Comparative Life-Cycle Analysis of Insulation Materials in a Dwelling, Addressing Alternative Heating Systems and Life Spans

Seyedeh Shiva Saadatian, Fausto Freire, and Nuno Simões

***Abstract*—Insulation materials can play a significant role not only in supporting essential savings in operating costs but also in decreasing the environmental load of the building stock. This paper presents an integrated energy, cost and environmental life-cycle analysis for three types of insulation material [polyurethane (PUR), extruded polystyrene (XPS) and expanded polystyrene (EPS)] applied to a Portuguese reference building for single-family houses. The insulation materials were considered in external thermal insulation composite systems (ETICs). The seasonal calculation method was implemented to calculate operational energy. Life-cycle costing was employed following the net present value method. Alternative heating systems (heat pumps vs electric heaters) were assessed and a sensitivity analysis was performed to analyze the influence of the discount rate (5 and 7%) and building lifespan (30 or 50 years). The results of comparative assessment showed that the net present value gained by EPS along 50 years lifespan of the building was 16% more than XPS with the lowest value, and the required energy as well as global warming impact caused by XPS was approximately 9% more than PUR with the lowest value. The results also indicated that changing the heating system from electric heater to heat pump, decreased energy required for space heating by 10%, and increasing the discount rate from 5 to 7% caused the reduction of total net savings from 31% (EPS) to 41% (PUR). In addition, reduction of the building lifespan from 50 to 30 years decreased total net savings from 23% (EPS) to 28% (XPS). The results provide useful insight for building design decisions, energy management policies, etc., supporting the identification and prioritization of those parameters, in order to improve building performance.**

***Index Terms*—Life-cycle assessment, life-cycle cost analysis, sensitivity analysis, thermal insulation material.**

I. INTRODUCTION

Building sector accounts for more than 40% of global energy use and CO_2 emissions in International Energy Agency (IEA) member countries [1]. Thermal insulation of building envelope is regarded as an effective factor to reduce energy demand in buildings [2]-[14]. This research study includes the comparative assessment of external thermal insulation composite system (ETICS) with three alternative insulation materials applied to a reference building for new single-family houses in Portugal. This study has chosen three common types of insulation materials, namely Expanded polystyrene (EPS), Extruded polystyrene (XPS) and Polyurethane (PUR) which are more used in Portuguese buildings. In this paper, the life-cycle processes by the insulation materials including production, transport and operation phase have been characterized in terms of energy and environmental impacts. The required energy for other operation phase activities such as lighting, cooking, domestic hot water and electric appliances has been excluded since it is not affected by the wall solutions.

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Seyedeh Shiva Saadatian is with the Department of Mechanical Engineering, University of Coimbra, Portugal (e-mail: shivasaadatian@student.dem.uc.pt).

Fausto Freire is with the ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Portugal (e-mail: fausto.freire@dem.uc.pt).

Nuno Simões is with the CICC — Construction Sciences Research Unit, Civil Engineering Department of University of Coimbra, Portugal (e-mail: nasimoes@itecons.uc.pt).

II. METHODOLOGY

A. Life-Cycle Assessment

Life-cycle assessment (LCA) is a methodology to evaluate the potential impacts throughout the product's life. The general framework of LCA consists of four interrelated phases: goal and scope definition; life-cycle inventory (LCI); life-cycle impact assessment (LCIA) and interpretation [9], [15]-[23]. A life-cycle model was developed for a reference building for new single family houses (with a living area of 165m^2 and wall area of 163.13m^2) located in Bragança, Portugal. The functional unit nominated for this study was 1 square meter of living area over a period of 50 years (building lifespan). This paper aims to conduct a comparative assessment of ETICS with three alternative insulation materials in terms of energy, cost and environmental performances during use-phase following a base scenario according to the declared functional unit. This study has chosen three common types of insulation materials, namely Expanded polystyrene (EPS), Extruded polystyrene (XPS) and Polyurethane (PUR) which are more used in Portuguese buildings. The other additional goal is assessment of alternative heating systems (heat pumps vs electric heaters) and implementing a sensitivity analysis to analyze the influence of discount rate (5 and 7%) and the building lifespan (30 or 50 years). Table I presents inventory data relating with alternative insulation materials and thicknesses applied in ETICS. CML 2000 LCIA method was applied in order to evaluate an environmental impact of global warming (GW).

TABLE I: BUILDING MATERIALS INVENTORY (BASE SCENARIO)

Insulation materials	Thickness (mm)	Mass per functional unit (kg)
XPS	40	1.20
EPS	40	1.00
PUR	40	1.40

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B. Energy Performance Assessment

Energy assessment throughout the life-cycle perspective provides the improvement of building performance and energy efficiency in building [16], [24], [25]. 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 [26]-[28]. Some studies have emphasized on the wide share of energy consumption by operation phase of buildings [25], [29], [30].

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 [12], [31].

The energy performance of the building when changing type and thickness of insulation materials was calculated with seasonal calculation method (based on ISO 13790) [32].

C. Life-Cycle Cost Analysis

A life-cycle cost analysis provides a comprehensive relationship between initial investment for insulation materials and benefits of heating and cooling costs reduction in the use-phase. In this study, a life-cycle cost analysis was implemented by net present value method. Net present value (NPV) of each insulation material was calculated by Equation (1). Discount rate was considered 5% for the base scenario.

$$NPV(i,N) = \sum_{t=0}^{N} \frac{Rt}{(1+i)^t} \tag{1}$$

where, t represents the time of the cash flow (Building lifespan), i represents the discount rate, R_t represents the net cash flow (cash inflow – cash outflow).

III. Results

A. Comparative Assessment Related With the Base Scenario

The energy, cost and environmental assessment of three alternative insulation materials according to the base scenario is presented in Table II. Lifespan of the building was considered 50 years for the base scenario. In addition, electric heaters were assumed as heating system with efficiency value of 1 for the base scenario and discount rate was considered 5%.

TABLE II: Energy, Cost and Environmental Assessment (Base Scenario)

Insulation materials	Required energy (KWh/m^2)	NPV (€)	GW (kg CO_2 eq.)
XPS (40mm)	2534	6275.09	190658.2
EPS (40 mm)	2492	7483.89	187498.1
PUR (40 mm)	2307	7477.70	173578.7

The results show that the net present value gained by EPS along 50 years lifespan of the building is 16% more than XPS with the lowest value. On the other hand, the required energy as well as global warming impact resulted by XPS is approximately 9% more than PUR, which is the lowest.

B. Alternative Heating Systems (Heat Pumps Vs Electric Heaters)

In this paper, an alternative heating system has been considered with different value for the efficiency. In based scenario, heating system was assumed electric heaters with efficiency value of 1, whereas in this scenario heat pump was considered as an alternative system with efficiency value of 3.2. It should be mentioned that other parameters such as lifespan and discount rate were considered as the same as base scenario. Table III presents the energy, cost and environmental assessment of alternative insulation materials based on the new alternative heating system.

TABLE III: Energy, Cost and Environmental Assessment (Based on the New Alternative Heating System)

Alternative insulation materials	Required energy (KWh/m^2)	NPV (€)	GW (kg CO_2 eq.)
XPS (40 mm)	2289	6275.09	172224.4
EPS (40 mm)	2247	7483.89	169064.3
PUR (40 mm)	2062	7477.70	155144.9

Changing the heating system from electric heaters to heat pump resulted the reduction of required energy for space heating, as well as reduction of global warming impact by 10%.

C. A Sensitivity Analysis — Alternative Building Lifespans

In this paper, the building lifespan was considered 50 years for the base scenario. In this subsection, a sensitivity analysis was performed to analyze the influence of building lifespan on required energy for space heating, global warming and net savings. An alternative building lifespan of 30 years has been assumed. It should be mentioned that other parameters such as heating system and discount rate were considered as the same as base scenario. Table IV presents the energy, cost and environmental assessment of alternative insulation materials based on the building lifespan of 30years.

TABLE IV: Energy, Cost and Environmental Assessment (Based on the Building Lifespan of 30 Years)

Alternative insulation materials	Required energy (KWh/m^2)	NPV (€)	GW (kg CO_2 eq.)
XPS (40 mm)	1373.4	4641.99	103334.6
EPS (40 mm)	1348.2	5789.73	101438.6
PUR (40 mm)	1237.2	5513.97	93086.9

By considering different lifespans for the reference building, it concludes that increasing the lifespan of the building has an influence on the net present values gained by the insulation materials.

The results show that the reduction of building lifespan from 50 years to 30 years caused the reduction of required energy and global warming by 46% and total net present value by 26% for XPS and PUR and 23% for EPS.

D. A Sensitivity Analysis — Alternative Discount Rates

As aforementioned, discount rate was considered 5% for the base scenario. A sensitivity analysis was performed to analyze the influence of discount rate on total net savings. An alternative discount rate of 7% has been assumed. It should be mentioned that other parameters such as lifespan and heating system were considered as the same as base scenario. Table V presents the net present values of alternative insulation materials based on the discount rate of 7%. By increasing the discount rate, no changing was occurred relating with the required energy and global warming for the alternative insulation materials.

TABLE V: NET PRESENT VALUES (BASED ON DISCOUNT RATE OF 7%)

Alternative insulation materials	NPV (€)
XPS (40 mm)	3751.84
EPS (40 mm)	4866.29
PUR (40 mm)	4443.60

The results show that the increase of discount rate from 5% to 7% caused the reduction of net present values by 40% for XPS, 35% for EPS and 41% for PUR.

IV. CONCLUSION

Buildings are responsible about 40% of primary energy consumption and therefore CO_2 emissions [33]. Thermal insulation of building envelope is considered as an effective factor to reduce energy demand in buildings [2]-[4], [6], [8], [34], [35]. This study has chosen three common types of insulation materials, namely Expanded polystyrene (EPS), Extruded polystyrene (XPS) and Polyurethane (PUR) which are more used in Portuguese buildings. This paper aims to conduct a comparative assessment of ETICS with three alternative insulation materials during the operation phase when applied to the reference building for new single-family houses in Portugal. In addition, it aims to assess alternative heating systems (heat pumps vs electric heaters) and perform a sensitivity analysis to analyze the influence of discount rate (5 and 7%) and the building lifespan (30 or 50 years).

By considering different lifespans for the reference building, it concludes that increasing the lifespan of the building has an influence on the net present values gained by the insulation materials. The results show that the net present value gained by EPS along 50 years lifespan of the building is 16% more than XPS with the lowest value.

On the other hand, the required energy as well as global warming impact resulted by XPS is approximately 9% more than PUR, which is the lowest. In addition, changing the heating system from electric heater to heat pump caused the reduction of required energy for space heating, as well as reduction of global warming impact by 10%. The reduction of building lifespan from 50 years to 30 years resulted the reduction of required energy and global warming by 46% and total net present value by 26% for XPS and PUR and 23% for EPS. Subsequently, the increase of discount rate from 5% to 7% caused the reduction of net present values by 40% for XPS, 35% for EPS and 41% for PUR.

Regarding the 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 lifecycle cost, applying EPS and PUR gain more benefit in comparison with XPS. On the other side, less benefit is achieved after applying XPS in order to more initial investment for XPS.

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Seyedeh Shiva Saadatian was born in Tehran, Iran in 1985. She earned her bachelor degree in industrial engineering from AZAD University of Tehran in 2009. She gained her master degree in energy for sustainability from University of Coimbra in 2014. She is a PhD candidate in sustainable energy systems at University of Coimbra under the MIT Portugal Program.