Multiple Impacts of Energy Efficiency Technologies in Portugal

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Abstract Portuguese programs aimed at fostering Energy Efficiency (EE) measures often rely on cost–benefit approaches only considering the use phase and neglecting other potential impacts generated. Therefore, this work suggests a novel methodological framework by combining Hybrid Input–Output Lifecycle Analysis (HIO-LCA) with the Portuguese seasonal method for computing the households' energy needs. A holistic assessment of the energy, economic, environmental, and social impacts connected with the adoption of EE solutions is conducted aimed at supporting decision-makers (DMs) in the design of suitable funding policies. For this purpose, 109,553 EE packages have been created by combining distinct thermal insulation options for roofs and façades, with the replacement of windows, also considering the use of space heating and cooling and domestic heating water systems. The findings indicate that it is possible to confirm that various energy efficiency packages can be used to achieve the best performance for most of the impacts considered. Specifically, savings-to-investment ratio (SIR), Greenhouse gases (GHG), and energy payback times (GPBT and EPBT) present the best performances for packages that exclusively employ extruded polystyrene (XPS) for roof insulation (packages 151 and 265). However, considering the remaining impacts created by the investment in energy

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efficiency measures, their best performances are obtained when roof and façades insulation is combined with the use of space heating and cooling and DHW systems to replace the existing equipment. If biomass is assumed to be carbon–neutral, solution 18,254 yields the greatest reduction in GHG emissions. Given these trade-offs, it is evident that multiobjective optimization methods employing the impacts and benefits assessed are crucial for helping DMs design future EE programs following their preferences.

Keywords Energy efficiency · Hybrid input–output lifecycle analysis · Multiple benefits

1 Introduction

Considering the current energy standards, 75% of the European Union (EU) buildings are inefficient and more than 85% of these will still be operating in 2050. Additionally, the building sector accounts for about 40% of energy consumption and 36% of GHG emissions in the EU. Therefore, in the scope of EU long-term strategy of carbon neutrality by 2050, was recognized the need of accelerating the renovation rate of the European buildings to reach a carbon–neutral competitive economy and promoting growth and job creation (European Commission, 2019; 2021).

In Portugal, the residential building stock presents a similar behavior being responsible for more than 30% of final energy consumption, which increased by 1.6% during the period 2014–2019 (Energy Observatory, DGEG & ADENE, 2021). Also, about 66% of the Portuguese buildings were built before 1990, the year when EE requirements were introduced for new buildings and approximately one-third of the building stock built before 2012, reveals repair needs on the roof and exterior façades, leading to low energy performance levels, thus contributing to energy poverty, energy consumption and emissions generation (INE, 2012). To address the urgency of accelerating the buildings' renovation, Portugal has been deploying several programs aimed at promoting EE growth in this sector of which we can highlight the energy efficiency Fund, the support program for more sustainable buildings and the energy consumption efficiency promotion plan (in Portuguese—PPEC) (Presidency of the Council of Ministers, 2013, 2020, 2021). However, the evaluation of the EE measures to be funded is usually grounded on cost–benefit bases, mainly accounting for energy and emission savings during the operation phase, thus neglecting other potential benefits and impacts connected with all lifecycle (LC) phases of the measures selected. An example is that almost all the measures dedicated to promoting the EE in the residential sector, that are part of the Portuguese long-term strategy for the renovation of buildings, rely only on the assessment of costs and calculation of energy and emission savings during their operation phase (Presidency of the Council of Ministers, 2021). Nevertheless, the right assessment of the energy, economic, environmental, and social improvements of investing in EE should allow DMs to make well-grounded decisions when it comes to the choice of which EE measures should be funded in the residential sector. According to Reuter et al. (2020), a broader understanding of the attainable EE multiple benefits is necessary to facilitate the promotion of EE policies. This idea is in line with the European Renovation Wave establishing the need of using a better definition of the best criteria to be considered in the assessment of the energy-related savings in the new funding instruments. In this manner, one the objectives of the Recovery and Resilience Plan (RRP) is to improve the EE in residential buildings aiming at achieving the reduction of energy consumption and GHG emissions, the reduction of energy poverty, the improvement of indoor comfort and air quality and the creation of employment (European Commission, 2020; Ministry of Planning, 2021; Presidency of the Council of Ministers, 2021). In addition, the investment in EE measures may produce benefits other than energy savings and emissions reductions, like poverty alleviation, industrial productivity and competitiveness, energy security, job creation, energy prices moderation and health and well-being related benefits (Ryan and Campbell, 2012).

With the foregoing in mind, this work proposes a novel holistic approach that integrates a Hybrid Input–Output Lifecycle Analysis (HIO-LCA) framework with methods for calculating the energy performance of buildings (a seasonal method employed by the Portuguese building energy certification system), to evaluate the energy, economic, environmental, and social impacts and benefits of investing in EE solutions in the Portuguese residential sector generated throughout their LC assessment, thus helping DMs in the design of suitable EE funding policies.

2 Literature Review

As mentioned before, generally the operation is the only LC phase that is usually accounted for in the design of EE funding programs. However, when the nearly zero-energy buildings strategy is considered, the assessment of other lifecycle phases becomes even more important. Hence, other avenues of research addressing a broader range of impacts are required to support DMs in the design of suitable EE policies. In this context, the economic input–output LCA (EIO-LCA) makes it possible to assess the direct and indirect impacts of the entire economy connected to the production of a product or the provision of a service, avoiding the time-consuming and truncation problems inherent to the LCA approach. However, the EIO-LCA methodology is not free of limitations, as it can suffer from aggregation problems (Hendrickson et al., 1997; Suh, 2006; Crawford, 2009; Säynäjoki et al., 2017). In this context, an HIO-LCA framework should thus be used. This top-down approach pursues the simplification of LCA, extending conventional Input–Output (IO) matrices with environmental, energy, social or economic impacts, accounting for the transactions of all activity sectors/ industries, implying that the boundary of the analysis becomes very broad and inclusive, and the circularity effects are also included (Hendrickson et al., 1998, 2006; Bilec et al., 2006; Strømman et al., 2009; De Carvalho et al. 2016; Singh et al., 2018a, b). Hybrid methodologies have been used in distinct contexts. For example, to assess the employment impacts of renewable energy technologies

(Oliveira et al., 2014; Henriques et al., 2017), to assess the energy consumption and carbon emissions of a residential building during its lifetime (Zhan et al., 2018), or to compute of the embodied and operational energy of residential buildings in Lebanon (Stephan & Stephan, 2014). Nevertheless, the application of this sort of approach in the context of EE actions is not abundant, with only a few studies found in the literature. In this context can be mentioned the application of an energy and environmental extended EIO-LCA model to assess the benefits arising from the tax deduction for energy retrofit actions in the Italian building stock by Cellura et al. (2013), the assessment of the energy, economic, environmental, and social impacts of fostering the investment in electric energy-efficient appliances in India made by Singh et al. (2018a, b), which were later on combined with multiobjective interval portfolio theory in Singh et al. (2019) to support public DMs on the design of EE investment programs regarding different investment strategies. In the field of EE in the Portuguese residential sector, different types of studies have been conducted over the past few years by Asadi et al. (2012), Oliveira et al. (2014), Tadeu et al. (2018) and Henriques et al. (2020), although the impacts, the technologies and/or LC phases considered present some gaps that are intended to be fulfilled with this work.

This paper is organized as follows: in the next section, we describe the methodological framework proposed. Subsequently, some illustrative results are discussed. Finally, some conclusions are drawn, and future work developments are suggested.

3 Methodology

The analysis starts with the identification of retrofit technologies generally employed in the Portuguese residential sector—also known as “business as usual”. Subsequently, the corresponding best EE available technologies were chosen by analyzing several existing funding schemes (i.e., PPEC and LTRS PT). The manufacture, packaging, installation, and maintenance (MPIM) phases of the selected measures are then evaluated through the HIO-LCA approach, which combines Portuguese Supply and Use Tables (SUT) for the year 2017 at basic prices with impact data (INE, 2017, 2019; OECD, 2017; Oliveira et al., 2014). To calculate the multiplier effects of each activity or component (the matrices of direct and indirect coefficients) for the chosen energy, economic, environmental, and social indicators, the total output of each relevant activity or component of the technologies under analysis is linked to the corresponding product using the adjusted rectangular IO table. The retrofitting strategies considered in this case study involve the application of six types of insulation systems to the roofs and façades, with five different thicknesses, the replacement of the single-glazed aluminum frame windows with double-glazed aluminum or PVC frame windows combined with ten types of space heating and cooling and DHW appliances (see Table 1). The thickness of the insulation measures considered in this study did not exceed 120 mm, since there is a lack of available data for higher thicknesses and because this value meets and even exceeds the minimum energy requirements set out by the Energy Performance Regulation of Residential Buildings (Ministry of Economy & Employment, 2013).

Table 1 EE measures

Façade insulation		Roof insulation		Windows		Systems					
Type	Thickness (m)	Type	Thickness (m)	Frame	Glass	DHW + Heating	Heating + Cooling	Heating	Cooling	DHW	Backup
EPS	0.04 0.06 0.08 0.10 0.12	EPS	0.04 0.06 0.08 0.10 0.12	Aluminium	double	Conventional boiler	Air-source heat pump	Electric heater	Portable AC	Gas water heater	Solar collector
ICB		ICB									
Rock wool		Rock wool		PVC		Condensing boiler					
Glass wool		Glass wool								DHW Heat Pump	
PUR		PUR		Aluminium	Simple	Biomass boiler			No cooling system		No solar collector
XPS		XPS								Electric water heater	
No insulation	N/A	No insulation	N/A			DHW + Heating heat pump					

Source Authors' own elaboration

Then, using the seasonal method employed by the Portuguese building energy certification system (Decree-Law 101-D/2020), the annual households' energy requirements for space heating and cooling and DHW are calculated, before and after the interventions on the building envelope. Those needs will be later used to assess the impacts linked to the operation phase of the building. The impacts obtained with this approach were the total primary energy savings (TPES) and the energy payback time (EPBT)—as energy-related impacts; employment and gross value added (GVA) produced during the MPIM phases, savings to investment ratio (SIR) and net present value (NPV)—a proxy of the economic impacts; greenhouse gases (GHG) savings and GHG Payback Time (GPBT)—as environmental impacts and impact on the household budget and reduction of premature deaths—as social impacts. The schematic representation of the methodological approach's implementation proposed is presented in Fig. 1. To simulate the impacts of the EE measures adopted, a single dwelling T2, located in Coimbra, built between 1961 and 1991, was chosen as a reference scenario. Regarding the characterization of the constructive solutions, this building does not have insulation on the roof and façades and single-glazed aluminum frame windows are applied in its envelopment, also uses electric heaters for space heating and gas-fired water heater for DHW, while space cooling is guaranteed by natural ventilation.

The remaining characteristics of the building can be found in Pinto and Fragoso (2018) and Tenente et al. (2021).

In this work, the combined implementation of EE efficiency measures is preferred over the application of single ones, for the sake of the maximization of the energy savings of a building as well as the minimization of the costs linked to the installation phase. For example, if insulation is applied to the roofs and façades the energy savings are not the same as the sum of both individual measures and the operational costs would be significantly reduced, since the work could be done sequentially using just a part of the resources. With the foregoing in mind, the construction of different EE packages raises the problem of finding a common lifespan for each technology considered to compute the NPV, SIR, GPBT, and EPBT, for the reason that the

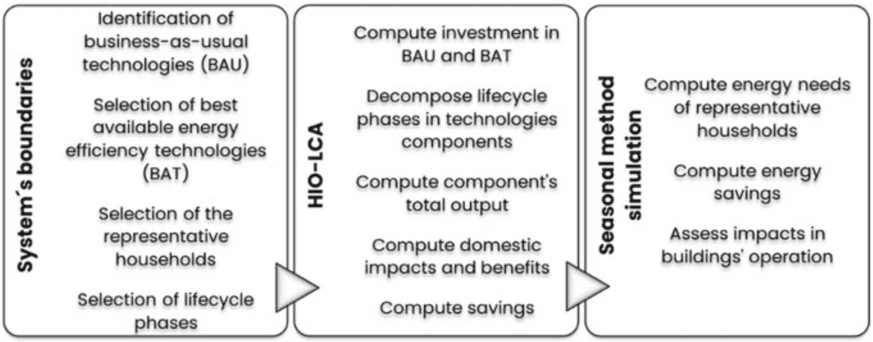

Fig. 1 Schematic representation of the methodological approach. *Source* Authors' own elaboration

lifespan of the insulation measures (50 years) and that of the space heating and cooling and DHW systems (12 to 25 years) do not match, thus being impractical to extend the analysis period to the full life of the efficiency resources being analyzed. On the other hand, if the lifespan of the building was considered, some of the technologies would have to be replaced before, leading to bias in the study. Therefore, the alternative to computing the NPV and SIR is to depreciate the costs of the technologies over their lifespan and to compute the GPBT and EPBT by annualizing the embodied energy (Woolf et al., 2017). It is important to note that the combination of individual EE measures considered led to the construction of new 109,553 packages which will be later compared with our reference scenario in the results section.

Rectangular Input–Output model

Originally developed by Wassily Leontief, IO analysis allows to compute the embodiments of production factors (e.g. labor and energy) and pollutants (e.g. CO2 emissions and waste), per unit of final consumption of commodities, by obtaining the total factor multipliers using IO tables that can be obtainable in diverse structures, according to three main criteria (Miller & Blair, 2009; Sargento et al., 2011): (1) symmetric or rectangular format; (2) total or domestic-use flows; (3) valuation prices (basic prices or purchasers' prices). Rectangular tables at purchaser's prices (in particular, the SUT framework) were firstly introduced by the European System of Accounts (ESA) in 1995, having the ability to consider both the primary and secondary commodities of each industrial sector (Horowitz & Planting, 2006). The Supply/Make matrix is of industry-by-commodity type, giving information on the industrial production of commodities. On the other hand, the Use matrix is of commodity-by-industry type, providing information on the commodities consumed by industries and final users. This format is called rectangular, because the number of commodities included in the model may be higher than the number of industries (Miller & Blair, 2009). Since the SUT framework requires either the consideration of industry or product technology assumption, this work used the industry technology assumption due to the input structure of an industry that remains unchanged regardless of its product mix, meaning that the technology assigned to the production of secondary products of an industry depends on the industry where it is produced (Miller & Blair, 2009; Raa & Rueda-Cantuche, 2007).

To start this approach each element of the use table (u_{ij}) is divided by the total output of industry j (g_i) and each element of the supply table (m_{ij}) is divided by the total demand of product i (q_i), to obtain the partitioned matrix D:

D $= \begin{bmatrix} 0 & Q \\ S & 0 \end{bmatrix}$, where each element of Q is given by $\frac{u_{ij}}{g_j}$ and each element of S is obtained by $\frac{m_{ij}}{q_j}$.

From D, considering the final demand aggregated into a single vector and then employing the general formulas for computing the inverse matrix it is possible to obtain the expression (1) (for further details see Miller & Blair, 2009).

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

From the rectangular IO model, it is possible to derive the expression (3) which is analogous to the Leontief inverse matrix, delivering an industry-by-commodity total requirements table, representing the total (direct and indirect) variation of each impact considered from industry j caused by the variation of one unit of final demand of commodity i (Miller & Blair, 2009; Locker et al. 2009). First, it is necessary to calculate the direct impact coefficients R, where each element,r_{kj}, is the amount of impact k produced per monetary unit of industry j's output (Hendrickson et al., 1998, 2006; Marques et al., 2006). Hence, the level of impacts associated with a given vector of total outputs is expressed in the expression (2) where **r** is the vector of impact levels:

$$\boldsymbol{r} = R\boldsymbol{x} \tag{2}$$

Consequently, when parameter x_i in Eq. (2) is replaced by the equation presented on the inferior left side of (1) it is obtained:

$$\boldsymbol{r} = R\left[S(I - QS)^{-1}\right]\boldsymbol{y} \tag{3}$$

In the assessment of the domestic impacts directly linked to each LC phase, the SUT format at basic prices was used, removing the imports.

4 Results

In this section, the main results found are presented in Tables 2 and 3 and discussed hereafter.

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Starting with the performance of our reference building, its annual total primary energy consumption (TPEC) can go up to 0.15 TJ, the GHG emissions can achieve 5.24 tonnes of CO2eq, the costs related to energy supply and environmental impacts, exempted of taxes can reach 1937€, the household energy bill can attain 3722€, and the potential number of premature deaths caused by particulate matter emissions can achieve about 6.48E-09. Regarding GVA and employment impacts created during the MPIM phases, since none of the business as usual (BAU) technologies in place will be produced again to be part of the energy efficiency packages, their value is null.

According to our analysis, results show that the solutions which exclusively employ extruded polystyrene (XPS) for roof insulation present the highest SIR and the lowest GPBT and EPBT. Package nº 151, which only adds 40 mm of thickness'

Table 2 Impacts of EE packages accounting for biomass CO2 emissions

Package	Façades		Roof		Windows	SHC	DHW	Solar heater	GHG savings	GPBT	EPBT	SIR	NPV	Jobs	GVA	Impact on Household budget	Premature deaths	Energy Savings
Nº	Type	m	Type	m	Type	Type	Type	Yes /No	Tons CO2eq	Days	Days	Ratio	€	Nº	€	%	Nº	TJ
151	0	0	XPS	0.04	SAW	EH	GWH	No	1.81	0.335	0.190	23.83	654.4	0.000198	5.76	11.96	2.09E-09	0.0537
265	0	0	XPS	0.06	SAW	EH	GWH	No	1,98	0.327	0.185	20.68	710.5	0.000207	6.09	13.07	2.28E-09	0.0587
10,965	XPS	0.08	XPS	0.08	SAW	AHP	GWH	Yes	4.51	7.449	2.874	4.20	1301.0	0.00285	103	29.38	1.50E-09	0.1318
18,150	XPS	0.12	XPS	0.10	SAW	AHP	EWH	No	4.17	3.270	1.446	4.42	1196.6	0.0016	57.1	26.35	4.18E-09	0.1191
18,331	XPS	0.12	XPS	0.12	DPW	BB		Yes	2.85	21.589	5.234	2.38	913.7	0.00484	174	30.79	−2.64E-07	0.1290
18,335	XPS	0.12	XPS	0.12	DPW	DHW + H + C HP		Yes	4.62	13.717	5.758	1.75	757.9	0.00696	244	30.27	−4.05E-09	0.1350
18,339	XPS	0.12	XPS	0.12	DPW	AHP	DHP	Yes	4.64	9.825	3.876	2.59	1079.9	0.00424	151	30.06	−1.05E-09	0.1348
91,257	ICB	0.12	ICB	0.12	SAW	DHW + H + C HP		Yes	4.54	17.219	7.316	1.15	226.45	0.00997	402	30.03	−6.20E-09	0.1334

Source Authors’ own elaboration

Table 3 Impacts of EE packages assuming carbon-neutrality of biomass

Package	Façades		Roof		Windows	SHC	DHW	Solar heater	GHG savings	GPBT	EPBT	SIR	NPV	Jobs	GVA	Impact on Household budget	Premature deaths	Energy Savings
Nº	Type	m	Type	m	Type	Type	Type	Yes /No	Tons CO2eq	Days	Days	Ratio	€	Nº	€	%	Nº	TJ
151	0	0	XPS	0.04	SAW	EH	GWH	No	1.81	0.335	0.190	23.83	654.4	0.000198	5.76	11.96	2.09E-09	0.0537
265	0	0	XPS	0.06	SAW	EH	GWH	No	1,98	0.327	0.185	20.68	710.5	0.000207	6.09	13.07	2.28E-09	0.0587
10,965	XPS	0.08	XPS	0.08	SAW	AHP	GWH	Yes	4.51	7.449	2.874	4.20	1301.0	0.00285	103	29.38	1.50E-09	0.1318
18,150	XPS	0.12	XPS	0.10	SAW	AHP	EWH	No	4.17	3.270	1.446	4.42	1196.6	0.0016	57.1	26.35	4.18E-09	0.1191
18,254	XPS	0.12	XPS	0.12	SAW	BB		No	5.08	7.008	3.133	3.82	1164.6	0.00275	99.8	29.98	−3.7E-07	0.1233
18,331	XPS	0.12	XPS	0.12	DPW	BB		Yes	5.02	12.572	5.234	2.52	1004.9	0.00484	174	30.79	−2.64E-07	0.1290
18,335	XPS	0.12	XPS	0.12	DPW	DHW + H + C HP		Yes	4.62	13.717	5.758	1.75	757.9	0.00696	244	30.27	−4.05E-09	0.1350
91,257	ICB	0.12	ICB	0.12	SAW	DHW + H + C HP		Yes	4.54	17.219	7.316	1.15	226.45	0.00997	402	30.03	−6.20E-09	0.1334

Source Authors' own elaboration

Note XPS—Extruded polystyrene; ICB—Insulation cork board; SAW—Single-glazed aluminium window; DAW—Double-glazed aluminium window; DPW—Double-glazed PVC window; EH—Electric heater; GWH - Gas water heater; EWH—Electric water heater; DHW + H + C HP—DHW + heating and cooling Heat pump; BB—Biomass boiler; AHP Air-source Heat Pump; DHP—DHW heat pump

XPS, allows the annual savings to exceed the annualized investment 23.83 times, while package 265, which only adds XPS with 60 mm of thickness, minimizes the time needed to recover the embodied energy and GHG emissions in the MPIM phases, up to 0.185 days and 0.327 days, respectively. Regarding packages that combine roof and façades insulation with space heating and cooling and DHW systems, package 10,965 composed of XPS with 80 mm of thickness for roof and façades insulation and a heat pump for replacing the electric heater for space heating is the solution with the highest annualized NPV that can go up to 1301.00€. Solution 18,150 allows reducing up to 65.23% of the potential number of premature deaths and consists in adding XPS with 120 mm and 100 mm of thickness to the façades and roof, respectively, by a heat pump to replace the electric heater and by an electric water heater to substitute the gas-fired water heater. The solution that maximizes the household budget is package 18,331 composed of XPS with 120 mm of thickness for insulation of roof and façades, double-glazed PVC frame windows to replace the single-glazed aluminum windows in use, and a biomass boiler for space heating and DHW. This solution allows for increasing the budget of a family in the poverty risk threshold by up to 31%. Package 18,335 made of XPS with 120 mm of thickness for insulation of roof and façades, double-glazed PVC frame windows, and a heat pump for space heating and cooling and DHW, is the solution that reaches the highest energy savings of about 0.1350 TJ. Package 91,257, which includes adding insulation cork board (ICB) with a thickness of 120 mm for roof and façade insulation and a heat pump for space heating and cooling as well as DHW, is the greatest way to increase economic and labor benefits. With this method, 0.00997 annualized full-time equivalent employment can be produced in the MPIM stages, and the GVA can increase to 402.00€. Finally, the package that maximizes the GHG savings (4.64 tons of CO2eq) is the 18,339 composed of XPS with 120 mm of thickness for insulation of roof and façades, double-glazed PVC frame windows, and a heat pump for space heating and cooling and a DHW heat pump for DHW.

After describing the best performances in each impact attained by the packages considered is important for the DMs to understand that trade-offs are always needed for selecting the best EE solutions to be funded. Therefore, taking into account the annualized SIR of the remaining packages this value varies from 1.15 to 20.68. In terms of TPES and GHG savings, the variation of these impacts can range from 0.0537 TJ to 0.1348 TJ, and from 1.81 tonnes of CO2eq to 4.62 tonnes of CO2eq, respectively. This results in an EPBT that can range from 0.190 to 7.32 days and a GPBT that can range from 0.335 to 17.21 days. The annualized NPV can change between 226.45€ and 1196.60€. During the MPIM phases, the employment and GVA creation values per year of the technologies' lifespan can range between 0.000198 and 0.00696, or 5.76€ and 244.00€, respectively. By using packages 151, 265, and 10,965, the potential number of premature deaths can be decreased by 32.61, 35.58, and 23.41%, whereas packages 18,331, 18,335, 91,257, 18,339, and 18,254 will result in an increase of up to 4119.57%, 63.20%, 96.75%, 16.38%, and 5773.64%, respectively. Finally, using packages 18,335, 91,257, 18,339, and 18,254, the household budget can increase by up to 30%.

If carbon-neutrality of biomass is considered the solution that allows achieving the highest GHG savings, changes from package 18,339 to package 18,254 composed of XPS with 120 mm of thickness for insulation of roof and façades, double-glazed PVC frame windows, and a biomass boiler for space heating and DHW. This solution can maximize the GHG savings by up to 5.08 tons of CO2eq. Additionally, in package 18,331 GHG emissions and the annualized GPBT decrease by 2.17 tons of CO2eq and about 9 days, respectively, while SIR can increase up to 0.14 and NPV reach 91.20€.

The findings show that the methodology outlined in this study should be supported in the decision-making process for the funding of EE measures because it allows for the development of a comprehensive evaluation of the impacts of investing in the technologies being examined, integrating the manufacturing, packaging, installation, and maintenance phases with the operation phase. Another benefit of this methodology is its ability to interact with different methodologies for assessing the energy needs of buildings, such as the seasonal approach employed in this study or the dynamic simulation method. In addition to 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.

5 Conclusions and Further Research

This paper presents a novel methodological approach that integrates an HIO-LCA framework with the Portuguese seasonal method employed by the Portuguese building energy certification system for calculating the energy performance of buildings, to evaluate the energy, economic, environmental, and social benefits/impacts of investing in distinct EE packages in the Portuguese residential sector. These packages have been created through the combination of thermal insulation options for roofs and façades, with the replacement of windows, also considering the use of space heating and cooling and DHW systems using a solar collector as a backup. Through this methodology different lifecycle phases are considered, in addition to operation, the SUT structure is employed instead of the symmetric format for reasons of more comprehensiveness, and DMs are supported to design suitable EE funding policies. This methodology was tested using the characteristics of a T2 single dwelling built between 1961 and 1991, located in Coimbra.

Our findings suggest that package 151 presents the highest SIR; package 265 minimizes the EPBT and GPBT; package 91,257 is the best solution to increase the economic and labor benefits; package 18,339 is the "cleanest" one; package 10,965 has the highest annualized NPV; package 18,331 maximizes the household budget of a family under poverty risk; package 18,150 has the highest potential to reduce premature deaths, and solution 18,335 reaches the highest energy savings. If carbon-neutrality is assumed for biomass, the minimization of GHG savings is obtained with solution 18,254.

Given these trade-offs, it is evident that multiobjective optimization methods that incorporate the impacts and benefits assessed by the methodology described in this study are essential for assisting DMs in modeling different investment strategies and designing future EE programs that reflect their preferences. Further research is also expected to cover the assessment of other Portuguese locations, other sorts of impacts (i.e., on public budget and energy poverty), and the consideration of the end-of-life phase.

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