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INTEGRATED LIFE-CYCLE ANALYSIS OF SIX INSULATION MATERIALS APPLIED TO A REFERENCE BUILDING IN PORTUGAL

Fevereiro, 2014

UNIVERSIDADE DE COIMBRA

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FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

Integrated life-cycle analysis of six insulation materials applied to a reference building in Portugal

Dissertação apresentada para obtenção do grau Mestrado em Energia para a Sustentabilidade

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Coimbra, Fevereiro, 2014

Acknowledgments

I would like to express my appreciation to those who provided their time and knowledge in helping me complete this dissertation. First and foremost, I extend my thanks to my supervisors, Professor Fausto Freire and Professor Nuno Simões for accepting me as their student. During the planning and development of this dissertation, they had constructive roles in providing valuable and useful suggestions and engaging me in new ideas. I was fortunate to have the opportunity to be supervised by Professor Freire although he was too busy to accept any supervision. I was very grateful to have the course of Industrial Ecology presented by Professor Fausto Freire that enabled me to learn from his experiences every week. Through Professor Nuno Simões, I had a chance to have a working place in the Institute for Technological Research and Development in Construction Sciences (ITeCons) and had the opportunity to get his suggestions and helps during my work. I was fortunate to have the support of the Faculty of Sciences and Technology of the University of Coimbra, more specifically the Department of Mechanical Engineering and the Center for Industrial Ecology and also ITeCons. This work has been framed under the Energy for Sustainability Initiative of the University of Coimbra and supported by the Energy and Mobility for Sustainable Regions - EMSURE - Project (CENTRO-07-0224-FEDER-002004).

I would also like to thank specially to Carla Rodrigues, who shared her knowledge with me and also attended in my presentations. I would also thank my colleagues, Joana Bastos, Amir Safaei, Pedro Marques, Sérgio Fernando Tadeu and Márcio Gonçalves for their contributions during this process.

To my close friends and family, especially my mother who is not attending in Portugal but she always supports me.

And finally especial thanks to Behrang for his unquestionable supports and calmness provided during my life.

Abstract

Thermal insulation of buildings has an important role in the reduction of energy consumption and environmental impacts of buildings; however, the environmental impacts of high insulation levels can be significant and a life-cycle perspective should be followed to identify optimal insulation levels minimizing overall Life-cycle impacts. Moreover, life-cycle cost perspective and energy performance of a building are also significant criteria which should be taken into account.

The main goal of the thesis is to perform a comparative economic and environmental assessment of different thermal insulation materials applied to a reference building for new single-family houses in Portugal. The environmental life-cycle analysis was performed following two approaches; from cradle to gate and also adding the use phase. For the operation phase, building energy performance analysis of insulation materials was calculated with seasonal calculation method based on ISO standard 13790. An additional objective is to evaluate the total life-cycle costs.

A life-cycle model was implemented for the six common insulation materials using CML 2001 and Cumulative Energy Demand (CED) life-cycle impact assessment methods. Furthermore, a consequential analysis was conducted from cradle to gate and use-phase of insulation materials to find out critical thicknesses which are not beneficial to increase the thickness. The results show that Expanded Polystyrene has lower contributions to Acidification (AP), Eutrophication (EP), Ozone layer depletion (ODP) and Global warming (GWP) impact categories which in terms of ODP it performs 75% better than Glass Wool with the highest impact and owing to EP impact category, it performs 96% better comparing with Insulation Cork Board. The results also show that for most of insulation materials, thicknesses greater than 160 mm are not beneficial due to the increased embodied emissions of insulation materials will exceed the reduced emissions from decreasing the building energy consumption. The gained benefits after applying insulation materials during 30 years building lifespan are much higher than the initial investments including material costs and installation labor fees.

Keywords: Thermal insulation material, life-cycle assessment, life-cycle cost analysis, final and primary energy demand

Resumo

O isolamento térmico dos edifícios assume um papel importante na redução do consumo de energia e dos impactes ambientais associados aos edifícios. No entanto, os impactes ambientais associados ao fabrico e consequente aplicação de isolamento podem também ser significativos. Uma avaliação de ciclo de vida é por isso importante para a identificação de níveis óptimos de isolamento, de forma a minimizar os impactes ao longo do ciclo de vida. A perspectiva de ciclo de vida a nível económico e o desempenho energético dos edifícios são também questões importantes a considerar.

O objectivo principal desta tese é desenvolver uma avaliação comparativa de diferentes materiais de isolamento aplicados a um edifício de referência, para habitação unifamiliar nova em Portugal. A avaliação assenta em particular nas vertentes. económica e ambiental. A análise ambiental de ciclo de vida foi desenvolvida numa perspectiva "cradle-to-gate", e integrando também a fase de utilização. Na fase de utilização, a análise do desempenho energético do edifício para os vários isolamentos foi efectuada com base no método de cálculo sazonal estabelecido na norma ISO 13790. Foram também avaliados os custos associados ao ciclo de vida dos isolamentos.

O ciclo de vida do seis materiais de isolamento foi efectuado, com recurso a dois métodos de avaliação de impactes: CML 2001 e "Cumulative Energy Demand" (CED). Foi também desenvolvida uma análise consequencial dos diferentes isolamentos, para a perspectiva "cradle-to-gate" e para a fase de utilização, no sentido de identificar níveis de isolamento a partir dos quais aumentar a espessura não adicionará benefícios ambientais. Os resultados mostram que o Polistireno Expandido tem contribuições reduzidas nas seguintes categorias de impacte: Acidificação (AP), Eutrofização (EP), Depleção da camada do ozono (ODP) e Potencial de aquecimento global (GWP). No caso da ODP, o Polistireno Expandido tem um desempenho 75% melhor que a Lã de Vidro, que apresenta o maior valor. Na EP, este tem um desempenho 96% melhor do que a Placa de Aglomerado de Cortiça Expandida. Os resultados mostram ainda que para a maioria dos materiais de isolamento, espessuras superiores aos 160 mm não oferecem benefícios, dadas as emissões incorporadas nos materiais de isolamento, que superam a redução devida à diminuição de consumo de energia na fase de utilização. De uma forma geral, os benefícios económicos da aplicação de materiais de isolamentos ao longo dos 30 anos de tempo de vida do edifício são muito superior aos investimentos iniciais associados aos custos dos isolamentos e respectiva instalação.

Palavras-chave: Material de isolamento térmico, avaliação de ciclo de vida, avaliação económica de ciclo de vida, consumo de energia primária e final

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List of Abbreviations

ICB	Insulation Cork Board
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
PUR	Polyurethane
GW	Glass Wool
RW	Rock Wool
LCA	Life-cycle Assessment
LCI	Life-cycle Inventory
LCIA	Life-cycle Impact Assessment
CED	Cumulative Energy Demand
CML	Center of Environmental Science of Leiden University
GHG	Green House Gas
ETICS	External Thermal Insulation Composite Systems
ITeCons	The institute for Technological Research and Development in Construction Sciences
COP	Coefficient of Performance
NPV	Net Present Value
GDEG	General Directive for Energy and Geology
EPD	Environmental Product Declaration
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
ODP	Ozone Layer Depletion Potential
NRPE	Non-renewable Primary Energy
RPE	Renewable Primary Energy
EDP	Energias de Portugal

1. Introduction

Building sector accounts for more than 40 percent of global energy use and CO_2 emissions in IEA member countries (International Energy Agency (iea) 2013). Thermal insulation of building envelope is regarded as one key measure to reduce energy consumption of buildings (Kayfeci, Keçebaş, and Gedik 2013). The common materials which are most used for insulation of buildings in Portugal, namely Insulation Cork Board (ICB), Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyurethane (PUR), Glass Wool (GW) and Rock Wool (RW). Each of these materials has different physical properties such as specific thermal resistance, i.e. the efficiency of material to resist against the heat flow as a result of suppressing conduction) and environmental impacts.

1.1. Background and Motivation

A large and growing body of literature has investigated the environmental assessment of buildings in a life-cycle perspective. A life-cycle energy analysis was performed on an office building in Canada (Cole and Kernan 1996) and on a single-family house in Sweden (Adalberth 1997). Later, Peuportier has integrated for the first time thermal dynamic simulation with LCA (Peuportier 2001). A LCA was applied to the comparative evaluation of three single family houses in France: a standard construction made of concrete blocks, a solar house made of stones and wood and a well-insulated wooden frame reference house. This study concluded that the increase of CO2 emissions of the standard concrete blocks house compared to the well-insulated wooden house represents 18% of the total emissions for the wooden house, but accounting for end-of-life processes may reduce this value. Since then many LCA studies have been performed not only in residential buildings (Adalberth 1997; Basbagill et al. 2013; Blengini and Di Carlo 2010; Cuéllar-Franca and Azapagic 2012; Gustavsson and Joelsson 2010; Keoleian, Blanchard, and Reppe 2001; Monteiro and Freire 2012; Rossi, Marique, and Reiter 2012; Thiers and Peuportier 2012; Thormark 2002) but also in commercial/services buildings (Chau et al. 2007; Wallhagen, Glaumann, and Malmqvist 2011). Many review papers have also been published (Sartori and Hestnes 2007; Sharma et al. 2011; Zabalza Bribián, Aranda Usón, and Scarpellini 2009).

LCA studies in residential buildings follow many approaches. In some of them different types of buildings were assessed (Forsberg and von Malmborg 2004; ISO 14044 2006; Van Ooteghem and Xu 2012), or in some of them different locations were compared (Sartori and Hestnes 2007; Wallhagen et al. 2011; Zabalza Bribián et al. 2009), or different envelope solutions were evaluated (Monteiro and Freire 2012). Adalberth compared four buildings with different constructive solutions and analyzed the importance of knowing which phase in the life cycle has greater environmental impact, if there are similarities between environmental impacts and energy use; or if there are differences between subsisted environmental impacts due to the selection of the construction. Considering an occupation phase of 50 years for the dwellings, this study concluded that the greatest environmental impact occurs during the use phase. Also, 70–90% of the environmental categories arise in this phase. Approximately 85% and 15% of energy consumption occurs during the occupation and manufacturing phases, respectively (Adalberth 1997).

There are many life-cycle studies of insulation materials in buildings. In some of them production and end of life scenario were studied (Ardente et al. 2008; Schmidt et al. 2004), while others studied the total life-cycle of insulation material (Keoleian et al. 2001; Papadopoulos and Giama 2007).

As discussed, different insulation materials compared throughout a LC approach; however, previous studies have not assessed together the criteria of economic, environmental and energy from raw materials extraction to the operation phase of the building. Schmidt et al conducted LCA study of three insulation materials for roof insulation (Schmidt et al. 2004). Stone wool as a traditional material, flax as a crop grown material and paper wool as a recycled material were compared throughout the LCA approach. In this study, the use phase was not considered but the production, installation and disposal were included. It was concluded that stone wool has the lowest energy consumption. Paper wool has the lowest environmental impacts (Global warming and Acidification) and flax has the highest. Moreover, the most significant features in LCA of insulation materials are the quality and the fitness of insulation leading to decrease the heat loss in buildings.

The environmental performance of a building with two insulation materials; stone wool and extruded polystyrene was evaluated (Papadopoulos and Giama 2007). The results of the study were used to set operating performance indicators and environmental performance evaluation. A correlation between life-cycle of insulation materials and building was evaluated and defined with energy consumption indicators. The thickness of stone wool with the given density is measured 8 cm and for XPS, 5 cm according to the same functional unit. Also the mass of 2 kg and 1.55 kg per m^2 are required for stone wool and XPS, respectively. Furthermore, for the production of 1 kg of stone wool, 0.3 kWh energy a consumed and the energy consumption of XPS production is 0.86 kWh/kg. Therefore, according coefficients derived by Greek data, the environmental impact of 1 m^2 insulated by stone wool is 0.8 kg eq. CO_2 and 1.79 kg eq. CO_2 for XPS.

A LCA of kenaf-fiber insulation board was conducted with the aim of evaluating its eco-profile and also comparing different insulating materials, such as polyurethane, flax rolls, glass wool, stone wool, mineral wool and paper wool (Ardente et al. 2008). It showed that the significant decrease in the environmental impacts was obtained by the use of natural fibers. The comparison between the remained insulation materials showed that synthetic materials have the highest GHG emissions and the lowest related to mineral wools. However, kenaf fibers could have less GHG emissions by adoption of different disposal scenarios. The reduction of energy consumption could be achieved by incineration with energy recovery and electricity production and also the use of recycled materials in the manufacturing process.

Anastaselos, Giama, and Papadopoulos 2009 presented an assessment tool for energy, economic and environmental assessment of thermal insulation solutions. The consequences of the study are useful for comparing various building materials and thermal insulation solutions. The tool provides the approaches for users to make decisions depending on obtaining energy efficiency, lower costs and better environmental performances. Since double cavity walls and the external Thermal Insulation Composite Systems (ETICS) are used throughout Europe, the assessment tool was applied to them. Three major levels were evaluated by the assessment tool. First level considered building materials and it emphasized insulation materials. Second level considered thermal insulation solutions and the third level considered the building as a whole. The system boundaries of the study included the material production, transport, installation and operation. The demolition was out of the system boundaries. To conclude, ETICS is preferred according to its energy, cost and environmental performance. In comparison with the traditional building, the energy consumption, environmental emissions and cost of the typical building were reduced by up to 20% in the production and operation phase. Environmental emissions were decreased for instance CO_2 by 16.8%, SO_2 by 17%, PO_4 by 15.78%, C_2H_4 by 14%. Moreover, the total energy consumption was reduced by 17% and the total cost by 13% (Anastaselos, Giama, and Papadopoulos 2009).

Following the use of Net Present Value, there are studies which have compared several economic proposals and concluded that NPV is a proper approach that can be employed on projects. Maximizing NPV has been studied as an objective before project planning (Bragg 2013; Ittelson 2009). A study about thermal insulation of building external walls was carried out in terms of economic aspect (Dylewski and Adamczyk 2011). Thermal insulation can be considered as an investment and the reduction of required energy for heating of a building can be considered profit. The maximum net present value of thermal insulation investments are defined by the optimum thickness of the insulation layer. Three issues were evaluated in this study; energy sources, wall constructional materials and insulation materials. The best solution were determined related to optimization of two criteria; economic and environmental performance. Four building constructional materials and four heating sources were chosen for the assessment. Moreover, four insulation materials namely foam PIR, polystyrene foam, mineral wool and eco-fiber were selected for the analysis. The results showed that eco-fiber has the lowest GHG emissions in the production phase. The building use phase had the highest environmental impacts because of energy for heating of the building. The best performance throughout two criteria of economic and environmental feature was achieved by polystyrene foam and eco-fiber.

Energy assessment throughout the life-cycle perspective provides the improvement of building performance and energy efficiency in building.(Basbagill et al. 2013; Rossi et al. 2012; Thormark 2002) Rossi et al carried out a study on three buildings in three different climates (Belgium, Portugal and Sweden).(Rossi et al. 2012) For each location, a different life-cycle scenario was considered. Monthly temperatures, buildings insulation thicknesses, energy sources, heating and cooling systems were defined for each scenario. There were several parameters influenced on the LCA of residential buildings: the climate related to the temperatures and the buildings insulation thicknesses, the use of different materials, the energy sources and the heating/cooling system.

Many studies have mentioned the importance of each stage of a building life-cycle (Adalberth 1997; Forsberg and von Malmborg 2004; Sharma et al. 2011). Some studies have emphasized on the wide share of energy consumption by operation phase of buildings (Blengini and Di Carlo 2010; Chau et al. 2007; Sharma et al. 2011; Thormark 2002).

Another assessment conducted in the literature is the economic assessment of the investments based on the thermal insulation of external walls of the building, such as: net present value, profitability indicator and payback period (Dylewski and Adamczyk 2011). All features considerably depend on the parameters of thermo insulating material (cost of purchase, cost of assembly, thickness and thermal conductivity), but also on the type of a heat source (cost of obtaining heat for heating purposes, real annual increase of heating cost) as well as wall parameters (heat transmittance coefficient without thermo insulation).

To sum up, many studies have been published on the LCA of buildings and building insulation materials. However, a gap in the literature was found regarding the absence of studies which evaluated the thermal insulation materials by means of different criteria, such as total life-cycle costs, heating and cooling energy needs, as well as life-cycle environmental impacts. Research should be made on comparison between different thermal insulation materials and evaluate the best one in the domains of energy, cost and environmental impacts. Portugal is one of the main producers of Insulation Cork Board (ICB) and few studies were carried out on LCA of ICB from raw material extraction to the operation phase. One of the studies conducted on LCA of cork just in raw material extraction (Rives et al. 2012). Moreover, there are few studies to compare insulation cork board as a natural insulation material with other materials according to life-cycle costs, useful required energy, as well as life-cycle environmental impacts. Economic assessment of insulation materials is considered as one of the key issues in the decision-making process by stakeholders in the building sector. Moreover, this analysis provides the opportunities to increase the environmental performance of insulation materials within their life-cycle and also consequential analysis of a further increase of insulation materials thicknesses. It also helps the decision makers to find the optimal choice with regards to environmental criteria. Most relevant studies existed in the literature review are presented in Table 1.

Table 1 – Surveyed studies through life-cycle assessment of insulation materials and buildings

Surveyed studies	Year	Insulation Materials	Environmental Assessment					Energy Assessment	Economic Assessment	Assumptions
			Functional unit	System boundary	Method	Impact categories	Software	Method	Method	
Peuportier et al	2001	Building	a unit of living area (1 m^2) under the same conditions which providing same comfort level (given set point temperature)	The fabrication of building components, their transport and recycling processes and waste treatment.	CML	CML indicators	-	Dynamic Simulation COMFIE	-	Assuming a 100 km transport by truck for all materials
Schmidt et al	2004	Stone Wool, Paper Wool and Flax	50 years use-phase and an R-value of 1 m^2K/W	Cradle to grave	CML & EDIP & CED	GWP, AP,EP & photo-oxidant creation potential	-	-	-	The fate of the material over a 100-year period is assumed to be same.
Reginald Tan & Hsien Khoo	2005	EPS and corrugated paperboard (CPB) (used in packaging,)	the weights of the original EPS and CPB inserts required to perform the same protective function	cradle-to-gate & various end-of-life cases	Eco-indicator 99	climate change, AP,EP, ecotoxicity, fossil fuels and respiratory inorganics	Simapro	-	-	zero pollution is assumed for the 'use' stage, It is assumed that the same amount of energy is spent in the packaging of the electronic product for both inserts
Papadopoulos & Giama	2007	XPS & SW	. producing 1 kg of stone-wool	Cradle to gate	Eco-indicator 95	Greenhouse effect, AP,EP, Smog ,Solid wastes, Liquid wastes, Water eutrophication	Simapro	-	-	-
Ardente et al	2008	Kenaf - fibres insulation board	a thermal resistance R of 1 (m2 K/W)	cradle to gate	CML	Global energy requirement (GER), GWP, AP, Nutrification potential (NP), Photochemical ozone creation potential (POCP), ODP, Negligible Water consumption, Total wastes	-	-	-	Concerning to the disposal phase, the option of incineration1 is assumed.
Anastaselos et al	2009	EPS, XPS, MW, PUR	for the building materials is kg emission/kg building material and MJ/kg building material for the embodied energy	Cradle to gate and use phase	CML & EI99	CO2, SO2, PO4, C2H4	Simapro	TRNSYS software	-	the conventional life span of 70 years is assumed
Blengini & Carlo	2009	whole building	1 m2/year	Cradle to grave	Eco-Indicator 99	ODP, AP, EP and photochemical ozone creation potential (POCP)	Simapro7	the software application Edilclima EC501	-	-
Zabalza Bribián et al.	2011	EPS,PUR, Cork slab,Cellulose fibre,Wood wool	One kg of material	gate to grave	CED & CML	primary energy demand ,GWP, and water demand	Simapro	-	-	-
Dylewski & Adamczyk	2011	Foam PIR, Polystyrene Foam, Mineral Wool,	1m3 of an insulating material	Use-phase	Eco indicator 99	3 endpoints : Human Health environment quality, consumption of natural resources	Simapro 7.1	-	NPV	-
José V. Ferreira & Idalina Domingos	2011	Buildings	1 m2/year provide the same indoor reference conditions	the heating, cooling and DHW systems	EI99	abiotic depletion, AP, EP, GWP, ODP, human toxicity, aquatic ecotoxicity and terrestrial ecotoxicity	Simapro7.3	-	-	-
Monteiro & Freire	2012	seven alternative exterior walls for the same house	the building living area over the building life span of 50 years	construction and use phase	CED & CML2001 & EI99	GWP, ODP, abiotic depletion, AP, and EP	Simapro7	seasonal quasi-steady state method		it was assumed that the occurring changes would not affect the market, the house is occupied by a 4-person family,
Barbara Rossi et al	2012	Building	a unit of living area (1 m2) can be used as functional unit under the same conditions	cradle-to-gate	CML 1992	GHG emissions and primary energy	-	Dynamic Simulation COMFIE	-	finishing of steel structures is not includedThe end-of-life stages are not included,no maintenance or repair is taken into account,
Rives et al	2012	Cork	a tonne of raw cork material	Raw Material Extraction and Transpotation	CML 2001	GWP, AP, EP, human toxicity	Gabi 4.4	-	-	-
Nuno Gonçalo Sequeira Correia Pargana	2012	ICB, EPS, XPS, PUR, SW, LECA	thermal resistance R of 1 m2K/W	Cradle to gate	CML	Abiotic depletion, AP, EP, GWP, ODP, Photochemical ozone creation potential	Simapro7	-	Comparing initial costs	-

1.2. Thesis Objective

The objective of the thesis is to compare six common insulation materials applied to a reference building for new single-family houses located in three climate zones of Portugal. This study aims to perform economic and environmental assessment of the six insulation materials, namely Insulation Cork Board (ICB), Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyurethane (PUR), Glass Wool (GW) and Rock Wool (RW) following two approaches: from cradle to gate and also adding the use-phase. For the operation phase, building energy performance analysis of insulation materials was calculated with seasonal calculation method based on ISO standard 13790. It also aims to perform a consequential analysis of increasing the thickness of insulation materials in terms of environmental impact categories to find critical thicknesses that it is not beneficial to increase thicknesses. An additional goal of this study is to evaluate the total life-cycle costs.

1.3. Thesis Structure

The dissertation consists of five chapters. Firstly, it starts with introduction in which a literature review is presented. The objective of the study and structure of the dissertation are explained. The second chapter presents the methodology and methods, giving the framework of life-cycle assessment in the buildings context and describing the life-cycle impact assessment methods used in this study. Third chapter describes the case-study and presents life-cycle inventory analysis associated with insulation materials and the reference building energy performance. Fourth chapter analyses and discusses the main results. Finally, fifth chapter summarizes the main conclusions, discusses limitations and proposes topics for further research.

2. Methodology

2.1. Introduction

The methodology used in this dissertation integrates environmental and energy assessment with life-cycle cost analysis. A life-cycle model is implemented for the environmental assessment. The results for the environmental impacts were calculated using an impact assessment method called CML method and a single issue method called Cumulative Energy Demand (CED) was used to calculate the total primary energy. The energy performance of the reference building is calculated by means of seasonal calculation method for heating and cooling energy needs for the building during the use phase. Life-cycle cost of the insulation materials is evaluated according to net present value method. The details of the methodology used in this research are presented in sections 2.2, 2.3 and 2.4.

2.2. Life-Cycle Assessment

Life-cycle assessment (LCA) is a methodology to evaluate the potential impacts throughout the product´s life from cradle to grave (from raw material extraction through production, use and finally its end of life). The general framework of LCA is defined by ISO standards. LCA consists of four interrelated phases: goal and scope definition; life-cycle inventory (LCI); life-cycle impact assessment (LCIA) and interpretation (ISO 14040 2006).

a. Goal and scope definition: the purpose of the study, definition of the functional unit, system boundaries, necessary data etc. are defined in this step. The functional unit is a reference parameter that describes the primary function of a product (or service) in order to characterize the product performance while executing its function (ISO 14044 2006).
b. Life-Cycle Inventory (LCI): the inventory analysis with collecting data and calculation procedures in order to quantify all the inputs and outputs of the system studied. Quantified inputs for each stage of the building will include the use of energy, raw materials and construction materials, etc. (Rebitzer et al. 2004)

c. Life-Cycle Impact Assessment (LCIA): classification and evaluation of the results of the inventory analysis relating its results to the associated environmental effects by using a selected impact categories (ISO 14040 2006; Rebitzer et al. 2004).
d. Interpretation: the results of the preceding phases are evaluated in accordance with the objectives defined in the study in order to be able to establish conclusions and final recommendations. Different techniques are used including sensitivity analysis on the data, an analysis of the relevance of the different stages of the process and an analysis of alternative scenarios (ISO 14044 2006).

In this study, the LCIA results was assessed by applying the same inventory life-cycle to two methods: the cumulative energy demand (CED) to account for the life-cycle non-renewable primary energy requirements, and an environmental method (CML 2001) to evaluate multiple environmental impacts.(global warming potential, acidification potential, eutrophication potential and ozone layer depletion potential)

2.2.1. Cumulative Energy Demand (CED)

The Cumulative Energy Demand (CED) has been used as an indicator for energy systems. The assessment of the environmental impacts related to a product or process is based on one parameter: the total energy demand for production, use and disposal expressed in primary energy (Althaus et al. 2009). Energy resources found in nature, such as coal, crude oil and natural gas are called primary energy resources.

The CED method calculates the total primary energy (PE) use (MJeq) throughout the life cycle based on the Higher Heating Value (HHV) and distinguishes renewable (R) and non-renewable (Non-R) energy sources. It constitutes a widely used indicator to assess energy life-cycle performance of buildings (Althaus et al. 2009).

2.2.2. CML 2001

In 2001, the Centre of Environmental Science of Leiden University (CML) published a new operational guide to the ISO standards. The operational guide to conduct a LCA project provided a procedure. This operational guide provides a list of impact categories for the impact assessment phase, which is divided to three groups: mandatory impact categories, additional impact categories and other impact categories. Mandatory impact indicators are used in most LCA projects, additional indicators are seldom used and other indicators are not operational in LCA projects (Althaus et al. 2009).

CML is a problem-oriented approach which ends the modelling before the finishing of the impact pathway and connects the life-cycle inventories to the mid-point categories such as acidification and eutrophication (Althaus et al. 2009; Hamzah Sharaai, Noor Zalina, and Sulaiman 2010).

In this study, during classification the inventory results are organized to four impact categories by CML method and non-renewable primary energy impact category by CED method. Table 2 and 3 present the description of assessed impact categories in this study.

Table 2 - Description of the environmental impact categories assessed by CML method

Environmental Impact Categories	Description	Unit
Global Warming (GWP)	Potential contribution of a substance to the greenhouse effect.	[kg CO_2 eq.]
Ozone Layer Depletion (ODP)	Destruction of stratospheric ozone layer by anthropogenic emissions from a substance.	[kg CFC^{-11} eq.]
Acidification (AP)	Increase of the acidity of water and soil by acidifying substances and processes.	[kg SO_2 eq.]
Eutrophication (EP)	Increase of the concentration of nutrients, mainly Nitrogen and Phosphorus in a body of water and soil.	[kg PO_4 eq.]

Table 3 - Description of the environmental impact category assessed by CED method

Environmental Impact Categories	Unit
Non-renewable primary energy (NRPE)	[MJ]

2.3. Building Energy Performance – Seasonal Calculation Method

The seasonal calculation method was based on ISO standard 13790. This calculation method is the simple seasonally calculation which is done by algebraic equations. Calculation of heating and cooling energy demand is dependent on a macroscopic level of heat gains and losses (ISO 13790 2008; Kim, Yoon, and Park 2013).

There are several advantages for using simplified calculation method in comparison with dynamic calculation method. Firstly, there are less numbers of inputs. Secondly, the calculation rules and equations are clear to understand. Finally, there is a transparency to correlate the inputs and output (ISO 13790 2008; Kim et al. 2013).

In this work, calculations were first carried out by using the climate data of Beja (zone I1-V3), Leiria (zone I2-V2) and Bragança (zone I3-V2), according to the Portuguese building thermal regulation (REH) (Decreto-Lei n.º 118/2013 2013; Diário da República 2.ª série — N.º 234 2013; Regulamento de Desempenho Energético dos Edifícios de Habitação (REH) 2013), considering the temperatures of 18ºC and 25ºC as set point respectively for the heating and cooling seasons.

The calculation of energy demand for cooling and heating seasons was performed by an Excel file prepared by the Institute for Technological Research and Development in Construction Sciences (ITeCons). This Excel file is according to the updated version of REH. The energy needs for heating and cooling are calculated for each climate zone while primary energy is obtained by multiplying the primary energy factor to the final energy and final energy is calculated from the useful energy by the following equation;

Equation 1 – Final energy calculation

$$Final\ energy = \frac{Heating\ needs}{Efficiency\ of\ heating\ system} + \frac{Cooling\ needs}{Efficiency\ of\ cooling\ system} \tag{1}$$

Equation 2 – Primary energy calculation

$$Primary\ energy = \frac{Heating\ needs}{Efficiency\ of\ heating\ system} * PEF + \frac{Cooling\ needs}{Efficiency\ of\ cooling\ system} * PEF \tag{2}$$

2.4. Life-Cycle Cost Analysis – Net Present Value

The net present value of a project is described as the sum of present values of yearly net cash flows during the project period (Bragg 2013; Ittelson 2009). NPV can be defined as the difference amount between investments and benefits. It takes into account the inflation and returns of money relating to the present time and future.

The formula for the calculation of Net Present Value is as Equation 3:

Equation 3 - Calculation of Net Present Value

$$NPV\ (i, N) = \sum_{t=0}^{N} \left(\frac{R_t}{(1+i)^t} \right) \tag{3}$$

t – represents the time of the cash flow,

i – represents the discount rate,

R_t – represents the net cash flow (cash inflow – cash outflow).

3. Life-Cycle Model and Inventory

3.1. Goal and Scope Definition

The main goal of this study is to perform a comprehensive LCA of six insulation materials applied to a reference building for new single-family houses in Portugal from cradle to gate and use-phase in terms of building energy performance, environmental impacts and life-cycle cost analysis. It also aims to perform a consequential analysis of increasing thickness of each insulation material to find out the critical thickness of each insulation material per selected impact category.

The system boundary of this study is from raw material extraction of each insulation material to the operation phase of the insulation materials applied to a reference building with lifespan of 30 years (COMMISSION DELEGATED REGULATION No 244 2012). The LCA approach is conducted with a functional unit of providing a thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material. Due to the durability of insulation materials more than 50 years and lifespan of 30 years for the building, the maintenance phase in this study is neglected.

3.2. Life-Cycle Inventory Analysis

In the inventory analysis, data are collected due to quantify and measure the materials and energy flows (ISO 14040 2006). Environmental Product Declaration (EPD) of each insulation material was used as the major source of data. EPD is a product certification which is an approach of quantifying the environmental impact of a product according to ISO 14040 series of standards. Firstly, from raw material acquisition through production phase of each insulation material are assessed according to EPDs. Secondly, for the building operation phase, the required energy for heating and cooling after applying each insulation material is calculated with an Excel file prepared by the Institute for Technological Research and Development in Construction Sciences (ITeCons). This Excel file is according to the Portuguese building thermal regulation (REH) (Decreto-Lei n.º 118/2013 2013; Diário da República 2.ª série — N.º 234 2013; Regulamento de Desempenho Energético dos Edifícios de Habitação (REH) 2013).

3.2.1. Thermal Insulation Materials

Thermal comfort is a critical factor for building occupants and thermal insulation is one way to achieve it. Unwanted heat losses and gains are decreased by applying the thermal insulation in buildings. It also mitigates the energy demand of heating and cooling systems.

Less operating cost and more thermal comfort are resulted from the appropriate use of thermal insulation. It not only decreases the operating cost but also lowers the size of HVAC equipment required. The life of finite resources is extended and can be conserved for future generations. To restrict the energy transfer between inside and outside the building is the main objective of the thermal insulation. It lengthens the indoor thermal comfort period and extends the building life by preventing vapour and moisture (Al-Homoud 2005; Dylewski and Adamczyk 2011; Papadopoulos and Giama 2007).

Primary property of an insulation material is its thermal conductivity. "Thermal conductivity (λ) is the time rate of steady state heat flow (W) through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, induce by a unit (1 K) temperature difference across the sample" (Al-Homoud 2005). Thermal conductivity shows the ability of a material to transfer heat and its unit is presented in W/(m.K).

"Thermal transmittance or U-value is the rate of heat flow through a unit surface area of a component with unit (1 K temperature difference between the surfaces of the two sides of the component" (Al-Homoud 2005). The unit of thermal transmittance is expressed by W/(m^2.K).

The efficiency of a thermal insulation material is dependent on its thermal resistance (R-value), i.e. the efficiency of material to resist against the heat flow because of suppressing conduction, convection and radiation. The unit of R-value is expressed by (m^2.K)/W.

Equation 4 – Thermal Resistance of a building component consisting of homogenous layers (ISO 6946 2007)

$$R_T = R_{si} + R_1 + R_2 + R_3 + \ldots + R_n + R_{se} \qquad (4)$$

Where

R_{si} represents the internal surface resistance,

R_1, R_2 …R_n represent the design thermal resistance of each layer,

R_{se} represents the external surface resistance.

Equation 5 – Thermal transmittance

$$U = \frac{1}{R} \tag{5}$$

The classification of insulating materials is described as follows;

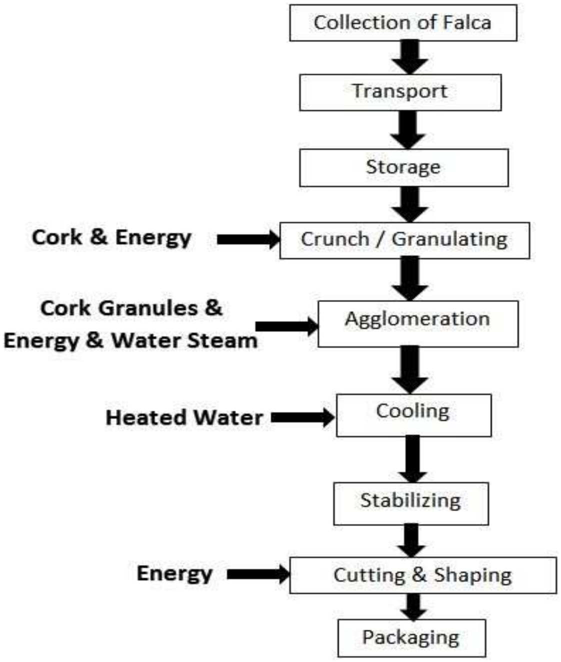
- Inorganic mineral materials; such as mineral wool (Glass Wool and Rock Wool),
- Organic oil-derived materials; such as Polyurethane (PUR), Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS),
- Organic animal/plant derived materials; such as Insulation Cork Board (ICB). (Al-Homoud 2005)

In this dissertation six insulating materials are singled out for comparison as described below;

3.2.1.1. Insulation Cork Board (ICB)

Portugal is one of the main producers of cork in the world. In its production phase, the cork is removed from the trunks and branches of oak trees each nine years. By pruning the branches of oak trees, Falca, a mixture of virgin cork, cork wastes and cork parings, is gained. Extracted Falca is transported to the cork factory and then, it becomes granulated by grinding. Then in drying process, rotating dryers provide the chosen level of moisture for the cork granules and make them agglomerated. After the agglomeration in this phase, the blocks are removed out to be cooled by water. Finally, the blocks are cut and shaped in several thicknesses according to their use (Rives et al. 2012). Figure 1 shows the main processes of ICB production.

Figure 1 – Main Processes of ICB Production (Pargana 2012)

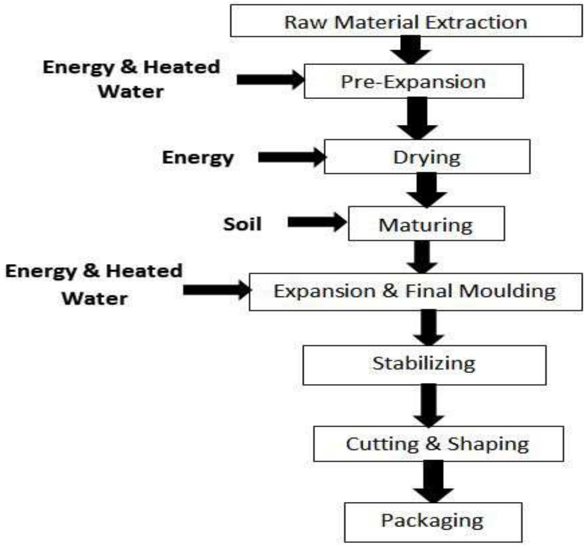


The source of data for evaluating the environmental impacts of ICB from cradle to gate was a master thesis (Pargana 2012) based on an experimental study done on ICB made in Portugal (Gil, Marreiros, and Silva 2011). The environmental impacts of ICB from cradle to gate are presented in the fourth chapter.

3.2.1.2. Expanded Polystyrene (EPS)

Expanded polystyrene is derived from crude oil and consists of solid beads of polystyrene. The structure of its cells, which is a closed air-filled, provides an effective capacity for EPS as an insulation material. Thermal conductivity of EPS depends on its density. EPS does not absorb moisture and damp, humidity or moisture does not have effects on its thermal and mechanical properties. EPS will last as long as the building itself. External agents such as fungi or parasites do not change EPS (Petter Jelle 2011). Figure 2 presents the main processes of EPS production.

Figure 2 – Main Processes of EPS Production (Petter Jelle 2011)

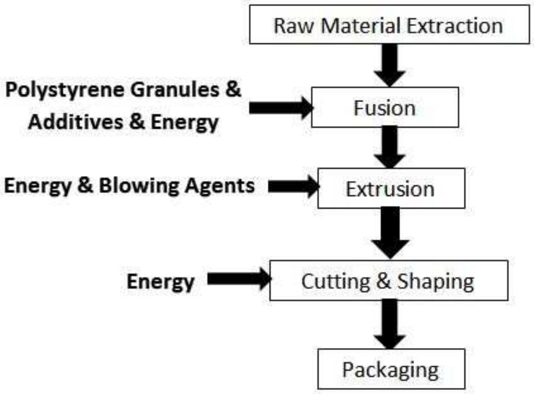


The source of data for evaluating the environmental impacts of EPS from cradle to gate was an EPD from Belgium which its assessed EPS had similar technology to EPS in this study (EUMPES 2013). The environmental impacts of EPS from cradle to gate are presented in the fourth chapter.

3.2.1.3. Extruded Polystyrene (XPS)

Extruded polystyrene is also made of crude oil and it consists of melted polystyrene. In its production phase, an expansion gas such as HFC, CO_2 or C_6H_{12} is used in the extrusion phase. The thermal conductivity of XPS is dependent on the density and its thickness. XPS is ignited and melted easily and lots of heat and poisonous smoke are released after its burning (Petter Jelle 2011; Zhang et al. 2011). Figure 3 shows the main processes of XPS production.

Figure 3 - Main Processes of XPS Production (Petter Jelle 2011)

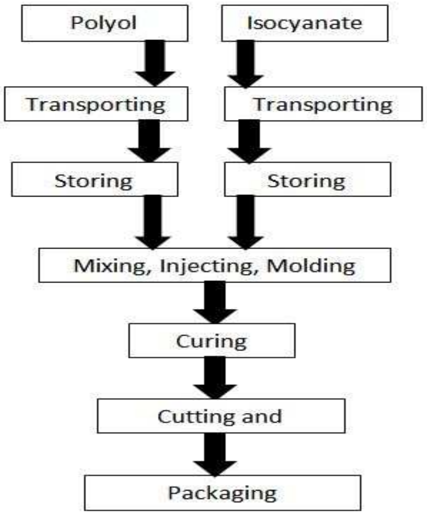


The source of data for environmental assessment of XPS from cradle to gate was an EPD from Belgium which its assessed XPS had similar technology to XPS in this study (EXIBA 2010). The environmental impacts of XPS from cradle to gate are presented in the fourth chapter.

3.2.1.4. Polyurethane Foam (PUR)

Polyurethane foam consists of two main ingredients; isocyanate and polyol. Polyurethane foams are divided into three classes; rigid, semi-rigid and flexible. Rigid polyurethane foams are used as insulation material in buildings. It contains a low-density gas in the cells. It has outstanding thermal insulation properties (Petter Jelle 2011). Figure 4 presents the main processes of PUR production.

Figure 4 – Main Processes of PUR production



The source of data for environmental assessment of PUR from cradle to gate was an EPD from Germany which its assessed PUR had similar technology to PUR in this study (IVPU 2010). The environmental impacts of PUR from cradle to gate are presented in the fourth chapter.

3.2.1.5. Glass Wool (GW)

Glass wool is made of the glass fibres and it can be produced in slab or roll shape. Fibres consist of glass obtained from the mixture of natural sand and recycled glass at 1450ºC (Petter Jelle 2011).

The source of data for environmental assessment of GW from cradle to gate was an EPD from Slovenia its assessed GW had similar technology to GW in this study (URSA 2013). The environmental impacts of GW from cradle to gate are presented in the fourth chapter.

3.2.1.6. Rock wool (RW)

In production of Rock wool the volcanic stone are combined with coke in composition furnace ad after that the melt goes to the spinning machine and the fibres are spun in this machine. Then before going to the curing oven, oil and binder are added and required density is adjusted. The adjusted properties are remained after the curing process (ROCKWOOL 2013).

The source of data for environmental assessment of RW from cradle to gate was an EPD from Czech Reprublic which its assessed RW had similar technology to RW in this study (ROCKWOOL 2013). The environmental impacts of RW from cradle to gate are presented in the fourth chapter.

The declared values of the thermal conductivity and density of the assessed insulation materials in this dissertation from Portuguese producers are presented in Table 4 as follows;

Table 4 – Physical properties of the assessed insulation materials

	ICB	EPS	XPS	PUR	GW	RW
Density ρ [kg/m^3]	100	25	32	40	22	70
Thermal Conductivity λ [W/(m.K)]	0.040	0.034	0.035	0.023	0.033	0.033

The cost of the assessed insulation materials and the installation labor fees associated with each one of the materials are presented in Table 5 as follow;

Table 5 - Materials Costs and Installation Labor Fees (www.cype.pt 2014)

Insulation Material	Price (€/(mm.m^2))	Installation Labor Fee (€/m^2)
ICB	0.200	2.642
EPS	0.073	5.117
RW	0.140	4.857
GW	0.060	2.934
XPS	0.158	10.710
PUR	0.300	10.710

3.2.2. Energy Needs of the Reference Building

3.2.2.1. Introduction to the Reference Building

Reference buildings in each area represent the average and typical buildings of that area. In Portugal, definition of the reference buildings at a national level is carried out by Portuguese General Directive for Energy and Geology (GDEG) and the Portuguese Energy Agency (ADENE) with reviewing the national building thermal regulation codes (RCCTE) (Serra et al. 2013).

The Portuguese reference buildings are two household classes; single-family and multi-family houses, and four years of construction; before 1960, 1961-1990, 1991-2012 and new buildings.

This study works on the new building type of Portuguese reference buildings which is situated in three climate zones of Portugal: Beja, Leiria and Bragança. The characteristics of a new reference building in Portugal are as follows (Decreto-Lei n.º 118/2013 2013; Diário da República 2.ª série — N.º 234 2013; Regulamento de Desempenho Energético dos Edifícios de Habitação (REH) 2013);

Table 6 – Characteristics of Portuguese new reference building

Number of Bedrooms	Number of Floors	Number of Fronts	Usable Area (m^2)	Height (m)	Area of the facades (including glazing) (m^2)	Area of Walls (m^2)
3	2	4	165	2.7	196.13	163.13
U-value of Roof W/(m2.K)	U-value of Windows W/(m2.K)	Winter Solar Factor	Summer Solar Factor	U-value of floors	Winter Renovation Rate	Summer Renovation Rate
0.39	2.90	0.68	0.28	0.40	0.4	0.6

3.2.2.2. Reference Building Energy Assessment

Energy consumption is increasing in order to the increase of population and development of living quality. Building sector is one of the contributors having a considerable potential of reducing the energy consumption. One approach to save the building energy is applying thermal insulation materials contributing to the reduction the heat transfer.(Ucar and Balo 2010)

The use phase of insulation materials in a building includes energy demands for heating and cooling of the building. Electrical systems, with an efficiency of 1 for heating and energy efficiency ratio (EER) of 2.8 for cooling, are adopted for heating and cooling system of the reference building as a default system. Figures 5 to 9 present the heating and cooling needs with default heating and cooling system.

The Portuguese climate data are divided to three climate zones in heating season (I1,I2 and I3) and three climate zones in cooling season (V1,V2 and V3). The reference building in this study was located in three climate zones with various altitudes (z): Beja (I1/V3,z=178m), Leiria (I2/V2,z=126m) and Bragança (I3/V2,z=680m).

The annual heating and cooling energy demands were calculated based on a seasonal calculation by an Excel file prepared by the Institute for Technological Research and Development in Construction Sciences (ITeCons). This Excel file is according to the Portuguese building thermal regulation (REH) (Decreto-Lei n.º 118/2013 2013; Diário da República 2.ª série — N.º 234 2013; Regulamento de Desempenho Energético dos Edifícios de Habitação (REH) 2013). Temperatures of 18ºC and 25ºC are considered as set point for heating and cooling respectively. The reference building for single-family houses is simulated for the previously described scenarios in order to assess the influence of the insulation level on the energy performance of the building. Table 8 and 9 present the annual heating and cooling energy for the reference building in three climate zones for each type of insulation materials respectively. They show the results for the reference building without insulation material, considering the U-value of 2 W/(m^2.K) for the wall (ITE50 2006), for different insulation materials and also for the reference U-value for each climate zones (I1=0.5 W/(m^2.K), I2=0.4 W/(m^2.K) and I3=0.35 W/(m^2.K)). The heating and cooling energy required after applying the insulation materials is calculated for thicknesses from 20 mm to 200 mm (10 mm by 10 mm). In table 8 and 9, thicknesses of 30, 80 and 150 mm are presented. In terms of building solution, it was considered that the insulation material was applied externally. In this way thermal inertia did not change.

The environmental impacts of1 kWh electricity produced in Portugal are presented in Table 7 with the relevant source of data.

Table 7 - Environmental emission of 1 kWh Electricity Production

	kg CO_2 eq./kWh	kg SO2 eq./kWh	kg PO_4 eq./kWh	kg CFC_{11} eq./kWh	MJ/kWh
1 kWh Electricity Production	0.36	0.0064	0.00118	4.27E-8	9.52
Data Sources	(Diário da República 2.ª série — N.º 234 2013)	Eco-invent V2.05	Eco-invent V2.05	Eco-invent V2.05	Eco-invent V2.05

Table 8 – Annual heating energy (kWh/m^2.year) for the reference building in three climate zones per type of insulation material

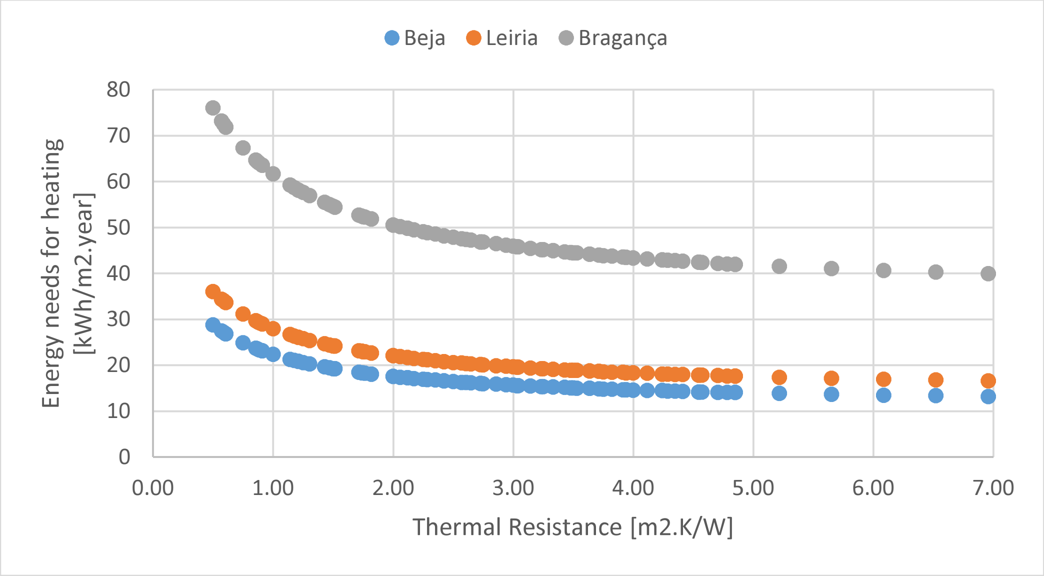
Zones	Without Insulation Material	With Reference U-Value	With Insulation Materials																	
			ICB			EPS			XPS			PUR			GW			RW		
			30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm
Beja I1	50.3	19.3	24.9	17.6	14.8	23.4	16.8	14.3	23.7	16.9	14.4	20.3	15.1	13.4	23.2	16.6	14.2	23.2	16.6	14.2
Leiria I2	62.8	22.1	31.2	22.1	18.6	29.3	21.0	18.0	29.7	21.2	18.1	25.4	18.9	16.8	29	20.8	17.9	29	20.8	17.9
Bragança I3	121.3	48.6	67.4	50.6	43.9	64.1	48.6	42.7	64.7	48.9	42.9	57.0	44.6	40.3	63.6	48.2	42.5	63.6	48.2	42.5

Table 9 - Annual cooling energy (kWh/m^2.year) for the reference building in three climate zones per type of insulation material

Zones	Without Insulation Material	With Reference U-Value	With Insulation Materials																	
			ICB			EPS			XPS			PUR			GW			RW		
			30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm	30 mm	80 mm	150 mm
Beja V3	39.8	31.4	33.0	30.8	29.9	32.6	30.5	29.7	32.7	30.6	29.7	31.7	30.0	29.3	32.5	30.5	29.7	32.5	30.5	29.7
Leiria V2	7.8	8.4	8.1	8.4	8.5	8.2	8.4	8.5	8.1	8.4	8.5	8.2	8.5	8.6	8.2	8.4	8.5	8.2	8.4	8.5
Bragança V2	12.2	12.1	12.0	12.1	12.2	12.1	12.1	12.2	12.1	12.1	12.2	12.1	12.2	12.2	12.1	12.2	12.2	12.1	12.2	12.2

The results of the annual heating and cooling energy for the reference building in three climate zones are provided in the figure 5 and figure 6 respectively.

Figure 5 - Annual heating energy (kWh/m^2.year) for the reference building in three climate zones for various thermal resistances considering the six insulation materials



The results in Figure 5 show that in Bragança, more energy needs for heating the building. In all climate zones, the annual heating energy needs is decreasing by the increasing the thermal resistance of insulation materials. Furthermore, there is a value for the thermal resistance that increasing more than this value is not economical due to not having any effect on reduction of energy needs.

Figure 6 - Annual cooling energy (kWh/m^2.year) for the reference building in three climate zones for various thermal resistances considering the six insulation materials

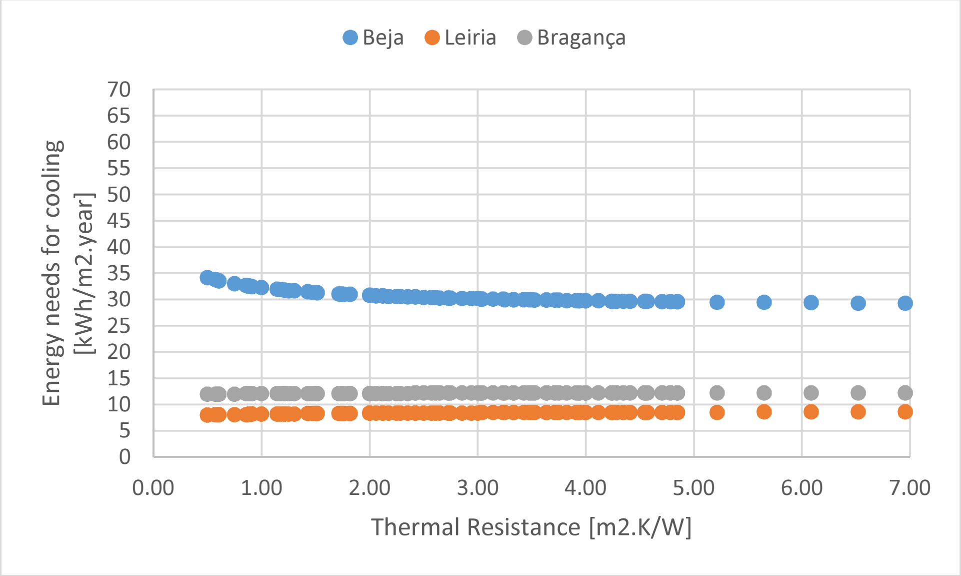


Figure 7 presents the annual energy needs for cooling and heating the building for various thicknesses of insulation materials in each climate zone.

Figure 7 - Annual heating and cooling energy (kWh/m^2.year) for the reference building in each climate zone for various thicknesses of the six insulation materials

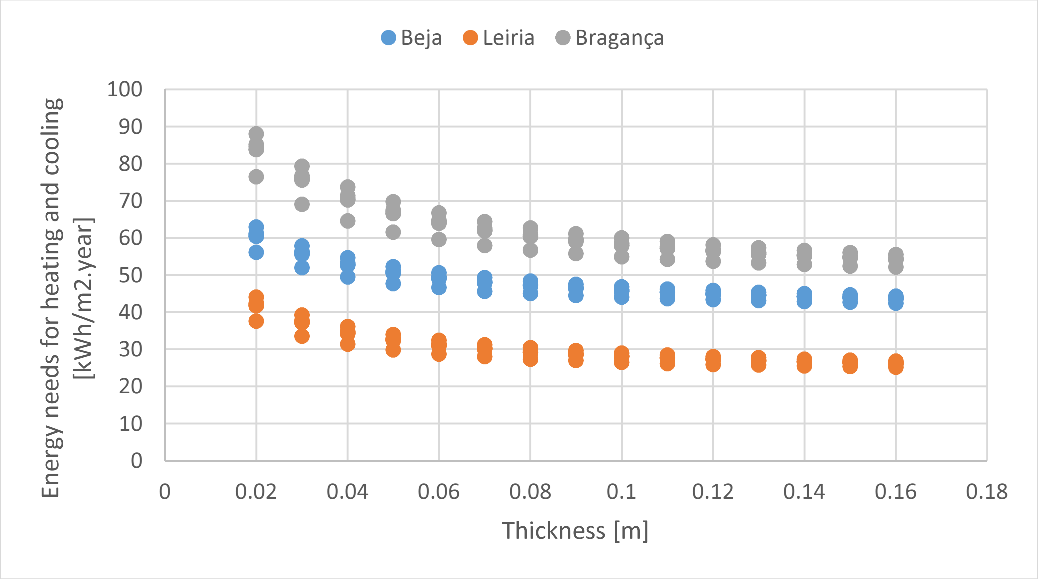
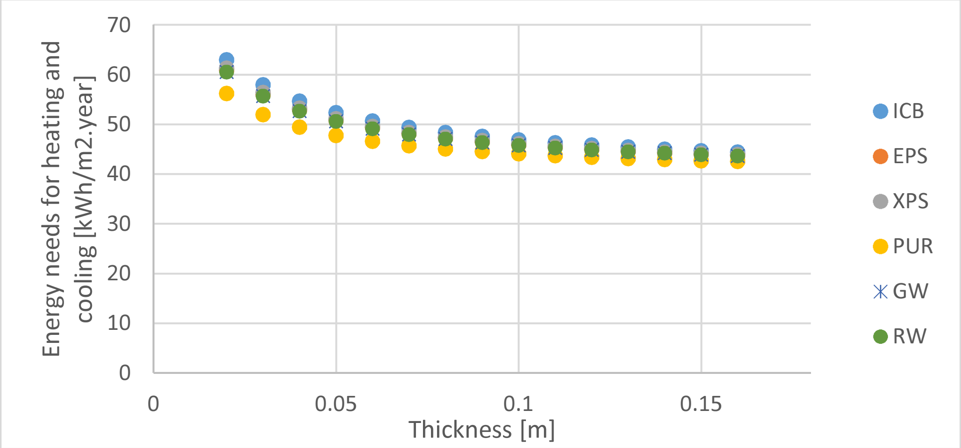


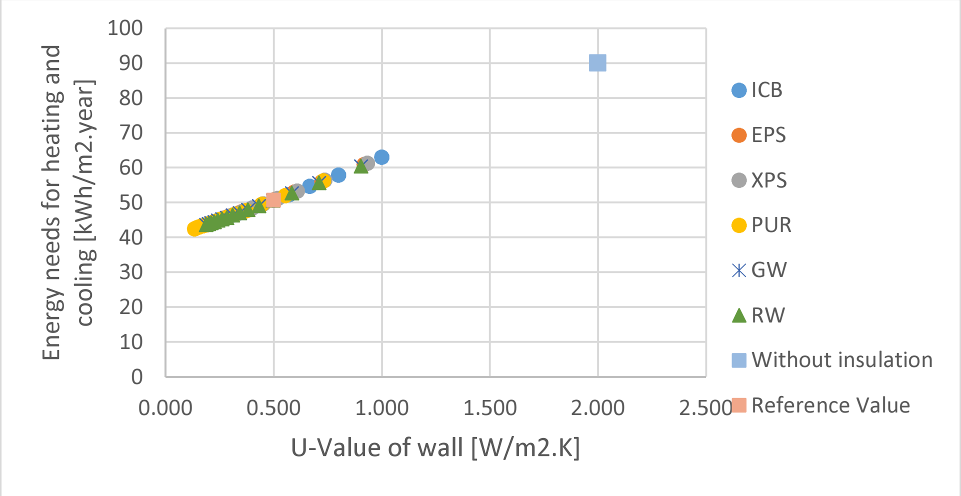
Figure 8 shows the annual energy needs for cooling and heating the building for various thicknesses of insulation materials in Beja just to show the differences between materials. According to the Figure 8, PUR has better function in saving the energy. On the other side, ICB needs more energy for heating the building in comparison with other insulation materials.

Figure 8 - Annual heating and cooling energy (kWh/m^2.year) for the reference building in Beja for various thicknesses



The annual energy needs for cooling and heating the building for various insulation materials according to the U-value of the wall in comparison with the reference building without insulation material and also with the reference U-value of the wall in Beja are demonstrated in Figure 9. Reference U-value of the wall depends on the climate zones. For instance, the reference U-value of the wall in Beja, Leiria and Bragança are defined 0.50, 0.40 and 0.35 W/m^2.K respectively.(Regulamento de Desempenho Energético dos Edifícios de Habitação (REH) 2013) There is a huge difference between the energy needs of the building for heating and cooling without insulation material and with insulation materials.

Figure 9 - Annual heating and cooling energy (kWh/m^2.year) needs for various insulation materials according to the U-value of the wall in Beja

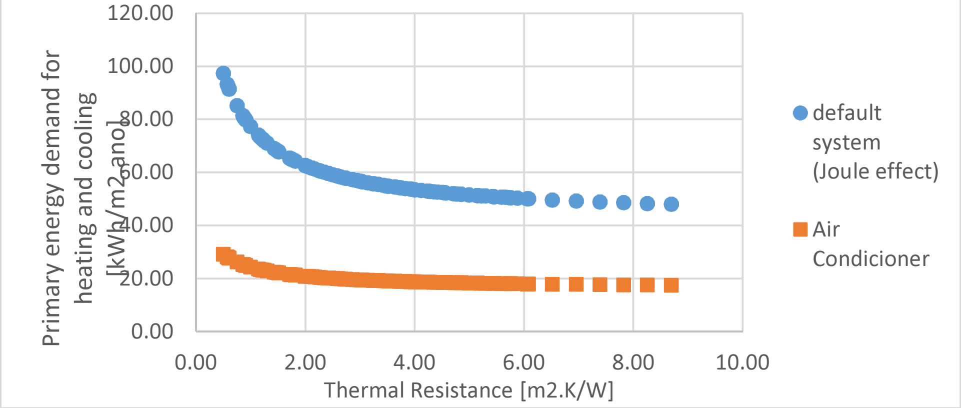


The default heating system for this study, a joule effect system, is compared according to the amount of required primary energy with an air conditioner with a coefficient of performance (COP) of 4.1 for Leiria in Figure 10. The properties of default system and the air conditioner are presented in Table 10.

Table 10 – Equipment properties

Equipment	Function	Efficiency/COP/EER	Fuel	Primary Energy Factor (PEF)
Default system (Joule effect system)	Heating	Efficiency = 1	Electrical	2.5
Default system (Air conditioner)	Cooling	EER = 2.8	Electrical	2.5
Air conditioner	Heating	COP = 4.1	Electrical	2.5

Figure 10 – Primary energy demands for heating and cooling the building in Leiria with different equipment



4. Results and Discussions - Life-Cycle Impact Assessment

In this chapter, the impact assessment results are presented. The aim of LCIA phase is to assess the results collected from the LCI phase and to evaluate their environmental impact. In the LCIA phase, a list of impact categories is selected and the LCI results are compacted and explained by the category indicators. The category indicators characterize the potential environmental impacts and reveal the emissions for every impact category (Budavari et al. 2011; Goedkoop et al. 2008).

In this chapter, firstly materials are compared for each impact category within provided EPDs from cradle to gate. Secondly, by considering use-phase of materials after applying to the reference building, a consequential analysis is performed due to 10 mm extra insulation material for each impact category in each climate zones to trade off the increased embodied emissions of insulation materials and reduced emissions of materials after applying to the reference building. Finally three scenarios are defined to compare the base scenario with them.

4.1. Comparison of Insulation Materials - Cradle to gate

In this part, each insulation material is assessed from raw material extraction through production phase and the environmental impacts were presented from each insulation material EPD which was referred in LCI phase. Functional unit was defined in the third section as providing the thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material. Table 11 shows the reference flows provided by each insulation material per functional unit. Reference flow is the quantified amount of a product system which provides the performance described by the functional unit (ISO 14040 2006).

Table 11 - Reference flows of insulation materials providing thermal resistance of 1 m^2.K/W within an area of 1 m^2

	ICB	EPS	XPS	PUR	GW	RW
Mass	4 kg	0.85 kg	1.12 kg	0.96 kg	0.73 kg	2.31 kg
Thickness	40 mm	34 mm	35 mm	23 mm	33 mm	33 mm

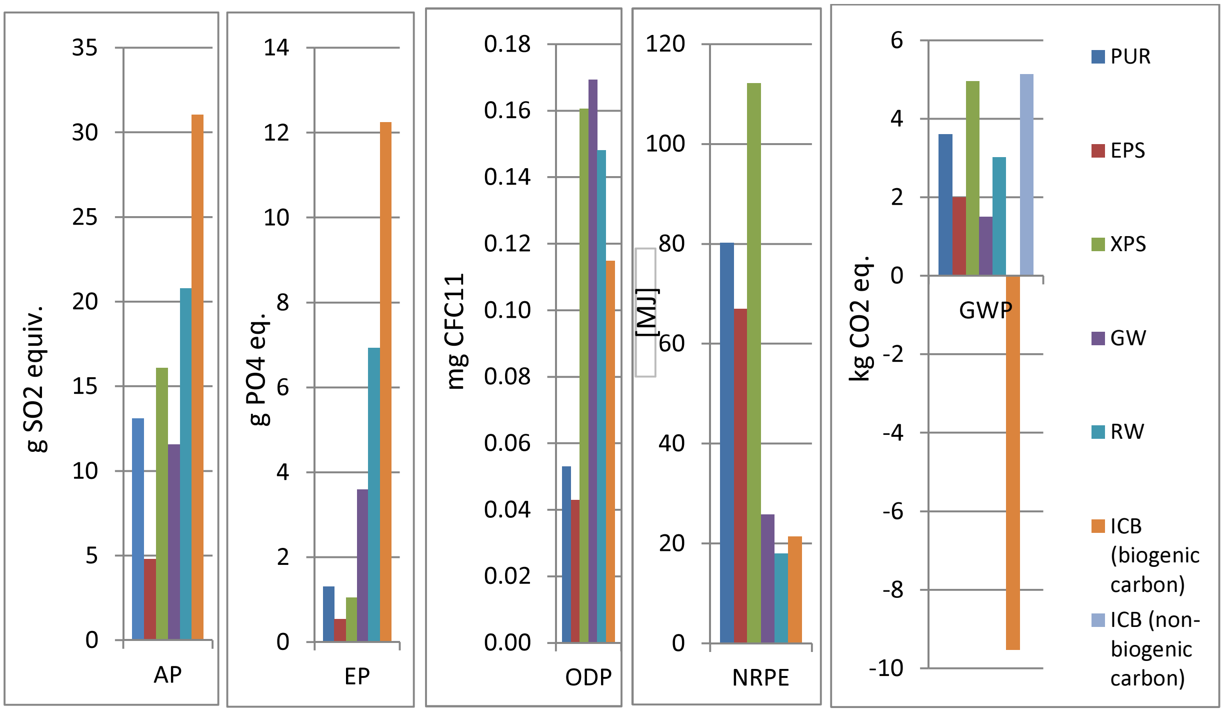
Table 12 presents the environmental impact categories of the six insulation materials per functional unit (EUMPES 2013; EXIBA 2010; Gil et al. 2011; IVPU 2010; Pargana 2012; ROCKWOOL 2013; URSA 2013). A1 refers to the raw material extraction, A2 to transport and A3 to the production phase of insulation materials.

Table 12 – Environmental impact categories referred to insulation materials per functional unit (providing thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material) (A1-A3)

Impact Category	Unit	EPS (0.85 kg)	XPS (1.12 kg)	PUR (0.96 kg)	ICB (4 kg)	GW (0.73 kg)	RW (2.31 kg)
NRPE	MJ	6.7E+01	1.12E+02	8.00E+01	2.14E+01	2.58E+01	1.80E+01
GWP	Kg CO_2 eq.	2.0E+00	4.95E+00	3.60E+00	-1.30E+01	1.49E+00	3.02E+00
ODP	Kg CFC_{11} eq.	4.3E-08	1.61E-07	5.30E-08	1.15E-07	1.69E-07	1.48E-07
AP	Kg SO_2 eq.	4.8E-03	1.61E-02	1.31E-02	3.10E-02	1.16E-02	2.08E-02
EP	Kg PO_4 eq.	5.3E-04	1.05E-03	1.30E-03	1.23E-02	3.60E-03	6.93E-03

The meaningful comparison between insulation materials according to their environmental impact is provided in Figure 11 for each impact category after assessing the environmental impact categories referred to all insulation materials with the specified functional unit of providing thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material from cradle to gate.

Figure 11 - Comparison between all insulation materials from cradle to gate with the same functional unit (providing thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material)

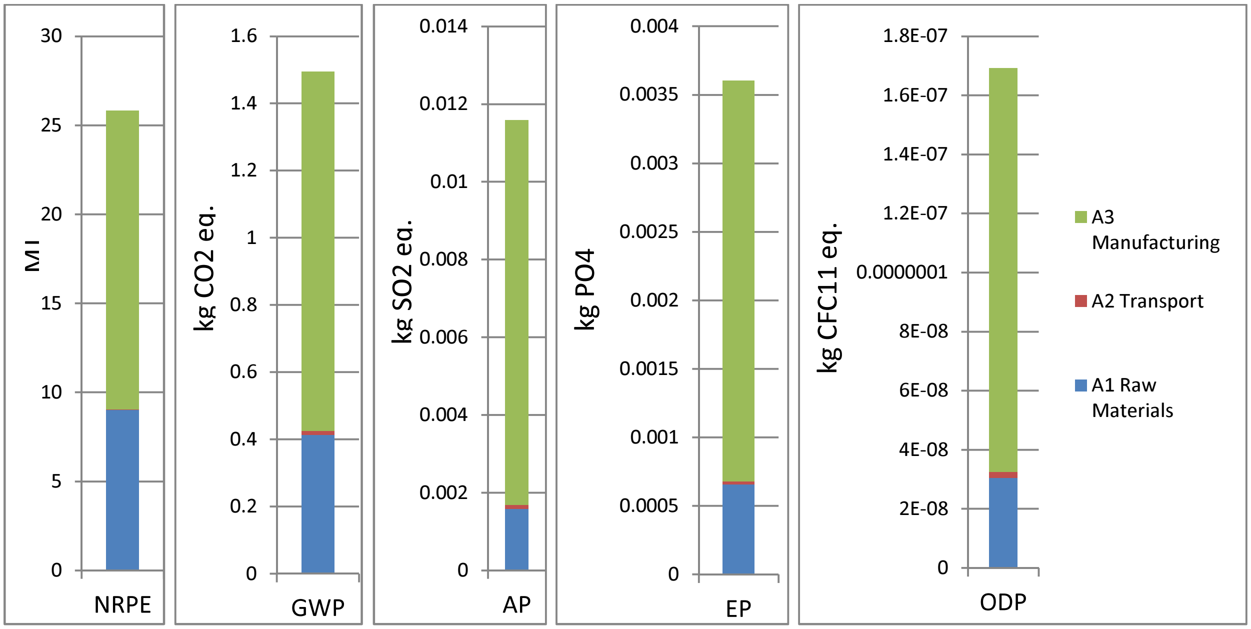


Considering non-renewable primary energy, the highest impact belongs to XPS due to the use of polystyrene which is a petroleum derivate product as a non-renewable primary energy. XPS contributes more than 6 times to NRPE comparing with lowest one for RW. Regarding NRPE, RW, GW and ICB have the best environmental performances.

Regarding global warming potential impact category, ICB due to the absorption of CO_2 by raw cork during biomass growth has negative value. In this study CO_2 uptake was considered. 1 kg of ICB consists of 0.65 kg biogenic carbon which corresponds to -2.37 kg CO_2 eq. to GWP and 0.35 kg non-biogenic carbon which corresponds to 1.28 kg CO_2 eq. to GWP (Garcia and Freire 2013; Gil et al. 2011). XPS has the highest GWP impact and the lowest impact belongs to GW which is 70% lower than XPS.

Owing to ODP impact category, EPS has the lowest impact category which performs 75% better than GW which has the highest ODP impact. It should be indicated that more than 80% of ODP impact in GW belongs to its production phase due to the use of blowing agents during its production phase and fibers with the length of less than 3μm could be harmful. In the production areas, the concentration of more than 500000 fibers/m^3 could be dangerous for the environment (Papadopoulos, Karamanos, and Avgelis 2002). In this impact category, PUR also shows an appropriate environmental performance. Figure 12 shows environmental impacts of GW in each phase.

Figure 12 - Environmental impact categories referred to GW (0.73 kg) in each phase per functional unit (providing thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material)

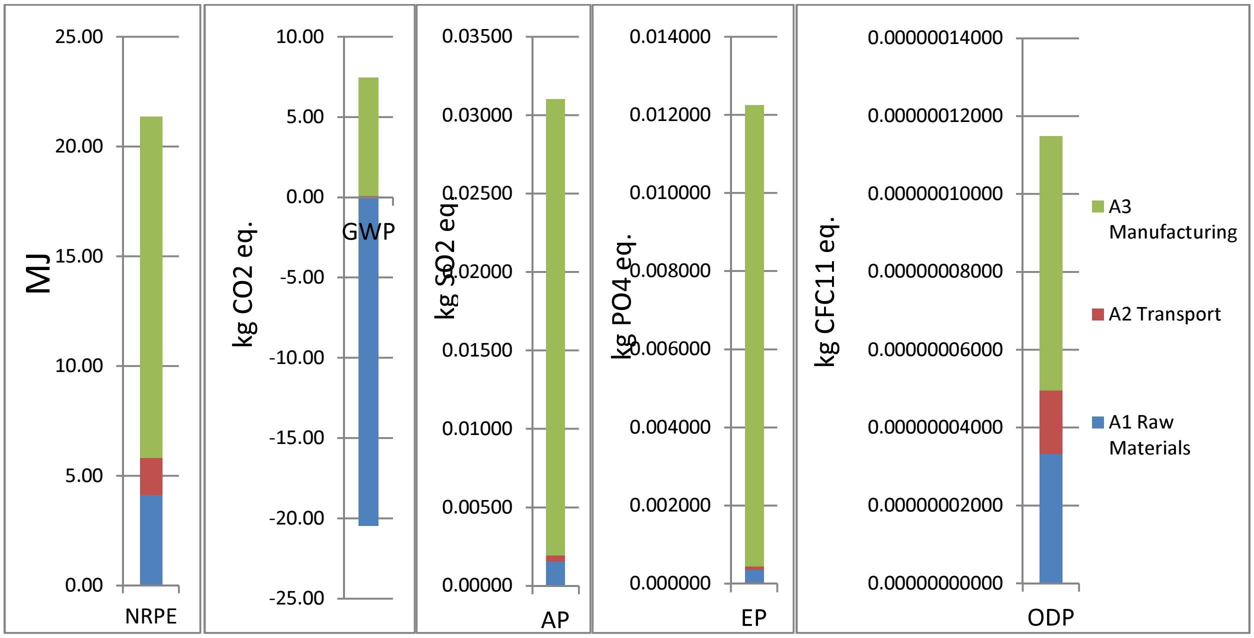


Considering acidification potential impact category, ICB shows the highest AP impact with 0.031 kg SO_2 eq./m^2 while the best environmental performance regarding AP impact category is EPS with 0.0048 kg SO_2 eq./m^2. AP impact of ICB is about 85% more than EPS. It should be noted that about 94% of AP impact of ICB refers to its production phase because of the combustion of the boiler in ICB production phase.

Owing to EP impact category, EPS has the lowest impact while the highest impact belongs to ICB. In this impact category, EPS performs 96% better performance comparing with ICB. It should be mentioned that 96% of EP impact of ICB refers to its production phase due to the increased production of dead biomass which results the depletion of oxygen in the water or soil. Due to the mentioned decrease, it consumes more oxygen. This results changes in species composition and death of organisms (Budavari et al. 2011). Considering this impact category, XPS and PUR also perform appropriate performances.

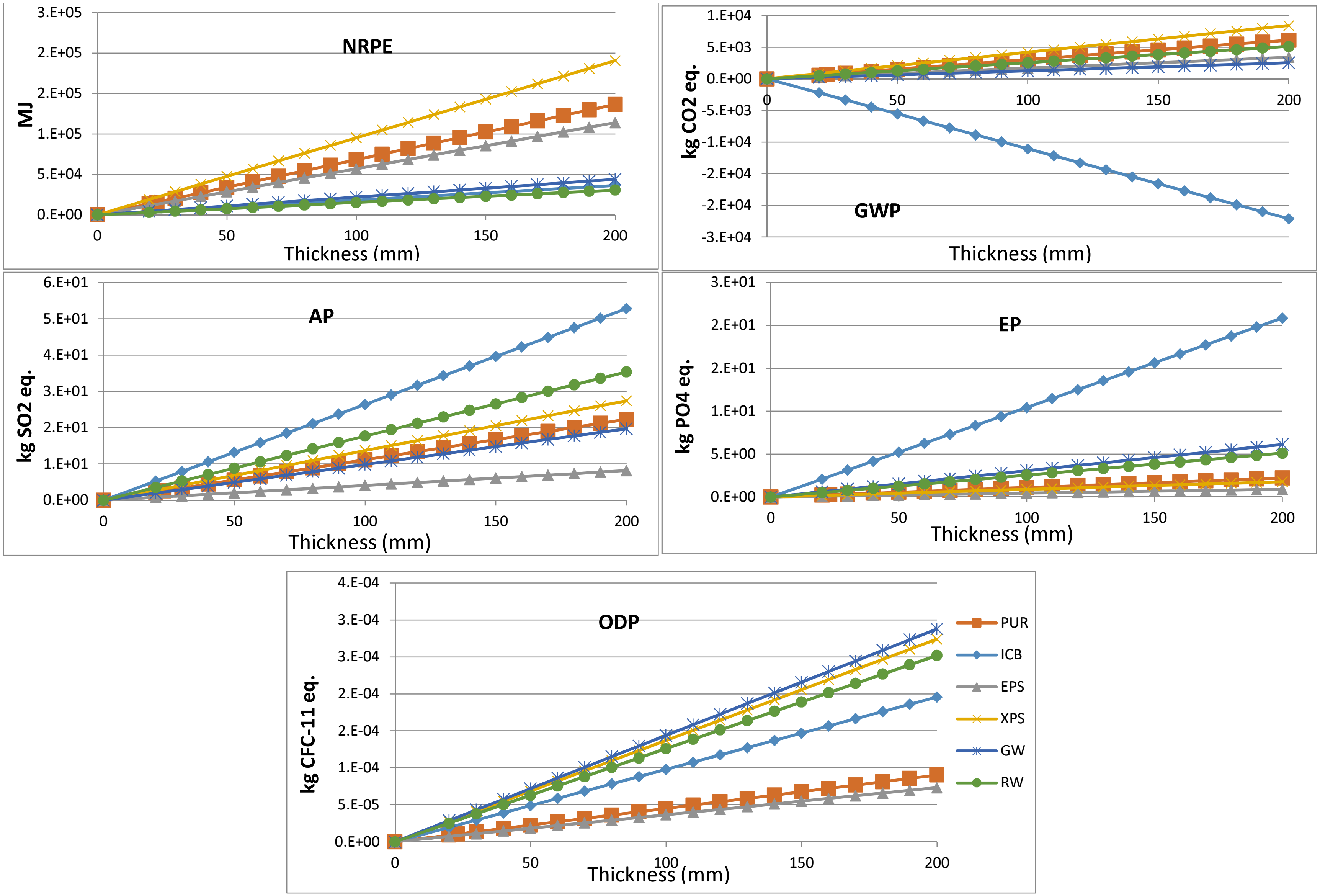
Figure 13 presents the environmental impact categories of Insulation Cork Board (ICB) for each phase from cradle to gate.(Gil et al. 2011; Pargana 2012)

Figure 13 - Environmental impact categories referred to ICB (4 kg) in each phase from cradle to gate per functional unit of providing thermal resistance of 1 m^2.K/W for 1 m^2 area of an insulation material



In Figure 14, increase of embodied environmental impacts due to extra 10 mm insulations up to 200 mm according to the thickness of materials are presented. This figure shows that increase of embodied emission of insulation materials due to 10 mm extra insulation material shows a linear evolution.

Figure 14 – Increase of each environmental impact category for each insulation material due to 10 mm extra insulation material up to 200 mm



4.2. Consequential LCA of increased insulation in a reference building for new single-family houses in Portugal: a comparison of insulation materials

It is crucial to find out which thickness of each insulation material attains maximum benefit in environmental performance. Here, one is a dependent variable (benefit from reduction of energy consumption and environmental impacts) and the other is an independent variable (increasing the insulation material environmental impacts). Marginal analysis will try to evaluate whether the increase or reduction of an independent variable will cause the dependent variable to fall or rise maximally. The process of identifying the benefits and costs of different thicknesses by examining the incremental effect on total revenue and total cost caused by one unit (extra 10 mm of the insulation material) change in the output or input of each alternative. Marginal analysis supports decision-making based on marginal or incremental changes to resources instead of one based on total or average values (Www.investopedia.com 2013). Incremental marginal costs and decreasing marginal benefits of each insulation material due to extra 10 mm insulation material are calculated. Total net benefit is achieved by subtracting the marginal cost (embodied emission of an insulation material) from the marginal benefit (reduced emissions due to decrease the energy consumption). Negative net benefit shows that increasing the thermal insulation thickness is not beneficial.

Marginal analysis is performed for each insulation material in each impact category. Marginal cost in this study refers to the increase of embodied environmental impacts due to 10 mm extra insulation material and marginal benefit is associated with the reduction of environmental impacts due to extra 10 mm insulation material. The increasing of environmental impacts of each insulation material due to extra 10 mm insulation material is linear but the reduction of environmental impacts of each insulation material due to extra 10 mm insulation material is not linear. Figure 15, 16, 17, 18 and 19 present marginal analyses due to extra 10 mm insulation material for each insulation materials related with GWP, AP, EP, ODP and NRPE respectively. The graphs start from 30 mm thickness because of 10 mm extra insulation material to the initial selected thickness of 20 mm and continue up to 200 mm. These graphs present the results in logarithmic scale. The environmental impacts of insulation materials and the environmental emissions of 1 kWh Electricity production were presented in LCI section.

Figure 15 – Marginal analysis of NRPE due to 10 mm extra insulation material in Beja, Leiria and Bragança for each insulation material up to 200 mm

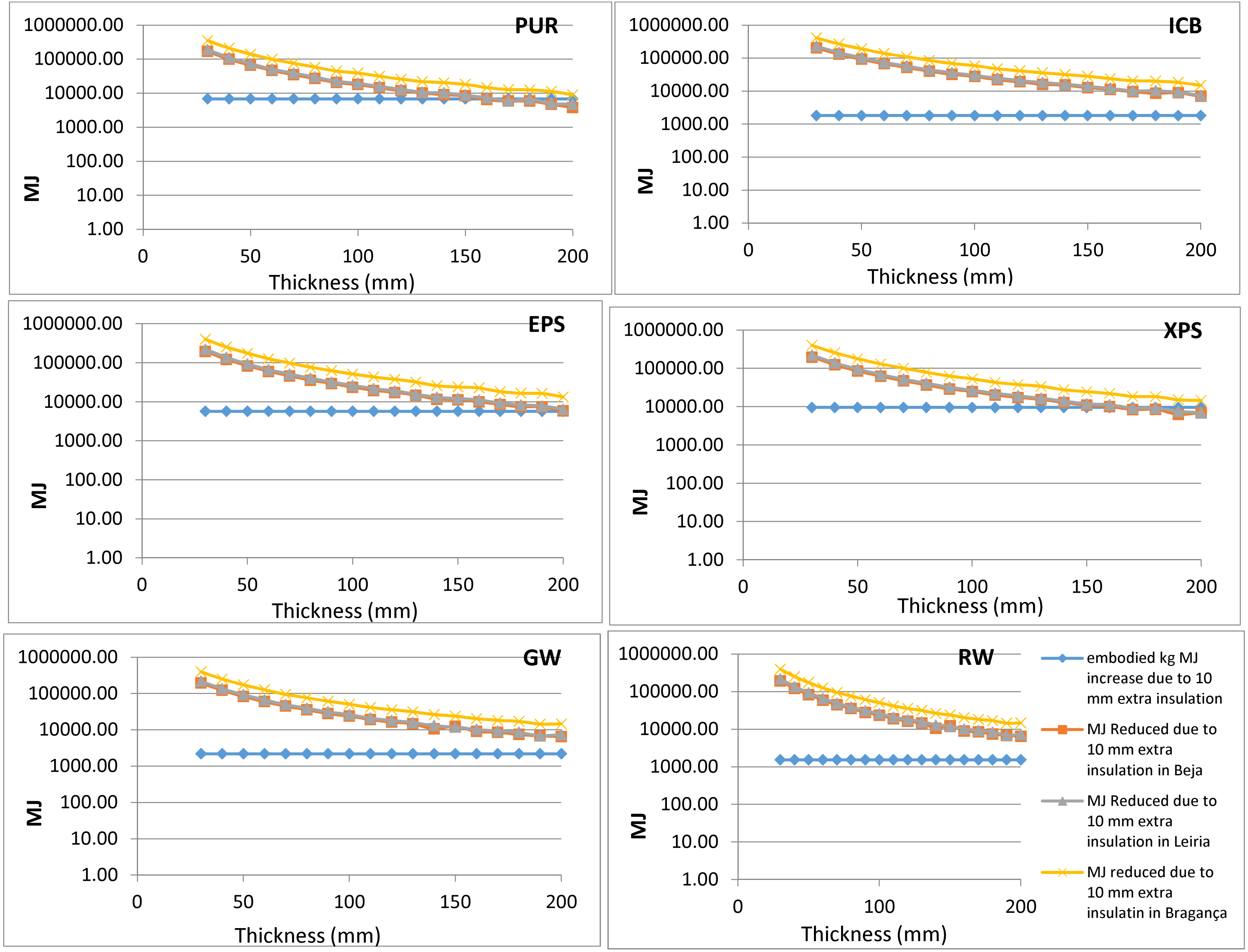


Figure 16 - Marginal analysis of GWP due to 10 mm extra insulation material in Beja, Leiria and Bragança for each insulation material up to 200 mm

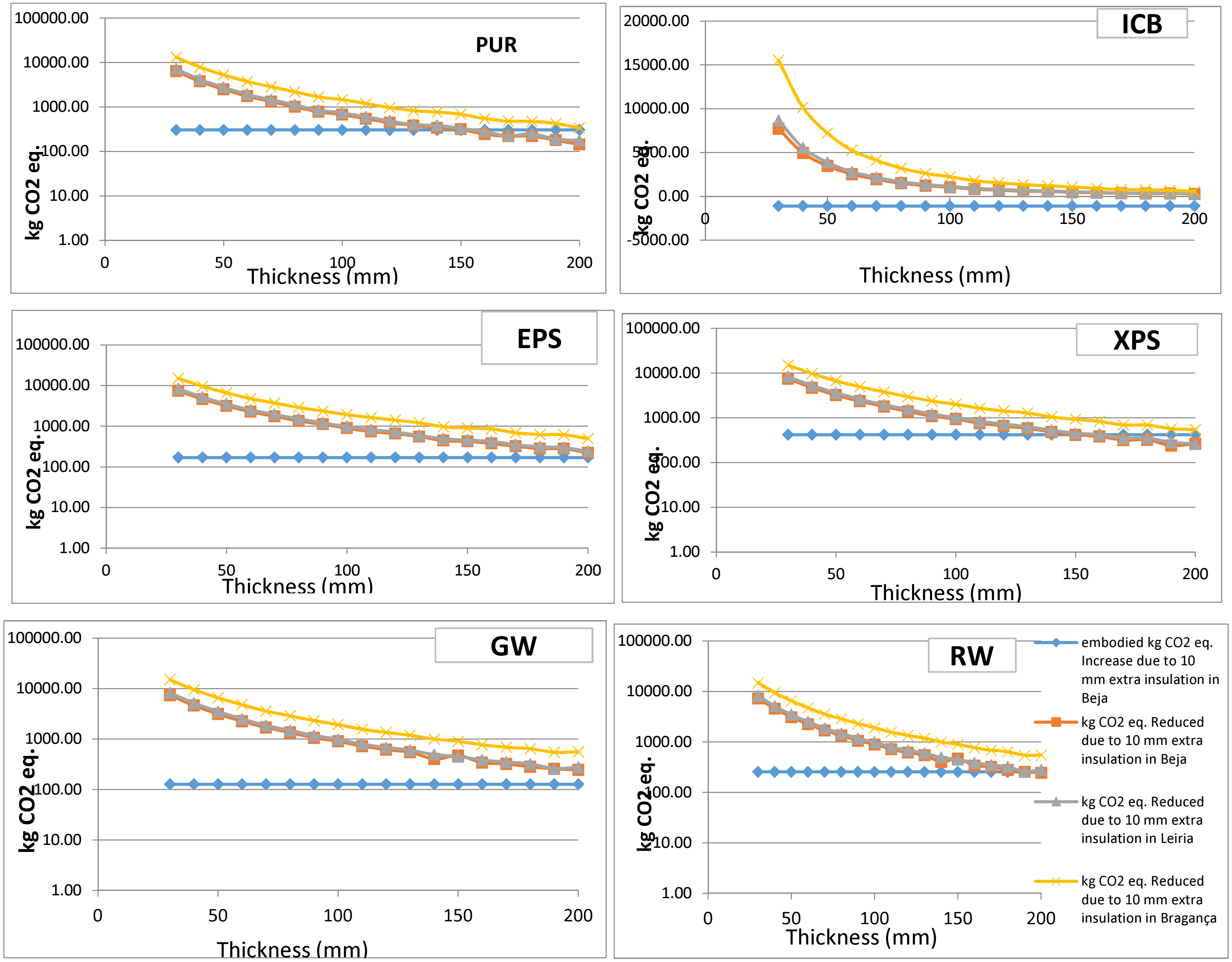


Figure 17 - Marginal analysis of AP due to 10 mm extra insulation material in Beja, Leiria and Bragança for each insulation material up to 200mm

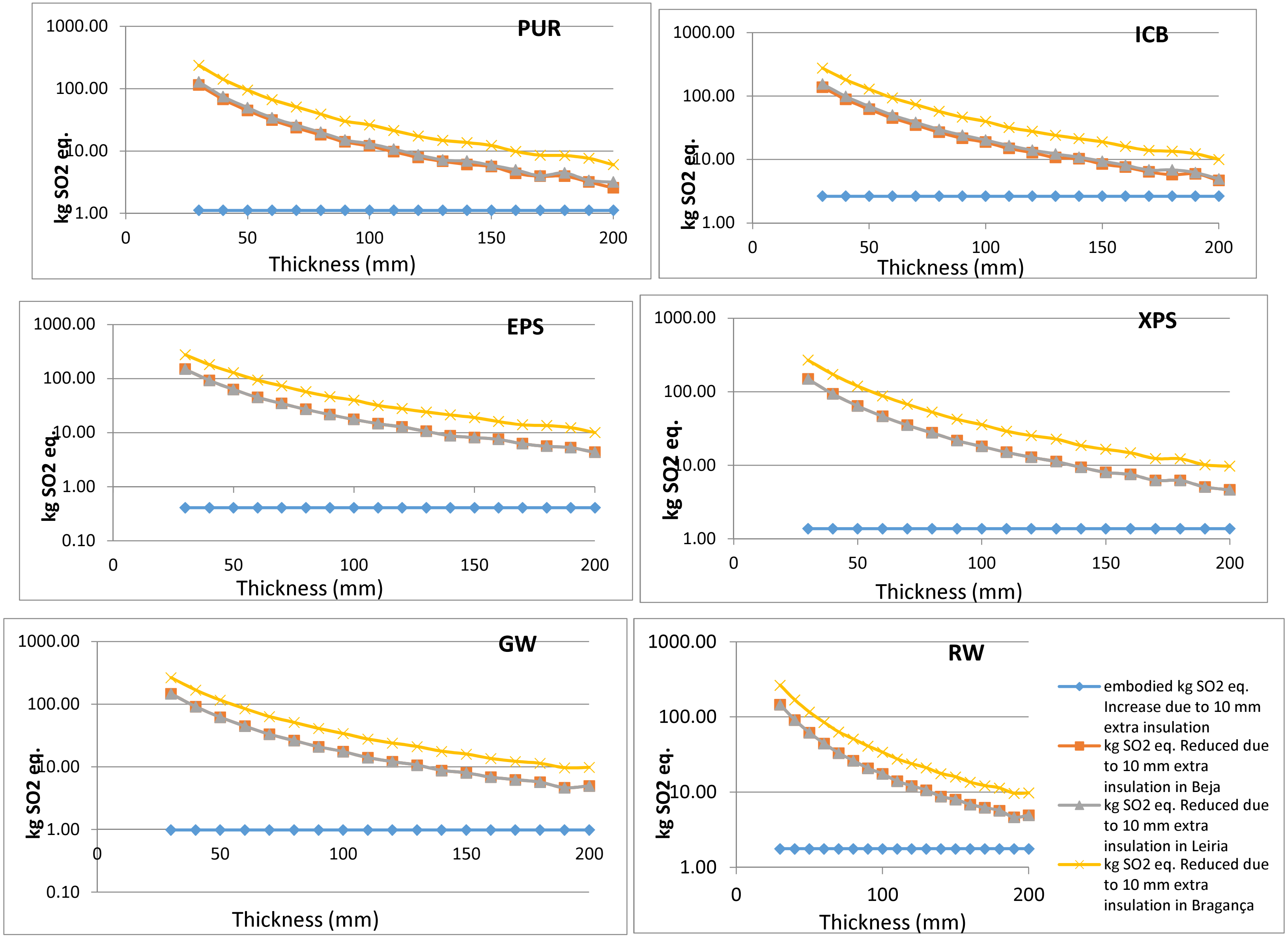


Figure 18 - Marginal analysis of EP due to 10 mm extra insulation material in Beja, Leiria and Bragança for each insulation material up to 200 mm

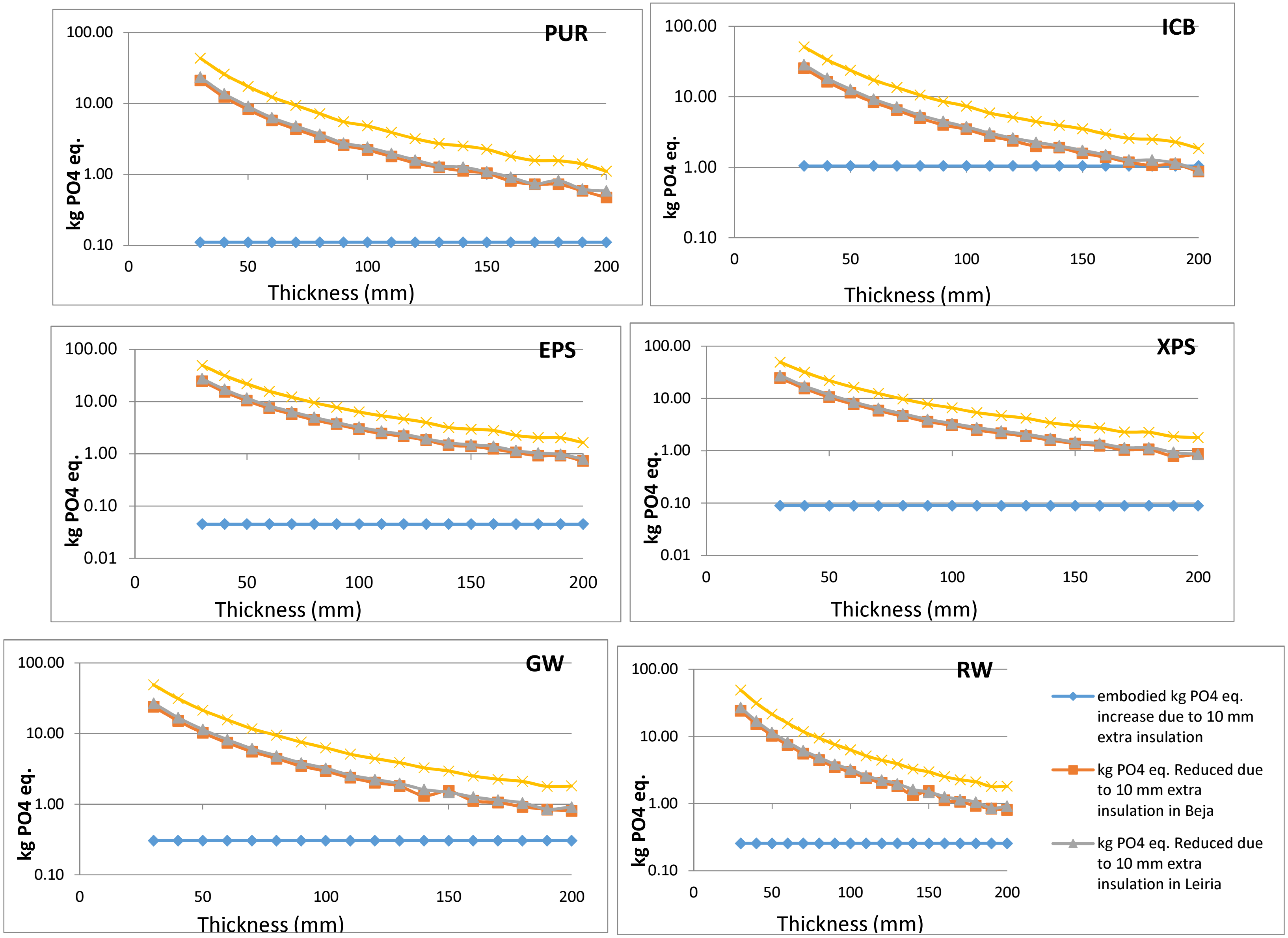
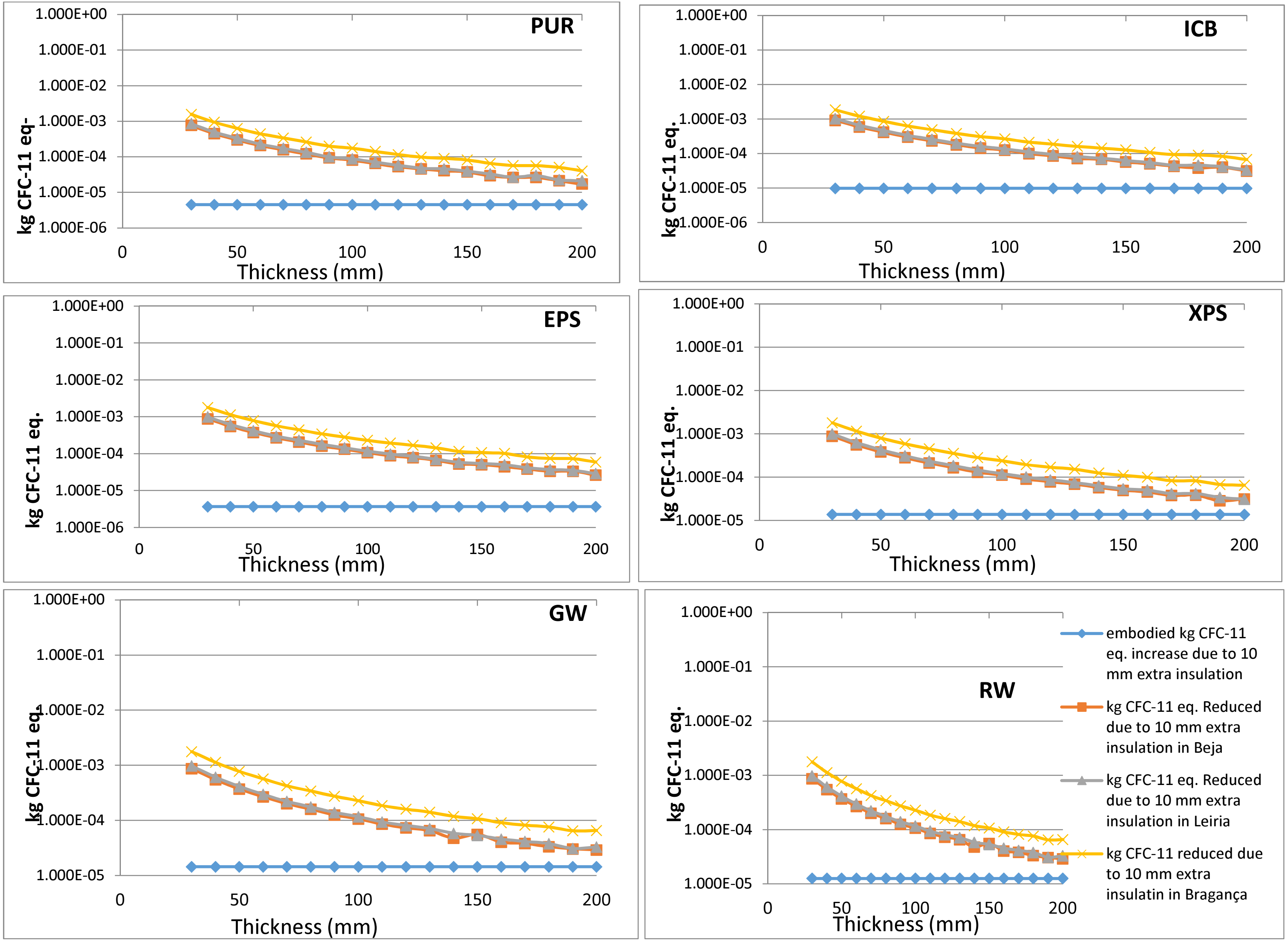


Figure 19 - Marginal analysis of ODP due to 10 mm extra insulation material in Beja, Leiria and Bragança for each insulation material up to 200 mm



As can be seen in marginal analysis figures, embodied environmental emissions of insulation materials are increased due to extra 10 mm insulation materials linearly but the emissions in order to the energy consumption of the reference building due to 10 mm extra insulation materials are reduced not linearly. It is significant that the increasing thickness of insulation material does not make sense if the amount of increased emissions due to 10 mm extra insulation material exceeds the amount of reduced emissions due to 10 mm extra insulation material. There is a critical thickness for each insulation material that it is not beneficial to increase the thickness. For instance, regarding GWP impact category, thicknesses more than 150 mm in Beja and Leiria are not beneficial due to the increased embodied emissions with thickness of 160 mm will exceed the reduced emission of PUR after applying to the reference building. In Bragança, thicknesses more than 200 mm are not beneficial. By changing the climate zones from Beja to Bragança due to the more energy needs for heating the building application of PUR to the building saving more energy and more reduction of emissions comparing with Beja, the critical thickness will be increased by around 50 mm.

In comparison of insulation materials, application of PUR to the reference building results less energy needs for heating and cooling the building. On the other hand, application of ICB to the reference building requires more energy for heating and cooling the building in comparison with other insulation materials.

It should be noted that insulation materials with higher impact in each impact category from cradle to gate has the lower critical thickness in comparison with other materials regarding this impact category. For instance, considering NRPE impact category in Figure 11, XPS and PUR showed the highest impacts. Therefore, critical thicknesses of these two materials must be lower than the other materials. As it was presented in Figure 15, critical thicknesses of XPS and PUR were 170 mm but for other materials were more than 200 mm.

4.2.1. Sensitivity Analysis

Many sensitivity analyses can be made on this study. Two sensitivity analyses are performed on this dissertation. Firstly, marginal analysis is conducted due to extra thermal resistance of 1 m^2.K/W for one of insulation materials, PUR in Beja. Increasing embodied emissions of PUR and also reduction of emissions after applying PUR to the reference building are calculated due to 1 m^2.K/W extra PUR. Secondly, different lifespans are considered for the reference building, 20 years and 40 years. Again, marginal analysis is performed to calculate the embodied emissions of PUR and also reduction of emissions after applying PUR to the reference building in Beja with various lifespans: 20 years and 40 years.

4.2.1.1. Marginal Analysis due to 1 m^2.K/W extra insulation material in Beja

In this defined scenario, embodied environmental emissions of insulation materials and emissions in order to the energy consumption of the reference building are calculated due to 1 m^2.K/W extra insulation material in Beja. By increasing the thermal resistance of insulation materials, much more material is needed to produce and increasing the thermal resistance after a critical value is not beneficial in order to have more embodied environmental emission than decreasing the energy needs of the building. Figure 20 presents the marginal analysis due to 1 m^2.K/W extra material in Beja. In this scenario, the default heating and cooling system was considered. This figure shows that each insulation material has different critical thermal resistance which is not beneficial to increase the thermal resistance after this value.

Figure 20 - Marginal analysis due to extra 1 m^2.K/W thermal resistance of PUR in Beja

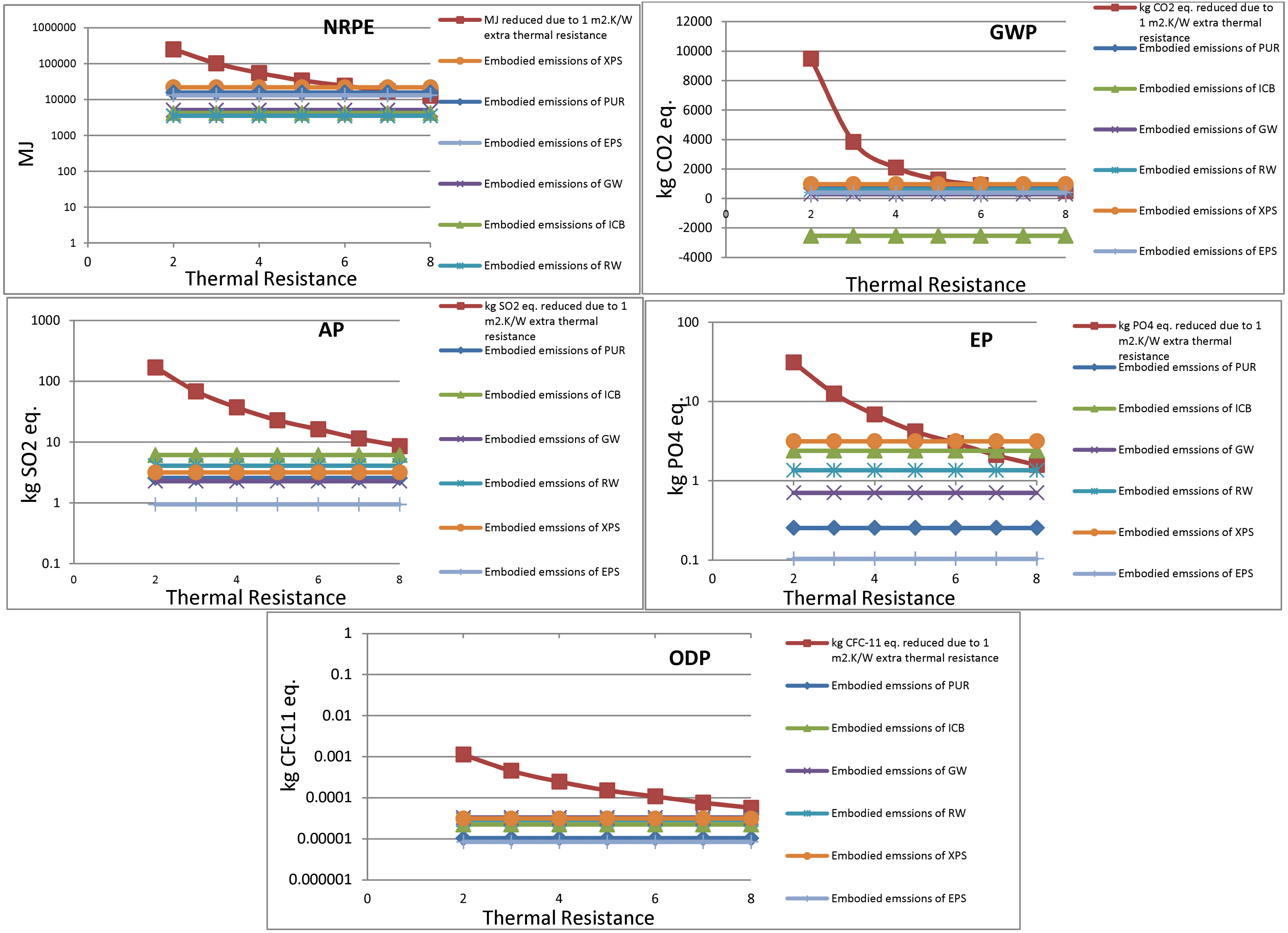


Table 13 shows different thermal resistances of PUR in terms of different thicknesses.

Table 13- Different thermal resistances of PUR in terms of different thicknesses

Thermal Resistance (m^2.K/W)	1	2	3	4	5	6	7	8
Thickness (mm)	23	46	69	92	115	138	161	184

Marginal analysis due to extra 10 mm insulation material is more valid and more results are obtained for the analysis in the assessed range from 20 mm to 200 mm. Thermal resistances from 1 to 8 m^2.K/W are existed for PUR in this assessed range of thickness but for instance, for ICB within this assessed range of thickness, thermal resistances are from 1 to 5 m^2.K/W due to its higher thermal conductivity comparing to PUR.

4.2.1.2. Marginal analysis due to 10 mm extra insulation material (PUR) in 20 years and 40 years lifespan for the reference building in Beja

In this study, lifespan of the residential building is considered 30 years (COMMISSION DELEGATED REGULATION No 244 2012). In this scenario, 20 years lifespan and 40 years lifespan are considered for the reference building in order to perform the marginal analysis due to extra 10 mm insulation material of PUR in Beja. Figure 21 and 22 present this scenario for life span of the building 20 years and 40 years respectively. In this scenario, the default heating and cooling system was considered.

Figure 21 - Marginal analysis due to extra 10 mm PUR in Beja considering lifespan of 20 years for the reference building

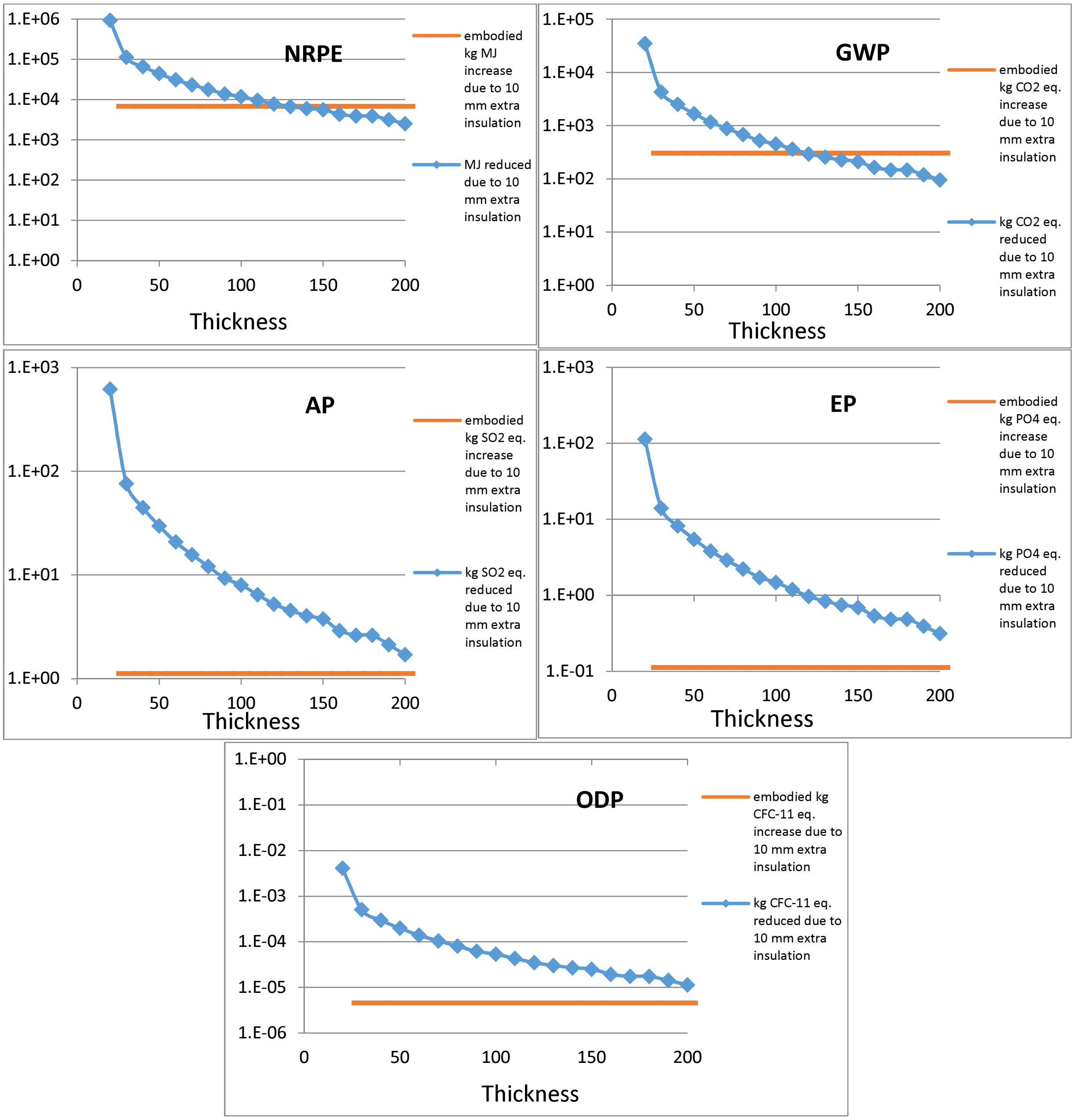
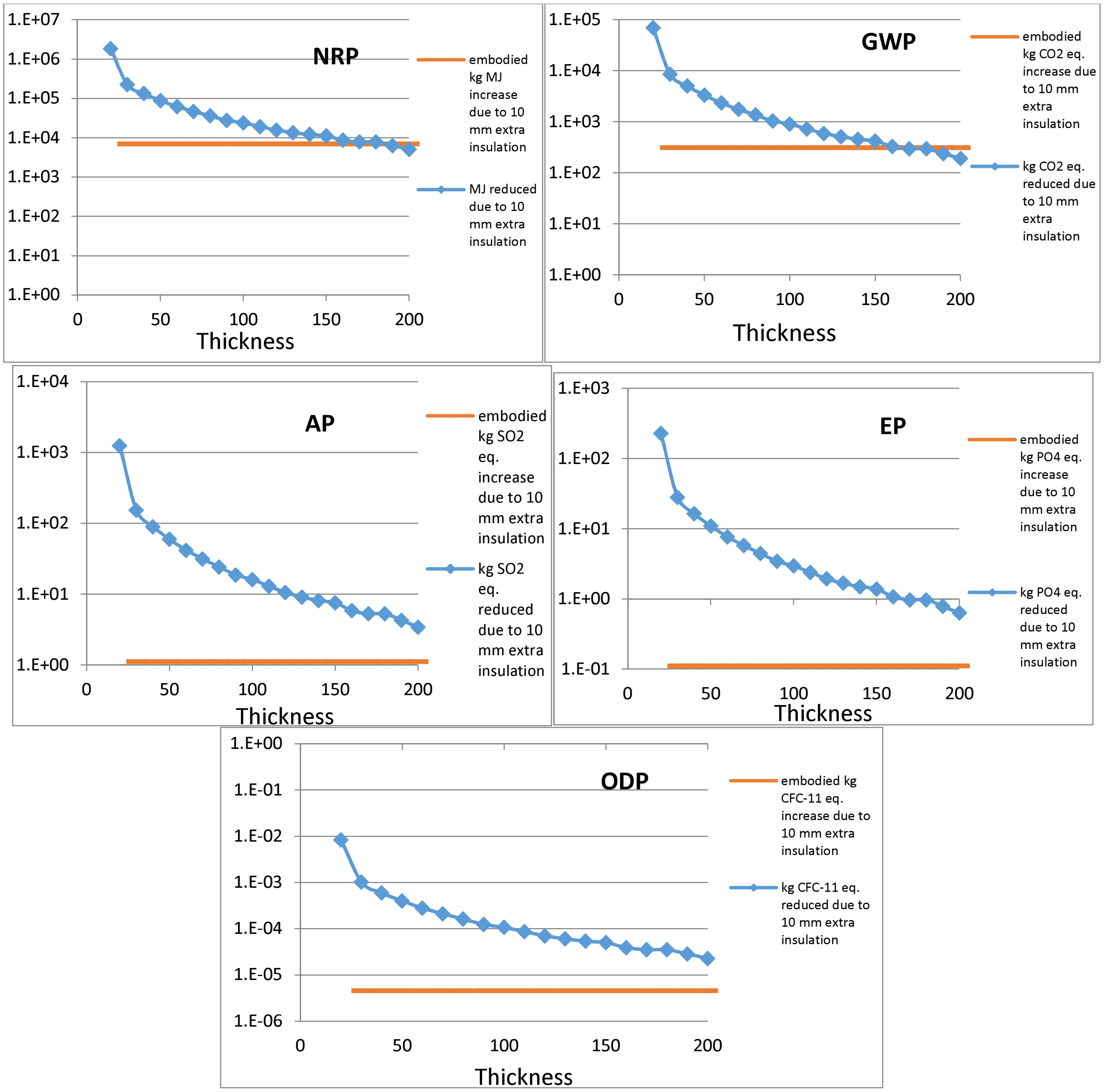


Figure 22 - Marginal analysis due to extra 10 mm PUR in Beja considering lifespan of 40 years for the reference building



By considering different lifespans for the reference building, it concludes that increasing the lifespan of the building has an influence on the critical thickness of the insulation material. Decreasing the lifespan of the building from 30 years to 20 years causes 30 mm reduction of the critical thickness of PUR from 160 mm to 130 mm. On the other hand, increasing lifespan of the building from 30 years to 40 years causes the increase of the critical thickness of PUR from 160 mm to 180 mm. It shows that reducing lifespan of the building around 30% results the decrease of critical thickness of PUR by around 20% due to the amount of saved energy after application of PUR becomes lower while lifespan of the building is reduced.

4.2.1.3. Marginal analysis due to 10 mm extra insulation material (PUR) for the reference building in Leiria considering air conditioner as heating and cooling system

In this study, the default heating and cooling system was presented in Table 10 which was a joule effect system for heating and an air conditioner for its cooling system. In this scenario, the heating default system is also substituted by an air conditioner system which was also presented in Table 10. Then, a marginal analysis was conducted due to 10 mm extra thickness for PUR in Leiria for each impact category. This scenario is presented in Figure 23.

Figure 23 – Marginal analysis due to 10 mm extra insulation material (PUR) in Leiria considering an air conditioner system instead of heating default system in the study

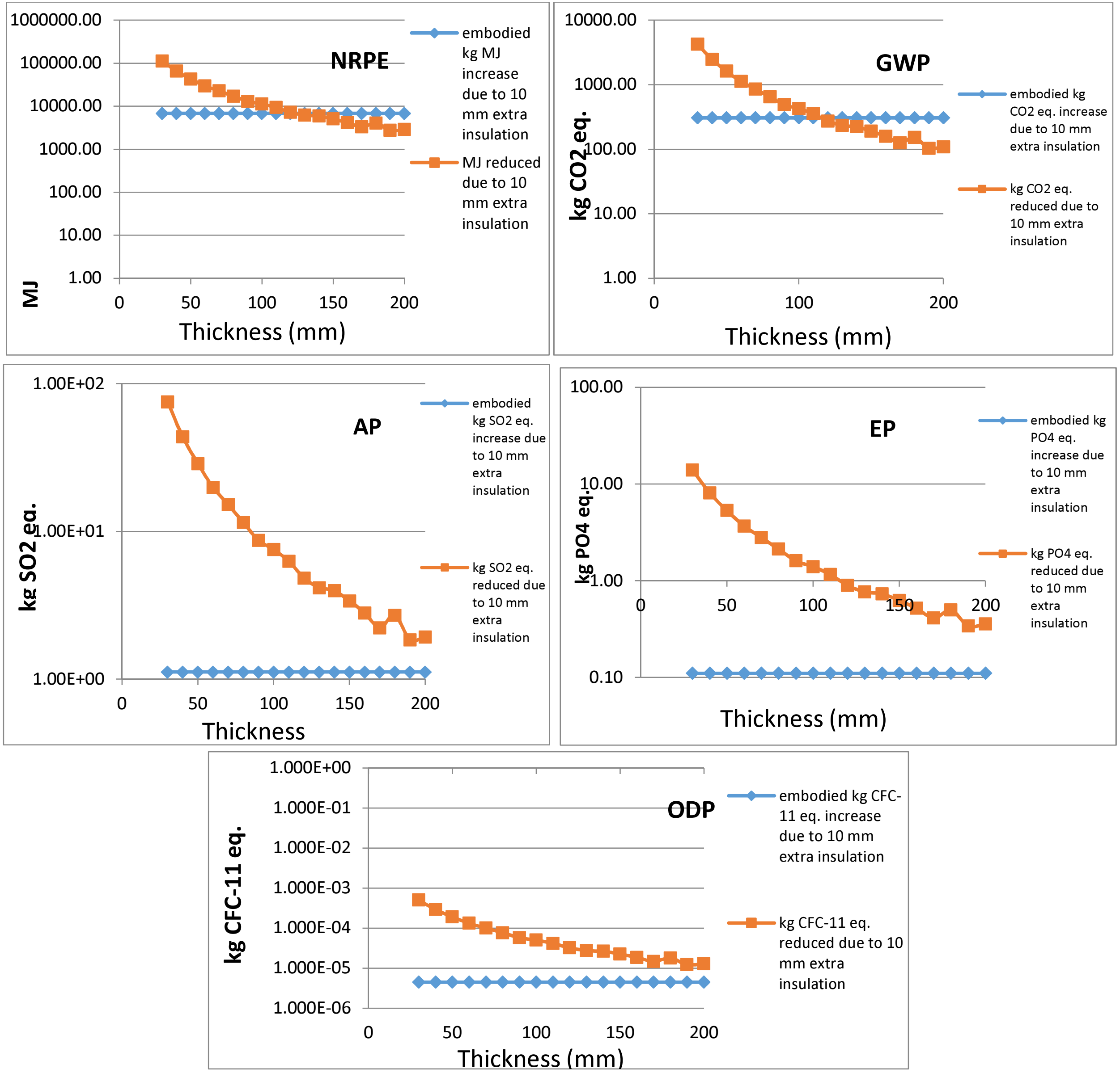


Figure 23 shows that changing the heating system to an efficient system, has an effect on reducing the amount of critical thickness of PUR. Increaing the efficiency of the heating and cooling system causes the reduction of energy consumption. Therefore, by considering more efficient heating system, increased embodied emissions of an insulation material will exceed the reduced emissions after applying to the building in lower thicknesses. For instance regarding NRPE, increasing the efficincy of the heating system about 4 times reduced the critical thickness of PUR about 30%.

4.3. Life-Cycle Cost Analysis

A life-cycle analysis can prove that spending more investment due to applying the insulation materials can reduce the heating and cooling costs. Additional benefit is providing thermal comfort for the building occupants (Ucar and Balo 2010). In this study, the amount of net energy cost savings is calculated within net present value method by Equation 3.

The cost of each insulation material for the alternative thicknesses for each insulation material which provides a thermal resistance of 1 m^2.K/W for the whole usable area of the wall without glazing (163.13 m^2) and the installation labor fees for the whole wall area without glazing and finally the initial investment for each insulation material which consists of the cost of each insulation material and its installation labor fee after applying to the reference building walls are presented in Table 14. It should be mentioned that 10% loss is considered for insulation materials in application to the reference building walls.

Table 14 - Insulation material costs (€) for alternative thicknesses for the whole area of the wall without glazing (163.13 m^2) per functional unit of providing a thermal resistance of 1 m^2.K/W and considering 10% loss in their application and Installation labor fees for insulation materials to apply to the reference building walls (€) and also initial investment for insulation materials (€)

Insulation Material	Material Price (€)	Installation Labor Fee for whole wall area without glazing (€) (www.cype.pt 2014)	Initial Investment (€)
ICB 40 mm	1435.54	430.908	1866.45
EPS 34 mm	445.38	834.687	1280.06
XPS 35 mm	992.32	792.257	1784.58
PUR 23 mm	1238.16	478.623	1716.78
GW 33 mm	355.30	1747.122	2102.42
RW 33 mm	829.03	1747.122	2576.15

In this study, the net present value method is conducted for the alternative thicknesses for each insulation material to make a meaningful comparison. The benefit from applying the insulation materials is resulted from the reduction of the heating and cooling cost. The annual reduction of heating and cooling cost is obtained from the annual reduction of final energy for cooling and heating in Beja, Leiria and Bragança. The default heating and cooling was considered in the calculation of required energy .Table 15 presents the annual benefit after reduction of required final energy for heating and cooling the whole usable area of the building after applying each insulation material in three climate zones. The price of electricity is taken from EDP webpage (Energias de Portugal) for a simple tariff which is 0.1528 (€/kWh) (EDP 2014).

Table 15 - Annual benefit from the reduction of required energy for heating and cooling in three climate zones after applying the insulation materials per functional unit of providing a thermal resistance of 1 m^2.K/W (€/year)

Beja	Leiria	Bragança
770.95	873.78	1503.54

Net present value of each insulation material is calculated by Equation 3. In this equation, i represents the interest rate. In this study, interest rate considered is 5% and net present value is calculated for each insulation material. Table 16 presents the net present values after applying each insulation material with alternative thicknesses which provide thermal resistance of 1 m^2.K/W in Beja, Leiria and Bragança. It should be mentioned that 30 years lifespan are assumed for residential building.(Commission Delegated Regulation No 244/ 2012)

Table 16 - Net present value after applying insulation materials for 30 years lifespan in Beja, Leiria and Bragança (€)

Zones	ICB 40 mm	EPS 34 mm	XPS 35mm	PUR 23 mm	GW 33 mm	RW 33 mm
Beja	9985	10571	10067	10135	9749	9275
Leiria	11566	12152	11648	11715	11330	10856
Bragança	21247	21833	21328	21396	21011	20537

Figure 24 shows the insulation materials cost, installation labor fees and benefits after applying the insulation materials to the reference building in Beja, Leiria and Bragança. This figures proves that all materials benefits from reduction of energy consumption in each climate zone are the same due to the same functional unit of providing thermal resistance of 1 m^2.K/W but the materials costs and installation costs are different and theses costs make differences due to select a material in terms of more gained benefit. Initial investment of RW 33 mm is about 2 times more than initial investment of EPS 34 mm. It shows that applying RW 33 mm to the reference building achieves less benefit in order to high initial investment associated with its application.

Figure 24 – Benefits and initial investments consist of insulation materials costs and their installation labor fees after applying the insulation materials to the reference building with functional unit of providing a thermal resistance of 1 m^2.K/W in Beja, Leiria and Bragança

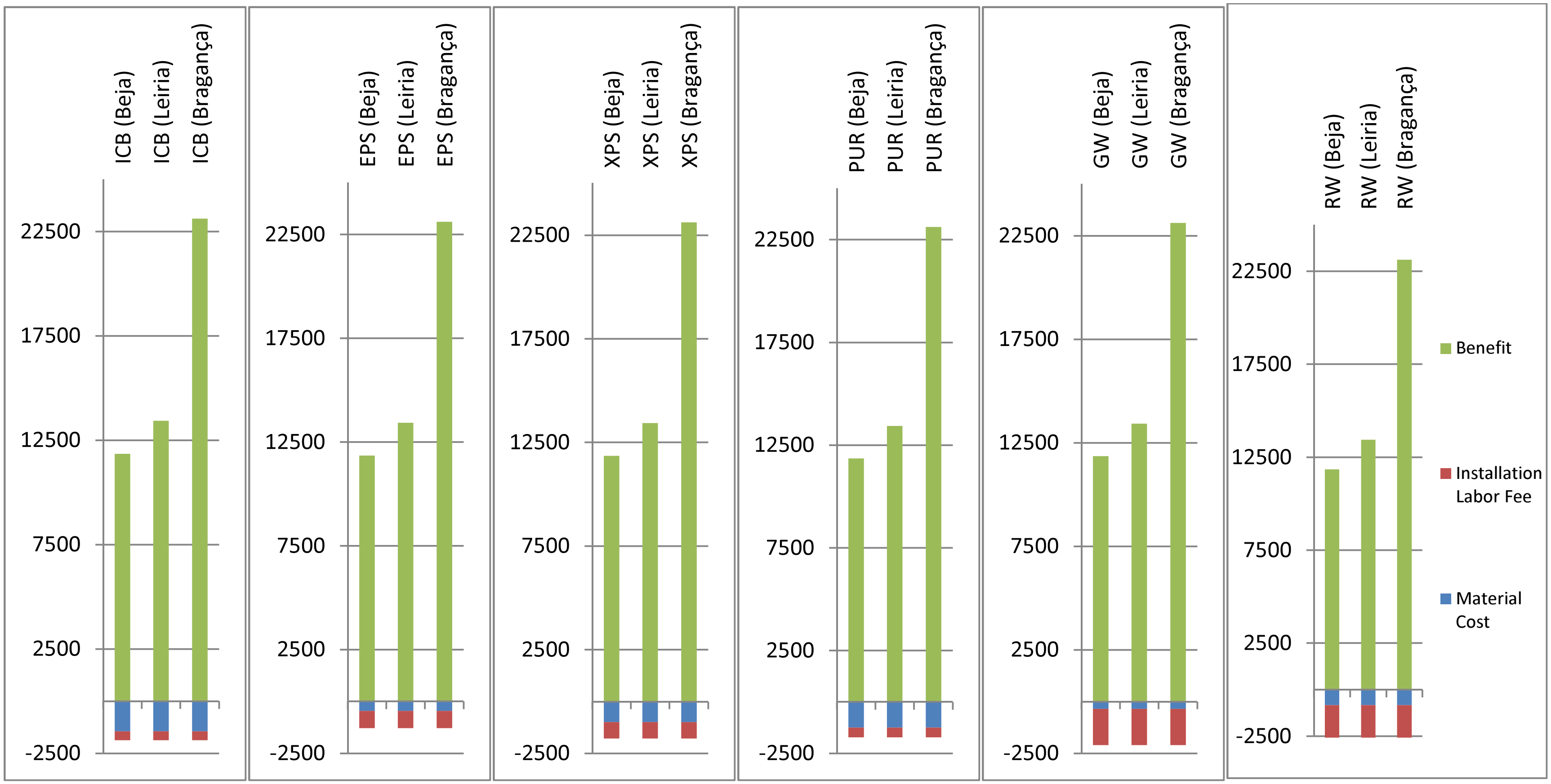


Figure 24 shows that Bragança because of requiring more energy for heating the building, the benefit of applying insulation materials is more than Beja and Leiria. In all climate zones, initial investment of RW 33 mm is about 2 times more than initial investment of EPS 34 mm. It shows that applying RW 33 mm to the reference building achieves less benefit in order to high initial investment associated with its application.

5. Final Remarks

Buildings are responsible about 40% of primary energy consumption and therefore CO_2 emissions.(International Energy Agency (iea) 2013) One solution to address this issue is applying insulation materials to the building for reducing the heat transfer and also provides thermal comfort for occupants. Several studies have been carried out on insulation materials but few of them were conducted simultaneously within three criteria of required primary energy, environmental life-cycle assessment and also life-cycle cost. Furthermore, Portugal is one of the main producers of insulation Cork Board (ICB) and there are few studies about assessing ICB in these three criteria and compare it with other insulation materials. This study has chosen six common types of insulation materials, namely Insulation cork board (ICB), Expanded polystyrene (EPS), Extruded polystyrene (XPS), Polyurethane (PUR), Glass wool (GW) and Rock wool (RW) which are more used in Portuguese buildings. The alternative insulation materials were evaluated within three criteria; required primary energy, life-cycle environmental impacts and life-cycle cost while applied to a reference building for new single-family houses in Portugal in three climate zones: Beja, Leiria and Bragança.

In this study, the LCA methodology was performed following two approaches; from cradle to gate and also adding the use phase. Building energy performance analysis of insulation materials in the operation phase was calculated with seasonal calculation method based on ISO standard 13790 by an Excel file prepared by the Institute for Technological Research and Development in Construction Sciences (ITeCons). Another goal is to evaluate the total life-cycle cost of each insulation material.

A life-cycle model was conducted for the six common insulation materials using CML 2001 and Cumulative Energy Demand (CED) life-cycle impact assessment methods. Furthermore, a consequential analysis was conducted from cradle to gate and use-phase of insulation materials to find out critical thicknesses which are not beneficial to increase the thickness. By the consequential analysis, increased embodied emissions of each material due to 10 mm extra thicknesses and reduced emissions after applying to the reference building were calculated to trade off. The life-cycle cost analysis was performed by net present value method which proved which one of the insulation materials in 30 years lifespan of the building gains more benefit.

To sum up in terms of environmental performances from cradle to gate based on each insulation material EPDs , XPS contributes more than 6 times to NRPE comparing with the lowest one for RW. Regarding global warming potential impact category, ICB due to the absorption of CO_2 by raw cork during biomass growth has negative value. XPS has the highest GWP impact and the lowest impact belongs to GW which is 70% lower than XPS. Owing to ODP impact category, EPS has the lowest impact category which performs 75% better than GW with the highest ODP impact. Considering acidification potential impact category, ICB shows the highest AP impact with 0.031 kg SO2 eq./m^2 while the best environmental performance regarding AP impact category is EPS with 0.0048 kg SO2 eq./m^2. Owing to EP impact category, EPS has the lowest impact while the highest impact belongs to ICB. In this impact category, EPS performs 96% better performance comparing with ICB.

According to the marginal analysis from cradle to gate and use-phase of insulation materials, by increasing the embodied emissions of insulation materials and reducing the amount of emissions due to the decrease of energy consumption decreases due to extra 10 mm insulation material, there is a critical thickness for each insulation material that increasing the thickness is not beneficial and embodied emissions of insulation material will exceed the reduced emissions after applying the insulation material to the building. For instance, regarding GWP impact category, thicknesses more than 150 mm in Beja and Leiria are not beneficial due to the increased embodied emissions with thickness of 160 mm will exceed the reduced emission of PUR after applying to the reference building. In Bragança, thicknesses more than 200 mm are not beneficial. By changing the climate zones from Beja to Bragança due to the more energy needs for heating the building, applying PUR to the building will save more energy and cause more reduction of emissions comparing with Beja. Therefore, the critical thickness will be increased by around 50 mm. Also insulation materials with higher impacts regarding each impact category from cradle to gate has the lower critical thickness in comparison with other materials. For instance, considering NRPE impact category, XPS and PUR showed the highest impacts. Therefore, critical thicknesses of these two materials were lower than the other materials. As it was presented, critical thicknesses of XPS and PUR were 170 mm but for other materials were more than 200 mm. The reduction of the building lifespan and the increase of the efficiency of heating and cooling systems caused the reduction of the critical thickness of each insulation material per impact category due to the decrease of the reduction of emissions in lower duration and lower decrease of emissions due to 10 mm extra insulation material respectively.

Regarding the third criterion of life-cycle cost of materials, net present value method was conducted for each insulation material. Results showed that the gained benefit of applying insulation materials during the building lifespan was much higher that the initial investment including the material cost and its installation labor fees. It was concluded that in terms of life-cycle cost, applying EPS and PUR gain more benefit in comparison with other materials. On the other side, less benefit is achieved after applying RW in order to more initial investment for RW. Bragança because of requiring more energy for heating the building, the benefit of applying insulation materials is more than Beja and Leiria. In all tables initial investment of RW 33 mm is about 2 times more than initial investment of EPS 34 mm. It shows that applying RW 33 mm to the reference building achieves less benefit in order to high initial investment associated with its application.

5.1. Limitations and Future Research

In this study, there are various limitations and assumptions as following;

- The insulation materials inventory data were gathered from different environmental product declarations (EPD) of each insulation material;
- Transportation from insulation material factory to the reference building was not considered in the assessment;
- The packaging data was not included in the assessment of insulation materials;
- The environmental impacts of installation of insulation materials to the building was not considered in this study;
- The LC model in this dissertation did not include the end of life phase because it is difficult to predict this phase since the buildings have a long lifetime;
- The environmental emission per kWh of electricity produced in Portugal was gathered from eco-invent database of Simapro which must be updated;

Further research which will be addressed in future are as following;

- The inventory data of insulation materials were based on EPDs of materials. Therefore, the real data will be gathered from Portuguese producers;
- Installation data and packaging data will be gathered due to be considered in the environmental assessment of insulation materials;
- Transportation distances from insulation materials factories to the reference building will be calculated due to be considered in the environmental assessment of insulation materials;
- New materials will be chosen to compare with the studied conventional materials within three different criteria of the building energy performance, environmental impacts and life-cycle cost analysis.

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