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Integrating multiple impacts and lifecycle assessment in the evaluation of energy efficiency funding programs

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ABSTRACT

Investments in energy efficiency are widely recognized as a cornerstone of sustainable energy strategies and climate change mitigation efforts, offering not only environmental benefits but also delivering substantial socio-economic gains. However, conventional evaluation frameworks tend to focus predominantly on operational energy savings, often neglecting broader lifecycle effects.

This study introduces a comprehensive approach that integrates the Hybrid Input-Output Lifecycle Assessment methodology into Portugal's 2021 Energy Consumption Efficiency Promotion Plan framework. By incorporating Gross Value Added, Impact on the Public Budget and embodied energy and greenhouse gas emissions this approach expands convectional Primary Energy Savings, Net Present Value and Benefit-Cost Ratio calculations typically employed in cost-effectiveness analysis, allowing a comparative evaluation of the results.

The findings reveal significant variations in evaluation outcomes, with Net Present Value rising by over 4,000%, Benefit-Cost Ratio increasing by more than 34%, and two measures changing position in the funding priority ranking. These results highlight the transformative potential of the proposed methodology for guiding energy policy, supporting a more equitable and effective allocation of public funds. By

incorporating broader lifecycle impacts and societal benefits, the approach also enhances the robustness of EE evaluations, paving the way for improved decision-making in national and international energy programs.

Keywords

Multiple Benefits; Energy Efficiency; Hybrid Input-Output Lifecycle Assessment; Energy Consumption Efficiency Promotion Plan.

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Introduction

Energy efficiency (EE) has long been recognized as a foundational element of sustainable energy systems and climate change mitigation strategies (Jaffe & Stavins, 1994). By reducing energy demand without compromising performance or comfort, EE supports energy security, lowers emissions, and drives economic competitiveness. Yet, a persistent gap remains between the potential and actual uptake of energy efficiency measures (EEMs), often due to financial, social, institutional, and technical barriers (Dolšak, 2023; IEA, 2014; Ryan & Campbell, 2012; Tzani et al., 2022). In addition, conventional evaluation frameworks often adopt a limited scope, prioritizing operational energy savings while overlooking lifecycle, rebound, and economy-wide effects, thus failing to fully capture the multidimensional value of EE (Russell et al., 2015).

To address this gap, the European Union (EU) has adopted the "Energy Efficiency First" (EE1st) principle as a core policy approach. Enshrined in directives such as the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD) (European Parliament and of the Council, 2023, 2024), EE1st requires that energy demand reduction be prioritized before supply-side investments (BPIE, 2024). These policies increasingly call for a holistic assessment framework that not only accounts for operational savings but also captures the multiple environmental, social, and economic benefits of EEMs across their lifecycle, ensuring their integration into key planning and investment decisions.

Studies incorporating multiple benefits (MBs) into cost-benefit analyses have shown results up to 3.5 times higher than traditional models focusing solely on direct investment costs and operational energy and emissions savings, highlighting the critical importance of a comprehensive evaluation approach to accurately reflect the true value of EE investments (IEA, 2014; Ürge-Vorsatz et al., 2016; Zhang et al., 2016).

Despite the evidence on the value of MBs, national EE funding schemes, such as Portugal's Energy Consumption Efficiency Promotion Plan (PPEC), continue to apply conventional evaluation methods. This limited scope may lead to the undervaluation of impactful measures and hinder alignment with broader EU policy goals.

A growing body of literature and European-funded research has highlighted the need for a more holistic understanding of EE's MBs and reveals persistent gaps that need to be filled. Most studies often focus mainly on operational savings, overlooking key lifecycle phases (Clinch & Healy, 2001; Reuter et al., 2020; Scheer & Motherway, 2011; sEEnergies, 2022; Triple-A, 2022). Assessments that do consider additional lifecycle phases typically rely on Process Lifecycle Analysis (P-LCA) to assess the environmental impacts related to energy consumption (COMBI, 2018; MICAT, 2023). Nevertheless, when P-LCA is used to assess the energy and environmental impacts of specific EE measures, it omits the social and economic effects of their use (EERAdata, 2022). Moreover, the use of Input-Output (IO) models which are capable of capturing broader cross-sectoral impacts and the complex interdependencies along supply chains remains limited (COMBI, 2018; MICAT, 2023; Reuter et al., 2020; Triple-A, 2022). This is particularly evident in EE assessments, where analyses are typically limited to the use phase and focus on a narrow set of benefits. As a result, simplified evaluation approaches are commonly adopted, overlooking the wider economic repercussions across multiple sectors of activity.

To bridge the identified limitations, this study proposes an integrated framework that combines a Hybrid Input-Output Lifecycle Assessment (HIO-LCA) framework with the Portuguese PPEC evaluation system. The objective is to enhance the performance of PPEC's evaluation methodology for selecting EEMs by incorporating broader socio-economic and environmental indicators, namely, Gross Value Added (GVA), financial contributions from job creation, and embodied energy and emissions across manufacturing, packaging, installation, and maintenance (MPIM) stages. These additional dimensions are integrated into the standard feasibility assessments based on Primary Energy Savings (PES) and Net Present Value (NPV), and the merit-based ranking system grounded in the Benefit-Cost Ratio (BCR) and policy relevance. By comparing this extended methodology with the standard PPEC traditional framework, we aim to assess whether incorporating additional benefits materially changes the prioritization of EE measures.

Applying the proposed approach to a real-world policy instrument yields novel insights, demonstrating its potential to produce more robust and comprehensive results than conventional evaluation methods. This, in turn, can substantially inform and enhance decision-making processes related to EE investments. Beyond testing the robustness and equity of the approach, the study also provides findings that are relevant to shaping broader national and EU-level energy policy agendas.

The paper opens in with a presentation of the research problem and the study's primary objective. Next section outlines the methodology, including a description of the PPEC program, the HIO-LCA model for assessing MPIM impacts, the selected EE measures, the benefits considered, and the study's novel contributions. Then the results are presented and discussed, while last section concludes with key findings, policy implications, and recommendations for future research.

Methods

The approach employed in this research (see Figure 1) seeks to provide a transparent and replicable framework to enhance EE funding evaluation frameworks using MBs. It builds upon and refines the existing methodology of the PPEC by broadening the scope of analysis to include additional socio-economic and environmental benefits, as well as previously neglected lifecycle stages of EEMs. This expanded approach aims to improve the accuracy and relevance of the evaluation by incorporating upstream impacts and new dimensions of value creation.

The methodology proposed in this study is structured into four sequential phases. In phase one, data are collected on technology-related-costs including installation, removal, disposal, administrative, and transaction costs, as well as energy consumption data for both current and replacement technologies. Avoided electricity and gas supply costs resulting from energy savings are also considered.

In the second phase, the analysis extends beyond operational impacts by incorporating upstream effects using a HIO-LCA model. This model targets the MPIM phases of EE technologies. By incorporating investment values and detailed information on the technological components and associated services (such as installation), the HIO-LCA framework estimates both direct and indirect impacts. These include GVA, job creation, and the embodied energy and GHG emissions. This expansion allows the framework to assess the broader economic activity triggered across various industrial sectors involved in EE technology deployment. Further details of the HIO-LCA model are presented in Section "Hybrid Input–Output Lifecycle Analysis.

Phase 3 integrates the results from both operational and MPIM phases into a refined evaluation model aligned with the PPEC. This improved framework monetizes the avoided energy supply, net GHG emission reductions, GVA, and positive impacts on public budgets resulting from the fiscal effects of job creation (Impact on Public Budget, IPB), as detailed in Section "Benefits considered". The evaluation process applies three main criteria: the PES test, the Societal Test incorporating the NPV, and the BCR. Measures must first satisfy both the PES and NPV criteria to advance to merit-based ranking through BCR. Additionally, the alignment of each measure with existing national policies on EE is considered to ensure coherence with broader strategic objectives. These metrics are further described in the next section.

In phase 4, the results from the refined evaluation are used to produce a new ranking of EE measures. This ranking is directly compared with that produced by the conventional PPEC methodology. The differences between the two rankings highlight the added value of the refined approach, particularly its capacity to capture upstream and broader socio-economic impacts that are typically overlooked in standard evaluations.

The methodological details of the refined PPEC framework and the HIO-LCA model are provided in the following sections.

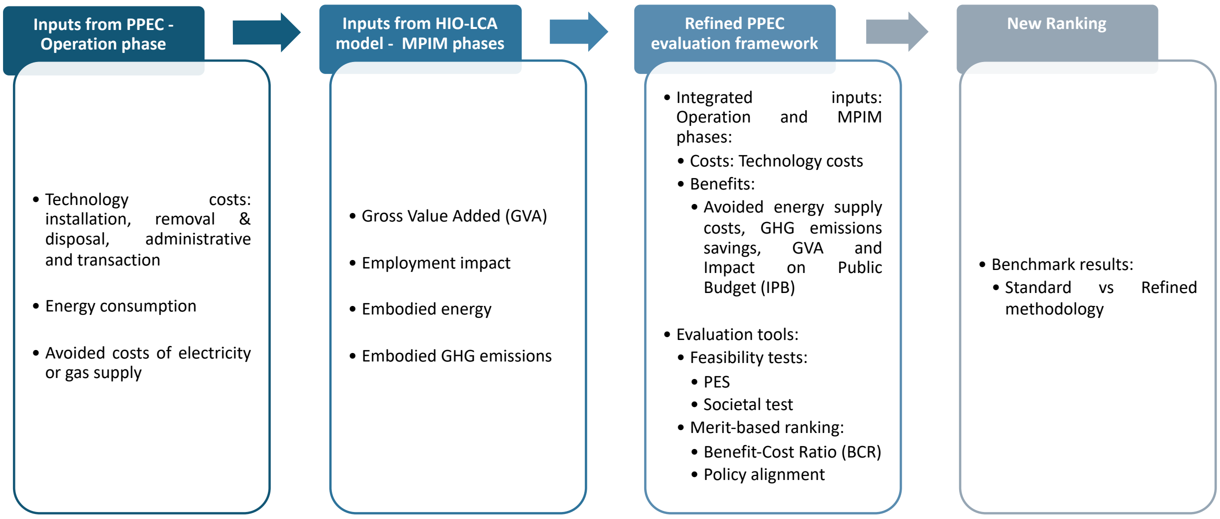

Figure 1. Schematic representation of the methodology.

Energy Consumption Efficiency Promotion Plan - PPEC

Launched in 2006 by the Energy Services Regulatory Authority (ERSE), PPEC was originally designed to promote efficiency in the electricity consumption (ERSE, 2006). Its most recent updates expanded the scope to include natural gas efficiency measures, promoting an integrated approach to energy systems and reinforcing the objectives of Portugal's National Energy and Climate Plan (NECP) 2020–2030 (ERSE, 2021b).

PPEC is structured as a competitive funding program, open to public and private entities that submit EE proposals. These proposals fall into two categories: tangible measures, involving direct interventions such as the installation of EE technologies or the replacement and disposal of inefficient equipment, primarily targeting the residential, commercial and services, and industrial and agricultural sectors; and intangible measures, which focus on promoting behavioral change through initiatives such as training programs, awareness campaigns, and energy audits aimed at encouraging sustainable practices.

Tangible measures are assessed based on technical feasibility, cost-effectiveness, and their estimated potential energy savings. In contrast, intangible measures are evaluated against a set of qualitative criteria, including the clarity and quality of the proposal, its potential to address market barriers and generate multiplier effects, equity considerations, the level of innovation, and the promoter's capacity to implement the initiative (ERSE, 2021b).

Although intangible measures contribute to long-term energy-saving efforts, this work focus exclusively on tangible measures within the residential sector, as they provide quantifiable indicators for assessing the effectiveness of a new holistic framework applied to EE funding programs. Other sectors have been excluded from this study due to the current lack of sufficient data for an in-depth evaluation.

Funding Criteria and Evaluation

To determine the eligibility for funding under PPEC, tangible measures undergo two key evaluations (see Appendix A for detailed formulas):

- PES Test – Measures the reduction in primary energy consumption achieved by replacing standard equipment with more efficient alternatives.
- Social Test – Determines the societal value of a measure by calculating the NPV of its long-term benefits, incorporating both benefits and costs.

Measures that achieve positive PES and NPV values are admissible for selection. Once measures meet eligibility criteria, they are ranked using a merit-based scoring system, divided equally between:

- ERSE's economic assessment (50%), based on:
  - Benefit-Cost Ratio (BCR): Proportional and ordered scores reflecting relative efficiency.

    - Share of Direct Investment (DI): Proportion of funding allocated to equipment and installation costs.
- Directorate-General for Energy and Geology's (DGEG) policy alignment (50%), based on:
    - National coverage
    - Alignment with national policy and legislation
    - Support for the development and implementation of measures to promote EE
    - Diversification of promoters
    - Coordination with other instruments to encourage EE

Since the EE measures considered remain the same, the political evaluation of the EE measures remains constant. The next section explores the integration of the HIO-LCA methodology to enhance impact evaluation within the PPEC framework.

Hybrid Input–Output Lifecycle Analysis

HIO-LCA has emerged as a robust framework for evaluating the wide spectrum impacts of EE investments. By integrating conventional process-based lifecycle assessment (P-LCA) with IO modeling, HIO-LCA bridges the limitations of P-LCA and economic IO lifecycle analysis (EIO-LCA) (Henriques & Sousa, 2023). This hybrid approach offers the dual advantage of system completeness and technological specificity, addressing key challenges such as truncation and time-consumption issues in P-LCA, as well as the sectoral aggregation and homogeneity assumptions inherent to EIO-LCA (Crawford, 2009; Säynäjoki et al., 2017; Suh, 2004). This methodological synergy is especially valuable in the context of evaluating funding programs aimed at promoting the widespread adoption of EEMs through competitive selection processes.

At its core, IO analysis provides a vectorized representation of intersectoral economic flows, tracking goods and services over defined timeframes (Leontief, 1986). When extended, such as to incorporate environmental dimensions, IO models offer two primary pathways: one expands the technical coefficients matrix to endogenize environmental interactions, enhancing dynamic modelling interactions but increasing complexity and limiting the flexibility of the analysis (Leontief, 1970, 1973; Miller & Blair, 2009), while the other externally extends the technical coefficients matrix to maintain a separation of economic and environmental accounts for greater methodological flexibility (Hendrickson et al., 2006; Miller & Blair, 2009). HIO-LCA aligns with the latter, retaining modularity to assess a wide range of environmental and economic indicators without recalibrating the entire model. This flexibility allows HIO-LCA capturing both embodied and operational impacts across multiple lifecycle phases, providing a more holistic representation of diverse EE technologies and making it well-suited for policy evaluation and investment planning.

Building on Tenente et al. (2024, 2025), this paper proposes the use of the HIO-LCA framework to assess the national-scale effects of EE investments, incorporating a broader set of socio-economic and environmental indicators. This refined approach strengthens EE policy by ensuring that funding decisions reflect long-term, economy-wide effects. By applying the HIO-LCA approach to large-scale EE programs like PPEC it is ensured that EE performance is accurately understood, improving funding mechanisms and advancing sustainable, high-impact energy policies.

The implementation of the HIO-LCA methodology begins with the identification of baseline and EE technologies (see Table 3). This forms the basis for evaluating the socio-economic and environmental effects associated with each technology by capturing both direct impacts on EE-related industries and indirect effects generated through their upstream supply chains. The analysis adapts and extends the framework initially proposed by Breitschopf et al. (2012) while leveraging the advancements introduced by Tenente et al. (2025). An important premise of this approach is that the industries represented in the model serve as suitable proxies for national industries in the EE sector in terms of input structures and impacts and benefits per unit of output.

The HIO-LCA implementation involves several key steps:

- System Boundary Definition: This step involves establishing the system boundaries. The process begins with the identification of standard technologies currently used in residential buildings, along with their corresponding EE alternatives. This identification is informed by data from the PPEC program (ERSE, 2022b).

- Cost estimation in EEMs: Costs associated with investment, installation, and maintenance of selected measures are compiled from PPEC (ERSE, 2022b), professional pricing tools (CYPE Ingenieros S.A, 2021) and supplier surveys. These costs are adjusted for inflation and excluding taxes and markups to reflect net economic input values (FFMS, 2020).
- Domestic output calculation: EE technologies are broken down into their constituent components and associated activities across MPIM phases. EE-related expenditures are then allocated to these components and activities based on detailed technical and survey data. In order to account only for the impacts and benefits generated nationally, the import shares, derived from OECD IO data (OECD, 2017b), are subtracted to isolate the domestic portion of expenditures. These are then attributed to the relevant industry sectors within the IO model, resulting in the sectoral alignment and the accuracy of derived impact coefficients.
- Impact estimation: The model quantifies total impacts (direct and indirect), resulting from increased final demand for EEMs. Total impacts capture the cascading effects across upstream industries that supply intermediate goods and services to primary EE technology industries (Miller & Blair, 2009).

  To account for total impacts the model extends the analysis using a rectangular IO framework, conceptually aligned with the Leontief inverse matrix approach (Hendrickson et al., 1998, 2006), represented by Equation (8):

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

  where $[S(I - QS)^{-1}]$ represents the total production required per unit of final demand; S captures market share coefficients, indicating the proportion of each product supplied by different industries; I is the identity matrix; Q represents the technical coefficients matrix, detailing direct input dependencies per unit of industries' output ; and $\boldsymbol{y}$ symbolizes the final demand for EE products. Using this formula the model ensures that all chain reactions throughout the economy are accurately captured and attributed back to industry-specific contributions.

The application of a rectangular IO model, based on Supply and Use Tables (SUTs), better reflects real-world economic structures by distinguishing between primary and secondary commodities produced within each industry (Horowitz & Planting, 2006). This allows for more accurate modeling of embodied energy and emissions, as well as GVA and job creation, as it better reflects real economic complexity and sectoral heterogeneity.

This analysis aligns the 2017 SUTs at basic prices (OECD, 2017a) with satellite accounts from Portugal's National Statistics Institute (INE, 2017). Data from 2018-2020 were excluded due to data unavailability and COVID-related distortions. By integrating SUTs with satellite accounts, this approach streamlines the P-LCA process for assessing the environmental and socio-economic impacts.

Selected EE measures

Selected EEMs for this analysis comprise a range of equipment replacements and system upgrades aimed at improving efficiency in the residential sector (see Table 1). Specifically, IBD_TR1 and IBD_TR2 involve the replacement of conventional air conditioning and domestic hot water systems with high-efficiency heat pumps, with the option of integrating photovoltaic systems for self-consumption. PORTGAS_TR1 focuses on replacing natural gas-fueled water heaters with safer and more efficient models, while GOLDENERGY_TR1 entails the installation of intelligent thermostats to optimize indoor climate control. LISGDL_TR1 addresses the replacement of outdated atmospheric boilers with sealed or condensing boilers to improve energy performance and reduce emissions. The assessment was based on a detailed dataset from ERSE (2022a, 2022b), covering technical, financial, and social parameters of each measure.

Table 1. Approved PPEC measures for the residential sector.

Nomenclature	Promoter	Measure	Sector
IBD_TR1	Iberdrola	Efficient thermal energy	Residential
IBD_TR2	Iberdrola	DHW heat pump	
PORTGAS_TR1	Portgas	More efficient water heaters	
GOLDENERGY_TR1	Goldenergy	Smart thermostats	
LISGDL_TR1	Lisboagas GDL	Replacement and disposal of energy equipment with more efficient equipment	

Benefits considered

As previously noted, a comprehensive evaluation of EE initiatives must account for MBs to support more informed decision-making. This section outlines the benefits addressed in this work and how they were used to recalibrate the metrics of PPEC.

The following benefits were considered:

- PES: Defined as the difference in primary energy consumption between business as usual technologies and best available EE technologies. For the PES test, embodied energy during MPIM phases of best available EE technologies are included alongside with operation consumption.
- Avoided costs of electricity or gas supply: Estimated by monetizing the net energy savings of EE technologies, computed as the difference between PPEC-calculated savings and the energy consumed during their MPIM phases. Monetization parameters were retrieved from (ERSE, 2021a).
- Environmental benefits (societal perspective): These include the avoided externalities, such as GHG emissions, impact on public health or use of natural resources due to the reduction in energy demand (electricity and natural gas). The environmental benefits are calculated based on the net reduction in electricity and gas supply determined by subtracting energy consumed during MPIM phases to the total avoided energy supply. The benefits are monetized using unitary cost estimations from ERSE (2021a).
- GVA: Represents the economic value generated during MPIM phases of EE technologies. This indicator is estimated via the HIO-LCA model.
- IPB: Quantifies the fiscal return generated through employment creation across different industry sectors during the MPIM phases. This includes income taxes and social security contributions arising from the jobs created because of the adoption of EEM. The total public budget impact is calculated using the Equation (9).

$$IPB = \sum_j^n (FTE_j * \overline{In}_j * Ir_j) \quad (9)$$

where FTE_j represents the number of full-time equivalent jobs created in sector *j*; $\overline{In}_j$ is the average annual income per employee in sector *j*; Ir_j denotes the effective income tax and social contribution rate in sector *j*; *j* represents each sector involved in the MPIM of the EE technology under evaluation and *n* is the total number of sectors considered.

The standard PPEC evaluation did not account for other positive externalities, such as socio-economic impacts, particularly those related to employment and GVA. Recognizing the importance of these factors, we incorporated them into this study to more comprehensively reflect a wide range of social benefits that a given measure may generate.

The lifecycle phases addressed in this work encompass MPIM (using HIO-LCA) and operation (using the PPEC methodology). Due to data limitations, the end-of-life impacts are excluded, however, prior studies estimate their contribution at under 5% of total lifecycle impacts (Ortiz et al., 2010).

Novelties

To overcome the limitations of current energy efficiency (EE) evaluation frameworks, the proposed methodology introduces three novelties: (1) the integration of HIO-LCA into the PPEC framework, enabling more comprehensive assessments of feasibility and benefit-cost ratios by capturing full lifecycle impacts; (2) enhanced use of national SUTs to model economic and environmental interactions within EE supply chains; and (3) a scalable, internationally applicable structure that supports cross-country comparisons and broad applicability across sectors and funding schemes.

Results and Discussion

This section presents the outcomes from the implemented methodology, followed by a comparative assessment and recalibration of key indicators.

Table 2 summarizes the PPEC impacts associated with each EEM analyzed, including operational energy savings, societal benefits, and costs. These values serve as a foundation for recalculating PES, NPV, and BCR by incorporating the additional effects derived from the HIO-LCA framework, as detailed in Table 3.

Table 2. PPEC impacts.

Measures	PES	Costs		Benefits	
		PPEC	Social	Environmental benefits from a societal perspective.	Avoided costs of electricity or gas supply
	Toe/year	(€)	(€)	(€)	(€)
IBD_TR1	43.72	112,344	334,798	19,287	488,107
IBD_TR2	13.55	41,098	157,601	5,803	152,227
PORTGAS_TR1	159.28	685,125	940,000	129,026	825,699
GOLDENERGY_TR1	41.18	104,545	150,560	33,360	330,132
LISGDL_TR1	254.26	799,433	1,279,609	205,965	1,318,074

Table 3. MPIM impacts.

Measures	MPIM impacts						
	GVA	Employment	Impact on public budget	Embodied GHG emissions		Embodied energy	
	€	Nº of jobs	€	Tons of CO2eq	€	Toe	€
IBD_TR1	34,315.47	0.96	5,570.26	23.67	299.77	7.06	4,597.31
IBD_TR2	16,740.14	0.50	3,542.66	8.56	127.40	2.93	1,868.94
PORTGAS_TR1	362,279.42	10.25	51,686.85	310.19	3,577.04	82.96	87,754.63
GOLDENERGY_TR1	35,180.37	1.16	4,411.62	14.62	224.87	5.03	3,015.95
LISGDL_TR1	282,300.88	7.75	49,651.49	206.83	2,566.60	57.90	65,258.57

To account for environmental effects, a detailed analysis of the materials and services involved in the MPIM phases of each measure was carried out, reflecting the separate reporting of unit costs for electricity and gas. Using energy balance tables from DGEG (2023) allowed to compute the proportional contributions of electricity and gas to the total energy input we estimated (see Table 4). It is important to note that the cumulative percentages did not sum 100%, as minor energy vectors were excluded due their negligible contribution to the overall energy use.

GVA was already expressed in euros, while employment impacts were translated into IPB, reflecting the fiscal return generated through job creation. These indicators provide a monetary representation of broader socio-economic impacts.

Table 4. Shares of energy vectors in each EE measure.

Measures	Energy vectors	
	Gas (%)	Electricity (%)
IBD_TR1	32.28	64.76
IBD_TR2	33.79	62.77
PORTGAS_TR1	32.70	66.10
GOLDENERGY_TR1	36.23	57.80
LISGDL_TR1	32.90	61.00

New PPEC rankings

Using the refined methodology outlined previously, the PES, NPV, and BCR values were recalculated based on the updated inputs from Tables 2 and 3, with the results summarized in Table 5.

Table 5. Old and new scores for BCR, PES and social test.

Measures	Old BCR	New BCR	Old PES (toe)	New PES (toe)	Old NPV (€)	New NPV (€)
IBD_TR1	4.52	4.83	874.4	867	172,595	207,584
IBD_TR2	3.85	4.29	271.0	268	428	18,715
PORTGAS_TR1	1.39	1.86	1,911.4	1,828	14,724	337,360
GOLDENERGY_TR1	3.48	3.82	494.2	489	212,932	249,283
LISGDL_TR1	1.91	2.24	3,051.1	2,993	244,430.3	508,557

Finally, the updated ERSE scores were determined (see Table 6). These revised scores were then combined with the unchanged DGEG values to obtain the final PPEC scores, which served as the basis for the updated ranking of EEMs.

Table 6. New PPEC rankings.

Measures	ERSE – Old score	ERSE – New score	DGEG score	PPEC – Old score	PPEC – New score	Old ranking	New ranking
IBD_TR1	98.53	98.53	84.00	91.27	91.27	1º	1º
IBD_TR2	83.59	85.07	84.00	83.80	84.54	2º	2º
PORTGAS_TR1	45.43	49.14	79.00	62.21	64.07	**3º**	**4º**
GOLDENERGY_TR1	59.32	69.27	64.00	61.66	66.64	**4º**	**3º**
LISGDL_TR1	52.98	54.83	64.00	58.49	59.42	5º	5º

The findings of this study highlight the significant impact of incorporating MBs on EE assessment and decision-making. As reflected in Table 5, key performance metrics responded notably to the inclusion of additional effects.

PES saw modest reductions, with decreases of 1% observed in IBD_TR1, IBD_TR2, and GOLDENERGY_TR1, and a maximum decrease of 4% for PORTGAS_TR1. In contrast, NPV experienced dramatic increases, reaching up to 4,271% for the second EEM proposed by Iberdrola. BCR also improved, with a notable rise of 34% for efficient water heaters (PORTGAS_TR1). These results indicate that although the inclusion of embodied energy and GHG emissions slightly diminished the societal benefits, the positive contributions of GVA and IPB more than offset these impacts, ultimately enhancing the overall cost-effectiveness of all proposed EEMs.

As depicted in Table 6, these changes had a direct effect on project rankings. While IBD_TR1 maintained its top position with an unchanged ERSE score (98.53), GOLDENERGY_TR1 moved ahead of PORTGAS_TR1, highlighting the influence of lifecycle performance in the evaluation. This shift illustrates the critical role that broader benefit integration plays in shaping funding priorities and investment decisions in EE programs.

Although all measures considered in the 2021 PPEC edition (used here as a case study) were ultimately approved, this has not always been the case in previous editions. Therefore, the methodological approach adopted in this study could prove instrumental in future decision-making contexts, potentially increasing the potential for borderline or underappreciated measures being approved.

Conclusions

Enhancing EE remains a priority for EU Member States, given its cost-effectiveness and crucial role in reducing environmental impacts. Aligning with this goal, the EU mandates national strategies to meet EE targets and reduce GHG emissions necessitating robust evaluation frameworks to guide and assess these strategies. Despite ongoing efforts, there is still considerable potential to better capture the full value of EE, particularly by integrating broader and societal benefits.

This paper presents an enhanced evaluation methodology that integrates HIO-LCA into PPEC. The proposed framework expands beyond traditional metrics—PES, NPV, and BCR—by incorporating lifecycle-based benefits such as GVA, IPB, and embodied energy and emissions across MPIM phases. The approach leverages national SUTs and is compatible with international databases, ensuring broader applicability and potential for cross-country benchmarking.

The application of this enhanced methodology demonstrated that incorporating additional benefits can substantially affect the prioritization of EEMs. Two measures shifted in ranking, and all showed notable improvements in NPV and BCR, specifically NPV rose by over 4,000% and BCR by more than 34%, highlighting the value of a comprehensive evaluation. Although PES slightly declined across all measures due to the inclusion of embodied energy and GHG emissions, the overall cost-effectiveness improved, as the positive impacts of GVA and IPB more than compensated for these reductions. The findings confirm the relevance and effectiveness of the proposed methodological approach, which adds significant value by enhancing the robustness and reliability of the assessment process through a comprehensive, scalable, and data-driven framework that captures the lifecycle, economic, and societal impacts of energy efficiency investments, supporting more informed, transparent, and impactful policy and funding decisions.

Despite these advantages, limitations remain. The current IO model's level of sectoral aggregation may obscure variations in technology-specific impacts, while the homogeneity assumption could oversimplify inter-sector differences. Enhancing disaggregation, particularly for employment-related impacts, could improve insights into job types and their relevance to the energy transition. The methodology also lacks detailed data on end-of-life phases, relying on secondary sources, which affects the completeness of lifecycle assessments.

Future research should explore the inclusion of wider range of energy benefits—such as reduced energy poverty and public health gains—and apply this framework to other EE funding programs. Doing so would strengthen investment planning and promote more effective, equitable, and sustainable energy transitions.

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Appendix A – PPEC Evaluation Framework

A1. PPEC Eligibility Criteria

1. Primary Energy Savings (PES) Test

This test estimates the reduction in primary energy consumption resulting from the replacement of a standard technology (*i*) with a more efficient alternative (j). It is calculated as:

$$PES = \sum_{t=0}^{n} C(toe)_{i,t} - \sum_{t=0}^{n} C(toe)_{j,t} \tag{1}$$

Where:

- $C(toe)_{i,t}$ represents the primary energy consumption of standard technology in year *t*.
- $C(toe)_{j,t}$ represents the Primary energy consumption of efficient technology in year *t*.
- n is the technology lifespan (years).

2. Social Test (Net Present Value – NPV)

Determines the societal value of a measure by calculating the NPV of its long-term benefits, incorporating both benefits and costs. It is given by Equation (2):

$$NPV = \sum_{t=0}^{n} \frac{B_{St} - C_{St}}{(1+d)^t} \tag{2}$$

Where:

- B_{st} represents the benefits from a societal perspective associated with the efficiency measure in year t. These benefits include the avoided costs of electricity or gas supply, as well as the environmental externalities avoided with the reductions in electricity and natural gas consumption.
- C_{st} corresponds to the costs incurred in year t due to the implementation of the efficiency measure. These costs encompass installation, removal and disposal of the replaced equipment, net of its residual value, along with administrative and transaction costs supported by the promoter, the participating consumer and the partner in the measure.
- *d* is the discount rate.

A2. Merit-based System

3. Benefit-Cost Ratio (BCR)

$$BCR_j = \frac{\sum_{t=o}^{n} \frac{B_{st}}{(1+d)^t}}{\sum_{t=o}^{n} \frac{C_{PPEC_t}}{(1+d)^t}} \tag{3}$$

Where:

- C_{PPEC_t} represents the costs subsidized by the PPEC related to the EE measure in year t and d represents the discount rate.
- C_{st} corresponds to the costs incurred in year t due to the implementation of the efficiency measure. These costs encompass installation, removal and disposal of the replaced equipment, net of its residual value, along with administrative and transaction costs supported by the promoter, the participating consumer and the partner in the measure.
- *d* is the discount rate.

4. Proportional BCR Score (BCR_p)

$$BCR_p = 50\frac{BCR_j}{BCR_{max}} \tag{4}$$

Where:

- BCR_{max} represents the highest BCR value among all evaluated measures.

5. Ordered Benefit-Cost Ratio (BCR_o)

$$BCR_o = 25 - (k-1)\frac{25}{q} \tag{5}$$

Where:

- q is the number of measures
- k is the measure's position in the list.

6. Direct Investment in Equipment Index (DI)

$$DI = \frac{DC_{PPEC_J}}{C_{PPEC_j}} \tag{6}$$

Where:

- DC_{PPEC_j} represents the cost of equipment acquisition subsidized by the PPEC
- C_{PPEC_j} corresponds to total cost of the measure subsidized by the PPEC

A3. DGEG Evaluation – Policy Scoring

Projects undergo a political evaluation conducted by the Directorate-General for Energy and Geology (DGEG) (Office of the Assistant Secretary of State for Energy, 2021), which assigns qualitative scores, based on five qualitative dimensions (see Table A.1).

Table A.1. DGEG qualitative criteria for tangible measures within PPEC.

DGEG criteria	Weighting
National coverage	10 points
Alignment with national policy and legislation	40 points
Support for the development and implementation of measures to promote EE	30 points
Diversification of promoters	10 points
Coordination with other instruments to encourage EE	10 points