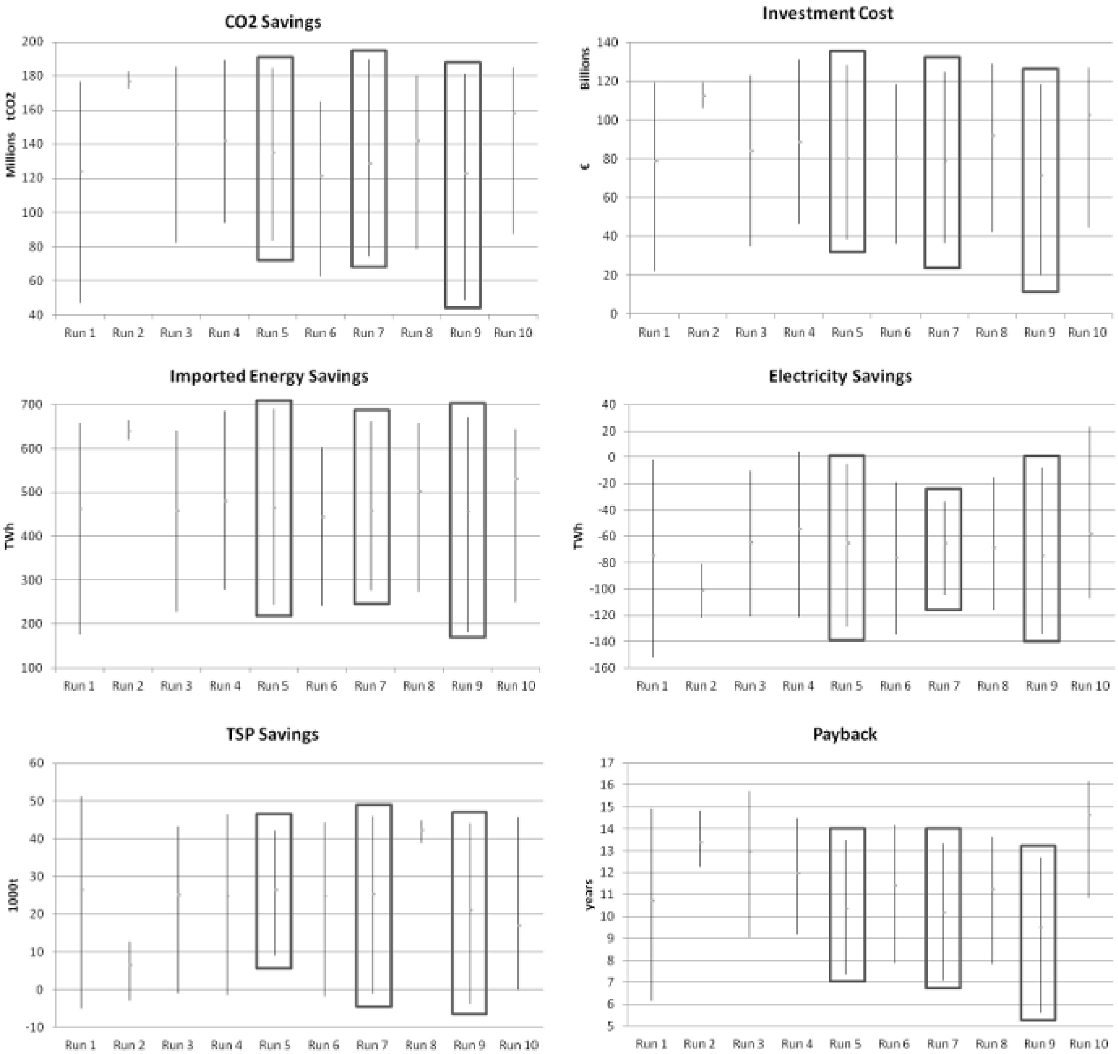

Figure 27 - Range of objectives by run, energy agencies perspective using 85 EE measures

In addition to the consistency found using the screening process, the preferred alternatives from the search using the screening process were compared with the preferred alternatives from the search using 678 EE measures. The main finding from this comparison was that all alternatives found using the screening process were preferred to the alternatives that did not use it. Besides, the values of the objectives found using the screening process were better and more dispersed, as presented in Figure 29. The better and more dispersed values of the objectives were reflected in higher and more dispersed final energy savings, presented in Figure 28.

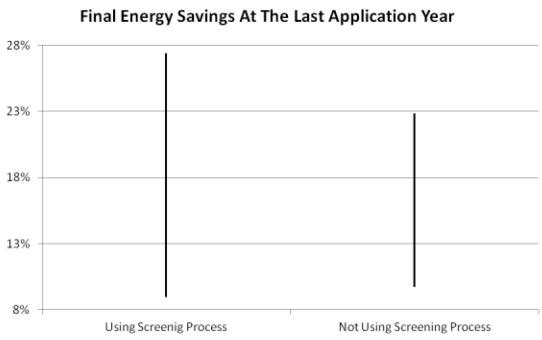

Figure 28 – Range in percent of final energy savings from plans at the last application year

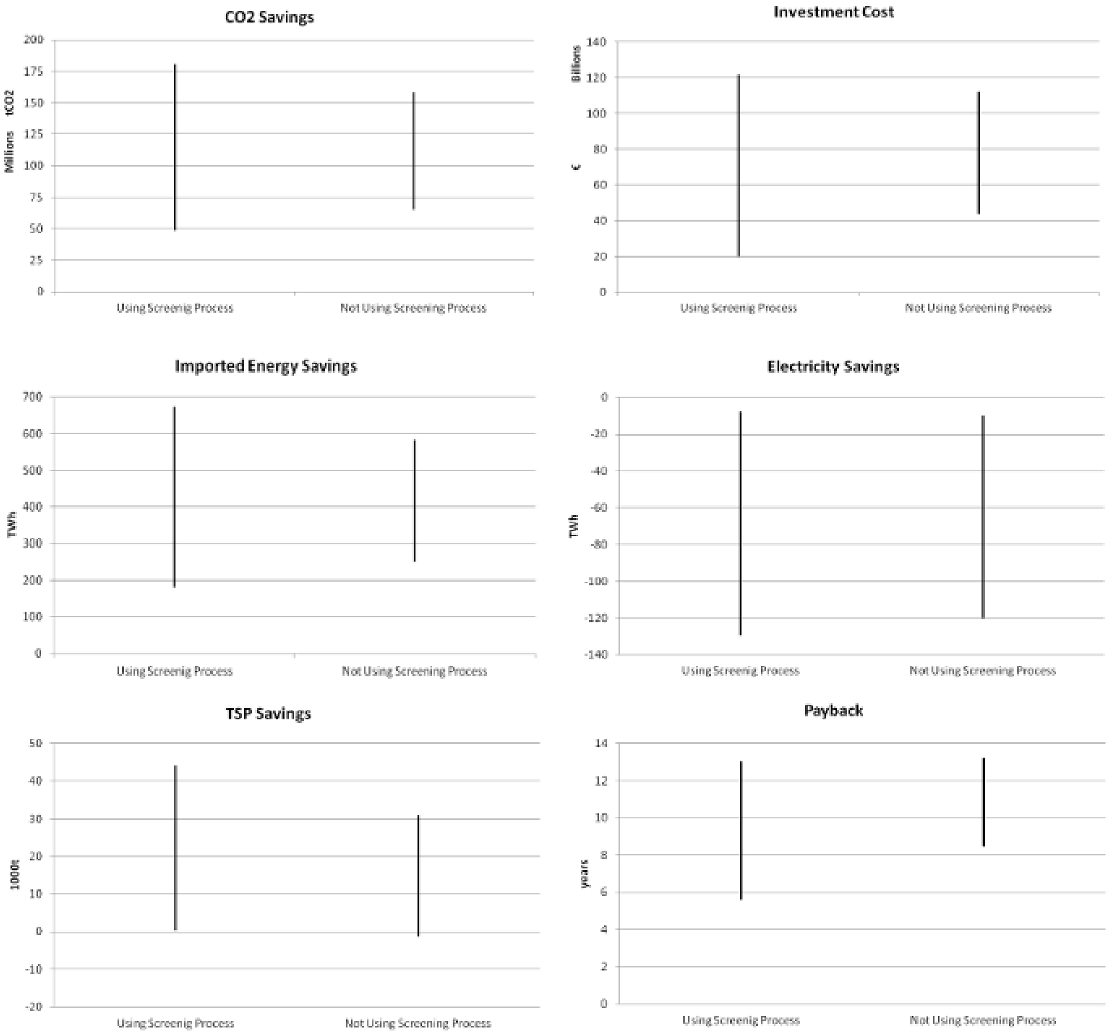

Figure 29 - Results using and not using the screening process for the energy agencies perspective

After the analysis performed, it is possible to consider that the search for energy efficiency plans is more effective and more consistent using the outranking relation of ELECTRE III to perform the screening of measures for the preferred ones before searching for alternatives (plans). Consequently, it is possible to carry out some preliminary analysis on the plans reflecting the energy agencies' perspective. First, observing Figure 28 and Figure 29, it is possible to establish a first assessment about the range of values that can be achieved in each objective and the possible savings in relation to the last application year.

The first important result, following the preferences from the energy agencies in Portugal, an energy efficiency plan would cost to the society a minimum amount rounding 20,000 M€ to reach the minimum restriction of 9% savings in the last application year, caring to get the best from the all the fundamental objectives and using the measures available. This does not say that there would not be a cheaper plan according to different decisions' preferences, but it gives an order of magnitude of the likely costs to reach targets and the desires of the decision makers. It must however be made clear that the society will bear a significant part of this cost even without any efficiency plan, since even in the reference scenario there will be many equipments (cars, fridges, TVs, etc) replaced in the next 9 years. Therefore the value presented is the total cost and not the added cost in relation to "doing nothing".

A second important results is that the accumulative imported energy savings and CO_2 emissions savings can reach values as high as 670 TWh and 180 Mt CO_2, respectively, until 2016 in Portugal by the application of EE measures if no limitation on the application of measures and the quantity of measures (in this case up to 58 measures) is applied to energy efficiency plans.

Another interesting fact is the negative electricity savings, showing that to reach improvements in the security of energy supply, reductions in emissions in general and final energy savings it may be necessary to increase the use of electricity. This is not a surprise since the electricity mix is reducing its carbon content along the years and increasing the share of endogenous resources (vide Table 5 and Table 8 for values and trends on emissions and imported energy). But to fully understand this result it important to recall that the effects of the changes in the demand over the electric supply system was left outside the boundaries of this work.

In order to observe some "trade-offs" between achieved objectives values, the plans that achieved the "best" values from the preferred set of alternatives are presented in Table 66. They were also normalized between 0 and 1 and presented in Figure 30 for better visual comparison.

Table 66 – Objective values and final energy savings for plans with limit values of objectives

Plan with limit objective	Final energy savings	CO2 emissions savings (tCO2)	Investment cost (M€)	Imported energy savings (TWh)	Electricity savings (TWh)	TSP emissions savings (t)	Payback (years)
max. CO2 savings	27.3%	180,953,575	118,353	672	(116)	41,169	12.66
min. Cost and min. Payback	9.0%	48,780,503	20,184	181	(11)	36,619	5.61
max. Imported energy savings	27.2%	180,947,713	121,812	673	(108)	38,276	13.03
max. Electricity savings	9.5%	49,384,262	21,619	184	(8)	41,299	5.89
max. TSP savings	18.3%	111,789,983	65,416	420	(53)	44,099	9.58

In Figure 30, it is possible to observe the "trade-offs" between 2 groups of objectives. The first is composed by the payback, investment cost and the electricity savings; the second is composed by CO_2 emissions savings and imported energy savings (and final energy savings which is not an objective). Clearly, in order to maximize the CO_2 emissions savings and the imported energy savings it is necessary to give up on the first group. The objective related to TSP emissions seems to be maximized independently of the change in other objectives values.

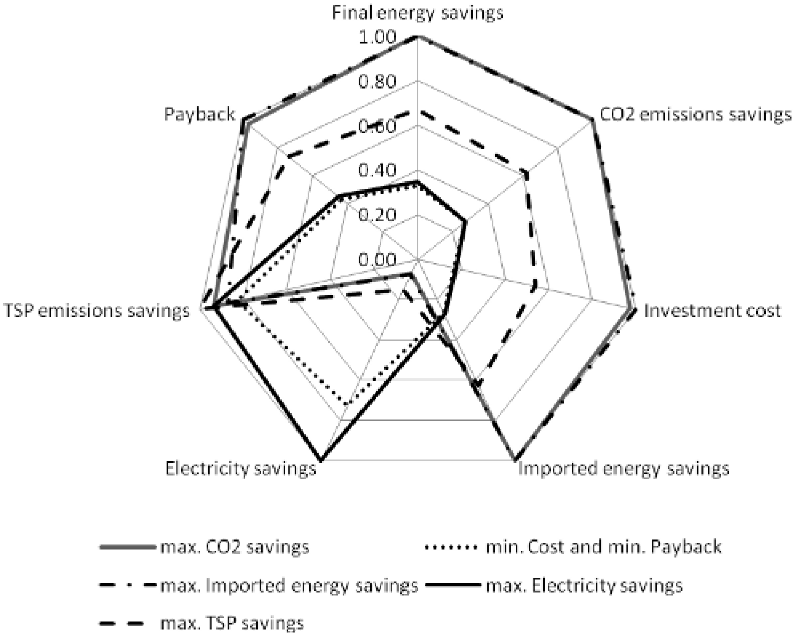

Figure 30 – Normalized objectives and final energy savings for Plans with "best" limit values

6.4.1. Assessing energy efficiency measures

Screening the EE measures, as presented in section 6.4, improved the search for better and more fitted EE plans. Besides the benefits for the search process, the screening process allowed the assessment of the selected EE measures to be present in energy efficiency plans. This assessment was performed for each decision maker preference defined in section 6.2. That screening process allowed finding the most fitted measures for each decision maker perspective, having sets of EE measures varying from 80 measures for the First Cost perspective up to 244 for the Equal Weights perspectives. The list of the selected measures is presented at the annex I. Each set of measures reflects the preferences from the respective decision maker and, therefore, not allowing a more general analysis of the measures selected, besides the fact that they do reflect the decision makers' preference and the potential final energy savings in the last application year were a key-factor in the final set of measures. However, if one observes the transversal selected measures that are common to all decision makers' preferences, it is possible to find the most relevant EE measures that can be used in energy efficiency plans for Portugal.

Table 67 presents the 39 transversal EE measures to all five decision makers' perspectives when performing only the screening of the preferred measures that are eligible to be in plans. It is possible to observe that the measures are distributed in all the four sectors modeled (domestic, industry, services and transports). The measures related to the domestic sector deal with the most representative end-uses, such as the domestic hot water and the ambient heating, and focus on both active and passive systems, such as changing heating systems and improving the insulation of houses. The measures linked to the industry sector just confirm the most applied measures in the sector, such as improving motors' efficiencies and the substitution of boilers for more efficient ones using more fitted energy carriers. The measures found for the service sector also confirm the actual trends, focusing on public lighting, lighting, electric motors and ambient cooling. However, there are measures in less recognized end-uses such as cooking and commercial refrigeration. The measures associated with the transports sector are the most different from the usual strategies, since they do not mention modal shift. This fact can be justified by the possible introduction of electric vehicles and their "promised" advantages in relation costs compared to the infrastructure costs needed by the public transports and the advantages from the use of electricity in the next years in Portugal (vide Table 5 and Table 8 for values and trends for emissions and imported energy).

Considering the energy context of Portugal and the diverse preferences among the decision makers' perspectives, it is plausible to say that the selected 39 EE measures are a reasonable starting point to build energy efficiency plans for Portugal (like a specific guideline such as the one found at the ESD [5]), and this set can be also used to make preliminary evaluations of existing plans.

Table 67 – Transversal EE measures (39) to all decision makers' preferences only for the screening process

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Domestic	All Households	Ambient Cooling	Electricity	Electricity	Replacement of ambient cooling systems for most efficient air conditioning
Domestic	All Households	Ambient Heating	Biomass	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Domestic	All Households	Ambient Heating	Biomass	Biomass	Improving wall Insulation to U = 0.38
Domestic	All Households	Clothes Drying	Electricity	Electricity	Replacement of tumble dryers for most efficient electric ones (label A, A+)
Domestic	All Households	Clothes Washing	Electricity	Electricity	Replacement of washing machines for most efficient ones (label A, A+)
Domestic	All Households	Computers	Electricity	Electricity	Replacement of computers for most efficient laptops
Domestic	All Households	Cooking	Biomass	Natural Gas	Replacement of hobs for most efficient natural gas hobs
Domestic	All Households	Dishwashing	Electricity	Electricity	Replacement of dishwashers for most efficient electric ones (label A, A+)
Domestic	All Households	Domestic Hot Water	LPG	Solar	Substitution of domestic hot water systems for most efficient solar water heaters + electric heat pump water heater
Domestic	All Households	Entertainment	Electricity	Electricity	Substitution of Audio Systems for most efficient ones
Domestic	All Households	Freezing	Electricity	Electricity	Substitution of freezers for most efficient freezers in market (A++)
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient fluorescent tube lamps
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient compact fluorescent lamps
Domestic	All Households	Refrigeration	Electricity	Electricity	Substitution of refrigerators for most efficient refrigerators in market (A++)
Industry	Cement	Motors	Electricity	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones
Industry	Chemicals Plastic and Rubber	Motors	Electricity	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones
Industry	Food and Beverage	Boiler Use	Biomass	Natural Gas	Substitution of boilers for most efficient natural gas boilers
Industry	Metal Machinery and Electro	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Industry	Metal Machinery and Electro	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones
Services	All Services	Ambient Cooling	Electricity	Electricity	Replacement of ambient cooling systems for most efficient heat pump systems
Services	All Services	Commercial Refrigeration	Electricity	Electricity	Replacement of reach-in refrigerators for most efficient ones

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Services	All Services	Cooking	Natural Gas	Electricity	Replacement of ranges for most efficient electric ranges
Services	All Services	Hot Water	Natural Gas	Solar	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater
Services	All Services	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 0.75 and 4 kW for most efficient ones
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 10 and 30 kW for most efficient ones
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 30 and 70 kW for most efficient ones
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 70 and 130 kW for most efficient ones
Services	All Services	Office Equipments	Electricity	Electricity	Replacement of computers for most efficient laptops
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Transports	Freight	Truck	Diesel	Electricity	Substitution of trucks for most efficient electric trucks
Transports	Freight	Truck	Gasoline	Electricity	Substitution of trucks for most efficient electric trucks
Transports	Passengers	Bus	Diesel	Electricity	Substitution of buses for most efficient electric buses
Transports	Passengers	Bus	Gasoline	Electricity	Substitution of buses for most efficient electric buses
Transports	Passengers	Cars	Diesel	Electricity	Substitution of individual transports for most efficient BEV

Using the measures found in Table 67 to make a preliminary evaluation of the actual energy efficiency plan for Portugal [7], it is possible to find measures in the actual plan that somehow match the measures in the table. The word “somehow” is used due to the lack of description of the measures, therefore, demanding some interpretations. Not considering the educational and behavioral measures, it is possible to match measures as:

- Incentives to replacement of cars (despite of not having more specifications on the type or technology of a car; besides being a new car following European regulations)
- Improvements in the bus fleet to low emission buses (any type)
- Incentives to replacement of refrigerators, freezers, washing machines and lamps for more efficient ones (fitting in class A or A+)
- Incentives to improvements in the insulation of houses
- Incentives to use heat pumps with high efficiency
- Substitution of office equipments for more efficient ones, as laptops
- Incentives for solar hot water in the domestic and service sectors
- Measures related to more efficient electric motors and lighting in the industry sector
- Incentives to more efficient heat production in the industry sector
- And improvements in public lighting

In a global perspective, the actual energy efficiency plan for Portugal seems to have its core measures belonging to the set of the most relevant ones encountered in this research, and despite the need for better and clearer specifications on the technical details and the calculations behind the savings, the national Portuguese plan appears to be a fitted plan to Portugal.

6.5. Comparing results for plans using different preferences

In order to get more insights to which extent the preferences of the decision makers may influence the final sets of measures in plans, and also to learn the range of the values for the attributes that quantify the achievement of the fundamental objectives, five decision makers’ perspectives were considered to search for possible plans, as defined in section 6.2. It is here recalled that these perspectives are: economic balanced, energy agencies, environmentalist, equal weights and first cost.

Following the same reasoning used in sections 6.3 and 6.4, there were executed 10 runs using randomly created populations to search for the most fitted EE plans for each decision maker’s perspective based on the respective pre-selected group of measures. The first analysis made on the results from all searches was to quantify how many EE measures were used in each decision maker perspective. Figure 31, in next subsection, presents the main findings from this analysis.

6.5.1. Impact of decision profile on the number of measures in plans

It was found that, independently of the perspective, there was no plan that used all the measures available. Furthermore, there were always a few measures that were never selected to be in any plan. However, the justification for this fact varies according to the decision maker perspective. The environmentalist perspective limits the use of measures simply by removing the direct concurrent measures on the pair end-use and energy carrier, making it possible to use all possible measures, because it allows having a higher value for costs and payback if benefits are observed in other objectives as emissions reductions. Minimizing the investment cost, as expected, works as a natural encouragement to use fewer measures, as confirmed observing the results from the First Cost and Economic Balanced perspectives. The quantity of measures for the Energy Agencies perspective plans is a balanced mix between costs, payback and the other benefits. Disconsidering the Equal Weights perspective, which yields results of different patters but which does not really reflect any decision preference, the search could find plans respecting constraints and decision makers' preferences using as few measures as 14 (economic balanced) up to 89 measures (environmentalist).

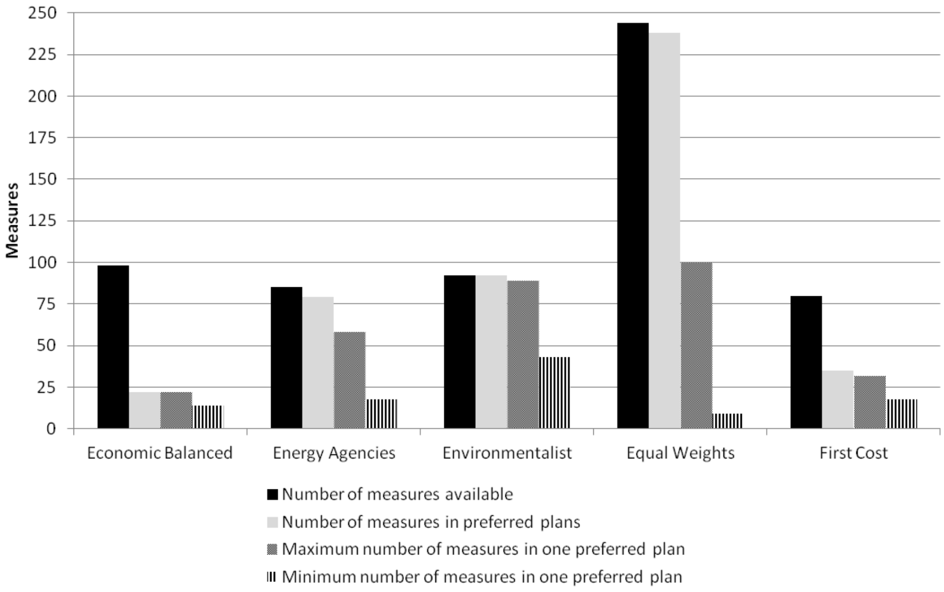

Figure 31 – Assessment of EE measures according to the decision makers' perspective

6.5.2. Impact of decision profile on the nature of the measures in the plans

Following the same reasoning used in sections 6.3 and 6.4, it is possible to find how frequently EE measures were selected to be in plans, accounting the influence of adding measures together to find “best” fitted values for the objectives of a plan.

Table 68 lists the main EE measures sorted by the frequency of appearance in all preferred plans considering all decision makers’ perspectives except Equal Weights. The Equal Weights perspective was not included from this comparison because it does not really reflect a decision preference and the appearance of measures in plans in this perspective was much dispersed, adding noise to the analysis. The top 20 measures vary their presence in plans from almost all plans (substitution of lamps for most efficient high intensity discharge lamps in the services sector) to 48% of the plans (replacement of motors with output range higher than 500 kW for most efficient ones in the industry sector) and include measures in the four sectors (domestic, industry, services and transports). The top measures by appearance in plans are very reassuring in what concerns the actual policies in Portugal, and somehow around the globe, since besides the measures to promote the use of electric trucks, which are a very recent technology and may pose concerns about its applications, all the other measures are mature and represent the most recent energy efficiency policies in use. The high use of technologies based on electricity, as listed in Table 68, confirms the benefits from the expected more endogenous and less carbon intensive power generation mix in Portugal for the coming years.

Examining the range of values reached for each objective for each decision maker’s perspective, presented in Figure 32 and Figure 33, it is possible to observe the objectives that have major importance in each perspective and the relation between objectives and final energy savings. The results in Figure 32 are very reassuring about the preferences of the decision makers, since higher values in CO_2 and TSP emissions savings are encountered for the perspective which values most these objectives (environmentalist), lower costs were found for the First Cost perspective and higher values for imported energy savings were found for the Energy Agencies perspective. As expected, the Equal Weights perspective found values for the objectives very dispersed in all objectives. Since costs and, apparently, the payback have an inverse relation with CO_2 emissions savings, imported energy savings and final energy savings, the First Cost and the Economic Balanced perspectives presented, in general, the lowest values for those objectives and stayed close to the restriction of 9% savings. However, the lowest payback found for a plan was encountered in a search guided by the preferences from the Energy Agencies.

Table 68 – Degree of application of the main EE measures for all decision makers´ perspectives (besides equal weights) for the respective preferred plans

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure	measures in plans (%)
Services	All Services	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	99
Domestic	All Households	Freezing	Electricity	Electricity	Substitution of freezers for most efficient freezers in market (A++)	96
Transports	Freight	Truck	Diesel	Electricity	Substitution of trucks for most efficient electric trucks	73
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient compact fluorescent lamps	71
Services	All Services	Ambient Heating	Diesel for Heating	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems	71
Domestic	All Households	Ambient Cooling	Electricity	Electricity	Replacement of ambient cooling systems for most efficient air conditioning	69
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones	68
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones	66
Industry	Metal Machinery and Electro	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	62
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones	61
Domestic	All Households	Clothes Washing	Electricity	Electricity	Replacement of washing machines for most efficient ones (label A, A+)	59
Domestic	All Households	Computers	Electricity	Electricity	Replacement of computers for most efficient laptops	57
Transports	Freight	Truck	Gasoline	Ethanol	Substitution of trucks for most efficient ethanol (E85) trucks	57
Domestic	All Households	Clothes Drying	Electricity	Electricity	Replacement of tumble dryers for most efficient electric ones (label A, A+)	56
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs	56
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 70 and 130 kW for most efficient ones	54
Domestic	All Households	Ambient Heating	Biomass	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems	53
Domestic	All Households	Cooking	Biomass	Natural Gas	Replacement of hobs for most efficient natural gas hobs	50
Industry	Cement	Boiler Use	Other	Natural Gas	Substitution of boilers for most efficient natural gas CHP	49
Industry	Cement	Motors	Electricity	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones	48

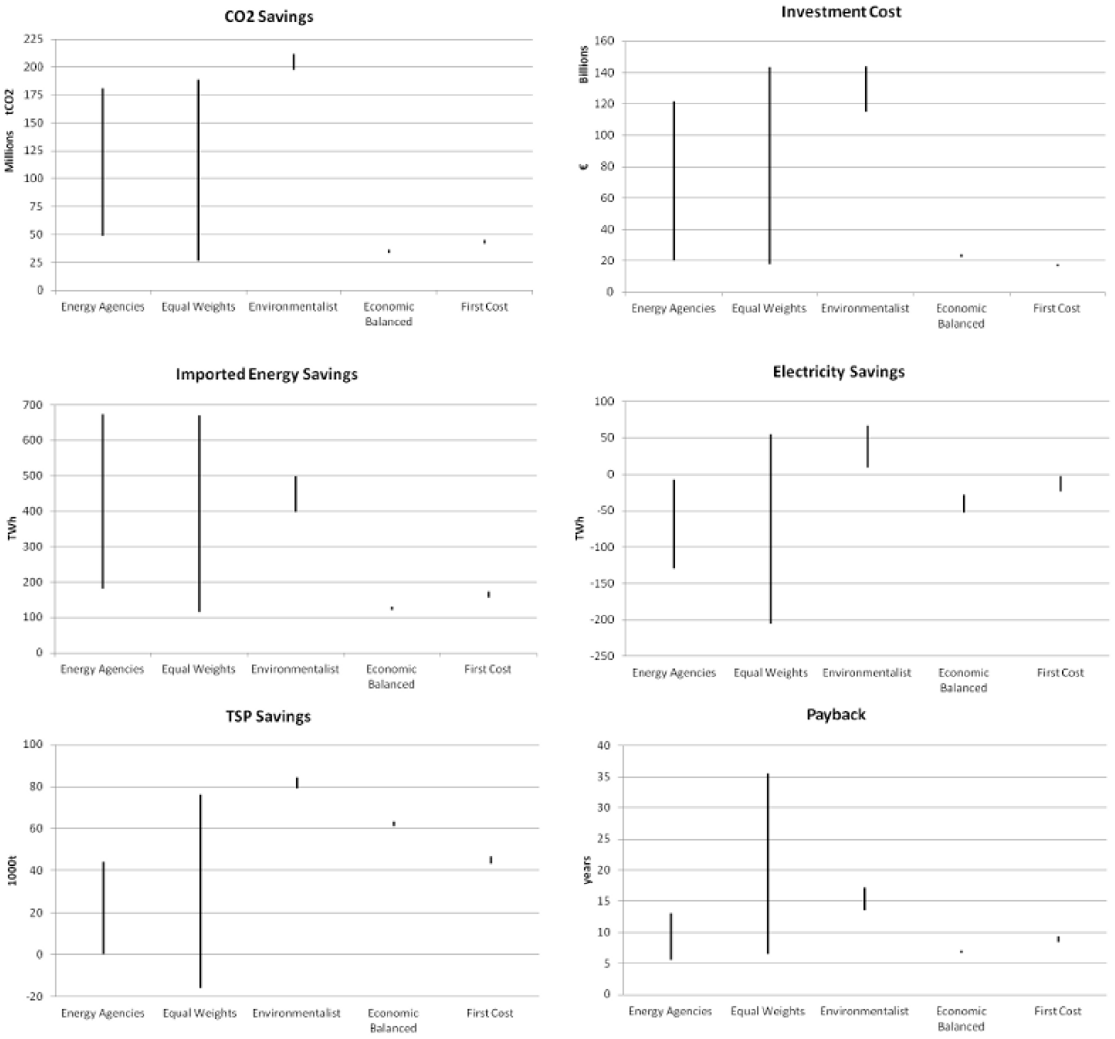

Figure 32 – Range of objectives of the preferred plans by decision makers' perspective

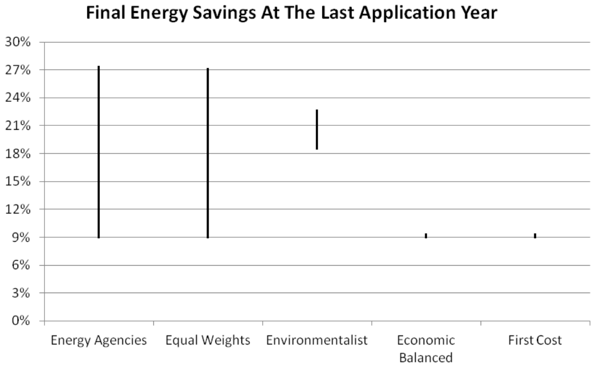

Figure 33 – Range of percentage final energy savings at the last application year, in the preferred plans of each decision maker perspective

6.5.3. Assessing plans with “best” limit values of objectives

With the intention to assess how the results from the plans behave in the six dimensions of the problem, the “best” limit values for each objective (among all the plans found) were listed in Table 69. The results are not directly comparable because each perspective reflects the preferences of the respective decision maker. However, the limit solutions can be compared to observe the “trade-offs” between their objectives to achieve the “best” value in one. Also, this table brings a numerical confirmation of the expected results from each decision maker’s perspective, as showing the cheaper energy efficiency plan, costing 16 673 M€, brought by the First Cost perspective.

Another interesting analysis regarding Table 69 is to compare both plans that achieved the minimum proportional final energy savings, 9%. Both plans are from different decision preferences, however, they illustrate the fact that there exists more than one plan capable of reaching the targets and showing different benefits for the objectives. It also shows that the payback is not directly related to the investment cost, and, despite the investment cost and the TSP savings, the plan presented by the first cost has no better objectives’ results than the one presented by the energy agencies’ perspective, and actually, if both plans were compared by the energy agencies’ perspective, the second solution (from the Energy Agencies) would be preferred.

Table 69 – Objective values and final energy savings for plans with limit values of objectives

Limit	Perspective	Final energy savings	CO2 emissions savings (tCO2)	Investment cost (M€)	Imported energy savings (TWh)	Electricity savings (TWh)	TSP emissions savings (t)	Payback (years)
max. CO2 savings	Environmentalist	20.6%	211,564,706	135,021	449	27	81,160	16.66
min. Investment cost	First Cost	9.0%	42,864,537	16,673	159	(14)	45,715	8.53
max. Imported energy savings	Energy Agencies	27.2%	180,947,712	121,811	673	(108)	38,276	13.03
max. Electricity savings	Environmentalist	19.2%	198,152,477	134,033	409	66	84,377	14.1
max. TSP savings	Environmentalist	19.2%	198,152,477	134,033	409	66	84,377	14.1
min. Payback	Energy Agencies	9.0%	48,780,503	20,184	181	(11)	36,619	5.61

The analysis performed in this section, using multiple decision makers’ perspectives, allowed the confirmation that the proposed approach to the problem of finding energy efficiency plans is respecting the decision makers’ preferences. It also enables to identify the more consistent measures independently the preference used, and to give insights about how much can be achieved in each objective and the possible “trade-off” in the other objectives.

6.6. Impact of limiting the maximum number of measures in plans

Despite the fact that the issues related with the mechanisms to implement the measures are generally outside the boundaries of this research, or, in fact, are left to be evaluated in a subsequent stage of the decision process, it was decided to observe possible impacts on the results of accounting for a common preference of the political decision, which is to focus only in a limited, often small number of measures to be supported. This political decision, generally, is not only a restriction per se, but a reflection of the effort needed to organize and manage each EE measure.

Following the same reasoning used in section 6.3, 10 runs using randomly created populations were executed to search for the most fitted EE plans, for the energy agencies' perspective based on the respective pre-selected group of measures and a restriction to the maximum number of EE measures in one plan. To assess this limitation, five constraints to the maximum number of measures in one plan were used: 100, 50, 25, 10 and 5 measures. To make the assessment only on the relevant solutions, all the solutions from all the runs for each constraint on the maximum number of measures were compared to find each set of preferred solutions. The impacts on the results from the constraint to the number of measures are presented in Figure 34 and Figure 35.

Besides the range of the objectives' values, both figures show the preferred set of solutions from the comparison between all sets (the set marked). Observing Figure 34 and Figure 35 it is possible to realize that lowering the maximum number of measures may also lower the quality (i.e., the best values found for the objectives) of the plans. This effect is generally not very noticeable for decreases up to 25 measures, but can be clearly seen in objectives as the imported energy savings or the payback if not allowing more than 10 measures. The exception is the investment cost, whose minimum limit has a significant increase when decreasing form 100 to 50 measures. However, the limitations still allow the plans to fulfill targets (even if allowing only 5 measures).

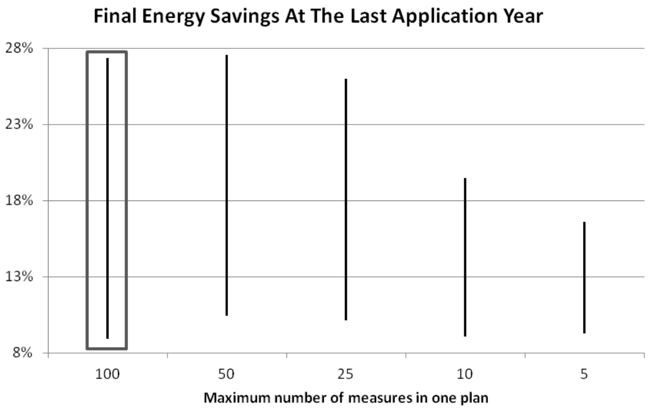

Figure 34 - Range of percentage final energy savings at the last application year; the rectangle identifies the preferred set of solutions

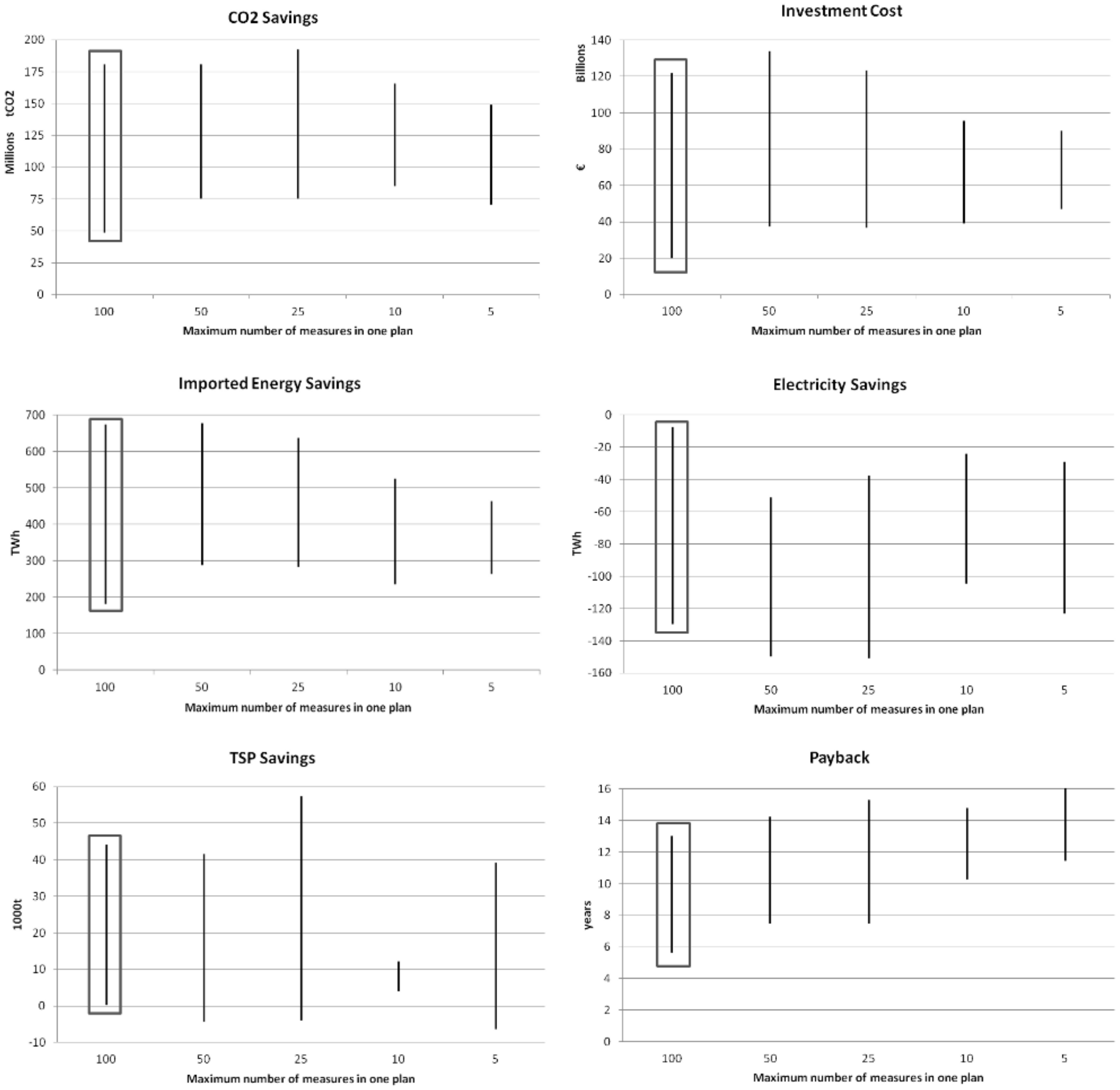

Figure 35 – Range of objectives resulted from the maximum number of measures permitted in plans; the rectangle identifies the preferred set of solutions

Despite the fact that it may impact the quality of plans, there are some benefits related to the implementation process of the measures, which are not accounted here, such as the cost of managing the measures.

Another important point to raise is that there is a tendency for the search algorithm to use as much as possible (in terms of measure size) from each of the most measures and this fact may introduce a risk on the success of plan, since it may be hard, to change all “equipments” used by an end-use to a new one. In a case where many measures are used, this risk is spread among measures. However, when a few measures are used, this risk is concentrated and may compromise the expected outcomes. The consequences of limiting the size of the measures in a plan are analyzed in the next section.

6.7. Impact of limiting the size of measures in plans

The previous section raised a potential policy problem of limiting the size of measures in energy efficiency plans. This problem is relevant because, despite the technical potential observed in a country for the implementation of an EE measure, it is risky to assume that all of its theoretical potential can be reached in practice. For this, it would be often necessary to mobilize a huge number of agents and participants. Despite all the advantages offered by the measures to the participants, not all of them may be available to embrace the measure, especially when investment is needed on the participant side. Also, they may just not be aware or interested in being part of the process. Being aware of such problem, it was decided to analyze the impacts of limiting the maximum application size of an EE measure in a plan to 100, 80, 50 and 20 percent of the modeled potential application. Following the same reasoning used in section 6.3, 10 runs for each restriction to the maximum size of a measure were executed, using randomly created populations, to search for the most fitted EE plans for the Energy Agencies’ perspective based on the respective pre-selected group of measures. To make the assessment only to the relevant solutions, all the solution from all the runs for each restriction were compared to find each set of preferred solutions. The impacts on the results from the restrictions are presented in Figure 36 and Figure 37. In addition to the range of the values of the objectives, both figures show the preferred set of solutions (the set marked) from the comparison between all sets. Observing Figure 36 and Figure 37 it is possible to conclude that the lower the maximum size of a measure is, the “worse” the outcomes from the plans are. It is also possible to observe that the dispersion of almost all the results is decreasing as the restriction on the measure size is increasing.

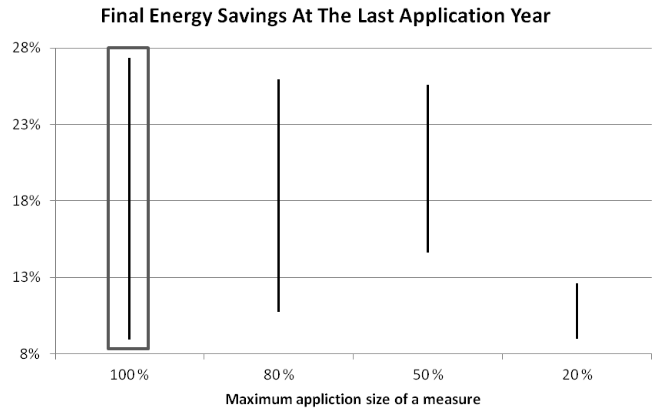

Figure 36 - Range of proportional final energy savings at the last application year

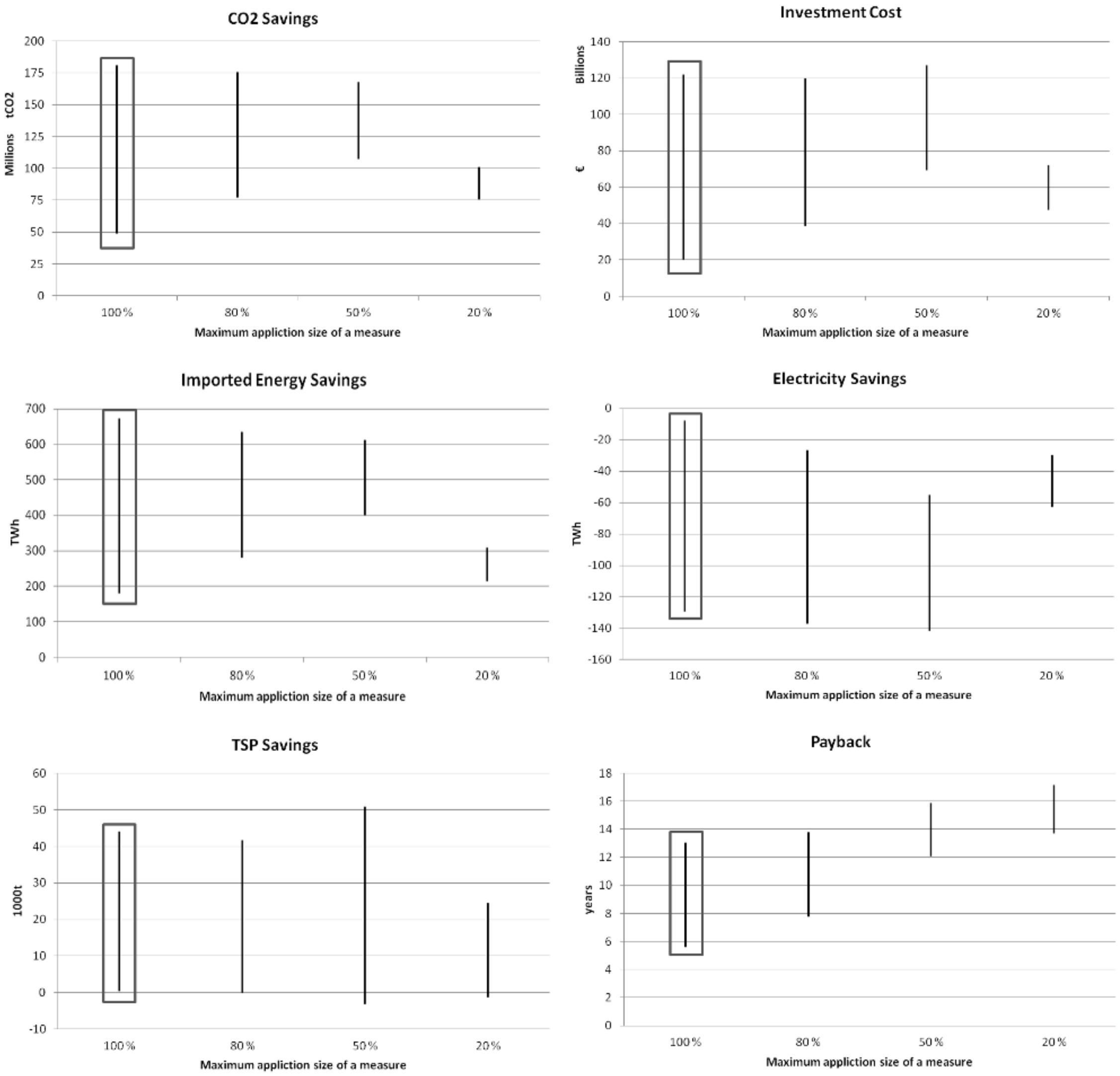

Figure 37 – Range of objectives by maximum permitted application size of a measure in plans

Still analyzing Figure 36 and Figure 37, for restrictions as low as 50% of the potential application size, it is still possible to reach high values for CO_2 savings, imported energy savings and final energy savings. However, those solutions with higher values are preferred to solutions with lower values, restricting the cheapest solutions to appear among the preferred solutions according to the Energy Agencies (Figure 38). Nevertheless, the case of existing feasible solutions for lower costs, and even lower emissions or imported energy savings, but excluding them from the final set of solutions due to preferences, is not applicable when the restrictions reach a maximum of 20% of the potential to apply EE measures, as can be observed in Figure 38. Figure 38 presents plots of the results of the objectives imported energy savings versus the investment cost. It can be clearly observed that the restriction of 20% affects the space of feasible solutions.

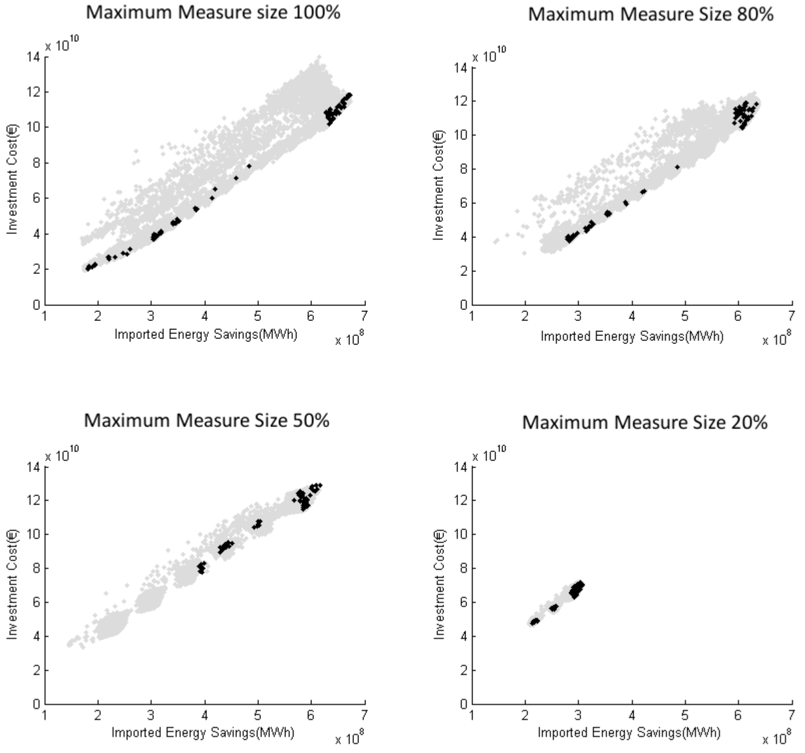

Figure 38 – Search for the Pareto-optimal front using restrictions on measure size; gray dots are inferior solutions and black dots are the preferred ones

Reducing the size of application of a measure also has another (logical) consequence: the increase in the number of measures in a plan. Observing Figure 39, it is possible to see the growth of both the maximum number of measures in a plan and the growth at the minimum number of measures in a plan. As the restrictions on the application of measures increase, it is expected that the plans resort to more measures to fulfill other restrictions, as minimum savings, and also to achieve the best results as possible.

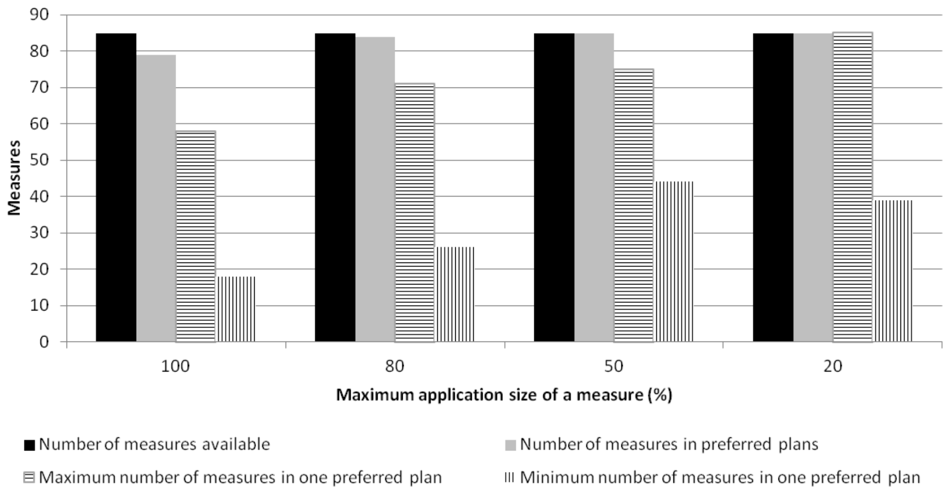

Figure 39 - Assessment of the number of EE measures in preferred plans according to their maximum application size

The analysis performed on the maximum application size of an EE measure in a plan thus showed that it is possible to apply such a restriction when searching for plans, but also that such limitation may affect the “quality” of the plans, in especial if the limit for the penetration (maximum size) of measures is set at 20% of the maximum potential.

6.8. Complementary procedures to converge into a plan

The set of methods proposed so far in this thesis was developed and organized to be used as a first iteration to help the decision process when building energy efficiency plans. Its result is a typically still large number of alternatives (plans) that best match the decision maker stated objectives. This process was illustrated for Portugal in this chapter, showing how to identify a number of preferred potential plans and the ranges of achievement possible in each of the six attributes of this work.

However, in a real decision process, it is still necessary to identify a much smaller number of plans, which may constitute the pool for the final choice from the decision makers, which at this final stage may bring into account preferences related with implementation. This number must be small enough to allow the decision makers to look at the actual configuration of each plan. Two different processes of achieving this convergence to a very of number of alternatives for the final choice are presented in this subchapter.

The first starts with further exploring the results from the previous sections to gain further insights, and possibly introducing new and more specific restrictions, such as the maximum budget available to implement the plan, the maximum number of measures to manage and how much they can really be implemented. The decision maker can even work on a “trade-off” analysis between plans to estimate relations between pairs of objectives in order to find until how much they are open to loose in one objective to benefit from the other. In theory, the budget limitation is decided after this stage, because there is a problem in pricing something for which the value is unknown. Furthermore, establishing a restriction “a priori” may compromise the achievement of the targets and the quality of the results. After this iteration, it is necessary to re-execute the hybrid NGSA-II algorithm to identify the new group of measures that are fitted to this more specific situation. In a case the number of available plans is still too big, it is recommend increasing the restrictions until a suitable group of plans is found. If the number of plans suggested by the method is still big, but the decision maker really feels indifferent among them, it is possible to resort to a facility provided by the search algorithm (hybrid NSGA-II) to bring a minimal number of most dispersed plans at the final “Pareto-optimal” front. The algorithm naturally brings the most dispersed solutions thanks to the crowding comparison performed (presented in chapter 5), and the limitation can be made operational by defining the size of the population for the last iteration of the algorithm equal to the desired number of solutions.

The second option of selecting a very low number of plans for the final set is to do directly the last procedure of method 1: to analyze the full range of preferred solutions and to choose N (a number defined by the decision maker) which are the most dispersed solutions taking into consideration all the objectives involved.

Here is presented an example using the preferred solutions from the runs performed at section 6.4 for the energy agencies’ perspective. These solutions are fed to the method, instead of starting random populations, and executed for only one generation limited by a population of six individuals to find the six most dispersed solutions. This single iteration is performed just to use the algorithm to perform the section of the final set of solutions based on the crowding distance and the defined number of solutions. The six selected plans presented as a “final” solution to the problem have their results presented in Table 70 , and their respective measures are presented in Table 71. Since the problem has 6 objectives to be optimized, the consequence of such search for the most dispersed solutions using a small number as six, brings the solutions with minimum and maximum values for the objectives (Table 70). Besides the actual measures used in each plan, Table 71 also presents the application size of each measure to be used as information about the measures and also to help deciding for a single plan to apply.

In general, the final intention in a decision process for designing and selecting an EE plan is to converge towards a single plan to be effectively applied to a country. Therefore, after following the previous process to reduce the total number of preferred plans to a very low number, the decision maker may finally select one. This final process can be as refined as applying another MCDA method to choose one, or it may simply result from the holistic assessment of the decision maker, possibly after consulting other opinions. In any case, it has been ensured that the final choice is made among the set that best corresponds to his stated objectives.

Table 70 – Results from 6 most dispersed alternative plans from the final set of preferred plans for the Energy Agencies decision perspective

Plan	Final Energy savings (%)	CO2 emissions savings (t)	Investment costs (M€)	Imported energy savings (TWh)	Electricity savings (TWh)	TSP emissions savings (t)	Payback (years)
1	26.4	174,224,999	117,580	646	(97)	43,225	12.90
2	26.8	176,808,059	119,804	658	(92)	42,709	12.87
3	9.1	48,920,950	20,520	181	(10)	36,843	5.68
4	23.1	173,305,128	103,508	637	(119)	(1,819)	11.87
5	10.2	52,609,391	23,897	196	(11)	45,329	6.15
6	26.75	178,471,168	115,204	660	(129)	39,579	12.57

Table 71 – Measures for the 6 most dispersed alternative plans from the final set of preferred plans for the Energy Agencies decision perspective

sector	sub-sector	target energy carrier	measure	Measure Size (%)					
				Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6
Domestic	All Households	Biomass	Improving wall Insulation to U = 0.38	100	100	80	0	100	100
Domestic	All Households	Natural Gas	Improving wall Insulation to U = 0.38	100	90	0	0	0	0
Transports	Passengers	Diesel	Modal shift from bus to trains	90	90	90	90	90	90
Domestic	All Households	Electricity	Improving windows (low-E) Insulation to U = 2.5 and air renovation = 1	100	20	0	0	0	60
Domestic	All Households	Diesel for Heating	Improving wall Insulation to U = 0.38	0	100	0	0	0	0
Domestic	All Households	Electricity	Improving wall Insulation to U = 0.38	0	80	0	0	0	0
Transports	Passengers	Natural Gas	Modal shift from bus to trains	0	100	100	100	100	100
Transports	Passengers	Gasoline	Modal shift from bus to trains	0	0	50	100	20	60
Services	All Services	Electricity	Replacement of ambient cooling systems for most efficient heat pumps	100	20	0	0	0	0
Domestic	All Households	Diesel for Heating	Replacement of ambient heating systems for most efficient centralized electric heat pump systems	100	0	0	0	0	0
Services	All Services	Fuel Oil	Replacement of ambient heating systems for most efficient centralized electric heat pump systems	100	100	100	100	100	100
Services	All Services	Diesel for Heating	Replacement of ambient heating systems for most efficient centralized electric heat pump systems	0	10	100	100	100	100
Domestic	All Households	Electricity	Replacement of ambient cooling systems for most efficient air conditioning	0	0	100	100	100	100
Domestic	All Households	Diesel for Heating	Replacement of ambient heating systems for most efficient centralized natural gas heating	0	0	70	100	90	60
Domestic	All Households	Electricity	Replacement of dishwashers for most efficient electric ones (label A, A+)	100	90	0	0	0	0
Domestic	All Households	Electricity	Replacement of computers for most efficient laptops	100	100	0	100	20	40
Domestic	All Households	Diesel for Heating	Replacement of hobs for most efficient natural gas hobs	100	100	10	100	30	60
Services	All Services	Electricity	Replacement of computers for most efficient laptops	0	100	60	100	60	60
Domestic	All Households	Biomass	Replacement of hobs for most efficient electric hobs	0	10	60	100	60	60
Services	All Services	Electricity	Replacement of motors with output range between 0 and 0.75 kW for	70	90	90	0	100	10

sector	sub-sector	target energy carrier	measure	Measure Size (%)					
				Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6
			most efficient ones (EFF3)						
Services	All Services	Electricity	Replacement of motors with output range between 10 and 30 kW for most efficient ones (EFF3)	100	90	10	0	20	40
Industry	Paper	Electricity	Replacement of motors with output range between 0.75 and 4 kW for most efficient ones (EFF3)	100	90	30	0	50	90
Industry	Cement	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones (EFF3)	100	0	100	100	100	60
Services	All Services	Electricity	Replacement of motors with output range between 0.75 and 4 kW for most efficient ones (EFF3)	0	100	0	0	0	60
Industry	Paper	Electricity	Replacement of motors with output range between 10 and 30 kW for most efficient ones (EFF3)	0	0	50	0	80	40
Industry	Paper	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones (EFF3)	0	0	0	100	20	10
Services	All Services	Electricity	Replacement of motors with output range between 30 and 70 kW for most efficient ones (EFF3)	100	90	0	0	0	60
Services	All Services	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones (EFF3)	0	100	60	100	60	60
Services	All Services	Electricity	Replacement of motors with output range between 70 and 130 kW for most efficient ones (EFF3)	0	80	0	0	0	0
Industry	Paper	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones (EFF3)	0	0	70	100	50	10
Industry	Chemicals Plastic and Rubber	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones (EFF3)	0	0	60	100	80	60
Industry	Cement	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones (EFF3)	0	0	30	0	50	90
Domestic	All Households	Electricity	Replacement of washing machines for most efficient ones (label A, A+)	100	100	0	0	0	0
Domestic	All Households	Electricity	Replacement of tumble dryers for most efficient electric ones (label A, A+)	100	100	0	100	20	10
Domestic	All Households	Electricity	Substitution of Audio Systems for most efficient ones	100	80	0	0	0	0
Services	All Services	Electricity	Replacement of reach-in refrigerators for most efficient ones	100	100	70	100	90	10
Services	All Services	Natural Gas	Replacement of ranges for most efficient electric ranges	70	100	100	100	100	100
Services	All Services	Diesel for Heating	Replacement of ranges for most efficient electric ranges	100	100	60	100	60	60
Services	All Services	LPG	Replacement of ranges for most efficient electric ranges	0	100	100	100	70	90
Industry	Food and Beverage	Diesel	Substitution of boilers for most efficient electric boilers	0	0	0	100	10	40
Industry	Food and Beverage	Biomass	Substitution of boilers for most efficient natural gas boilers	100	0	0	0	0	0
Industry	Cement	Other	Substitution of boilers for most efficient natural gas CHP	100	90	100	100	100	100
Industry	Cement	Other	Substitution of boilers for most efficient oil CHP	0	10	0	0	0	0
Domestic	All Households	Electricity	Substitution of freezers for most efficient freezers in market (A++)	100	90	100	100	100	100

sector	sub-sector	target energy carrier	measure	Measure Size (%)					
				Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6
Domestic	All Households	LPG	Substitution of domestic hot water systems for most efficient natural gas tankless water heaters	50	50	0	0	0	0
Domestic	All Households	LPG	Substitution of domestic hot water systems for most efficient solar water heaters + electric heat pump water heater	0	0	0	0	0	60
Services	All Services	Diesel for Heating	Substitution of hot water systems for most efficient electric tankless water heaters	100	90	0	0	0	0
Services	All Services	LPG	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater	30	90	0	0	0	0
Services	All Services	Natural Gas	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater	100	90	100	0	90	60
Services	All Services	Fuel Oil	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater	0	100	0	0	0	0
Transports	Passengers	Gasoline	Substitution of individual transports for most efficient BEV	0	0	0	0	0	60
Domestic	All Households	Electricity	Substitution of lamps for most efficient compact fluorescent lamps	100	90	100	100	100	80
Domestic	All Households	Electricity	Substitution of lamps for most efficient fluorescent tube lamps	100	100	0	0	0	0
Transports	Passengers	Diesel	Substitution of individual transports for most efficient PHEV	100	100	0	100	0	100
Transports	Passengers	Gasoline	Substitution of individual transports for most efficient PHEV	100	100	0	100	10	40
Domestic	All Households	Electricity	Substitution of lamps for most efficient compact fluorescent lamps	0	0	60	100	60	60
Services	All Services	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	100	100	100	100	100	100
Industry	Metal Machinery and Electro	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	100	100	100	0	90	60
Industry	Metal Machinery and Electro	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	100	0	100	100	100	60
Services	All Services	Electricity	Substitution of lamps for most efficient high intensity discharge lamps	100	0	100	100	100	40
Domestic	All Households	Electricity	Substitution of refrigerators for most efficient refrigerators in market (A++)	100	0	0	0	0	0
Transports	Freight	Diesel	Substitution of trucks for most efficient electric trucks	100	100	100	100	100	100
Transports	Freight	Natural Gas	Substitution of trucks for most efficient electric trucks	100	90	30	0	50	90
Services	All Services	Electricity	Substitution of lamps for most efficient LEDs	100	100	0	0	0	0
Services	All Services	Electricity	Substitution of lamps for most efficient LEDs	70	90	0	0	0	0
Transports	Freight	Gasoline	Substitution of trucks for most efficient ethanol (E85) trucks	0	10	0	0	0	0
Services	All Services	Electricity	Substitution of lamps for most efficient LEDs	0	100	0	0	0	0
Transports	Freight	Gasoline	Substitution of trucks for most efficient electric trucks	0	0	100	100	100	100

7. Conclusions and future research

Achievements

This research intended to develop a methodology to support the process of designing national energy efficiency plans with the following innovative functionalities:

- Formalizes the problem in a multiple objective framework.
- Performs a breakdown of the energy demand-side system of a country into end-uses, to characterize how energy is used and how EE measures can affect the system.
- Estimates the impacts of EE measures based on the description of the energy system demand-side and its physical limitations.
- Considers all the potential combinations of energy efficiency measures into plans and evaluates them in a multi-objective framework.
- Identifies a set of plans (combinations of measures) among the most adequate to the decision makers' preferences, for a final decision by the decision makers.

This was achieved through the following sequence of developments:

- A method to structure the problem in a multi-objective environment (described in chapter 2).
- A method to characterize the energy demand system, in order to enable the quantification of the effects and the limits of energy efficiency measures (described in chapters 3 and 4).
- Creating a database for physical-based energy efficiency measures (described in chapter 4).
- A method to search the multi-objective space in order to identify the plans that better correspond to the decision makers' preference and defined constraints (described in chapter 5 and with its potential use demonstrated in chapter 6 for the case of Portugal).

This research was guided by three principal research questions, which were responded along the work. The findings regarding each research question are presented and discussed below.

- How can fundamental objectives be identified and made operational for the construction of national energy efficiency plans?

Real decision problems are opportunities to pursue multiple objectives, and the problem of building and selecting an energy efficiency plan for a country is no different. Despite the natural formalization "of building a plan capable to contribute to an energy savings target", it could be established that the fundamental objectives of such plans are not actually reducing the energy use per se, but using (or directing) the energy savings in order to actually bring benefits to a country. With the intention of getting a better understanding of the problem and finding the fundamental objectives for energy efficiency plans, the "value-focusing thinking" methodology from Keeney [39] was adapted to the problem and used with a few decision makers representing local and national energy agencies. The result from this process was a set of six fundamental objectives showing the real intents behind the energy efficiency plans. The fundamental objectives were: i) minimizing the influence of energy use on climate change; ii) minimizing the financial risk from the investment on a plan; iii) maximizing the security of energy supply (or minimizing the energy dependency); iv) minimizing the investment costs; v) minimizing the impacts of building new power plants and transmission infrastructures; and vi) maximizing the local air quality. An effort was made to prevent that the identified objectives to be too specific of the Portuguese case and, even if they were only applied to the case study of Portugal, the methodology followed for its identification can be used in any context to find the most suited objectives.

- How to identify EE measures and quantify their energy savings from the energy efficiency measures?

Using the energy demand system characterization (described in chapter 3) and still using the "value-focusing thinking" concept to find energy efficiency opportunities, is was possible to build a database of energy efficiency measures based on the "improvements" of the technologies representing the end-uses described in the energy system methodology. This approach resulted in a large number of energy efficiency measures (1598), which since they were based on the characterization of the energy system, were automatically quantifiable.

- How can a comprehensive set of alternative combination of measures to build EE plans be established and evaluated in a systematic way, considering the several objectives identified and the preferences of the decision makers?

The problem of building and evaluating energy efficiency plans is a multi-objective problem and the alternatives to this problem comprehend all the feasible solutions in a constrained multi-dimensional search space. Such decision space is obtained by combining the available EE measures (M), and their respective degree of implementation (DI), totaling DI^M possible plans. Therefore, it would be virtually impossible to find the most fitted plans by analyzing them all explicitly, i.e., comparing each possible plan to one another, since there were identified 1598 EE measures. To overcome such problem, it was proposed the use of a multi-objective optimization algorithm to search for the most fitted decision makers' preference. Since the multi-objective algorithms do not perform a preference based search, it was proposed to join the NSGA-II, the chosen multi-objective genetic algorithm, to the outranking relations from the multi-criteria method ELECTRE III. The result was a hybrid multi-objective algorithm capable of finding a "Pareto-optimal" set of alternatives and reflects the preferences from the decision makers. This type of search does not result in a single solution, but helps the decision maker to have a better understanding of the whole problem, in especial showing the possible limits that can be achieved regarding each objective and giving insights to assess possible “trade-offs” to choose a plan, never forgetting that all presented alternatives (plans) already reflect the decision maker’s preferences, facilitating the “trade-off” process.

In order to test the use of the methodology and gain some insights, Portugal was used as a case study. With the intent to get more insights from the decision process, it was decided to build and compare five different decision maker’s perspectives. The groups intended to reflect the, sometimes opposite, preferences from the energy agencies, the environmentalist groups, and the economical oriented decision makers. For each group a pre-selection of the EE measures that were more fitted to each group to be available to build plans was performed. Since each group has its preference, the measures available for each group were compared in order to find the transversal measures among them. It was found that 39 EE measures were present in all groups, concluding that such measures can be considered “fitted” to Portugal and almost independent on the preference of the decision maker. Using this approach, it was found that most of the measures promoted by the existing energy efficiency plan for Portugal somehow find a correspondence to the measures in this list, concluding that the plan for Portugal is at least fitted to the country.

It was observed that most of the EE measures chosen to be present in plans for Portugal by the multi-objective method promote the use of electricity, by recommending the adoption of more efficient systems in replacement of the current ones also using electricity, or by recommending a shift of energy carrier to electricity. Since the electric mix and their characteristics for the period evaluated by the search algorithm (2008-2016) are considered exogenous inputs based on the actual policies applied to the power system [37,38], such “preference” for electricity reflects the efforts performed and intended by the Portuguese power supply to reduce the environmental loads and to increase the use of endogenous renewable resources.

Another interesting observation is the fact that no EE measures related to modal shift from private transport to mass transport were used in any preferred plan under any decision profile. This fact is attributed to two main reasons: first, the introduction of the electric vehicles and, second, to the management of the mass transport in Portugal. The option to have a measure to promote the use of electric vehicles was implemented supposing that the technology would be available in the present or the near future. The other contributing reason is the poor economic situation of the mass transportation companies in Portugal. In order to make possible to compare measures, the onus from keeping the companies running is distributed by the mobility offered by the companies and then compared to the onus of acquiring new private vehicles. Considering the benefits in terms of the objectives, the preferred plans did not pick measures representing the modal shift from private to mass transportation. However, if a better management or other more specific objectives are considered, this may change the observed preference for private cars, in special electric and hybrid vehicles, over the mass transport system.

Observing the range of values found for each objective under all the decision makers' perspectives used in the Portuguese case study, it was possible to conclude that the plans that achieved the "best" values on individual objectives were found in the plans reflecting the objectives that the decision makers valued the most. E.g., the perspective which valued the most the minimization of the investment costs found the minimum investment cost among all plans and all perspectives, however, limited the quality opposite objectives, such as the CO_2 emissions savings and the imported energy savings.

Another interesting trend detected in the Portuguese case study, is that the lower the maximum size of an EE measure is (e.g., the maximum number of fridges that is considered for replacement), the "worse" the outcomes from the plans are. It is also possible to observe that the dispersion of almost all the results decreases as the restriction on the measure size increases. Reducing the size of application of a measure also has another (logical) the consequence: the increase in the number of measures needed in a plan in order to be able to fulfill targets.

Still from the case study, it was possible to conclude that lowering the maximum number of measures allowed in an EE plan may lower the quality (i.e., the best values found for the objectives) of the plans. Also, lowering the maximum number of measures in a plan (about 10 measures) required the application of the selected EE measures to practically the maximum physically possible. This fact may introduce a risk on the success of plan, since it may be hard to change all "equipments" used by an end-use to a new one. In a case where many measures are used, this risk is spread among measures. However, when a few measures are used, this risk is concentrated and may compromise the expected outcomes.

Consequently, the binomial maximum number of measures in an EE plan and the maximum allowed size of an EE measure should be chosen with care, considering the risk of failing when implementing the EE plan.

Suggestions for future research

It is important to emphasize that the method developed in this research intends to provide better understanding on the problem and give insights about how fundamental objectives can be achieved through real physical-based measures. Therefore, after knowing what the decision makers want to achieve when building a plan, and which combination of EE measures best pursue the objectives within the considered constrains, it is time think on how such measures should be implemented. The research on ways of implementing Energy Efficiency measures and on ways of choosing among the several ways of implementing them is a suggestion for future research, involving areas traditionally separated from Engineering, as the Social Sciences.

Regarding the complete process of building energy efficiency plans, it would be interesting to continue this research by:

- Applying the methodology to other countries, if possible inserted in different energy contexts, in order to make a comparative analysis of the resulting preferred plans and the selected measures. This would enable finding more general conclusions and/or reaffirming the importance of the energy context.
- Using the methodology in different geographic areas, such as municipalities, to get insights about the applicability and value of such methodology for more localized policies.
- Introducing the effects of more behavioral measures besides the modal shift in the transports sector.
- Introducing a dynamic match between the supply-side and the demand-side in order to obtain more precise results on environmental loadings and imported energy.
- Introducing a calculation of the investment costs for the reference evolution, so that the actual burden of the improvements on energy efficiency due to the application of an EE plan can be assessed.
- Improving the convergence of the NSGA-II algorithm in order to obtain the “final” most fitted set of EE plans.
- To make computational experiments using other multi-objective optimization algorithms besides NSGA-II to find the preferred sets of plans.
- To use the methodology on behalf of a decision maker who would specify the weights for each objective and possibly also specify veto thresholds for some of the objectives.

This list is somehow the reflection of the fact that this research was performed in a relatively new area in terms of scientific structuring and methodological approaches.

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ANNEX I

Table 72 - Energy cost in Portugal by carrier in 2008

Energy carriers	Energy cost (€/MWh)
Bio Gas	73.62
Biodiesel	114.69
Biomass	30
Coal	30.33
Cold Water	52.73
Diesel	114.68
Diesel for Heating	94.38
Electricity	89.78
Ethanol	102.77
Fuel Oil	43.44
Gasoline (average)	154.31
Heat	45.70
Liquors	0
LPG	61.94
Methanol	102.77
Natural Gas	35.80
Oil for lighting	43.44
Other	43.44
Solar, Hydro, Wind, Geothermal	0

Sources: [45,149,150]

Table 73 – Technologies and their respective data for the energy efficiency measures

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Domestic	All	Ambient Cooling	Air conditioning	Electricity	-	4	0	%	0	345.01	0	€/kW	-	-	-	14	years
Domestic	All	Ambient Cooling	Air source heat pump	Electricity	-	4	0	%	0	401.87	0	€/kW	-	-	-	16	years
Domestic	All	Ambient Cooling	Average	Electricity	-	1.83	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Cooling	Cooling distribution system	Cold Water	-	1	0	%	0	0	0	€/kW	-	-	-	0	years
Domestic	All	Ambient Heating	Air source heat pump	Electricity	-	4	0	%	0	401.87	0	€/kW	-	-	-	16	years
Domestic	All	Ambient Heating	Average	Biomass	-	0.6	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Heating	Average	Diesel for Heating	-	0.8	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Heating	Average	Electricity	-	1	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Heating	Average	LPG	-	0.87	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Heating	Average	Natural Gas	-	0.87	0	%	0	-	0	€/kW	-	-	-	10	years
Domestic	All	Ambient Heating	Centralized natural gas heating	Natural Gas	-	0.85	0	%	0	111.21	25	€/kW	-	-	-	20	years
Domestic	All	Ambient Heating	Centralized wood and pellet-fuel heating	Biomass	-	0.6	0	%	0	162.65	25	€/kW	-	-	-	20	years
Domestic	All	Ambient Heating	Electric resistance heating	Electricity	-	1	0	%	0	19	0	€/kW	-	-	-	8	years
Domestic	All	Ambient Heating	Heat distribution systems	Heat	-	1	0	%	0	0	0	€/kW	-	-	-	0	years
Domestic	All	Ambient Heating	Wall insulation	-	-	0.38	0	W/m2.k	36.41	0	0	€/m2	-	-	-	50	years
Domestic	All	Ambient Heating	Window insulation	-	-	2.5	1	W/m2.k; m3/m3.h	85	0	0	€/m2	-	-	-	50	years
Domestic	All	Clothes Drying	Average	Electricity	-	367	0	kWh/yr	0	-	0	€	-	-	-	-	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Domestic	All	Clothes Drying	Tumble dryer	Electricity	-	143	0	kWh/yr	0	721.5	0	€	-	-	-	13	years
Domestic	All	Clothes Drying	Tumble dryer	Natural Gas	Electricity	303	26	kWh/yr	0	900	0	€	-	-	-	13	years
Domestic	All	Clothes Washing	Average	Electricity	-	342	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Clothes Washing	Washing machine	Electricity	-	207	0	kWh/yr	0	341	0	€	-	-	-	12	years
Domestic	All	Computers	Desktop + LCD Monitor	Electricity	-	100	0	kWh/yr	0	694	0	€	-	-	-	6	years
Domestic	All	Computers	Desktop + Monitor	Electricity	-	276	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Computers	Laptop	Electricity	-	25	0	kWh/yr	0	735	0	€	-	-	-	5	years
Domestic	All	Computers	Printers	Electricity	-	17	0	kWh/yr	0	102.5	0	€	-	-	-	4	years
Domestic	All	Cooking	Hobs	Biomass	-	3313.4655	0	kWh/yr	0	2520	0	€	-	-	-	50	years
Domestic	All	Cooking	Hobs	Diesel for Heating	-	797.0286	0	kWh/yr	0	2520	0	€	-	-	-	50	years
Domestic	All	Cooking	Hobs	Electricity	-	301.04	0	kWh/yr	0	361	0	€	-	-	-	13	years
Domestic	All	Cooking	Hobs	LPG	-	381.6	0	kWh/yr	0	234.5	0	€	-	-	-	15	years
Domestic	All	Cooking	Hobs	Natural Gas	-	381.6	0	kWh/yr	0	234.5	0	€	-	-	-	15	years
Domestic	All	Cooking	Ovens	Biomass	-	1054.9949	0	kWh/yr	0	2520	0	€	-	-	-	50	years
Domestic	All	Cooking	Ovens	Diesel for Heating	-	253.7709	0	kWh/yr	0	2520	0	€	-	-	-	50	years
Domestic	All	Cooking	Ovens	Electricity	-	108	0	kWh/yr	0	308	0	€	-	-	-	14	years
Domestic	All	Cooking	Ovens	LPG	-	205.2	0	kWh/yr	0	436	0	€	-	-	-	14	years
Domestic	All	Cooking	Ovens	Natural Gas	-	205.2	0	kWh/yr	0	436	0	€	-	-	-	14	years
Domestic	All	Dishwashing	Average	Electricity	-	303	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Dishwashing	Dish washer	Electricity	-	193	0	kWh/yr	0	558	0	€	-	-	-	12	years
Domestic	All	Domestic Hot Water	Average	Biomass	-	0.4544	0	%	0	-	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Average	Electricity	-	0.8832	0	%	0	-	0	€	-	-	-	10	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Domestic	All	Domestic Hot Water	Average	LPG	-	0.7151	0	%	0	-	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Average	Natural Gas	-	0.6838	0	%	0	-	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Average	Solar	Electricity	1	0.88	%	0	-	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Average	Solar	Natural Gas	1	0.72	%	0	-	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Biomass storage water heaters	Biomass	-	0.6	0	%	0	5320	50	€	-	-	-	20	years
Domestic	All	Domestic Hot Water	Electric storage water heaters	Electricity	-	0.95	0	%	0	492.59	0	€	-	-	-	13	years
Domestic	All	Domestic Hot Water	Electric tankless water heaters	Electricity	-	0.95	0	%	0	229	0	€	-	-	-	10	years
Domestic	All	Domestic Hot Water	Fuel oil storage water heaters	Fuel Oil	-	0.66	0	%	0	1037.04	0	€	-	-	-	13	years
Domestic	All	Domestic Hot Water	Heat distribution system	Heat	-	1	0	%	0	0	0	€	-	-	-	0	years
Domestic	All	Domestic Hot Water	LPG storage water heaters	LPG	-	0.72	0	%	0	655.56	0	€	-	-	-	13	years
Domestic	All	Domestic Hot Water	LPG tankless water heaters	LPG	-	0.82	0	%	0	744.44	0	€	-	-	-	20	years
Domestic	All	Domestic Hot Water	Natural gas storage water heaters	Natural Gas	-	0.72	0	%	0	655.56	0	€	-	-	-	13	years
Domestic	All	Domestic Hot Water	Natural gas tankless water heaters	Natural Gas	-	0.82	0	%	0	744.44	0	€	-	-	-	20	years
Domestic	All	Domestic Hot Water	Solar Hot Water + Electric support	Solar	Electricity	1	0.95	%	250	2346	0	€	-	-	-	19	years
Domestic	All	Domestic Hot Water	Solar Water Heaters + Electric heat pump	Solar	Electricity	1	2.33	%	250	4702.48	0	€	-	-	-	19	years
Domestic	All	Domestic Hot Water	Solar Water Heaters + Natural gas storage	Solar	Natural Gas	1	0.82	%	250	2876.56	0	€	-	-	-	19	years
Domestic	All	Domestic Hot Water	Water heat pump	Electricity	-	2.33	0	%	0	2481.48	0	€	-	-	-	10	years
Domestic	All	Entertainment	Audio Systems	Electricity	-	7	0	kWh/yr	0	185	0	€	-	-	-	10	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Domestic	All	Entertainment	CRT Tv	Electricity	-	96	0	kWh/yr	0	257.5	0	€	-	-	-	10	years
Domestic	All	Entertainment	DVDs	Electricity	-	8	0	kWh/yr	0	457	0	€	-	-	-	10	years
Domestic	All	Entertainment	LCD/LED Tv	Electricity	-	100	0	kWh/yr	0	771	0	€	-	-	-	10	years
Domestic	All	Entertainment	Plasma Tv	Electricity	-	177	0	kWh/yr	0	946	0	€	-	-	-	10	years
Domestic	All	Entertainment	Tv	Electricity	-	119	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Entertainment	Tv Receiver	Electricity	-	37	0	kWh/yr	0	212.85	0	€	-	-	-	10	years
Domestic	All	Entertainment	VCRs and DVDs	Electricity	-	23	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Freezing	Average	Electricity	-	555	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Freezing	Freezers	Electricity	-	213	0	kWh/yr	0	350	0	€	-	-	-	15	years
Domestic	All	Lighting	CFL	Electricity	-	65	0	lm/W	0	6.26	0	€	-	-	-	9800	hours
Domestic	All	Lighting	Fluorescent	Electricity	-	93	0	lm/W	0	41.77	0	€	-	-	-	19000	hours
Domestic	All	Lighting	Halogen	Electricity	-	33	0	lm/W	0	6.5	0	€	-	-	-	2000	hours
Domestic	All	Lighting	Incandescent	Electricity	-	11	0	lm/W	0	1.67	0	€	-	-	-	1000	hours
Domestic	All	Lighting	LED	Electricity	-	46	0	lm/W	0	50	0	€	-	-	-	22000	hours
Domestic	All	Refrigeration	Average	Electricity	-	450	0	kWh/yr	0	-	0	€	-	-	-	-	years
Domestic	All	Refrigeration	Refrigerators	Electricity	-	272	0	kWh/yr	0	783.5	0	€	-	-	-	15	years
Industry	All	Boiler Use	Average	Biomass	-	0.64	0	%	0	329630	1319	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	Coal	-	0.81	0	%	0	104855	419	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	Diesel	-	0.83	0	%	0	-	318	€/MW	-	-	-	10	years
Industry	All	Boiler Use	Average	Electricity	-	1	0	%	0	95257	381	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	Fuel Oil	-	0.83	0	%	0	79381	318	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	LPG	-	0.82	0	%	0	75413	302	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	Natural Gas	-	0.82	0	%	0	75413	302	€/MW	-	-	-	20	years
Industry	All	Boiler Use	Average	Other	-	0.81	0	%	0	-	318	€/MW	-	-	-	10	years
Industry	All	CHP	Average	Biomass	Biomass	0.66	0.22	%	0	264444	1058	€/MW	-	-	-	30	years
Industry	All	CHP	Average	Coal	Coal	0.66	0.22	%	0	260370	1041	€/MW	-	-	-	30	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Industry	All	CHP	Average	Fuel Oil	Fuel Oil	0.66	0.22	%	0	271852	1087	€/MW	-	-	-	30	years
Industry	All	CHP	Average	LPG	LPG	0.66	0.22	%	0	503333	2013	€/MW	-	-	-	30	years
Industry	All	CHP	Average	Natural Gas	Natural Gas	0.66	0.22	%	0	503333	2013	€/MW	-	-	-	30	years
Industry	All	Lighting	CFL	Electricity	-	58	0	lm/W	139759	1208333.33	14	€/MW, OeM €/MWh	-	-	-	10000	hours
Industry	All	Lighting	Fluorescent	Electricity	-	93	0	lm/W	223246	1305312.5	12	€/MW, OeM €/MWh	-	-	-	19000	hours
Industry	All	Lighting	HID	Electricity	-	119	0	lm/W	285714	744558.33	10	€/MW, OeM €/MWh	-	-	-	30000	hours
Industry	All	Lighting	Incandescent	Electricity	-	11	0	lm/W	26506	880333.33	27	€/MW, OeM €/MWh	-	-	-	1000	hours
Industry	All	Lighting	LED	Electricity	-	90	0	lm/W	216867	2875438.27	4	€/MW, OeM €/MWh	-	-	-	50000	hours
Industry	All	Motors	0 < 0.75 kW	Electricity	-	0.84	0	%	0	207	0	€	-	-	-	8	years
Industry	All	Motors	0.75 < 4 kW	Electricity	-	0.8688	0	%	0	365	0	€	-	-	-	8	years
Industry	All	Motors	10 < 30 kW	Electricity	-	0.9245	0	%	0	864	0	€	-	-	-	8	years
Industry	All	Motors	130 < 500 kW	Electricity	-	0.96	0	%	0	16792	0	€	-	-	-	8	years
Industry	All	Motors	30 < 70 kW	Electricity	-	0.941	0	%	0	4406	0	€	-	-	-	8	years
Industry	All	Motors	4 < 10 kW	Electricity	-	0.9	0	%	0	571	0	€	-	-	-	8	years
Industry	All	Motors	70 < 130 kW	Electricity	-	0.952	0	%	0	8864	0	€	-	-	-	8	years
Industry	All	Motors	> 500 kW	Electricity	-	0.96	0	%	0	69988	0	€	-	-	-	8	years
Services	All	Ambient Cooling	Air Source Heat pump	Electricity	-	3.3	0	%	0	214.14	3.51	€/kW	-	-	-	15	years
Services	All	Ambient Cooling	Average	Electricity	-	3	0	%	0	-	3.6	€/kW	-	-	-	10	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Services	All	Ambient Cooling	Cooling distribution system	Cold Water	-	1	0	%	0	0	0	€/kW	-	-	-	0	years
Services	All	Ambient Cooling	Systems Based on Absorption Cycles	Natural Gas	-	1	0	%	0	147.43	3.89	€/kW	-	-	-	23	years
Services	All	Ambient Heating	Air Source Heat pump	Electricity	-	3.3	0	%	0	214.14	3.51	€/kW	-	-	-	15	years
Services	All	Ambient Heating	Average	Diesel for Heating	-	0.77	0	%	0	-	2.4	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Average	Electricity	-	0.98	0	%	0	-	1.47	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Average	Fuel Oil	-	0.77	0	%	0	-	2.4	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Average	Heat	-	1	0	%	0	-	0	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Average	LPG	-	0.76	0	%	0	-	1.19	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Average	Natural Gas	-	0.76	0	%	0	-	1.19	€/kW	-	-	-	10	years
Services	All	Ambient Heating	Coal furnaces or boilers	Coal	-	0.6	0	%	0	28.45	2.4	€/kW	-	-	-	20	years
Services	All	Ambient Heating	Electric boilers	Electricity	-	0.94	0	%	0	44.31	1.47	€/kW	-	-	-	21	years
Services	All	Ambient Heating	Fuel oil furnaces	Fuel Oil	-	0.79	0	%	0	28.45	2.4	€/kW	-	-	-	20	years
Services	All	Ambient Heating	Heat distribution systems	Heat	-	1	0	%	0	0	0	€/kW	-	-	-	0	years
Services	All	Ambient Heating	Individual electric space heaters	Electricity	-	1	0	%	0	19	0	€/kW	-	-	-	8	years
Services	All	Ambient Heating	Natural gas boilers	Natural Gas	-	0.83	0	%	0	78.83	1.19	€/kW	-	-	-	25	years
Services	All	Ambient Heating	Natural gas furnaces	Natural Gas	-	0.78	0	%	0	24.33	2.4	€/kW	-	-	-	20	years
Services	All	Commercial Refrigeration	Reach-In Freezers	Electricity	-	3687	0	kWh/yr	0	2242.42	0	€	-	-	-	15	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Services	All	Commercial Refrigeration	Reach-In Refrigerators	Electricity	-	1262	0	kWh/yr	0	2023.72	0	€	-	-	-	15	years
Services	All	Commercial Refrigeration	Refrigerated Vending Machines	Electricity	-	2057	0	kWh/yr	0	2592.59	0	€/employee	-	-	-	14	years
Services	All	Cooking	Oven	Diesel for Heating	-	0.35	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Oven	Electricity	-	0.74	0	%	0	5.17	0	€/employee	-	-	-	14	years
Services	All	Cooking	Oven	Fuel Oil	-	0.35	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Oven	Heat	-	0.65	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Oven	LPG	-	0.46	0	%	0	3.42	0	€/employee	-	-	-	14	years
Services	All	Cooking	Oven	Natural Gas	-	0.46	0	%	0	3.42	0	€/employee	-	-	-	14	years
Services	All	Cooking	Range	Diesel for Heating	-	0.275	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Range	Electricity	-	0.85	0	%	0	0.51	0	€/employee	-	-	-	13	years
Services	All	Cooking	Range	Fuel Oil	-	0.275	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Range	Heat	-	0.275	0	%	0	-	0	€/employee	-	-	-	10	years
Services	All	Cooking	Range	LPG	-	0.3	0	%	0	0.92	0	€/employee	-	-	-	15	years
Services	All	Cooking	Range	Natural Gas	-	0.3	0	%	0	0.92	0	€/employee	-	-	-	15	years
Services	All	Hot Water	Average	Diesel for Heating	-	0.8	0	%	0	-	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Average	Electricity	-	0.88	0	%	0	-	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Average	Fuel Oil	-	0.8	0	%	0	-	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Average	Heat	-	1	0	%	0	-	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Average	LPG	-	0.72	0	%	0	-	0	€/m2	-	-	-	10	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Services	All	Hot Water	Average	Natural Gas	-	0.72	0	%	0	-	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Biomass storage water heaters	Biomass	-	0.6	0	%	0	13.17	0.12	€/m2	-	-	-	20	years
Services	All	Hot Water	Electric storage water heaters	Electricity	-	0.88	0	%	0	1.22	0	€/m2	-	-	-	13	years
Services	All	Hot Water	Electric tankless water heaters	Electricity	-	0.99	0	%	0	0.57	0	€/m2	-	-	-	10	years
Services	All	Hot Water	Fuel oil storage water heaters	Fuel Oil	-	0.8	0	%	0	2.57	0	€/m2	-	-	-	13	years
Services	All	Hot Water	Heat distribution system	Heat	-	1	0	%	0	0	0	€/m2	-	-	-	0	years
Services	All	Hot Water	LPG storage water heaters	LPG	-	0.72	0	%	0	1.62	0	€/m2	-	-	-	13	years
Services	All	Hot Water	LPG tankless water heaters	LPG	-	0.5	0	%	0	1.84	0	€/m2	-	-	-	20	years
Services	All	Hot Water	Natural gas storage water heaters	Natural Gas	-	0.72	0	%	0	1.62	0	€/m2	-	-	-	13	years
Services	All	Hot Water	Natural gas tankless water heaters	Natural Gas	-	0.5	0	%	0	1.84	0	€/m2	-	-	-	20	years
Services	All	Hot Water	Solar Water Heaters + Electric heat pump	Solar	Electricity	1	2.2	%	0.62	11.64	0	€/m2	-	-	-	19	years
Services	All	Hot Water	Solar Water Heaters + Electric support	Solar	Electricity	1	0.88	%	0.62	5.81	0	€/m2	-	-	-	19	years
Services	All	Hot Water	Solar Water Heaters + Natural gas storage	Solar	Natural Gas	1	0.72	%	0.62	7.12	0	€/m2	-	-	-	19	years
Services	All	Hot Water	Water heat pump	Electricity	-	2.2	0	%	0	6.14	0	€/m2	-	-	-	10	years
Services	All	Lighting	CFL	Electricity	-	58	0	lm/W	139759	1208333.33	14	€/MW, OeM €/MWh	-	-	-	10000	hours
Services	All	Lighting	Fluorescent	Electricity	-	93	0	lm/W	223246	1305312.5	12	€/MW, OeM €/MWh	-	-	-	19000	hours

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Services	All	Lighting	HID	Electricity	-	119	0	lm/W	285714	744558.33	10	€/MW, OeM €/MWh	-	-	-	30000	hours
Services	All	Lighting	Incandescent	Electricity	-	11	0	lm/W	26506	880333.33	27	€/MW, OeM €/MWh	-	-	-	1000	hours
Services	All	Lighting	LED	Electricity	-	90	0	lm/W	216867	2875438.27	4	€/MW, OeM €/MWh	-	-	-	50000	hours
Services	All	Motors	0 < 0.75 kW	Electricity	-	0.84	0	%	0	207	0	€	-	-	-	8	years
Services	All	Motors	0.75 < 4 kW	Electricity	-	0.8688	0	%	0	365	0	€	-	-	-	8	years
Services	All	Motors	10 < 30 kW	Electricity	-	0.9245	0	%	0	864	0	€	-	-	-	8	years
Services	All	Motors	130 < 500 kW	Electricity	-	0.96	0	%	0	16792	0	€	-	-	-	8	years
Services	All	Motors	30 < 70 kW	Electricity	-	0.941	0	%	0	4406	0	€	-	-	-	8	years
Services	All	Motors	4 < 10 kW	Electricity	-	0.9	0	%	0	571	0	€	-	-	-	8	years
Services	All	Motors	70 < 130 kW	Electricity	-	0.952	0	%	0	8864	0	€	-	-	-	8	years
Services	All	Motors	> 500 kW	Electricity	-	0.96	0	%	0	69988	0	€	-	-	-	8	years
Services	All	Office Equipments	Computers	Electricity	-	293	0	kWh/yr	0	-	0	€	-	-	-	-	years
Services	All	Office Equipments	Desktop + LCD Monitor	Electricity	-	97	0	kWh/yr	0	694	0	€	-	-	-	6	years
Services	All	Office Equipments	Laptop	Electricity	-	18	0	kWh/yr	0	735	0	€	-	-	-	5	years
Services	All	Public Lighting	HID	Electricity	-	39	0	lm/W	259909	2511351.85	9	€/MW, OeM €/MWh	-	-	-	30000	hours
Services	All	Public Lighting	Incandescent	Electricity	-	7	0	lm/W	259909	-	260	€/MW, OeM €/MWh	-	-	-	1000	hours

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Services	All	Public Lighting	LED	Electricity	-	87	0	lm/W	555556	15776413.26	11	€/MW, OeM €/MWh	-	-	-	50000	hours
Services	All	Public Lighting	Low/High-Pressure Sodium	Electricity	-	36	0	lm/W	259909	2511351.85	17	€/MW, OeM €/MWh	-	-	-	15000	hours
Services	All	Public Lighting	Mercury Vapor	Electricity	-	14	0	lm/W	259909	2511351.85	17	€/MW, OeM €/MWh	-	-	-	15000	hours
Services	All	Public Lighting	Metal Halide	Electricity	-	30	0	lm/W	259909	2511351.85	17	€/MW, OeM €/MWh	-	-	-	15000	hours
Transports	Freight	Rail	Average	Diesel	-	0.1547	0	kWh/pkm	0	-	-	€	0.2665	0.0384	€/tkm	19	years
Transports	Freight	Rail	Average	Electricity	-	0.1311	0	kWh/pkm	0	-	-	€	0.2665	0.0384	€/tkm	19	years
Transports	Freight	Truck	Average	Diesel	Biodiesel	0.3467	0.3467	kWh/tkm	0	98749	4939	€	0.1496	0.0727	€/tkm	28	years
Transports	Freight	Truck	Average	Fuel Oil	-	0.3467	0	kWh/tkm	0	98749	4939	€	0.1496	0.0727	€/tkm	28	years
Transports	Freight	Truck	Average	Gasoline	-	0.44	0	kWh/tkm	0	98749	4939	€	0.1496	0.0727	€/tkm	28	years
Transports	Freight	Truck	Average	LPG	-	0.4109	0	kWh/tkm	0	102082	4939	€	0.1547	0.0727	€/tkm	28	years
Transports	Freight	Truck	Average	Natural Gas	-	0.5317	0	kWh/tkm	0	102675	4939	€	0.1556	0.0727	€/tkm	28	years
Transports	Freight	Truck	CNG	Natural Gas	-	0.5317	0	kWh/tkm	0	102675	4939	€	-	-	-	28	years
Transports	Freight	Truck	Diesel	Diesel	Biodiesel	0.3467	0.3467	kWh/tkm	0	98749	4939	€	-	-	-	28	years
Transports	Freight	Truck	Electric	Electricity	-	0.0782	0	kWh/tkm	0	138248.6	8396.3	€	-	-	-	28	years
Transports	Freight	Truck	Ethanol	Ethanol	-	0.3733	0	kWh/tkm	0	98749	4939	€	-	-	-	28	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Transports	Freight	Truck	Gasoline	Gasoline	-	0.44	0	kWh/tkm	0	98749	4939	€	-	-	-	28	years
Transports	Freight	Truck	LPG	LPG	-	0.4109	0	kWh/tkm	0	102082	4939	€	-	-	-	28	years
Transports	Passengers	Bus	Average	Diesel	Biodiesel	0.166	0.166	kWh/pkm	0	201852	5377.78	€	0.2868	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Average	Gasoline	-	0.3217	0	kWh/pkm	0	201852	5377.78	€	0.2868	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Average	Natural Gas	-	0.177	0	kWh/pkm	0	222222	6544.44	€	0.3157	0.2344	€/pkm	15	years
Transports	Passengers	Bus	BEV	Electricity	-	0.0275	0	kWh/pkm	0	288888.5	9170.37	€	0.4105	0.2344	€/pkm	15	years
Transports	Passengers	Bus	CNG	Natural Gas	-	0.177	0	kWh/pkm	0	222222	6544.44	€	0.3157	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Diesel	Diesel	Biodiesel	0.166	0.166	kWh/pkm	0	201852	5377.78	€	0.2868	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Fuel Cell Diesel	Diesel	Biodiesel	0.235	0.235	kWh/pkm	0	937037	9170.37	€	1.3314	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Gasoline	Gasoline	-	0.217	0	kWh/pkm	0	201852	5377.78	€	0.2868	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Hybrid Diesel	Diesel	-	0.193	0	kWh/pkm	0	288888.5	9170.37	€	0.4105	0.2344	€/pkm	15	years
Transports	Passengers	Bus	Hydrogen	Hydrogen	-	0.239	0	kWh/pkm	0	937037	9170.37	€	1.3314	0.2344	€/pkm	15	years
Transports	Passengers	Bus	LPG	LPG	-	0.187	0	kWh/pkm	0	222222	6544.44	€	0.3157	0.2344	€/pkm	15	years
Transports	Passengers	Cars	Average	Diesel	-	0.4343	0.4343	kWh/pkm	0	16074	430	€	0.4634	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Average	Diesel	Biodiesel	0.4343	0.4343	kWh/pkm	0	16074	430	€	0.4634	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Average	Gasoline	-	0.5079	0	kWh/pkm	0	14815	430	€	0.4271	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Average	LPG	-	0.4263	0	kWh/pkm	0	16296	430	€	0.4698	0.0124	€/pkm	15	years
Transports	Passengers	Cars	BEV	Electricity	-	0.0868	0	kWh/pkm	0	25185	733.25	€	0.7261	0.0211	€/pkm	15	years
Transports	Passengers	Cars	CNG	Natural Gas	-	0.3284	0	kWh/pkm	0	16296	430	€	0.4698	0.0124	€/pkm	15	years

sector	subsector	end-use	technology	energy carrier	energy carrier2	η	η bkp	η unit	installation cost	component cost	O&M cost	cost unit	Shared cost	Shared O&M cost	Shared cost unit	lifetime	unit
Transports	Passengers	Cars	Diesel	Diesel	Biodiesel	0.2526	0.2526	kWh/pkm	0	16074	430	€	0.4634	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Ethanol	Ethanol	-	0.3333	0	kWh/pkm	0	15556	430	€	0.4485	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Fuel Cell Diesel	Diesel	Biodiesel	0.2849	0.2849	kWh/pkm	0	18519	430	€	0.5339	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Fuel Cell Gasoline	Gasoline	-	0.2849	0	kWh/pkm	0	18519	430	€	0.5339	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Fuel Cell Methanol	Methanol	-	0.2596	0	kWh/pkm	0	18519	430	€	0.5339	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Gasoline	Gasoline	-	0.2614	0	kWh/pkm	0	14815	430	€	0.4271	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Hybrid Diesel	Diesel	Biodiesel	0.2475	0.2475	kWh/pkm	0	20296	430	€	0.5852	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Hybrid Gasoline	Gasoline	-	0.2837	0	kWh/pkm	0	17407	430	€	0.5019	0.0124	€/pkm	15	years
Transports	Passengers	Cars	Hydrogen	Hydrogen	-	0.1389	0	kWh/pkm	0	17407	430	€	0.5019	0.0124	€/pkm	15	years
Transports	Passengers	Cars	LPG	LPG	-	0.4263	0	kWh/pkm	0	16296	430	€	0.4698	0.0124	€/pkm	15	years
Transports	Passengers	Cars	PHEV	Electricity	-	0.1175	0	kWh/pkm	0	18519	733.25	€	0.5339	0.0211	€/pkm	15	years
Transports	Passengers	Metro	Average	Electricity	-	0.0747	0	kWh/pkm	0	-	-	€	0.596	0.2616	€/pkm	19	years
Transports	Passengers	Rail	Average	Diesel	-	0.2256	0	kWh/pkm	0	-	-	€	0.3415	0.0774	€/pkm	19	years
Transports	Passengers	Rail	Average	Electricity	-	0.0835	0	kWh/pkm	0	-	-	€	0.3415	0.0774	€/pkm	19	years

Table 74 - Selected EE measures for the energy agencies perspective from the outranking relation of ELECTRE III screening process

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Domestic	All Households	Ambient Cooling	Electricity	Electricity	Replacement of ambient cooling systems for most efficient air conditioning
Domestic	All Households	Ambient Heating	Biomass	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Domestic	All Households	Ambient Heating	Diesel for Heating	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Domestic	All Households	Ambient Heating	Electricity	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Domestic	All Households	Ambient Heating	Natural Gas	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Domestic	All Households	Ambient Heating	Biomass	Biomass	Improving wall Insulation to U = 0.38
Domestic	All Households	Ambient Heating	Biomass	Biomass	Improving windows (low-E) Insulation to U = 2.5 and air renovation = 1
Domestic	All Households	Ambient Heating	Diesel for Heating	Diesel for Heating	Improving wall Insulation to U = 0.38
Domestic	All Households	Ambient Heating	Diesel for Heating	Diesel for Heating	Improving windows (low-E) Insulation to U = 2.5 and air renovation = 1
Domestic	All Households	Ambient Heating	Electricity	Electricity	Improving wall Insulation to U = 0.38
Domestic	All Households	Ambient Heating	Electricity	Electricity	Improving windows (low-E) Insulation to U = 2.5 and air renovation = 1
Domestic	All Households	Ambient Heating	Natural Gas	Natural Gas	Improving wall Insulation to U = 0.38
Domestic	All Households	Ambient Heating	Diesel for Heating	Natural Gas	Replacement of ambient heating systems for most efficient centralized natural gas heating
Domestic	All Households	Clothes Drying	Electricity	Electricity	Replacement of tumble dryers for most efficient electric ones (label A, A+)
Domestic	All Households	Clothes Washing	Electricity	Electricity	Replacement of washing machines for most efficient ones (label A, A+)
Domestic	All Households	Computers	Electricity	Electricity	Replacement of computers for most efficient laptops
Domestic	All Households	Cooking	Biomass	Electricity	Replacement of hobs for most efficient electric hobs
Domestic	All Households	Cooking	Biomass	Natural Gas	Replacement of hobs for most efficient natural gas hobs
Domestic	All Households	Cooking	Diesel for Heating	Electricity	Replacement of hobs for most efficient electric hobs

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Domestic	All Households	Cooking	Diesel for Heating	Natural Gas	Replacement of hobs for most efficient natural gas hobs
Domestic	All Households	Cooking	LPG	Electricity	Replacement of ovens for most efficient electric ovens
Domestic	All Households	Dishwashing	Electricity	Electricity	Replacement of dishwashers for most efficient electric ones (label A, A+)
Domestic	All Households	Domestic Hot Water	LPG	Natural Gas	Substitution of domestic hot water systems for most efficient natural gas tankless water heaters
Domestic	All Households	Domestic Hot Water	LPG	Solar	Substitution of domestic hot water systems for most efficient solar water heaters + electric storage water heater
Domestic	All Households	Domestic Hot Water	LPG	Solar	Substitution of domestic hot water systems for most efficient solar water heaters + electric heat pump water heater
Domestic	All Households	Entertainment	Electricity	Electricity	Substitution of Audio Systems for most efficient ones
Domestic	All Households	Freezing	Electricity	Electricity	Substitution of freezers for most efficient freezers in market (A++)
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient compact fluorescent lamps
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient fluorescent tube lamps
Domestic	All Households	Lighting	Electricity	Electricity	Substitution of lamps for most efficient compact fluorescent lamps
Domestic	All Households	Refrigeration	Electricity	Electricity	Substitution of refrigerators for most efficient refrigerators in market (A++)
Industry	Cement	Boiler Use	Other	Fuel Oil	Substitution of boilers for most efficient oil CHP
Industry	Cement	Boiler Use	Other	Natural Gas	Substitution of boilers for most efficient natural gas CHP
Industry	Cement	Motors	Electricity	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones (EFF3)
Industry	Cement	Motors	Electricity	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones (EFF3)
Industry	Chemicals Plastic and Rubber	Motors	Electricity	Electricity	Replacement of motors with output range higher than 500 kW for most efficient ones (EFF3)
Industry	Food and Beverage	Boiler Use	Biomass	Natural Gas	Substitution of boilers for most efficient natural gas boilers
Industry	Food and Beverage	Boiler Use	Diesel	Electricity	Substitution of boilers for most efficient electric boilers
Industry	Metal Machinery and Electro	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Industry	Metal Machinery and Electro	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 0.75 and 4 kW for most efficient ones (EFF3)

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 10 and 30 kW for most efficient ones (EFF3)
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 130 and 500 kW for most efficient ones (EFF3)
Industry	Paper	Motors	Electricity	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones (EFF3)
Services	All Services	Ambient Cooling	Electricity	Electricity	Replacement of ambient cooling systems for most efficient heat pump systems
Services	All Services	Ambient Heating	Diesel for Heating	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Services	All Services	Ambient Heating	Fuel Oil	Electricity	Replacement of ambient heating systems for most efficient centralized electric heat pump systems
Services	All Services	Ambient Heating	Fuel Oil	Electricity	Replacement of ambient heating systems for most efficient individual electric space heaters
Services	All Services	Commercial Refrigeration	Electricity	Electricity	Replacement of reach-in refrigerators for most efficient ones
Services	All Services	Cooking	Diesel for Heating	Electricity	Replacement of ranges for most efficient electric ranges
Services	All Services	Cooking	Fuel Oil	Electricity	Replacement of ranges for most efficient electric ranges
Services	All Services	Cooking	LPG	Electricity	Replacement of ranges for most efficient electric ranges
Services	All Services	Cooking	Natural Gas	Electricity	Replacement of ranges for most efficient electric ranges
Services	All Services	Hot Water	Diesel for Heating	Electricity	Substitution of hot water systems for most efficient electric tankless water heaters
Services	All Services	Hot Water	Fuel Oil	Solar	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater
Services	All Services	Hot Water	LPG	Solar	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater
Services	All Services	Hot Water	Natural Gas	Solar	Substitution of hot water systems for most efficient solar water heaters + electric heat pump water heater
Services	All Services	Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 0 and 0.75 kW for most efficient ones (EFF3)
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 0.75 and 4 kW for most efficient ones (EFF3)
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 10 and 30 kW for most efficient ones (EFF3)
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 30 and 70 kW for most efficient ones (EFF3)
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 4 and 10 kW for most efficient ones (EFF3)
Services	All Services	Motors	Electricity	Electricity	Replacement of motors with output range between 70 and 130 kW for most efficient ones (EFF3)
Services	All Services	Office Equipments	Electricity	Electricity	Replacement of computers for most efficient laptops

sector	sub-sector	target end-use	target energy carrier	energy carrier	measure
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient high intensity discharge lamps
Services	All Services	Public Lighting	Electricity	Electricity	Substitution of lamps for most efficient LEDs
Transports	Freight	Truck	Diesel	Electricity	Substitution of trucks for most efficient electric trucks
Transports	Freight	Truck	Gasoline	Electricity	Substitution of trucks for most efficient electric trucks
Transports	Freight	Truck	Natural Gas	Electricity	Substitution of trucks for most efficient electric trucks
Transports	Freight	Truck	Gasoline	Ethanol	Substitution of trucks for most efficient ethanol (E85) trucks
Transports	Passengers	Bus	Diesel	Electricity	Substitution of buses for most efficient electric buses
Transports	Passengers	Bus	Gasoline	Electricity	Substitution of buses for most efficient electric buses
Transports	Passengers	Bus	Diesel	Electricity	Modal shift from bus to trains
Transports	Passengers	Bus	Gasoline	Electricity	Modal shift from bus to trains
Transports	Passengers	Bus	Natural Gas	Electricity	Modal shift from bus to trains
Transports	Passengers	Cars	Diesel	Electricity	Substitution of individual transports for most efficient BEV
Transports	Passengers	Cars	Gasoline	Electricity	Substitution of individual transports for most efficient BEV
Transports	Passengers	Cars	Diesel	Methanol	Substitution of individual transports for most efficient fuel cell methanol cars
Transports	Passengers	Cars	Gasoline	Methanol	Substitution of individual transports for most efficient fuel cell methanol cars
Transports	Passengers	Cars	Diesel	Electricity	Substitution of individual transports for most efficient PHEV
Transports	Passengers	Cars	Gasoline	Electricity	Substitution of individual transports for most efficient PHEV