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Assessing energy, economic, environmental and social impacts of fostering energy efficiency technologies: a Portuguese case study

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Abstract

This work suggests an overarching methodology that couples Hybrid Input–Output Lifecycle Analysis with thermal dynamic simulation. This methodological framework allows for a comprehensive evaluation of the energy, economic, environmental, and social impacts of fostering energy efficiency solutions in the residential sector. The main goal is to provide practical guidance to decision-makers in the formulation of appropriate funding strategies. The energy efficiency solutions under scrutiny consist of replacing compact fluorescent lamps with light emitting diode lamps, applying expanded polystyrene and insulation cork board on roofs and facades and installing heat pumps, biomass boilers, and gas boilers for space heating. The findings suggest that switching to more efficient lighting devices brings environmental, energy, and health benefits, but it may also have adverse effects on the economy and employment. Regarding insulation, applying expanded polystyrene simultaneously to roofs and facades results in a 63% decrease in energy requirements. However, the manufacturing, packaging, installation, and maintenance phases result in 3,500 tons of greenhouse gas emissions and the consumption of 57TJ of primary energy, while 380 jobs and 11 M€ in gross value added are generated. Finally, heat pumps appear to be the most environmentally friendly equipment, while gas boilers have the highest lifecycle energy consumption, and biomass boilers have the highest economic and employment benefits, despite leading to the greatest potential of premature deaths.

Keywords Energy-efficient and sustainable buildings · Energy efficiency measures · Hybrid input–output lifecycle analysis · Multiple benefits

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1 Introduction

Approximately 40% of energy consumption and 36% of greenhouse gas (GHG) emissions within the European Union (EU) are attributed to the building sector. Furthermore, current energy standards indicate that 75% of the EU buildings are inefficient, and it is anticipated that over 85% will remain in use by 2050 (European Commission, 2019). Within the framework of the EU's comprehensive strategy to achieve carbon neutrality by 2050, it is imperative to acknowledge the pressing need to accelerate building rehabilitation efforts across Europe. This acceleration is pivotal for the realization of an economy that is not only carbon–neutral but also competitive on a global scale (European Commission, 2021).

The recent invasion of Ukraine has exposed the EU's weaknesses due to its energy dependence on Russian fuels, making this strategy even more relevant. Therefore, increasing buildings' energy efficiency (EE) becomes a crucial step in reducing energy consumption and GHG emissions. As the REPowerEU Plan outlines, promoting EE measures will ultimately reduce energy prices, the global demand for fossil fuels, and enhance energy security during the EU's clean energy transition (European Commission, 2022).

In Portugal, the building stock presents a similar behavior to its European counterparts, accounting for more than 30% of final energy consumption (Energy Observatory, DGEG and ADENE, 2021). Remarkably, approximately 66% of the Portuguese residential buildings were constructed before the introduction of the EE requirements for new buildings in 1990. Additionally, one-third of the building stock built before 2012 reveals repair needs on their roofs and exterior facades, leading to low energy performance levels. This situation significantly contributes to energy poverty, increased energy consumption, and higher emissions (INE, 2012).

Portugal has launched several schemes to encourage the growth of EE in the building sector to speed up building renovations. Among these projects are the Energy Efficiency Fund, the Energy Consumption Efficiency Promotion Plan, and the Support Program for More Sustainable Buildings (Presidency of the Council of Ministers, 2013, 2020, 2021). Nevertheless, the assessment of EE measures that qualify for funding usually depends on cost–benefit analysis, which primarily considers energy and carbon reductions at the operational stage, without looking at the full lifecycle (LC) impacts of the selected measures (Presidency of the Council of Ministers, 2021).

Nevertheless, a holistic assessment of the energy, economic, environmental, and social (EEES) benefits of investing in EE in the residential sector is essential to enable decision-makers (DMs) to make well-informed decisions regarding which strategies should be subsidized. In endorsing EE policies, a comprehensive grasp of the manifold benefits they entail becomes crucial. This perspective aligns seamlessly with both the Portuguese Long-Term Strategy for Building Renovation (LTRS PT) and the European Renovation Wave, underscoring the imperative for a more robust delineation of criteria in emerging financial instruments. These aligned objectives find resonance in the overarching aims of the Recovery and Resilience Plan. (European Commission, 2020; Ministry of Planning, 2021; Presidency of the Council of Ministers, 2021).

In consideration of the aforementioned, this study introduces an innovative holistic methodology that integrates a Hybrid Input–Output Lifecycle Analysis (HIO-LCA) framework with thermal dynamic simulation. The objective is to assess the EEES impacts associated with various EE retrofit solutions within the Portuguese residential sector.

The structure of this paper is as follows: Sect. 2 reviews the most significant works in the research field. Section 3 outlines the proposed methodological framework and provides a detailed description of the methods employed. In Sect. 4, the paper delves into the EEES impacts, introducing the reference building and detailing the EE technologies under consideration. Following this, Sect. 5 presents and discusses illustrative results. Lastly, the paper concludes by summarizing overall findings and offering suggestions for future research developments.

2 Literature review

As previously mentioned, when designing programs to promote EE measures, the assessments typically focus only on the operation phase of the LC. However, covering additional lifespan phases becomes even more crucial, especially when nearly zero-energy buildings strategy is considered. Therefore, it is crucial to identify further research directions that are imperative in assisting decision-makers (DMs) to craft well-suited policies capable of addressing a more extensive range of impacts beyond mere energy savings and emission reductions. These should encompass, among others, the reduction of poverty, advancements in industrial productivity and competitiveness, the fortification of energy security, the creation of new job opportunities, and the realization of benefits linked to health and well-being (Ryan & Campbell, 2012). In this framework, the Economic Input–Output Lifecycle Analysis (EIO-LCA) enables the evaluation of economy-wide direct and indirect impacts associated with the production of goods or the delivery of services. This approach helps circumvent the time-consuming and truncation problems inherent in the traditional Process Lifecycle Assessment (P-LCA) method. However, it is important to acknowledge that the EIO-LCA methodology also has its limitations, namely at the aggregation level (Crawford, 2009; Hendrickson et al., 1997; Säynäjoki et al., 2017; Suh, 2006). Therefore, the HIO-LCA framework is a more appropriate alternative to be used in this context.

Hybrid methodologies combining EIO-LCA with P-LCA have been employed in different contexts. In this regard, Oliveira et al. (2014) and Henriques et al. (2017) utilized a similar approach to assess the potential employment impacts resulting from the implementation of renewable energy technologies. Additionally, Stephan and Stephan (2014) used this type of analysis to compute the embodied and operational energy of residential buildings in Lebanon. Similarly, Zhan et al. (2018) applied an analogous methodology in the evaluation of the energy consumption and carbon emissions of residential buildings over the course of their lifetime.

However, the utilization of this approach for assessing retrofitting actions is relatively scarce, with only a limited number of relevant studies conducted in this specific field. Cellura et al. (2013) assessed the tax exemption benefits for energy retrofits of Italian buildings through the application of an energy and environmental extended EIO-LCA model. Singh et al., (2018a, 2018b) conducted a comprehensive evaluation of the social, economic, environmental, and energy impacts of promoting the adoption of electric EE appliances in India. Building upon their findings, Singh et al. (2019) further integrated these effects into a multiobjective interval portfolio model. This integration aims to support public DMs in devising effective EE programs tailored to diverse investment strategies.

In recent years, several studies have assessed EE in residential buildings in Portugal. However, there are still gaps that need to be addressed, such as considering different impacts, technologies, or LC phases. For instance, Asadi et al. (2012) optimized the retrofit cost, energy savings, and thermal comfort by considering external walls and roof insulation, different window types, and the installation of a solar collector. Oliveira et al. (2014) conducted a prospective analysis of the employment impacts resulting from EE investments up to the year 2020, considering as retrofit measures window frames, window glazes, and roof and wall insulation. Rodrigues and Freire (2017) conducted a cost, environmental, and energy assessment of roof and exterior-wall insulation retrofit solutions considering the removal of the original components, and construction and use phases of the building. Tadeu et al. (2018) employed an advanced cost-optimal model to evaluate the energy performance of a residential building constructed before 1960, considering different thermal insulation retrofit solutions and systems. More recently, the approaches used by Singh et al., (2018a, 2018b, 2019) were applied to industrial lighting systems by Henriques et al. (2020).

The utilization of the HIO-LCA methodology brings forth numerous significant benefits:

- It enables the evaluation of diverse impacts arising during the early LC phases of EE solutions, providing a comprehensive understanding of their effects;
- By employing the System of Environmental-Economic Accounting Supply and Use Tables (SUTs), the methodology attains greater comprehensiveness compared to symmetric Input–Output (IO) formats;
- The use of SUTs facilitates the updating of impact-related data, capturing the current behavior of production and supply chains of the technologies under study;
- The methodology can easily adapt to any type of technology, allowing for broad applicability in various scenarios;
- It reduces the time-consuming and truncation risks commonly associated with LC assessment approaches, resulting in more efficient evaluations;
- It is particularly suitable for assessing the impacts generated at the national level due to investments in EE, enabling policy-making and strategic decision-making.

On the other hand, the thermal dynamic simulation complements the HIO-LCA methodology with its own set of advantages:

- It accurately calculates energy consumption in reference buildings, considering variables such as occupants' behavior, climatic conditions, and construction features;
- It enables the assessment of the savings achieved through the implementation of distinct EE solutions, empowering effective decision-making processes;
- The seamless integration with LC assessment methodologies provides a more comprehensive view of the EEES impacts, enabling the expansion of the scope of studies conducted.

To the best of available knowledge, the assessment of the impacts of the investment in EE technologies in the residential sector using this kind of methodology has not yet been done in Portugal.

3 Methodology

The methodology employed in this study will be clarified in the following subsections. To facilitate a better understanding of how this approach is executed, three schematic representations (Figs. 1, 2, and 3) exemplify its application to one of the technologies under investigation. Subsequently, to attain the outcomes presented in the results section, the same approach is applied to the remaining EE solutions. As will be seen, the combined use of the HIO-LCA methodology and thermal dynamic simulation offers a robust and comprehensive approach for assessing the impacts of EE solutions throughout different LC phases, considering various influential factors. It goes beyond merely quantifying direct energy consumption impacts during the use phase, providing a more holistic understanding of the broader implications and benefits of investing in EE technologies.

3.1 System's boundaries

The first step of the implementation of this methodology consists of identifying the commonly used technologies in the Portuguese residential sector, referred to as "business as usual" (BAU), and their best available EE alternatives, also known as "best available technologies" (BAT). To identify the BAU technologies, the study will assess the results from energy consumption surveys coupled with information from the population and housing census. On the other hand, the identification of BATs will be accomplished through a review of several Portuguese EE funding schemes that are now in place. Next, the reference building is defined to assess the energy needs, costs, and impacts of the implementation of different EE solutions. Finally, the LC phases of the technologies addressed in this work will be established to carry out the next two steps of the implementation of the proposed approach (see Fig. 1).

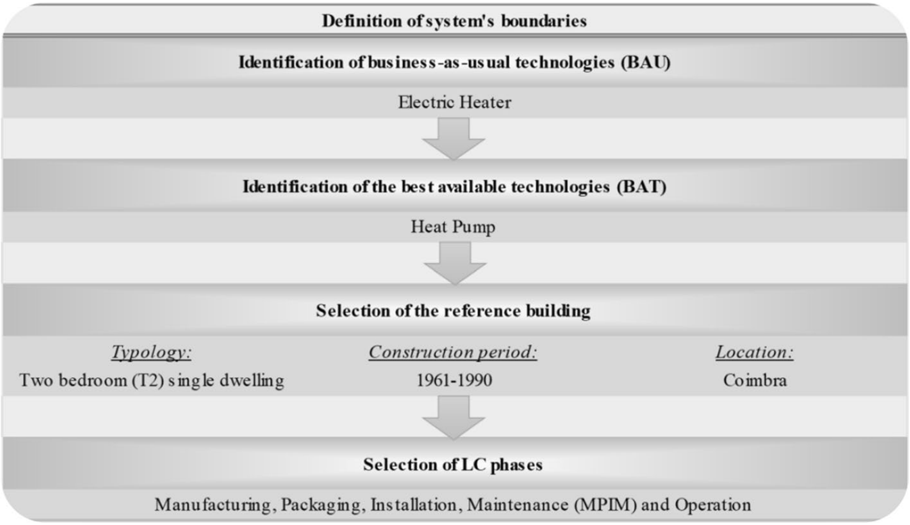

Fig. 1 Schematic representation of the definition of systems boundaries

3.2 The HIO-LCA approach

In the second step, the HIO-LCA approach will be applied to compute the EEES impacts associated with the Manufacturing, Packaging, Installation, and Maintenance (MPIM) phases of the selected EE measures. This approach follows the principles introduced by Breitschopf et al. (2012) and replicated by Singh et al. (2018a) and Henriques et al. (2020). The impacts considered for evaluation in this work include gross value added (GVA), energy costs, employment, number of pollution-related premature deaths, and GHG, acidifying gas (ACG), ozone precursor (O3PR), and particulate matter (PM2.5 and PM10) emissions.

This step is executed according to the scheme depicted in Fig. 2.

The HIO-LCA takes a comprehensive approach by combining elements of IO analysis and LC assessment. This method simplifies the P-LCA method by integrating conventional IO matrices with environmental, energy, social, or economic impacts. This expansion encompasses transactions across all activity sectors, leading to a more inclusive and holistic analysis that also considers circularity effects, as highlighted by various studies (Bilec et al., 2006; De

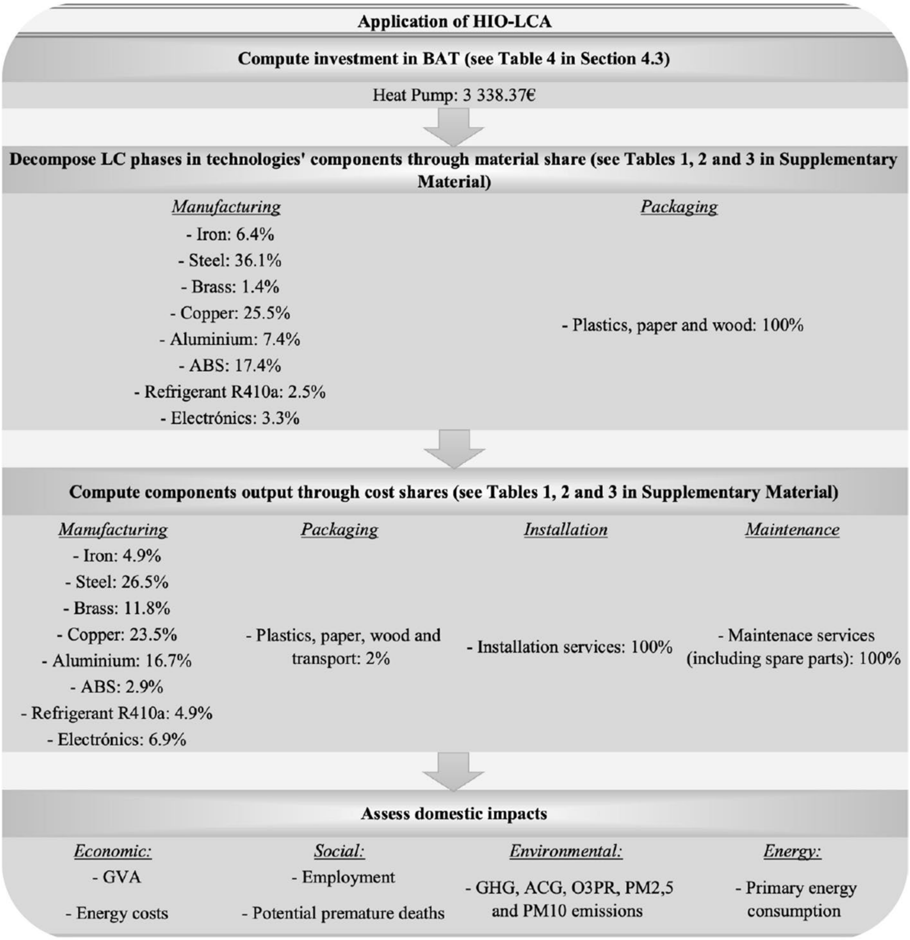

Fig. 2 Schematic representation of the application of the HIO-LCA method

Carvalho et al., 2016; Hendrickson et al., 1998, 2006; Singh et al., 2018a, 2018b; Strømman et al., 2009).

Originally developed by Wassily Leontief, the IO analysis allows for the computation of production factor embodiments (e.g., labor, energy) and pollutants (e.g., CO_2 emissions, waste) per unit of final consumption. This is achieved by deriving total factor multipliers from IO tables, which can vary in structure based on criteria such as symmetric or rectangular format, total or domestic-use flows, and valuation prices (basic prices or purchasers prices) (Miller & Blair, 2009; Sargento et al., 2011).

To apply the HIO-LCA framework in assessing EE measures, it is essential to isolate relevant activity sectors using supplementary data from surveys or technical sources (Vendries Algarin et al., 2015; Singh et al., 2018a; Henriques et al., 2020). Hybrid methodologies often leverage these data to complement LC information (see, e.g., Prakash & Bhat, 2012) or to disaggregate the IO sectors (see, e.g., Crawford, 2009).

In this work, HIO-LCA is applied, using a rectangular IO model (further described next) to evaluate the effects of funding EE solutions.

3.2.1 The rectangular input–output model

Rectangular tables, based on purchase prices or the SUT framework, facilitate the examination of primary and secondary commodities in each industrial sector (Horowitz & Planting, 2006). In this model, the use matrix follows a commodity-by-industry format, offering valuable insights about the commodities purchased by industrial and final demand sectors. On the contrary, the Supply/Make matrix follows an industry-by-commodity format, delivering information on the production of commodities by industries. Due to the possibility of having more commodities in the model compared to the number of industries, this configuration is referred to as a "rectangular" format (Miller & Blair, 2009). When utilizing the SUT framework, it is necessary to make assumptions about the product or industry technology used. This paper gives preference to the latter, so that the input structure of an industry remains invariant irrespective of its product mix (Miller & Blair, 2009; Raa & Rueda-Cantuche, 2007).

This approach requires the computation of the total demand of product i (q_i) and the total output of industry j (g_i). Therefore, considering the SUT framework, the total demand of product i at the purchaser's prices is:

$$q_i = \sum_{j=1}^{k} u_{ij} + \sum_{f=1}^{m} y_{if} = \sum_{j=1}^{k} m_{ji} + i_i + d_i + l_i, i = 1, \dots, n, \tag{1}$$

in which u_{ij} represents the quantity of commodity i utilized to produce industry j's output; y_{if} indicates the input of product i to final demand sectors f, including households, government, businesses, and exports; m_{ji} represents the value of commodity i generated by industry j in a specific year, encompassing primary and secondary produced commodities; i_i denotes the value of imports for commodity i; d_i and l_i, respectively, represent the amounts of margins and net taxes associated with commodity i.

The industry's total output at basic prices is:

$$g_j = \sum_{i=1}^{n} m_{ji} = \sum_{i=1}^{n} u_{ij} + \sum_{q=1}^{p} z_{qj}, j = 1, \dots, k, \tag{2}$$

in which z_{qj} represent the primary input q to industry j.

In the matrix format, the basic IO system of equations is given as:

$$\mathbf{g} = M\mathbf{e}_1 = U'\mathbf{e}_1 + Z'\mathbf{e}_2, \tag{3}$$

in which $\mathbf{e}_1$ and $\mathbf{e}_2$ denote column vectors of ones with suitable dimensions; $\mathbf{g}$ represents the column vector indicating the total output per industrial sector at basic prices; M stands for the supply table; U for the Use table, and the transpose is denoted by " $'$." Additionally, Z is the matrix of value-added inputs.

Finally, when considering the product level, the system of equations can be given as follows:

$$\mathbf{q} = U\mathbf{e}_3 + Y\mathbf{e}_4 = M'\mathbf{e}_3 + \mathbf{i}' + \mathbf{d}' + \mathbf{l}', \tag{4}$$

in which $\mathbf{e}_3$ and $\mathbf{e}_4$ represent column vectors of ones with appropriate dimensions; the column vector $\mathbf{q}$ signifies the total demand per product sector (at basic prices); Y stands for the matrix of final demand. The vector $\mathbf{i}$ corresponds to imports; $\mathbf{d}$ represents the vector of margins; and $\mathbf{l}$ is the vector accounting for net taxes.

Subsequently, to derive the segmented matrix D, each element in U and M is divided by the respective column totals of industrial output and demanded products. Matrix D is constructed from the matrices Q and S, along with two matrices composed of zeros:

$$D = \begin{bmatrix} 0 & Q \\ S & 0 \end{bmatrix},$$

in which $\frac{u_{ij}}{g_j}$ and $\frac{m_{ij}}{q_j}$ are the elements of Q and S, respectively.

From D, the subsequent matrix system is obtained:

$$\begin{bmatrix} 0 & Q \\ S & 0 \end{bmatrix}\begin{bmatrix} \mathbf{q} \\ \mathbf{g} \end{bmatrix} + \begin{bmatrix} \mathbf{y} \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{q} \\ \mathbf{g} \end{bmatrix} \Leftrightarrow \begin{bmatrix} \mathbf{q} \\ \mathbf{g} \end{bmatrix} = \begin{bmatrix} I & -Q \\ -S & I \end{bmatrix}^{-1}\begin{bmatrix} \mathbf{y} \\ 0 \end{bmatrix}. \tag{5}$$

By employing the general formulas for computing the inverse matrix it is possible to obtain expression (6) (for further details see Miller & Blair, 2009).

$$\begin{bmatrix} I & -Q \\ -S & I \end{bmatrix}^{-1} = \begin{bmatrix} (I - QS)^{-1} & (I - QS)^{-1}Q \\ S(I - QS)^{-1} & I + S(I - QS)^{-1}Q \end{bmatrix}. \tag{6}$$

Expression (8) may be obtained from the rectangular IO model and is similar to the Leontief inverse matrix. This expression yields an industry-by-commodity total requirements table, that represents the total (direct and indirect) variation of each energy, economic, environmental and social impact from industry j caused by the unit variation of final demand of commodity i (Locker et al., 2011; Miller & Blair, 2009). To do that, it is first necessary to compute the direct impact coefficients R. Each element, r_{kj}, is the amount of impact of type k produced per monetary unit of industry j's output (Hendrickson et al., 1998, 2006; Marques et al., 2006). As a result, the level of impacts associated with a given vector of total outputs can be expressed as:

$$\mathbf{r} = R\mathbf{x} \tag{7}$$

where $\mathbf{r}$ is the vector of impact levels. Hence, when x_j in Eq. (7) is replaced by the equation presented on the lower left side of (6), Eq. (8) it is obtained:

$$\mathbf{r} = R\left[S(I - QS)^{-1}\right]\mathbf{y} \tag{8}$$

To quantify the domestic impacts associated with each LC phase, the SUT format was employed using basic prices, and imports were excluded. The use of basic prices results in a more accurate representation of production costs (Eurostat, 2008).

3.2.2 Thermal dynamic simulation

The final step of the suggested approach uses an energy simulation tool, called thermal dynamic simulation to assess the impacts linked to the reference buildings' use phase, as illustrated in Fig. 3.

Thermal dynamic simulation is a tool that allows to determine the energy needs of buildings, new or existing, for lighting, ventilation, space heating and cooling, and domestic heating water (DHW). Using these data, the decision-making process can then be supported regarding the best EE measures to implement in these buildings to decrease the energy demand. To do so, however, the simulation program needs to be filled with descriptive data about the building, such as the envelopment features, dimensions, and occupancy patterns by the number of residents (Herrando et al., 2016; Sun et al., 2016).

There are currently several energy simulation software packages available, each with distinct degrees of sophistication and response to different inputs. Energy Plus is one of the most recognized and complete (Sousa, 2012). This building energy simulation tool began to be developed in 1996 sponsored by the Department of Energy (DOE) from the United States of America (USA), combining the best features from BLAST and DOE-2 along with innovative capabilities, such as the ability to be integrated with third-party software tools (Crawley et al., 2001).

In this work, Energy Plus was used to obtain the energy needs for space heating of the reference building, by creating a virtual model and selecting the most suitable occupancy and use profiles associated with the national reality. Therefore, to obtain energy simulations for reference buildings with a high degree of accuracy, the software was loaded with a representative profile of occupancy, considering a family of three people. It is assumed that the reference dwelling is occupied every day, assuming approximately a 100% occupancy rate during 9 h, a 90% occupancy rate during 3 h, a 50% occupancy rate during 5 h, and a 30% occupancy rate during 7 h. Moreover, ambient cooling is neglected as it represents only 1% of the energy consumption. These numbers for energy consumed on space cooling are consistent with the claim

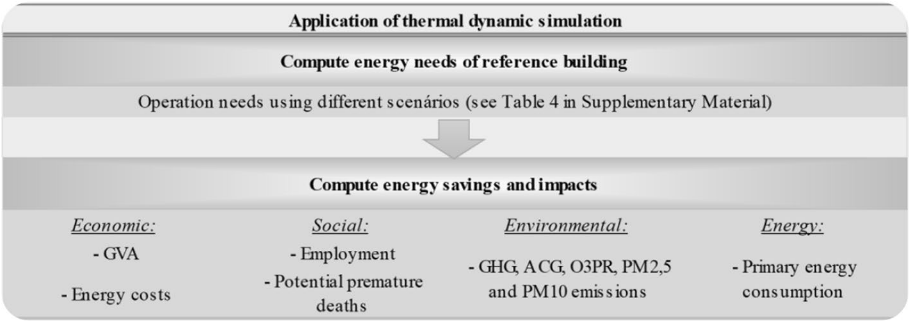

Fig. 3 Schematic representation of the application of thermal dynamic simulation

that in Portugal the use of air conditioning equipment for space cooling is reduced, with buildings often operating at free-floating temperatures.

4 Data and assumptions

To validate the proposed methodology, a single dwelling, built between 1961 and 1991, located in the region of Coimbra, with no insulation, was chosen as a case study. Various retrofitting strategies were simulated, involving the replacement of lighting systems, the application of three types of insulation systems with different thicknesses, and three types of space heating appliances. For representational purposes, the results will be extrapolated to encompass 15,000 dwellings of the same typology in the same area (INE, 2019; Presidency of the Council of Ministers, 2020) and a 50-year lifespan.

The assessment of the EEES impacts start with the application of the HIO-LCA methodology to the MPIM LC phases of the chosen retrofitting technologies. This is achieved by combining Portuguese SUTs at basic prices, using data for the year 2017 (the most recent data available), along with tables of impacts (INE, 2017, 2019; OECD, 2017; Oliveira et al., 2014). The GVA and emissions were computed using the OECD (2017) satellite accounts, while the employment and energy consumption were obtained from the National Statistics Institute (INE, 2017a, b). To assess the domestic intersectoral trade, imports had to be removed from both tables. This approach relies on the construction of an adjusted rectangular IO table, where the total output of each relevant activity or component of the technologies under analysis is linked to the corresponding product, to compute the multiplier effects of each activity/component (direct coefficients matrix and indirect coefficients matrix) for the most suitable indicators. Since the SUT matrices do not directly evaluate the EE technologies addressed in this study, these need to be disaggregated into their component costs, to further obtain the domestic output, which will then be matched with impact tables to assess the EEES impacts from investing in the EE technologies.

Finally, thermal dynamic simulations are employed in the operation phase to assess the households' energy needs, using the Energy Plus software. The impacts of this LC phase will be then computed using the conversion factors listed in Table 1.

4.1 EEES impacts

Numerous benefits and impacts that might assist the DM in creating effective financing strategies could result from investing in EE technologies. The methodology used in this study enables calculating the impacts depicted in Table 2.

4.2 Reference building

The residential building under consideration in this case study is a virtual representation of a single residence built in Coimbra between 1961 and 1991, assuming various occupancy patterns. This single dwelling has one floor which consists of one kitchen, one living room, two bedrooms, and two bathrooms. The building's main components are a simple 22 cm perforated brick masonry wall with an average thickness of 26 cm with a heat transfer coefficient of 1.76 watts per square meter per degree Celsius (U_{wall}: 1.76 W/m^2 °C), sloping roof covered with ceramic tile and lightened slab of 15 cm thick ceramic blocks and 2 cm stucco ceiling covering (U_{roof}: 2.80 W/m^2 °C) and single-glazed sliding metal windows

Table 1 Conversion factors

Impact		Unit	Conversion factor			References
			Electricity	Gas	Biomass	
Economic	Energy prices	€/kWh	0.2284	0.0773	0.050	Eurostat. (2022a, b); Presidency of the Council of Ministers, 2021
Social	Potential number of premature deaths	No of deaths/tons of $PM_{2,5}$	0.000101			European Environment Agency (2018, 2021)
Environmental	GHG	Tons of CO_2eq/TJ	84.2424	57.0210	114.3610	Pina et al. (2021); Gómez et al. (2006); Amaro et al. (2022); Ferreira et al. (2021); European Environment Agency. (2019)
	ACG	Tons of SO_2eq/TJ	0.0149	0.0626	0.0675	
	O3PR	Tons of NMVOCeq/TJ	0.0949	0.1155	0.1162	
	PM2.5	Tons of $PM_{2.5}$/TJ	0.0001	0.0009	0.1330	
	PM10	Tons of PM_{10}/TJ	0.0012	0.0009	0.1550	
Energy	Primary energy consumption	N/A	2.1	1	1	European Commission (2021)

Table 2 Impacts and units [based on Tenente et al. (2021)]

Impacts		Definition	Units
Economic	GVA	Monetary value for goods and services that have been produced, less the cost of all inputs and raw materials that are directly attributable to that production	10^6 €
	Energy costs	Cost of energy consumption for families connected with lighting and space heating	M€
Social	Employment	Number of jobs in full time equivalent (FTE)	Jobs
	Potential number of premature deaths	The number of premature deaths potential provoked by the production of emissions of $PM_{2.5}$	Nº
Environmental	GHG	GHG emissions	Tons of CO_2eq
	ACG	ACG emissions	Tons of SO_2eq
	O3PR	O3PR emissions	Tons of NMVOCeq
	$PM_{2.5}$	Emissions of particulate matter with 2.5 microns or less in diameter	Tons
	PM_{10}	Emissions of particulate matter with 10 microns or less in diameter	Tons
Energy	Energy consumption	Net domestic energy use—energy end use by resident production activities (NACE industries) and private households	TJ

Table 3 Characteristics of the reference fractions of a single dwelling

Construction period	Typology	Floor area	Number of floors	Ceiling height	Area of the facades' walls	Roof area
1961:1990	T2	100 m^2	1	2.7	93.2	100 m^2

without thermal break (U_{windows}: 4.10 W/m^2 °C). Pinto and Fragoso (2018) detail the complete features of these types of buildings, which are presented in Table 3.

The reason behind the choice of this reference building is based on what is defined by LTRS PT, which states that priority will be given to the segments with the worst performance in an initial phase, until 2030, which corresponds to the buildings built before 1990, even though the renovation of the entire building stock will be carried out until 2050 (Presidency of the Council of Ministers, 2021).

Three summer climate zones ($V1$, $V2$, and $V3$) and three winter climate zones ($I1$, $I2$, and $I3$) are used to categorize each region in Portugal. The winter climate zone is defined from the number of degree-days in the heating season, based on 18 °C, while the summer climate zone is defined from the average outdoor temperature in the conventional cooling season. Coimbra, a town in the center of Portugal, lies in climatic zone $I2V2$, with its climate parameters for the heating season being 1304 degree-days, and for the cooling season, 20.9 ºC (Ministry of Environment Spatial Planning and Energy-Directorate-General for Energy and Geology, 2013).

4.3 Energy retrofitting technologies

The retrofitting strategies considered in this case study involve the replacement of a compact fluorescent lamps (CFL) of 18W with a light emitting diode (LED) lamp of 14.5W in the kitchen and living room, the replacement of a 14W CFL lamp by a 10W LED lamp in each bedroom and bathroom, expanded polystyrene (EPS) and insulation cork board (ICB) with distinct thickness (40 mm, 100 mm and 140 mm) applied to the roof and facades and three types of space heating appliances (heat pump and biomass and gas boilers). Due to the limitation in data availability, the thickness of the insulation measures under consideration did not surpass 140 mm. However, this value satisfies and even exceeds, the minimum energy standards established by the energy performance guidelines for households (Ministry of Economy & Employment, 2013). Besides the use of CFL lamps and the lack of insulation in the building envelope, the BAU scenario also uses an electric heater for space heating. Table 4 shows the description of the features and costs (initial investment, installation, and maintenance) of BAU technologies as well as the alternative BATs. The investment costs in lighting systems were gathered from websites of big retailers, while the installation and maintenance expenses were disregarded because they are often handled by the home's owner or renter of the dwelling. The CYPE Ingenieros S.A (2021) database was used to collect the investment, installation, and maintenance costs of insulation and space heating. The costs presented in this section indicate values at basic prices by removing their margins and representing tax-free pricing and adjusting using the inflation rate (FFMS, 2020).

Table 4 Technologies features and costs

Technologies			Features	Costs		
Use	Type		Lifespan	Investment	Installation	Maintenance every 10 years
Lighting[a]	CFL	18 W	6 years	4.10 €/un	NA	NA
		14 W	8 years	2.58 €/un	NA	NA
	LED Lamp	14.5 W	14 years	5.33 €/un	NA	NA
		10 W	21 years	3.03 €/un	NA	NA
Insulation	EPS 40 mm thickness		50 years	6.00 €/m^2	4.17 €/m^2	0.23 €/m^2
	EPS 100 mm thickness			15.01 €/m^2	4.17 €/m^2	0.41 €/m^2
	EPS 140 mm thickness			20.97 €/m^2	4.17 €/m^2	0.53 €/m^2
	ICB 40 mm thickness		50 years	17.55 €/m^2	4.17 €/m^2	5.05 €/m^2
	ICB 100 mm thickness			45.56 €/m^2	4.17 €/m^2	6.77 €/m^2
	ICB 140 mm thickness			67.53 €/m^2	4.17 €/m^2	9.39 €/m^2
Space heating	Electric heater		20	320.00 €	NA	64.00 €
	Heat pump			2,561.56 €	82.11 €	694.70 €
	Gas boiler		12	1,366.69 €	124.94 €	1,269.01 €
	Biomass boiler			2,942.68 €	183.27 €	2,438.24 €

[a] 18W CFL and 14.5W LED lamp—3 h of operation per day during a 6000 h and 15,000 h lifetime, respectively. And 14W CFL and 10W LED lamp—2 h of operation per day during a 6000 h and 15000 h lifetime, respectively

Since the EE technologies' costs need to be disaggregated into their components to further calculate the impacts of investment made, Tables 1, 2, and 3 of Supplementary Material present the shares of materials and share of components' costs of each technology addressed.

5 Results and discussion

In this section, the main results found are presented in Tables 5 and 6.

According to the analysis carried out, replacing CFL with LED lamps yields environmental, energy, and health benefits, but comes at the expense of economic and employment loss. Specifically, in terms of the environmental impacts, this replacement saves about 4,851 tons of GHG, 2.1 tons of ACG, 7.3 tons of O3PR, and 1.1 tons of PM emissions. Moreover, adopting LED lamps instead of CFL leads to a reduction of about 25% in primary energy consumption and a decrease of 70% in potential premature deaths, contributing to energy and health benefits. However, there are economic drawbacks as well. The GVA and employment can experience a decline of up to 30%. The reasons behind these results can be twofold: Firstly, the electronic components required for LED lamps are mostly imported, and secondly, the manufacturing of CFL lamps needed is 2.5 times bigger than that of LED lamps. Nevertheless, it is worth noting that the substitution of CFL with LED lamps has the potential to positively impact family budgets by leading to 25% of savings, which can trigger other potential induced economic effects.

Table 5 Domestic impacts of MPIM phases of EE technologies

Technology	Manufacturing, packaging, installation and maintenance impacts								
	Economy	Employment	Emissions			Primary energy consumption	Particulate matter		Potential number of premature deaths
	GVA	Full-time equivalent	ACG	GHG	O3PR	Net domestic energy use	$PM_{2,5}$	PM_{10}	
	M€	Jobs	Tons of SO_2 eq	Tons of CO_2 eq	Tons of NMVOC eq	TJ	Tons	Tons	Nº
CFL	0.27	7.00	1.51	499.22	2.56	4.62	0.46	0.57	4.64E–05
LED	0.05	1.10	0.15	48.52	0.24	0.71	0.04	0.05	4.16E–06
EPS (40 + 140 mm)	11.44	380.70	11.80	3469.12	23.22	57.69	1.48	1.98	1.50E–04
ICB 40 mm + EPS 140 mm	23.89	593.76	15.65	4,707.19	29.16	80.92	1.87	2.55	1.89E–04
Gas boiler	34.27	975.61	48.30	23,089.51	78.23	275.76	4.56	6.01	4.61E–04
Biomass boiler	77.36	2,054.03	196.17	87,252.89	309.25	910.34	36.09	45.30	3.65E–03
Heat pump	21.09	544.36	36.54	17,630.06	58.74	210.68	4.06	5.09	4.11E–04

Table 6 Domestic impacts of operation phase of EE technologies

Technology	Operation impacts									
	Economy	Employment	Emissions			Primary energy consumption	Particulate matter		Energy costs	Potential number of premature deaths
	GVA	Full-time equivalent	ACG	GHG	O3PR	Net domestic energy use	$PM_{2,5}$	PM_{10}		
	M€	Jobs	Tons of SO_2 eq	Tons of CO_2 eq	Tons of NMVOC eq	TJ	Tons	Tons	M€	N°
CFL	9.17	69.80	3.24	18,264.60	20.58	405.43	0.21	0.27	13.76	2.17E–05
LED	6.96	52.99	2.46	13,864.49	15.62	307.76	0.16	0.20	10.44	1.65E–05
Gas boiler	65.65	499.65	420.00	379,542.00	774.00	6,707.99	6.00	6.00	144.02	6.07E–04
Biomass boiler	40.55	1,123.51	367.00	621,768.00	631.00	5,437.00	723.00	843.00	75.51	7.32E–02
Heat pump	62.42	475.12	22.05	124,321.44	140.10	2,759.67	1.46	1.82	93.63	1.48E–04

Regarding insulation, which is assumed to be installed on the facades and/or on the roof, the dynamic simulation demonstrated that the simultaneous application of EPS 40 mm to the façade and EPS 140 mm to the roof, defined as scenario 1, is the most effective. This is followed by the simultaneous application of ICB 40 mm to the façade and EPS 140 mm to the roof, which is defined as scenario 2 (See Table 4 in Supplementary Material). The reference building's estimated annual energy use without insulation is 5.1 MWh. However, when scenario 1 is considered, the energy requirements for space heating reach values of around 1.91 MWh per building, while scenario 2 provides values of 1.95 MWh per year, reflecting savings of approximately 63% and 62%, respectively. Considering the MPIM stages of various retrofitting measures, scenario 1 produces about 3,500 tons of GHG, 12 tons of ACG, 23 tons of O3PR, and 3.5 tons of PM emissions, consumes more than 57 TJ of primary energy, and has the potential to generate more than 380 jobs and 11 M€ of GVA. On the other hand, scenario 2 results in the production of 4,700 tons of GHG, 16 tons of ACG, 29 tons of O3PR, and 4.4 tons of PM emissions, as well as the consumption of more than 81 TJ of primary energy and the potential creation of more than 593 jobs and 24 M€ of GVA. By comparing these two scenarios, it can be shown that the latter increases employment by 56%, doubles GVA, and produces 1.4 times more embodied energy, roughly one-third more emissions, and potentially 26% more premature deaths than the former. The reasoning behind the results can be related to the fact that ICB is almost entirely produced in Portugal, thus contributing to higher impacts and benefits in the country. With these findings, it is demonstrated that, among the group of EE technologies supported by the programs to be implemented in Portugal, insulation is one of the best methods for energy savings. However, for its application to be more effective, and given that complete building insulation can be quite expensive, new support programs must be created to ensure that Portuguese families have access to loan programs that are easy to repay over time or paid with the money saved from energy savings. These initiatives will benefit financial agents, producers, and installers of this type of technology, as well as families, especially the poorest. The financial agents will get their money back, plus interest income, and still profit from the drop in technology prices brought on by their mass production, while producers will benefit from the total volume of technologies produced, and families will enjoy more thermal comfort and expand their budget without having to make an upfront investment.

Since the solutions of scenario 1 lead to the lowest energy demand, the impacts estimated were done considering the space heating appliances. According to these findings, the heat pump appears to be the "cleanest" technology as it produces 65% less GHG emissions, 87% less ACG emissions, 77% less O3PR emissions and around 45% less PM emissions than the gas boiler. It also produces 80% less GHG, 90% less ACG, 79% less O3PR, and around 99% less PM emissions than the biomass boiler. The results for the heat pump are mainly attributed to its operational performance, influenced by its efficiency coefficient of 3.5, contrasting with the gas boiler's and biomass boiler's respective efficiency coefficients of 0.8 and 0.95. However, the biomass boiler has the biggest potential to contribute to premature deaths since it produces roughly 72 times more PM emissions than the gas boiler. Regarding the GVA and employment, these impacts are higher for the biomass boiler, as well. In terms of GVA and employment impacts, the biomass boiler also shows higher values. The GVA it is roughly 41% higher than the heat pump's impact and about 20% higher than the gas boiler's impact, respectively. Employment has an impact that is 3 times greater than that of the heat pump and almost double that of the gas boiler. Despite this, the cost of the energy vector (biomass) used to create the energy needed to heat the buildings and its efficiency make the biomass boiler the solution that most increases the family budget during the operation of the equipment. Following the application of the insulation outlined in scenario 1, each building can save €315.32 per year when using a gas boiler, €204.99 per year when using a heat pump, and €165.33 per year when using a biomass boiler. Therefore, from the results, it is evident that both the heat pump and the biomass boiler are feasible alternatives to the gas boiler, especially considering the EU's requirement to reduce its gas consumption.

The findings of this study show that the methodology proposed should support the decision-making process for the funding of EE measures. This is because it allows for a comprehensive evaluation of the impacts of investing in the technologies being examined, integrating not only the operation phase but also the MPIM phases. Another advantage of this methodology is its compatibility with different methodologies for assessing the energy needs of buildings, such as the dynamic simulation approach employed in this study. In addition to assessing energy savings and GHG emissions, the use of IO methodologies also enables the examination of several other impacts and benefits that are crucial for decision-making when designing new programs to finance EE.

6 Conclusions

This paper presents a novel methodological approach that integrates an HIO-LCA framework with thermal dynamic simulation, to evaluate EEES benefits/impacts of investing in different EE measures in the Portuguese residential sector. The integration of the HIO-LCA methodology with thermal dynamic simulation offers several advantages, enhancing the capability to evaluate impacts across different LC phases of EE solutions. This combined approach allows for the updating of impact-related information, ensuring adaptability to various technologies, and overcoming time-consuming and truncation limitations that may arise in traditional assessments. One of the key strengths of this methodology is its suitability for assessing national-level impacts resulting from investments in EE. It provides valuable insights into energy consumption in reference buildings and enables the simulation of savings from different EE solutions. Additionally, it offers a comprehensive view of EEES impacts beyond just direct energy consumption during the use phase.

The measures considered are the replacement of CFL with LED lamps, the application of two types of insulation systems to the facades and roofs (EPS and ICB), and the installation of three types of space heating appliances (heat pump, biomass boiler, and gas boiler). The main objective of this proposed methodology is to support DMs in designing suitable EE funding policies by using the assessed impacts as a guide. The methodology was tested using data from 15,000 *T*2 single dwellings built between 1961 and 1991, in the region of Coimbra.

The findings suggest that replacing of CFLs with LED lamps brings environmental, energy, and health benefits; however, it decreases both the economic and employment benefits. These outcomes are linked to the fact that the electronic components of LED lamps are mainly imported, and because the number of CFLs required during the lifetime of the buildings is 2.5 times higher. Nevertheless, it is worth noting that the replacement of CFL with LED lamps also has the potential to increase family budgets, triggering other induced economic effects. Regarding insulation, the dynamic simulation showed that the most efficient solution is the simultaneous application of EPS to the façade and roof, leading to energy savings of about 63% compared to the reference scenario. For the MPIM phases, almost 3,500 tons of GHG emissions are produced, and more than 57 TJ of primary energy are consumed, while more than 380 jobs and 11 M€ in GVA are potentially created. After the application of insulation, the savings per building can go up to €315.32/year. Finally, concerning space heating technologies, the heat pump seems to be the "cleanest," the gas boiler is the equipment with the highest energy consumption during its LC, while the biomass boiler brings higher economic and employment benefits. On the other hand, the biomass boiler has the biggest potential to contribute to premature deaths. Despite that, the biomass boiler seems to be the cheapest solution.

It is recommended that DMs design new EE policies that encourage financial aid for families in the form of loans, especially to enhance the insulation of their homes. Although it has the biggest potential for energy savings among the group of EE technologies, this type of intervention is quite expensive. Additionally, heat pumps and biomass boilers should also be included in the support packages due to their feasibility as alternatives to gas equipment. This approach can result in more effective adoption of EE technologies, leading to increased profits for financial agents, producers, and installers, as well as improved thermal comfort for families. Moreover, families can expand their budget without an initial investment, while overall energy savings, emission reduction, and a decrease in potential premature deaths are promoted. Therefore, the results presented in this study support the claim stated by several experts that the cheapest and greenest energy is the energy not used. In this context, EE becomes a key strategy for the EU to cut energy consumption, while enabling the energy transition without compromising people's comfort. Ultimately, the goal is to create homes a place where people might feel better, and EE plays a crucial role in achieving this objective.

While the approach proposed in this study offers notable advantages, it is essential to address certain limitations in future research. One of these limitations is the need for a more detailed disaggregation of industrial sectors to accurately align equipment components with their respective sectors. This level of granularity will ensure a more precise representation of the interactions between different technologies and their impact on specific industries. Another limitation lies in the assumption of fixed technological coefficients, which implies that an industry's output level changes proportionally to alterations in input requirements. To improve the accuracy of the assessment, future studies could explore dynamic technological coefficients that account for varying production levels and technological advancements over time.

However, notwithstanding these limitations, the approach remains a reliable and valuable tool for depicting the linkages between EEES indicators, effectively aiding DMs in policy and strategy analysis. In addition to the outlined benefits, this approach also holds significant potential for examining the impact of promoting EE measures in other countries. This can be achieved by simply adjusting the published IO/SUT matrices of those countries.

Therefore, the combination of the HIO-LCA and thermal dynamic simulation approaches represents a valuable tool to assist DMs in formulating EE funding strategies guided by the EEES impacts assessed through it. In fact, by assessing these impacts, DMs will be empowered to make well-informed decisions regarding the EE initiatives to endorse in the residential sector.

Future research is currently underway to broaden the scope of this study by encompassing other EE solutions, including different types of insulation, space heating, and cooling systems, and DHW technologies. Additionally, the implementation of these solutions in various Portuguese locations will be explored to provide a more comprehensive assessment of their impacts and benefits across different contexts.

Furthermore, the evaluation of other types of impacts, such as the energy and GHG payback time, as well as the effects on the public budget and energy poverty, will be incorporated into the analysis. This expanded evaluation will offer a more holistic view of the implications of EE investments, considering not only immediate savings but also the long-term effects on energy consumption, emissions reduction, and economic welfare. Moreover, the proposed modeling framework will be integrated with multi-objective optimization models, enabling DMs to devise funding packages that align with the available budget and policy objectives. This empowerment of DMs will facilitate the design of tailored and effective EE funding strategies, contributing to the successful implementation of sustainable and impactful EE initiatives in the residential sector.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This work is neither a repetition of any work nor copied key data from other's work.

Informed consent All co-authors of this manuscript were notified about each step of the publication process, and all was done with their input and approval.

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