Evaluation of energy efficiency measures addressing the needs of energy poor households in rural areas

Co-funded by the European Union under project ID 101077272. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Project Acronym	RENOVERTY
Project Name	Home Renovation Roadmaps to Address Energy Poverty in Vulnerable Rural Districts
Project Coordinator	IEECP
Project Duration	3 years
Website	https://ieecp.org/projects/renoverty/

Deliverable No.	Deliverable 4.1
Dissemination Level	Public
Work Package	WP4
Lead beneficiary	UPRC
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Date	17/07/2024
File Name	RENOVERTY Deliverable 4.1

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Published in July 2024 by RENOVERTY.

Please cite as: **Apostoliotis A., Papantonis D., Flamos A. (2024).** *Evaluation of energy efficiency measures addressing the needs of energy poor households in rural areas. Deliverable 4.1. LIFE RENOVERTY project*. University of Piraeus Research Center (UPRC), Piraeus, Greece.

About RENOVERTY

RENOVERTY will foster energy efficiency building upgrades in the Central and Eastern Europe (CEE), South-eastern Europe (SEE) countries, as well as Southern European countries (SE), by setting the methodological and practical framework to build renovation roadmaps of vulnerable rural districts in a financially viable and socially just manner.

Specifically, the project aims to deliver tools and resources to support local and regional actors to build and execute operational single or multi-household roadmaps for rural areas. A scalable model will also be created to ensure the wide geographical replicability and implementation of the roadmaps by different actors at the EU level. Strategically, the project will contribute to minimising logistical, financial, administrative, and legal burdens caused by a complex and multi-stakeholder home renovation process. Additionally, RENOVERTY will ensure that building retrofits consider the social dimension by incorporating security, comfort, and improved accessibility in the roadmaps to further improve the quality of life of vulnerable populations.

Over the project’s three years, seven pilots located in Sveta Nedelja (Croatia), Tartu (Estonia), Bükk-Mak & Somló-Marcalmente-Bakonyalja (Hungary), Zasavje (Slovenia), Parma (Italy), Coimbra (Portugal), and Osona (Spain) will implement the roadmaps, while wider integration of rural and peri-urban development is foreseen in the long run.

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List of Abbreviations

CEE	Central and Eastern Europe
CO_2	Carbon dioxide
COP	Coefficient of Performance
EC	European Commission
EEM	Energy Efficiency Measure
EER	Energy Efficiency Ratio
EPCs	Energy Performance Certificates
EU	European Union
H2020	Horizon 2020
HVAC	Heating, Ventilation Air Conditioning
LAG	Local Action Group
LCSE	Levelised Cost of Saved Energy
MFH	Multi-family house
NPV	Net Present Value
PMV	Predicted Mean Vote
PP	Payback Period
PPD	Predicted Percentage of Dissatisfaction
REERs	Renovation Energy Efficiency Roadmaps
SE	Southern Europe
SEE	Southern Eastern Europe
SEER	Seasonal Energy Efficiency Ratio
SFH	Single-family house
SMB	Somló-Marcalmente-Bakonyalja

Executive Summary

The European Union aims to attain climate neutrality by 2050, while highlighting the need for a deep transformation of the economy to avoid social and regional disparities, aiming at achieving a green, fair and equitable energy transition for all. This vision of a fair socially acceptable clean energy transition brings the complex and multidimensional issue of energy poverty into the spotlight. Despite recent scientific and policy efforts focusing on mapping and comprehending energy poverty's driving forces, aspects and consequences, gaps in knowledge and practice remain.

Such gaps are identified in the case of rural areas, even though rural populations are at a significantly higher risk of facing energy poverty and social exclusion than urban ones. This situation is not merely coincidental, rather, it is influenced by various distinct characteristics inherent to rural areas that escalate the vulnerability of households to energy poverty.

According to existing knowledge, rural households are more likely to be energy poor due to several unique factors that characterise them, such as the characteristics of the building stock, the more limited choice of energy sources, increased energy expenses, limited educational and labour capabilities, geographical remoteness, difficulties in renovation, etc.

The RENOVERTY project aims to address these gaps by providing methodological and practical frameworks to address energy poverty and increase energy efficiency renovations in vulnerable rural districts in Central Eastern, Southern Eastern and Southern Europe. Specifically, RENOVERTY pilot areas concern the rural region of Osona in Spain, the rural region of Parma in Italy, the rural region of Coimbra in Portugal, the rural regions of Bükk and Somló-Marcalmente-Bakonyalja in Hungary, the rural regions of Sveta Nedelja and Žumberak in Croatia, the rural region of Tartu in Estonia, and the rural region of Zasavje in Slovenia.

The overarching objective of the project is the co-development, with all actors involved in the energy efficiency value chain, of individual tailor-made Renovation Energy Efficiency Roadmaps for the regions under study. These roadmaps are a very useful tool when aiming to foster renovations in cases with unique characteristics/ needs, like in the case of rural households, as they build on these specificities aiming to address them while being able to be replicated in more cases.

In this context, in this report we expand RENOVERTY activities, coupling the strengths of energy system modelling with qualitative and semi-quantitative techniques, implementing four (4) methodological steps guiding us from the (**i**)**.** updated framework of energy efficiency and energy poverty in rural areas, the (**ii**)**.** stakeholders need assessment, and the (**iii**)**.** RENOVERTY fieldwork (i.e., energy audits), as derived from the RENOVERTY report: "*Updating the energy poverty and energy efficiency framework in rural areas across the EU*"), to the application of the modelling assessment framework in real-life pilots, allowing for the evaluation of several Energy Efficiency Measures based on their impact in households' energy profiles and technoeconomic viability.

To do so, we employ and present the results from the **Dynamic high-Resolution dE-mand-sidE Management** (**DREEM**) model. DREEM is employed to apply a portfolio assessment framework that will determine the most suitable Energy Efficiency Measures in each case study, based on their energy-saving potential and their technoeconomic viability. The energy performance and technoeconomic evaluation are also complemented with avoided emissions calculation and thermal comfort analysis for each measure.

The Energy Efficiency Measures selected for each pilot are:

- **EEM_1 - Exterior wall insulation**: Insulating the main walls of the building under study from the outside, which commonly have solid walls with no cavities.
- **EEM_2 - Double-glazed windows**: Replacing single-glazing windows with energy-efficient glazing (double-glazed windows) to reduce heat loss.
- **EEM_3 - Roof insulation**: Insulated between and under the rafters of the roof itself, reducing the overall heat transfer coefficient by adding materials with low thermal conductivity (this measure applies only in the case of SFHs)
- **EEM_4 - Energy-efficient heating system** (*Boiler upgrade- gas*): In this case, the dwelling's outdated heating system is replaced by an efficient gas boiler with a higher efficiency ratio.
- **EEM_5 - Energy-efficient heating system** (*Boiler upgrade- biomass*): In this case, the dwelling's outdated heating system is replaced by an efficient biomass boiler with a higher efficiency ratio.
- **EEM_6 - Energy-efficient heating system** (*Heat pump*): In this case, the dwelling's outdated heating system is replaced by a heat pump with a higher efficiency ratio.
- **EEM_7 - Energy-efficient lighting**: In this case, the conventional tube lights and bulbs (fluorescent lamps) are replaced by high energy-efficiency ones (LED lamps).

Modelling results provide detailed information on the energy-saving potential, the environmental impacts, the cost-effectiveness, and the household profitability from the implementation of the different measures, indicating varying results across the different case studies. The energy-saving potential of the Energy Efficiency Measures is highly affected by the baseline situation of the building envelope and heating systems, underscoring the critical role of baseline conditions in determining the effectiveness of interventions aimed at reducing energy consumption and environmental footprint. By targeting areas and cases with greater inefficiencies, policymakers and stakeholders can prioritise interventions that yield significant improvements in both energy efficiency and environmental sustainability.

Furthermore, the variations in the applicability and the technoeconomic viability of the different measures highlight the benefits and the consequent necessity for European Union and national authorities to grant more funding for the needs of rural areas and offer strategies and plans that encourage regional and local development in a customised way, also to ensure targeted allocation and address the specific needs of vulnerable households.

To this direction, local and regional authorities can benefit from the knowledge derived from this report on the very local specificities of the most vulnerable areas under their responsibility. Additionally, they should be encouraged to conduct more similar actions to enhance research activities within their contexts, aimed at alleviating rural energy poverty. This involves collecting accurate data to identify energy-poor households, facilitating data-driven interventions that effectively address the issue. With this information at hand, they can act as intermediaries, recording the unique challenges faced by rural areas, including stakeholders and vulnerable communities in the energy efficiency policy discussion. They can also communicate specific inquiries and support national and EU authorities in developing and disseminating targeted policy measures and financial grants to rural areas.

Overall, our work seeks to serve as a basis to initiate discussions aimed at facilitating policy improvements that effectively address the needs of energy-poor households in rural contexts. Our analysis includes findings and recommendations, which if considered could support stakeholders and end-users to recognise the particularities of rural areas when it comes to the implementation of Energy Efficiency Measures and support policymakers in the effective design and implementation of energy efficiency policies to address energy poverty in rural contexts.

1. Introduction

During the last three decades, the European Union (EU) has been a global leader in fighting climate change through its ambitious policies (Oberthür, 2011; Wurzel et al., 2016), since 1991, when the first Community Strategy was launched with the goal of reducing carbon dioxide (CO_2) emissions and increasing energy efficiency.

EU initiatives such as the European "Green Deal" (2019), the “Clean energy for all Europeans package” (2019), “Fit-for-55”, along with the latest legislation following the 2022 Russia’s invasion of Ukraine, i.e., “REPowerEU” plan, offer a comprehensive strategy to attain climate neutrality by 2050, addressing the urgent challenge of climate change while fostering economic growth, increasing energy efficiency and safeguarding EU citizens’ well-being (Commission, 2019; Erbach et al., 2024; European Commission, 2022; Lutsch, 2017).

Through the coordination of these measures at the EU level, such legislations reinforce the vision that: “*the deep transformation of the economy needs to be managed well to avoid social and regional disparities, meaning that the clean energy transition must be fair and socially acceptable to all*”. In this context, the EU has launched a series of initiatives to ensure that all citizens, regardless of their location, benefit from the clean energy transition, with a focus on the pressing issue of energy poverty, so that “no one is left behind”.

Relevant legislative documents published by the European Commission (EC) describe energy poverty as “*a situation in which households are unable to access essential energy services and products, thus affecting the levels of heating, cooling, and lighting of homes, along with health and living standards*” (European Commission (EC), 2023). Energy poverty is considered a complex and multidimensional phenomenon, caused by various factors, such as low income, high energy and fuel prices and their volatility, inefficient buildings and appliances, geographic and climate factors, gender, family composition, health, household energy and transportation needs, etc. (European Commission (EC), 2023; Widuto, 2022).

Current efforts at both the scientific and the policy levels have significantly enhanced our understanding of the driving forces, aspects, and consequences of energy poverty. In this context, energy efficiency has been recognised as a critical policy area in order to address energy poverty, as it improves household living conditions, such as by enhancing thermal comfort and reducing damp problems, and helps meet ambitious climate change mitigation targets (Papantonis et al., 2022; Spyridaki et al., 2020).

The latter is particularly important also considering that at present, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient, while buildings are responsible for 40% of the EU’s energy consumption and 36% of the EU’s

CO_2 emissions, making the building sector the single largest energy consumer in the EU (Ruusu et al., 2019; Siddique et al., 2022).

Therefore, the EU's message, as communicated in several recent legislations, is clear: "*energy poverty must be tackled by addressing its root causes through structural and targeted measures, and in particular through energy efficiency*".

Indicative examples are the latest revised version of the Energy Efficiency Directive (2023), where a clear definition of energy poverty is provided, while the EC puts a stronger focus on alleviating energy poverty and empowering consumers through a series of wide-reaching measures, as well as the EU's "Renovation Wave" strategy, which sets tackling energy poverty and the upgrade of energy efficiency in the worst performing buildings as one of its main focus areas (European Commission, 2020; European Parliament, 2023).

In this context, it is worth to note that rural communities in many EU countries struggle with energy poverty issues, and in many cases to a considerably greater extent than the urban population. Research on specific urban-rural disparities has found significant regional differences across the EU, with rural areas in Central Eastern (CEE), Southern Eastern (SEE) and Southern Europe (SE) being traditionally much poorer and more excluded than urban contexts (Binelli & Loveless, 2014). Despite being more exposed to energy poverty than urban areas, substantial evidence suggests that significant gaps in knowledge and practice remain, particularly regarding energy poverty and energy efficiency in rural areas, contributing to rural areas in the EU lagging in the energy transition process (Dokupilová et al., 2021; Karpinska & Śmiech, 2020; Roberts et al., 2015).

1.1 Energy poverty in rural areas across Europe

This lagging is mostly identified in CEE, SEE, and SE countries, where populations are highly exposed to energy poverty (Oliveras et al., 2020; Salman et al., 2022).

Recent studies from Poland validate that energy poverty is higher among rural households (Sokołowski et al., 2020). Similar is the case in Czech Republic and Hungary, where it is indicated that energy poverty tends to be concentrated mostly in rural and peripheral regions (Bouzarovski & Herrero, 2017).

In the case of Greece, mountainous rural communities are extensively exposed to the phenomenon, mainly because of the cold climate and the generally lower incomes of rural residents (Katsoulakos & Kaliampakos, 2018). An analogous situation can be found in Spain, where rurality is a major factor in increased exposure to energy poverty (Aristondo & Onaindia, 2018).

In Italy, the percentage of the population that is unable to afford to pay their energy bills in rural areas is also greater than the national average (Matters, 2020), while a recent study examining several CEE countries (e.g., Lithuania, Estonia) verifies the exposure of rural populations to energy poverty (Karpinska & Śmiech, 2020).

This situation is not merely coincidental; rather, it is influenced by various distinct characteristics inherent to rural areas that escalate the vulnerability of rural households to energy poverty.

According to existing knowledge, rural households are more likely to be energy poor, due to the nature of the housing stock as well as the more limited choice of energy sources (Deng, 2012; M. Evans et al., 2014). Furthermore, residing in rural areas correlates with expenditure-based energy poverty, primarily because of the increased energy expenses encountered by households (Drescher & Janzen, 2021).

This disparity in energy costs can readily be ascribed to variances in grid access fees, stemming from geographical remoteness and lower population density, thus necessitating the distribution of grid costs over fewer inhabitants (McGookin et al., 2022). Moreover, even though the EU power grid is in general consistent, remote areas, such as rural ones, may have limited grid services provided, while, in some cases, rural households are built without permits, leading to access to energy in an illegal way. The latter increase exposure to energy poverty while hampering environmentally friendly ways to alleviate it, such as the production of micro-renewable (Furmankiewicz et al., 2021; Stavrakas et al., 2019).

1.2 Current state of energy efficiency policies to address energy poverty in rural areas

As already indicated, the poor energy efficiency of dwellings is a key factor contributing to rural energy poverty. In most EU countries, the rural housing stock is older and less efficient compared to urban housing, as much of it was built before the first thermal regulations established in the 1970s. Additionally, rural households often rely on outdated heating systems that are either inadequate for meeting their heating and cooling needs or too expensive to operate (Deng, 2012; M. Evans et al., 2014; Liu et al., 2023).

Additionally, most rural households in the EU still rely on extensive energy carriers, like coal and other high-carbon fossil fuels for heating, as well as fuelwood stoves and various electrical heaters (Deng, 2012; Kola-Bezka & Leki, 2024). These systems are not only inefficient and unable to adequately meet their heating or cooling needs but are also environmentally harmful.

In this context, implementing effective energy efficiency policies to combat energy poverty in rural areas is crucial for fulfilling the EU's vision of a green and fair energy transition, ensuring that rural communities are not left behind. Nevertheless, current efforts focused on the collection and assessment of existing energy efficiency policies targeting rural areas have revealed several shortcomings in the current policy implementation. Specifically, even when policies are intended to focus on rural areas, they often lack frameworks tailored to their unique characteristics, indicating that they have not thoroughly considered the specific needs of rural areas, and the urgent need for relevant research in these contexts. This is evident in several nationwide initiatives that provide financial incentives at the national level, mentioning rural areas but without any specific provisions for them. Additionally, there is a widespread lack of monitoring and evaluation of these actions, leading to a limited understanding of their effectiveness (Papantonis et al., 2024).

An additional issue raised by the experts working in RENOVERTY's pilot areas is that the eligibility for receiving financial assistance as part of policies is a critical issue, particularly in CEE, SEE and SE regions. For an applicant to be eligible to receive financial aid, it must be confirmed that the building undergoing renovation is legally registered, which can prove difficult, especially for buildings constructed before 1990.

1.3 Barriers to the implementation of energy efficiency policies to address energy poverty in rural areas

RENOVERTY has identified that shortcomings exist in the design and implementation of energy efficiency policies to address energy poverty in rural contexts. This is a result of the barriers to implementing energy efficiency, such as access to appropriate financing mechanisms, skilled workers/contractors, geographic isolation, and the general lack of awareness/scepticism, which often differ from those experienced in urban areas.

According to existing knowledge, the barriers that specifically affect the implementation of energy efficiency policies in rural areas can be grouped into three main categories: financial barriers, geographic barriers, and awareness and access barriers (Tahsildoost & Zomorodian, 2020).

Across the board, financial barriers are considered very important with regard to the implementation of Energy Efficiency Measures (EEMs) (Burbidge et al., 2021; Papantonis et al., 2022). According to Blomqvist *et al.* (2022) and Kaya *et al.* (2021), when it comes to rural contexts, ***lack of capital*** combined with the ***high*** *upfront costs* of energy efficiency effectively discourages its uptake, as renovation of rural dwellings is frequently more expensive and does not necessarily result in an adequate increase in the property value (Blomqvist et al., 2022; Future of Rural Energy in Europe, 2016; Kaya et al., 2021).

Moreover, rural households are also exposed to *lower median incomes* and *higher energy burdens*, which also hinder the ability of residents to invest in energy efficiency. The average income is 21% to 62% lower in rural areas than in urban ones, with this phenomenon being accentuated in Eastern European countries (Future of Rural Energy in Europe, 2012).

Rural populations are also exposed to several awareness barriers that can hinder the implementation of EEMs in such contexts. For example, *lack of technical knowledge* and *information* about energy efficiency aspects and options are met more often in rural contexts (Blomqvist et al., 2022). Moreover, residents of small towns and rural communities often rely on word-of-mouth recommendations from neighbours and trusted messengers (Winner et al., 2015). Therefore, the limited experience within rural residents' social network, combined with their scepticism of assistance programmes and a preference to "*do it yourself*," often limit rural residents' knowledge of and interest in accessing energy efficiency programmes, leading to a widespread lack of awareness or scepticism of existing resources among the rural population (Furmankiewicz et al., 2021; MacDonald et al., 2020).

The geographic nature of rural areas, which severely affects the quality of inhabitants life conditions, can also lead to several barriers to implementing EEMs. More specifically, due to geographic isolation, rural residents' access to financing, incentives, and professional services necessary for the implementation of energy efficiency projects is hindered. Geographic isolation is strongly related to the physical distance from resources (e.g., financial, human), along with the lack of economies of scale that lead to challenges and increased renovation costs for rural areas (Shoemaker et al., 2018).

Therefore, implementing EEMs in rural areas is not just a question of technical capacity; it is related to wider financial, social, and geographical challenges. The latter urges the need for rigorous scientific research, that combines both qualitative and quantitative outcomes towards better-informed decision-making and evidence-based policymaking that will ensure the effective design and implementation of energy efficiency policies which could support the alleviation of energy poverty in rural areas across the EU.

1.4 Energy modelling and Renovation Energy Efficiency Roadmaps

Over the past few decades, energy systems modelling has become a crucial tool to address the needs of informed decision-making and evidence-based policy development in Europe, as they have been used to simulate various energy transition scenarios and pathways, providing valuable insights into the potential evolution of energy systems (Kleanthis et al., 2022; Süsser et al., 2021).

Energy system models are not just abstract representations of reality; they interact closely with the social contexts in which they are embedded (Süsser et al., 2020; Süsser, Martin, et al., 2022). They serve as "discursive" or "negotiation" spaces, bringing together different social worlds—such as scientists and policymakers—and enabling these groups to create shared understandings, collaborate, and negotiate knowledge and policy (R. Evans, 2000; Star & Griesemer, 1989). While these models can significantly support governmental decision-making processes they are not the final word in policy decisions (Gilbert et al., 2018; Lopion et al., 2018).

As Pfenninger et al., 2014 note, "*energy system models are not only tools for defining scenarios and long-term planning strategies but also for expressing the semantics used to formalise the scattered knowledge about the complex interactions within the energy sector*". The field of energy system modelling is prolific, with numerous models being developed using various methodologies and approaches.

Given the broad scope of activities encompassed by the concept of "*energy efficiency*" and its multidimensional approach to tackling energy poverty, comprehensive energy modelling is essential (Abbas et al., 2021; Papada & Kaliampakos, 2018; Rahman, 2024). A useful tool that highlights the need of energy modelling and facilitates for the promotion of energy efficiency renovation actions to energy-poor households is the development of individual tailor-made Renovation Energy Efficiency Roadmaps (REERs) (Papantonis et al., 2024). REERs are even more important when aiming to foster renovations in cases with unique characteristics/ needs, like in the case of rural households, as they build on these characteristics/ needs aiming to address them while being able to be replicated in more cases.

In that case, a core aspect of energy modelling, demand-side management modelling, which focuses on studying energy patterns, energy efficiency concerns, and the behavioural analysis of end-users, can provide critical insights into the effectiveness of various EEMs. This is particularly important for identifying measures that are most effective in alleviating energy poverty (Stavrakas & Flamos, 2020) and can be included in the developed REERs. **By simulating different scenarios, thus, these models can evaluate the impact of specific interventions on energy consumption and costs, helping to pinpoint the most effective strategies for reducing energy poverty.**

Detailed simulations and scenario-based analyses can enable the application of an assessment framework that will support the creation of REERs, by not only suggesting technical improvements but also considering socioeconomic factors to ensure that measures are practical and sustainable for energy-poor households in the regions under study. Energy modelling can contribute to this effort by considering factors such as the specific characteristics of rural dwellings, the availability and affordability of energy sources, and the behavioural patterns of residents, to outline suggested measures, which can be specifically applied to rural areas and systematically address energy poverty.

Overall, this level of detail ensures that the proposed EEMs are not only theoretically sound but also practically applicable and beneficial in the real world. As a result, energy modelling can serve as a bridge between policymaking, research, and end-users, facilitating the development of evidence-based and tailor-made policies and plans. This approach enables the realisation of a green and fair energy transition by effectively addressing the challenges of energy poverty and enhancing energy efficiency. This is particularly crucial in understudied areas, such as rural ones, where the application of energy modelling can yield significant benefits.

1.5 Scope and Objectives

Given the multifaceted nature of energy poverty, particularly in rural areas, it is crucial to tailor solutions to meet the specific needs of households in these regions. A concrete challenge identified is that enhancing the uptake of energy efficiency in rural areas is not just a question of technical capacity; it is related to wider financial, social, geographical, and regulatory barriers.

This underscores the necessity for rigorous scientific research that integrates both qualitative and quantitative outcomes. As already mentioned, such research is crucial for informed decision-making and evidence-based policymaking, ensuring the effective design and implementation of energy efficiency policies aimed at alleviating energy poverty in rural areas across the EU.

RENOVERTY aims to address these challenges, by designing a series of scalable renovation roadmaps with operating models for rural areas in Croatia, Estonia, Hungary, Slovenia (CEE, SEE region) and Italy, Portugal, and Spain (SE region), while ensuring the replicability of the model in these regions and scaling it up to the EU level.

This report builds on the previous work undertaken within RENOVERTY and summarised in the report "*Updating the energy poverty and energy efficiency framework in rural areas across the EU*". Through this work, different aspects of energy poverty in rural areas have been identified and articulated. More specifically:

- ❖ Updates on energy poverty and energy efficiency frameworks through an extensive desk-research of more than 80 relevant scientific and policy literature sources, e.g., general characteristics and key challenges of rural areas, energy poverty in rural areas across Europe, specific characteristics of rural areas that contribute to their exposure to energy poverty, current state of energy poverty and energy efficiency policies in rural areas, barriers to designing and implementing energy efficiency policies to alleviate energy poverty in rural areas.

- The baseline assessment of existing needs regarding the alleviation of energy poverty and fostering the role of energy efficiency to that end, via a European-wide survey, which focused on stakeholders and experts in rural areas, conducted for the first time.
- Identification and assessment of the special characteristics of dwellings in rural and peri-urban areas in CEE, SEE, and SE, while also specifically focusing on dwellings inhabited by vulnerable populations. This has been achieved by the conduction of energy audits in more than 85 households in the pilot regions of the project.

These three pillars provided in-depth and up-to-date knowledge of the specificities of rural households when it comes to energy poverty and energy efficiency, while they supported the identification of the baseline situation of the housing stock in the areas under study, assisting us to proceed with the next steps forwards: creating and presenting portfolios of EEMs addressing the needs of energy poor households in the regions under study.

To do so, we employ and present the results from the **Dynamic high-Resolution dE-mand-sidE Management** (**DREEM**) model. DREEM is employed to apply a portfolio assessment framework that will determine the most suitable EEMs in each case study, based on the energy-saving potential and the technoeconomic viability of each EEM. The energy performance and technoeconomic evaluation are also complemented with avoided emissions calculation and thermal comfort analysis for each energy efficiency investment.

DREEM is a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, which expands the computational capabilities of existing building energy systems and demand-side models. It does so, by not only calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (consumers/ citizens), and, then for other energy system actors involved (e.g., suppliers, retailers) (Stavrakas & Flamos, 2020).

In the following sections, more details on the structure and the capabilities of the DREEM model are provided. As such, this report may easily be used both within and outside of the project, by policymakers and other relevant end-users from the field of policy and practice, using our findings to derive interesting and policy-relevant implications and recommendations. It can also be useful for researchers and other end-users from the field of academia that are interested in the ways that modelling tools can enhance the uptake of energy efficiency and address energy poverty, in unique contexts, like rural areas.

1.6 Structure of this deliverable

The remainder of this report is structured in the following sections:

- **Section 2** describes the methodological approach followed.

- **Section 3** analyses the identified patterns, needs, and specifications of the RENOVERTY case studies.
- **Section 4** provides a description of the DREEM model's capabilities as well as the further modifications and adjustments that took place towards its employment.
- **Section 5** presents the specifications of the analysed case studies, along with respective parameters that were used, etc. for the parameterisation of the DREEM model.
- **Section 6** presents results from the application of the DREEM model to the RENOVERTY case studies.
- **Section 7** provides a comparative analysis and discussion of modelling results.
- **Section 8** presents conclusions and implications from our work, while it highlights next steps and further research topics.

2. Methodological approach

This study follows a multi-method approach, coupling the strengths of energy system modelling with qualitative and semi-quantitative techniques. As depicted in **Figure 1,** our working approach consists of four (4) methodological steps to move from ***(i)*** the updated framework of energy efficiency and energy poverty in rural areas, ***(ii)*** the stakeholder needs assessment and ***(iii)*** the RENOVERTY field work (i.e., the energy audits), as derived from RENOVERTY report: "*Updating the energy poverty and energy efficiency framework in rural areas across the EU*"), to the application of the modelling assessment framework in real-life applications presented in this report, that will allow for the classification of potential EEMs based on their energy performance and technoeconomic viability.

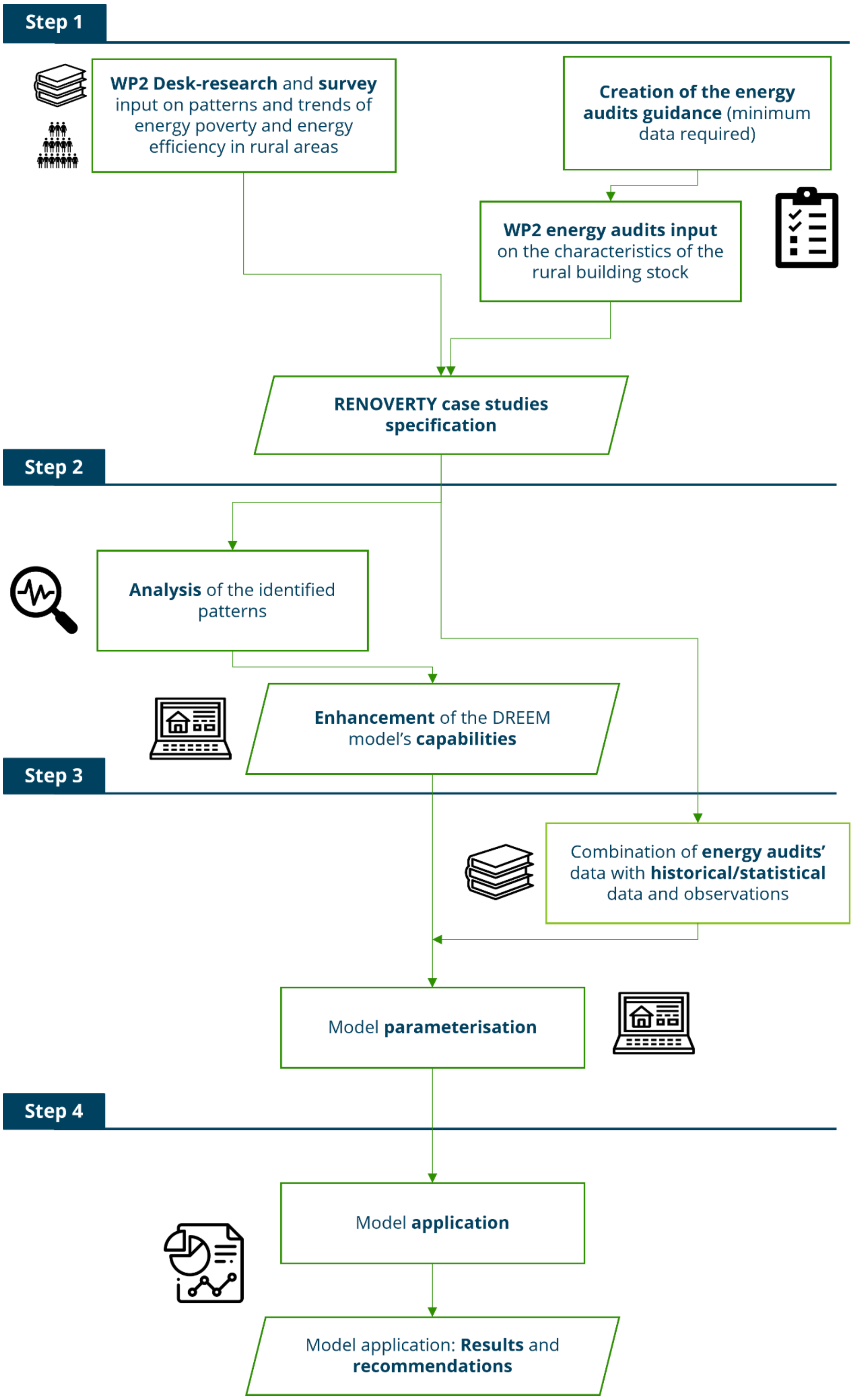

Figure 1. The methodological approach followed to apply the assessment framework for the classification of the most efficient EEMs to address the needs of energy-poor households in the RENOVERTY rural areas.

2.1 Step 1: Case studies specification

Updates of the framework of energy poverty and energy efficiency in rural areas have been conducted within RENOVERTY, based on insights and preliminary findings derived from extensive desk research and a needs assessment of relevant stakeholders and experts activated in rural areas across the EU.

In parallel, RENOVERTY field work, which included the conduction of energy audits in more than 85 households in the pilot rural areas of the project, i.e., the rural region of Osona in Spain, the rural region of Parma in Italy, the rural region of Coimbra in Portugal, the rural regions of Bükk and Somló-Marcalmente-Bakonyalja (SMB) in Hungary, the rural regions of Sveta Nedelja and Žumberak in Croatia, the rural region of Tartu in Estonia, and the rural region of Zasavje in Slovenia, provided us with critical insights on the specificities of the rural housing stock in CEE, SEE, and SE regions.

To address the DREEM simulation needs and identify the specificities of dwellings in the subject contexts, guidelines were prepared outlining the minimum data required from the RENOVERTY audits. The Data Inventory table developed within the EC-funded Horizon 2020 (H2020) crossCert project (publicly available) (Crosscert & Repository, 2024; Sayfikar & Jenkins, 2023) was used as a starting point for creating these guidelines, considering also the diversity of the RENOVERTY pilot countries.

Moreover, for the needs of the technoeconomic and environmental analysis, a relevant data acquisition template was developed and circulated to all pilot partners. The template included information regarding the cost of investments and energy, along with other investment and environmental parameters such as interest rates and emission factors, that facilitated the technoeconomic and environmental analysis suited to the different socioeconomic and geographical contexts of the RENOVERTY regions.

2.2 Step 2: Further development, modifications, and adjustments of the DREEM model

After analysing the identified patterns and trends of energy poverty and energy efficiency in rural areas and matching them to the DREEM modelling needs, we pinpointed key developments, modifications, and adjustments necessary to tailor the application of the EEMs' assessment framework to the specific needs of the rural areas under study. Consequently, the original modelling framework of DREEM was modified to address these new requirements.

2.3 Step 3: Parameterisation of the DREEM model

Building on the outcomes of **Step 1: Case studies specification** and **Step 2: Further development, modifications, and adjustments** of the DREEM model, at this step, DREEM is parameterised to effectively represent the pilot regions that will be simulated. To do so, we make use of the data collected from the energy audits, combined with statistical and historical observations, and the technoeconomic/environmental data acquired from the project's pilot experts.

The energy audits provide us with case-study based data on the weather/climate and building characteristics, along with the analysis of construction features, systems used in the building and other parameters (e.g., dwelling's occupancy, etc.)

For the simulation of the different EEMs, we also used information on the building characteristics (e.g., U-values[1] after the upgrade of the building envelope, etc.) from the EC-funded **TABULA**[2] ("Typology approach for building stock energy assessment") project, scientific literature and national documents sources.

TABULA was a three-year pr (June 2009- May 2012) involving thirteen European countries, among which, five out of the seven RENOVERTY countries (i.e., Estonia, Hungary, Italy, Slovenia, and Spain) (Ballarini et al., 2014). The objective of the project was to create a harmonised structure for "European building typologies" in order to estimate the energy demand of residential building stocks at the national level and, consequently, to predict the potential impact of EEMs and to select effective strategies for upgrading existing buildings. Each participating country developed a "National building typology", which is a set of model residential buildings ("building types"), each representing a building age class (i.e., a construction period) and a building size class (e.g., single-family house (SFH), multi-family house (MFH), apartment block, etc.). Each building type is characterised by specific energy-related properties, which reflect typical technical systems, construction features, and geometric characteristics of the represented construction period. Croatia and Portugal were not among the countries engaged in **TABULA**, so as inputs we used information from the scientific literature and national documents.

Finally, the technoeconomic and environmental data acquired from the pilot partners were also combined with national/EU data, providing us with useful information on energy and

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[1] U-value is a sum of the thermal resistances of the layers that make up an entire building element – for example, a roof, wall or floor. It also includes adjustments for any fixings or air gaps and provides a thorough estimation of the performance of the building in terms of thermal losses (Sen & Al-Habaibeh, 2021).

[2] https://webtool.building-typology.eu

investment costs, along with estimations on the environmental impact of the different EEMs in each case study.

2.4 Step 4: Model application and classification of energy efficiency measures

As a final step, we used the enhanced version of the DREEM model to apply the EEMs assessment framework and evaluate the different EEMs that address the needs of energy poor households in rural areas.

Modelling results were further analysed, presented to the rest of the RENOVERTY partners, and discussed to co-create robust recommendations for citizens, end-users, and stakeholders from the fields of policy and practice, in order to foster the development of the project’s REERs and contribute to the enhancement of energy efficiency to alleviate energy poverty in rural areas.

3. Case study specifications

A thorough analysis of the patterns and trends of energy efficiency and energy poverty in rural areas, based on the detailed documentation of their unique characteristics and current state, took place as part of the already published RENOVERTY report: "*Updating the energy poverty and energy efficiency framework in rural areas across the EU*".

This process, and especially the identification of the unique characteristics of rural dwellings through the conduction of more than 85 energy audits in vulnerable rural areas in CEE, SEE, and SE, allowed us to set the ground for the conduction of accurate simulations aimed at applying the assessment framework towards the development of portfolios of cost-effective EEMs.

An energy audit is a systematic inspection and analysis of the energy use and consumption of a building, providing detailed information about its energy characteristics, systems, and sources. Such data is crucial for understanding and addressing energy poverty in rural areas, as it highlights the contributing factors to its prevalence and severity.

Based on energy audit results, Energy Performance Certificates (EPCs) are issued for each dwelling. EPCs are instrumental in enhancing the energy performance of buildings and play a central role in the Energy Performance of Buildings Directive.

While the Energy Performance of Buildings Directive defines the overall approach to EPCs and energy audits, Member States' approaches vary. To address the latter, the RENOVERTY project developed a unified methodological approach for its pilot study, allowing each participating partner to use professional energy auditors according to their national methodology while ensuring data comparability across pilots. Guidelines were prepared outlining the minimum data required, adapted to identify specificities of dwellings in rural and peri-urban areas of CEE, SEE, and SE countries. These guidelines were based on the approach followed from the EC-funded H2020 crossCert project and adapted to the needs of the RENOVERTY pilot countries and simulations (Sayfikar & Jenkins, 2023). The data acquisition template for the RENOVERTY energy audits that was developed to facilitate the work presented under this report can be seen in **Table 1**.

Table 1. Data acquisition template from the RENOVERTY energy audits.

Weather/ Climate characteristics	Region/ Climate zone
	Heating degree days
	Cooling degree days
	Heating season's start/end date

	Cooling season's start/end date
Building characteristics	Type of building/ usage Year of construction Building size Total Floor area of the building [m^2] Habitable area [m^2] Total area of exterior walls of the buildings [m^2] Conditioned area [m^2] Net conditioned volume [m^3] For each wall: ▪ Type [roof/wall/floor/inner partition], ▪ Total area [m^2], ▪ U-value [W/(m^2·K)], Orientation] Total Roof area of the building [m^2] Total Window area of the building [m^2] For each window: ▪ type (window, skylight, door), ▪ system (e.g., 3-mm clear glazing + wooden frame), ▪ U-value [W/(m^2·K)], total area [m^2]
Construction features (U-values) (W/m²/K)	U_{wall} U_{floor} U_{roof} U_{window} Type of construction (e.g., reinforced concrete, wood, etc.)
Building systems	HVAC system (e.g., heating-only, cooling-only, heating and cooling, heating and domestic hot water (DHW), heating cooling and DHW, ventilation system) Type of system (e.g., standard boiler, condensing boiler, low-temperature boiler, heat pump, heat pump - variable flow-rate, electrical boiler, air-conditioning, etc.)

	Nominal capacity [kW]
	Coefficient of Performance (COP) / Seasonal COP (SCOP) / Energy Efficiency Ratio (EER) / Seasonal EER (SEER) (if available):
	Ventilation and pumping (e.g., constant flow-rate ventilation, variable speed ventilation, constant flow-rate pump, variable speed pump, etc.)
	Energy consumption (kWh/year)
	Air flow (m^3h/m_2)
	Lighting equipment (estimated number of lighting appliances)
	Lighting equipment capacity (e.g., traditional, LED bulbs, etc.)
	Installed power (W/m^2)
Other parameters	Occupancy (e.g., people/ m^2 or mean number of people using the building or building unit)
	Occupants' indicative working schedule (e.g., Weekdays 9:00–17:00)
	Occupancy schedule (e.g., working days, Saturdays, and Sundays start/end hours)

Figure 2 indicates a visualised overview of the RENOVERTY pilot areas, while in the following subsections, specific information for each pilot region and the RENOVERTY audits results are presented.

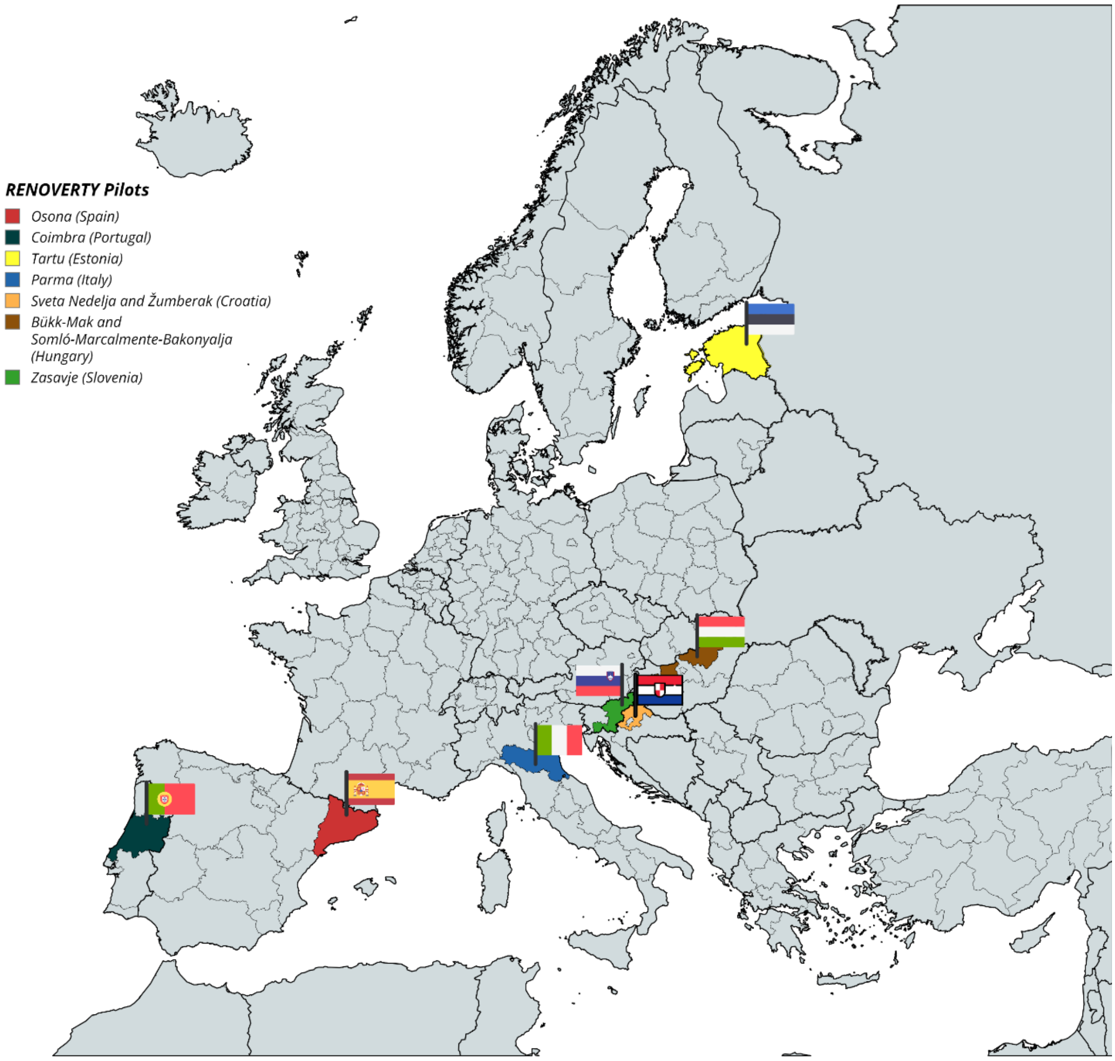

Figure 2. Presentation of the RENOVERTY pilot areas (visualisation developed using the online map-making tool “MapChart[3]”.

3.1 The rural region of Osona in Spain

Osona is a region located in the interior of Catalonia. Osona represents the most common oganisational structure of ural areas in Spain, a country with a high diversity of climates and therefore household energy needs. In Spain, 89% of municipalities are rural (considering a maximum of 2,000 inhabitants). Osona has 42 municipalities and is characterised by a climate marked by cold winters with thermal inversions and hot summers. For the carrying out of the energy audits and in order to help identify and better understand rural energy poverty, the selection of the households was carried out with the help of local social services and

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[3] https://www.mapchart.net

according to the following criteria: the two typologies of dwellings, SFH and MFH and by selecting families who have applied for social support to pay energy bills.

3.1.1 Energy audit results

In the rural region of Osona in Spain, a total of 20 buildings were audited, including 19 MFHs and one SFH. These buildings are predominantly occupied by three or more household members, especially after working ours and throughout the weekends. The MFHs were constructed between 1892 and 2010, with an average construction year of 1960, while the SFH was originally built in 1790 and reconstructed in 1967. Most of these buildings lack insulation, have old and inefficient windows and doors, and feature uninsulated roofs, all of which contribute to significant energy inefficiency. Various heating systems are used, including oil, natural gas, biomass boilers, electric radiators, and butane cookers. The majority of the audited buildings fall into energy efficiency classes E and G, with an average primary energy consumption of 223.49 kWh/(m²a).

3.2 The rural region of Parma in Italy

The province is typically divided into three zones from north to south: plains, hills and mountains. The northernmost, lowland part is bordered by the Po River. The main centres in the hill and mountain areas are located along the course of the main rivers, which descend from the Parma Apennines, flowing from south to north and flowing back into the Po. The climate is distinctly continental in the plains, with very hot summers and cold, wet and foggy winters. Climatic conditions improve in the Apennine foothills, where the annual temperature range decreases and summers are cooler. In the higher areas, the climate is typical of the mid-mountain zone, with intense humidity, cold winters and cool summers with frequent thermal inversions. Rainfall is moderate in the plains, more frequent and abundant in the Apennines, as are snowfalls, which are not lacking even in the plains and in the city of Parma itself, with an average of around 35/40 cm of snow every winter.

Weather conditions lead to the difficulty of maintaining house temperatures at adequate levels, especially during winter. This is due to both high energy and gas costs and inefficient buildings. Unfortunately, specific data from the pilot area are not currently available, but it is assumed that people affected by energy poverty are in line with the regional data, which stands at about 6% of households. One of the most rural areas in the province is in the Val di Taro, in which the audits were concentrated. To identify buildings, we have taken into consideration, with the support of the Local Action Groups (LAGs)[4], the year of construction, historical value, building size and whether the building is a SFH or MFH.

3.2.1 Energy audit results

In the rural region of Parma in Italy, 8 buildings were audited, comprising five MFHs and three SFHs. These buildings are generally occupied by two or more household members throughout the day, except for two cases where the spaces are either only occupied during holidays or are not inhabited at all. The multi-family buildings were constructed between 1960 and 1975, with an average construction year of 1966, while the single-family houses were built between 1900 and 1920, with an average construction year of 1907.

Similar to Spain, these buildings also lack insulation and have old windows and doors that contribute to energy inefficiency. Heating systems include oil and gas-fired boilers, liquefied petroleum gas boilers, and wood stoves. Most of the buildings are classified as energy efficiency class G, with an average primary energy consumption of 411.94 kWh/(m²a).

3.3 The rural regions of Bükk-Mak and Somló-Marcalmente-Bakonyalja in Hungary

The Bükk region is located in Northern Hungary, where mining and forestry were dominant in the past, which also influenced the development of villages. In the SMB area (located in Central Transdanubia) forestry is also important, but agriculture is dominant. Both of the Hungarian pilot areas (Bükk and SMB) include settlements where the majority of the dwellings are vulnerable from an energy performance point of view. In the Bükk area, air pollution is a particular problem in winter, when smog from inadequate fuel combustion settles in the river valleys. For the energy audits, house types that are typical of the areas were chosen (e.g., traditional farmhouses). As a result of the renovations and alterations that have been carried out, the use of materials in the buildings is very varied and therefore is difficult to classify. Local building materials include stone, clay, brick, and slag concrete. The residential buildings for the energy audit were selected with the help of local partners and LAGs.

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[4] Local Action Groups (LAGs) are integral components of the LEADER program, a European initiative designed to enhance rural development. LAGs are composed of representatives from local public and private socio-economic sectors who collaborate to develop and implement localised development strategies. These strategies are tailored to the specific needs and potential of their regions, fostering sustainable and integrated local development

3.3.1 Energy audit results

In the rural regions of Bükk-Mak and SMB in Hungary, 8 SFHs were audited, four in the Bükk-Mak area and four in the SMB area. These houses typically have two to four household members and are primarily occupied after working hours and throughout the weekends. The construction years of these houses range from 1868 to 1996, with an average construction year of 1937. The buildings are in poor condition, with mixed construction materials and inadequate thermal insulation. The heating systems include central heating with mixed fuel (wood and coal), natural gas, and wooden stoves while cooling systems are absent. Most houses fall into the energy efficiency class HH[5], with an average primary energy consumption of 367.80 kWh/(m²a).

3.4 The rural regions of Sveta Nedelja and Žumberak in Croatia

Sveta Nedelja and Žumberak are situated in central Croatia, not far from the country's capital Zagreb. Sveta Nedelja is one of the smaller cities, with a total of little more than 18,000 inhabitants, where almost half of its 14 settlements meet the criteria of rural areas. In contrast, the nearby Žumberak municipality has 610 inhabitants spread across more than 100 square kilometres, with low-population density following a continuous decrease. Žumberak is also listed within the areas of special state protection, based on its economic development, structural challenges and demographics. These two areas have been selected to help identify and better understand rural energy poverty in central Croatia, focusing primarily on SFHs as the most common type of rural dwellings in Croatia.

3.4.1 Energy audit results

In the rural regions Sveta Nedelja and Žumberak in Croatia, 15 SFHs were audited. These houses are typically occupied by two or more household members, with a significant number of retirees. The houses were built between 1920 and 1998, with an average construction year of 1966. They generally have no insulation, with old and inefficient windows and doors, and uninsulated roofs. The heating systems are mainly local wood heating with electric boilers for domestic hot water. Only three houses have cooling systems. The majority of the houses are categorised in the energy efficiency class D, with an average primary energy consumption of 375.28 kWh/(m²a).

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[5] Energy efficiency classification in Hungary: ***FF: Average condition***; ***GG: Approaching average condition***; ***HH: Poor condition***, II: ***Bad condition***.

3.5 The rural region of Tartu in Estonia

In Estonia, the focus lies on improving the energy efficiency and indoor climate of five typical designs of rural MFHs. The renovation rate of the rural multi-residential apartment buildings is one of the lowest in the sector and the national refurbishment effort has not improved the situation. As many of these buildings have not been updated since their manufacturing in the 1960s and 1970s, their energy performance and indoor quality are not up to modern standards. Even worse, after the closing down of collective farming communities as an outcome of structural reforms at the end of the 20th century, indoor heating in many of these buildings was reorganised from central heating systems to local or individual heating solutions, something these buildings were not designed for. As an outcome of a lack of refurbishment efforts and do-it-yourself modifications in the heating systems, these buildings can offer only a substandard quality of life to their inhabitants, who otherwise have very few opportunities for choosing alternative housing. The situation of the buildings has not been studied in detail, nor do we know the real scale of the problem. At the same time, these buildings are continuing to provide essential housing services for the rural centres that have not seen significant economic development during the last 30 years.

3.5.1 Energy audit results

In the rural region of Tartu in Estonia, 5 MFHs were audited, with approximately two members per apartment. These buildings were constructed between 1980 and 1991, with an average construction year of 1985. They have poor insulation properties, with aerated concrete walls and double-glazed Polyvinyl Chloride windows prone to air infiltration. Four buildings are connected to the district heating system, while one has various individual heating systems. The apartments are classified as energy efficiency class G, with an average primary energy consumption of 282.2 kWh/(m²a).

3.6 The rural region of Zasavje in Slovenia

The Zasavje region is the smallest in Slovenia, by surface area (264 km^2) and number of inhabitants. However, it is also the second most densely populated region in the country. It covers only three municipalities (Hrastnik, Trbovlje and Zagorje ob Savi) and has 42,824 inhabitants and 18,698 households. The average number of household members in Zasavje is 2.3 and the average age is 43.4 years (data for 2012). More than one-third of its gross value added comes from manufacturing and other industries, which makes it an industrial region.

A characteristic within the area is that heating is often based on wood fuels, while waste burning can occur too which both contribute to increased levels of indoor and outdoor air pollution. Larger SFHs or MFHs where only 1 to 2 people live have problems with appropriate heating in winter due to high costs and energy inefficient buildings. The issue of energy poverty in Zasavje is not fully elaborated and well-defined due to the lack of data at the regional and local levels. Based on the available indirect indicators, it can be estimated that around 10% of households are facing energy poverty. The reasons for this lie in the socioeconomic status of the affected households, which are tied to low-income families living in old and energy inefficient building stocks. The average age of the dwellings in the region is over 45 years, and less than one-third of the dwellings built before 1970 have been renovated.

3.6.1 Energy audit results

In the rural region of Zasavje in Slovenia, 12 houses were audited, including both SFHs and MFHs. These houses are typically occupied by three household members, mainly after working hours and during weekends. The construction years range from 1905 to 1979, with an average year of 1945. The buildings generally lack insulation, with brick or concrete walls and newer windows that cause humidity issues. Heating systems vary, including wood fuels, district heating, central heating, electric heating, and fuel oil boilers. Most houses are in energy efficiency class G, with an average primary energy consumption of 341.0 kWh/(m²a).

3.7 The rural region of Coimbra in Portugal

The RENOVERTY activities in Portugal concern two distinct locations in the District of Coimbra. The first is in the Tábua Municipality, a mountainous region in the centre of Portugal (60 km away from Coimbra). The climatic conditions of this region includes hot summers and very cold winters. The buildings are typically SFHs, with poor energy performance. Although some buildings made of stone can still be found, the majority are made of brick (single wall). Most of the population still relies on wood burning (open fireplace) for their heating needs.

The second is the small village of Arzila (around 650 inhabitants), part of the Coimbra municipality. It is located in the valley of the Mondego River, 30 km from the sea. Because of this, it has a fairly moderate climate, although rather humid. The village borders a marsh which is a natural reserve. The population used to rely on natural resources (fishing, agriculture) for their livelihood but now it is mainly a dormitory town with people working in nearby Coimbra. Buildings are all SFHs, some semi-detached with poor energy performance. Most houses are over 30 years old and have not undergone renovation. Again, most of the population still relies on wood burning for their heating needs.

3.7.1 Energy audit results

In the rural region of Coimbra in Portugal, 20 SFHs were audited, with the results of the 18 being available by the time of publishing this report. These houses are typically occupied by two or more household members. The houses were built between 1935 and 2006, with an average construction year of 1984. They generally have no insulation, with old and inefficient windows and doors, and uninsulated roofs. The heating systems are mainly local wood heating with electric boilers for domestic hot water. There is no cooling system for the buildings under study. The majority of the houses are categorised in the energy efficiency classes D and F, with an average primary energy consumption of 398.3 kWh/(m²a).

3.8 Overview of audit results and selection of energy efficiency measures

In this section, the results of the 86 residential buildings that have been audited from September 2023 to June 2024 are presented. The audited buildings in the selected pilot areas were constructed between 1868 and 2010, with an average year of construction of 1962. The average year of construction per pilot country is given in **Figure 3**.

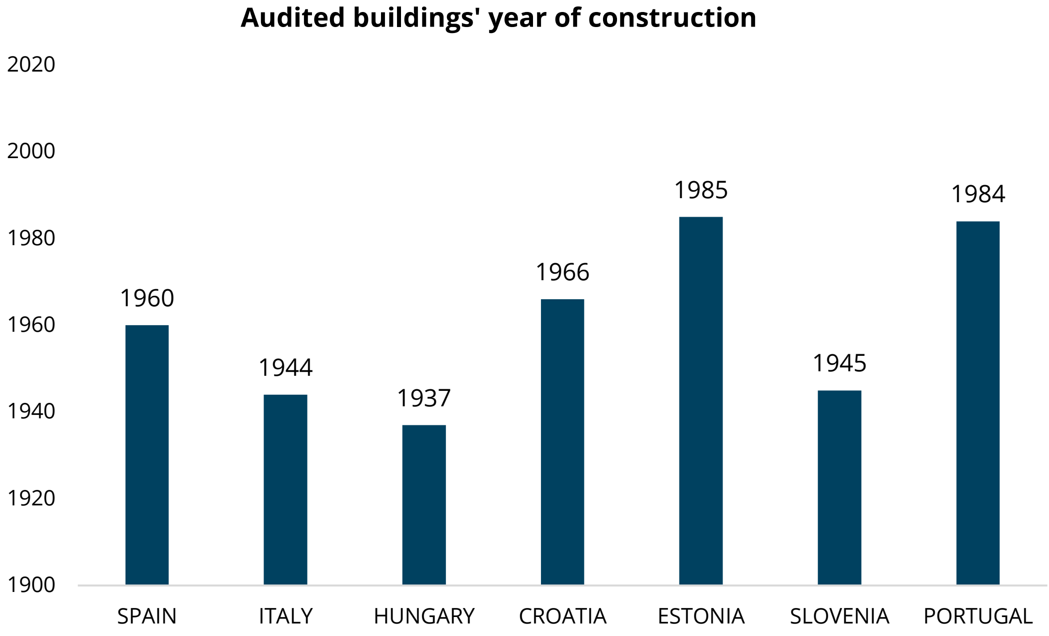

Figure 3. Year of construction of the audited buildings in the RENOVERTY pilot areas.

The audited buildings are mostly constructed using concrete and brick with non or minimal insulation, resulting in poor thermal performance. These buildings generally have low energy efficiency due to heat losses through walls, roofs and windows and, therefore, tend to have higher energy consumption compared to modern standards. Most heating systems use outdated and inefficient heating sources (e.g., natural gas, wood, and oil) that can pose health risks due to incomplete combustion, emissions of harmful particulate matter, poor indoor air quality, inadequate heat distribution, etc.

As shown in **Figure 4** and **Figure 5**, in all cases the annual primary energy consumption is higher than each country's households' average energy consumption (ODYSSEE-MURE, 2023), while their thermal transmittance values (U-values) also exceed the recommended values by EU standards (European Union, 2005).

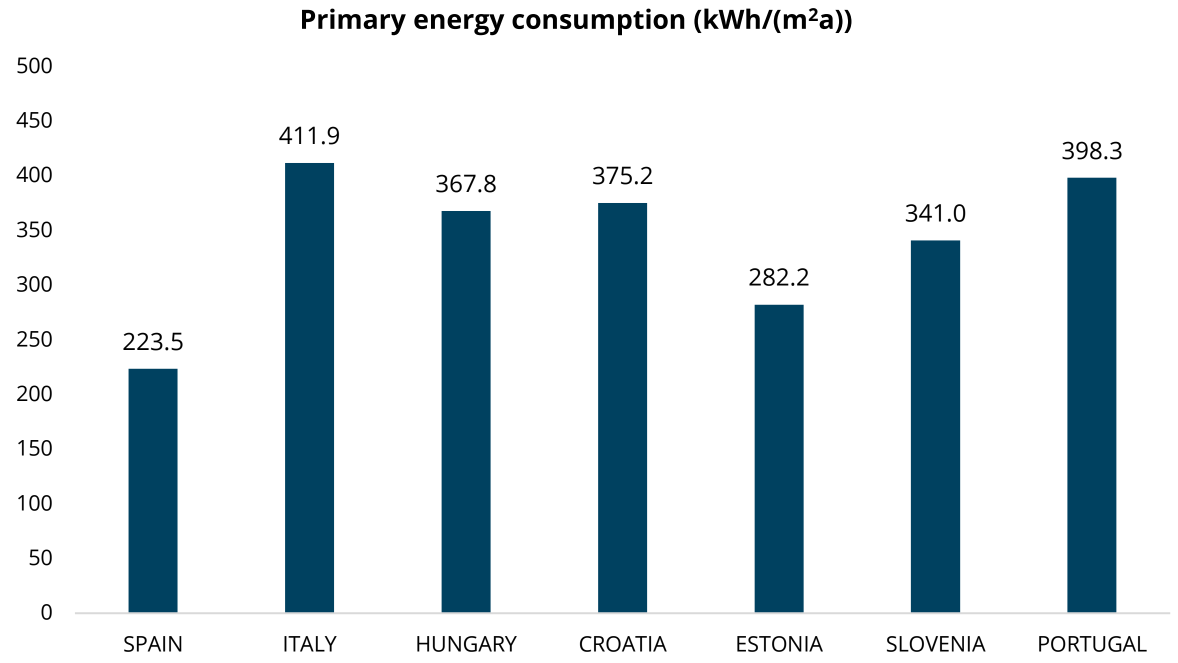

Figure 4. Primary energy consumption in audited buildings in the RENOVERTY pilot areas.

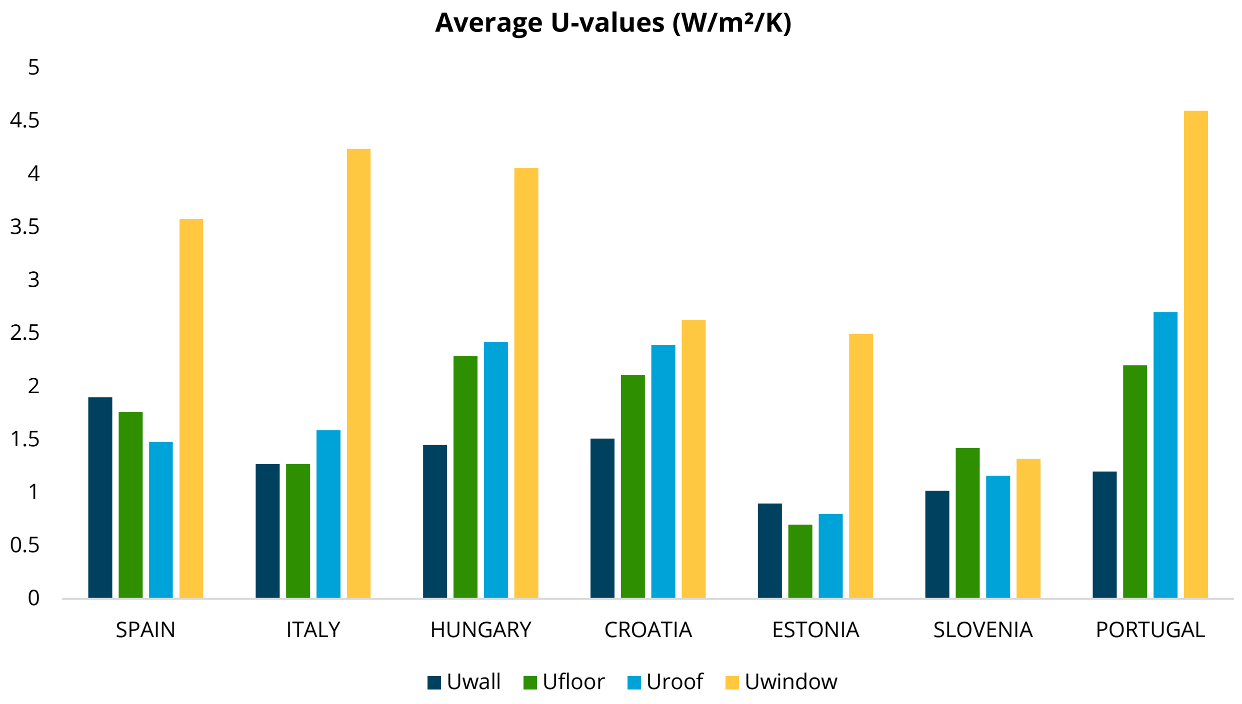

Figure 5. Thermal transmittance (U-values) of the audited buildings in the RENOVERTY pilot areas.

Retrofitting older buildings to improve energy efficiency can be challenging and costly, but it is also essential for addressing energy poverty among citizens living in such structures. As visible from the energy audit results, most audited buildings lack proper insulation, have outdated heating systems, and inefficient windows, resulting in higher energy bills and discomfort for occupants.

Considering these specificities of the rural housing stock, the following EEMs are evaluated for the RENOVERTY pilot regions:

- **EEM$_1$ - Exterior wall insulation**: Insulating the main walls of the building under study from the outside, which commonly have solid walls with no cavities.
- **EEM$_2$ - Double-glazed windows**: Replacing single-glazing windows with energy-efficient glazing (*Double-glazed windows*) to reduce heat loss.
- **EEM$_3$ - Roof insulation**: Insulated between and under the rafters of the roof itself, reducing the overall heat transfer coefficient by adding materials with low thermal conductivity (this measure applies only in the case of SFH)
- **EEM$_4$ - Energy-efficient heating system** (*Boiler upgrade- gas*): In this case, the dwelling's outdated heating system is replaced by an efficient gas boiler with a higher efficiency ratio.

- **EEM$_5$** - **Energy-efficient heating system** (*Boiler upgrade- biomass*): In this case, the dwelling's outdated heating system is replaced by an efficient biomass boiler with a higher efficiency ratio.
- **EEM$_6$** - **Energy-efficient heating system** (*Heat pump*): In this case, the dwelling's outdated heating system is replaced by a heat pump with a higher efficiency ratio.
- **EEM$_7$** - **Energy-efficient lighting**: In this case, the conventional tube lights and bulbs (fluorescent lamps) are replaced by high energy-efficiency ones (LED lamps).

4. Further model development, modifications, and adjustments

The **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (**DREEM**) model is a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, which expands the computational capabilities of existing building energy system and demand-side models, by not only calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (consumers/ citizens), and for other energy system actors involved (e.g., suppliers, retailers, distribution system operators) (Stavrakas & Flamos, 2020).

The main premise behind the development and the use of the DREEM model has been to grant citizens to the ability to have a more active participation into the energy transition, by first becoming more aware of the benefits of investing in new energy products and services.

In this context, the novelty of the model lies in its potential to be used in a wide range of applications, not only to assess the existing technological infrastructure, but also to support the development of business models and regulatory innovations, which maximise the value of energy products and services, and monetize them to fairly compensate citizens and other relevant energy market actors. Overall, the DREEM model:

- Embodies key features towards the simulation of renewable energy, energy efficiency, and other demand-flexibility actions, like demand response, in the building sector.
- Builds on the concept of modularity consisting of multiple components, each of which is composed of additional modules, allowing for more flexibility in terms of possible system configurations and computational efficiency (high time resolution and quick simulations) towards a wide range of scenarios, to study different aspects of end-use and energy transition (**Figure 6**).
- Provides the ability to incorporate technological breakthroughs in a detailed manner, such as the inclusion of heat pumps, or electric vehicles, in view of energy transitions envisioning the full electrification of the heating and transport sectors.
- Produces outputs for a group of buildings, for example a neighbourhood, a district, a municipality, or an energy community.
- Serves as a basis for modelling energy demand in the building sector, within the broader field of local, regional, and national energy systems, in different geographical/ climate and socioeconomic contexts of interest.

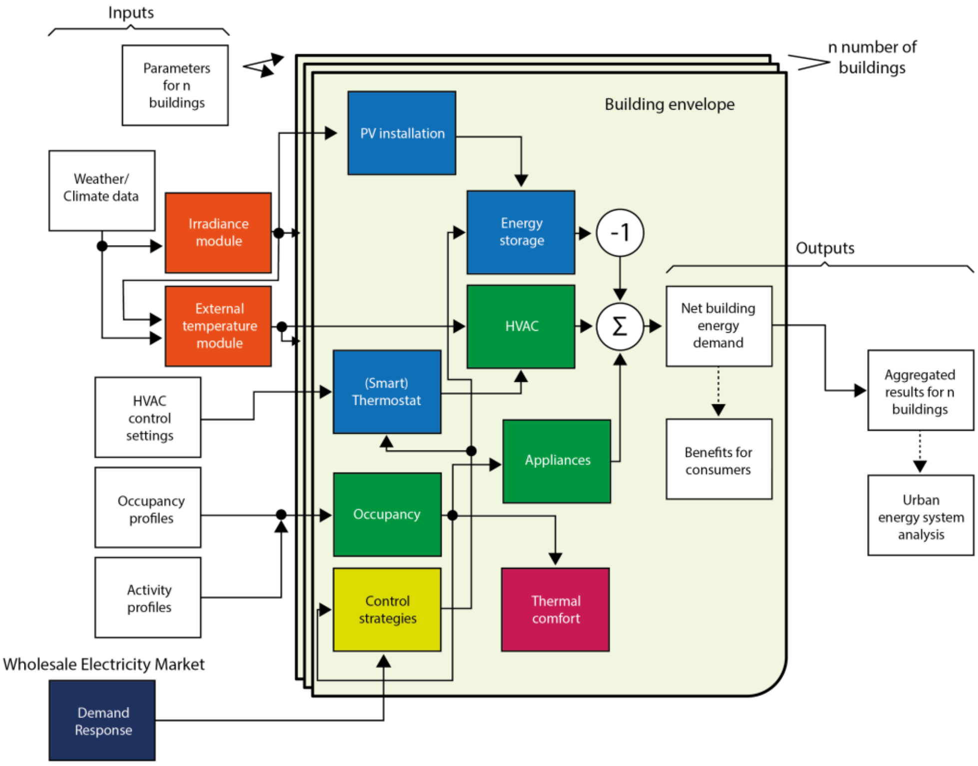

Figure 6. The original architecture of the DREEM model as presented by Stavrakas & Flamos, 2020.

All of the model's modules have been developed using the "Buildings" library, an open-source, freely available Modelica library for building energy and control systems (Bünning et al., 2017; Stavrakas & Flamos, 2020; Wetter, 2011; Zuo et al., 2016). Alongside the Modelica models, Python scripts have been developed to model parts of the model's components and to enable the interface with the Dymola simulation environment. DREEM is also part of the TEEM; the model is open access[6] under the "GNU Affero General Public License".

The updated RENOVERTY version of the model, including associate source code, datasets, and detailed documentations to enable the models' use, modification, and republication, will be distributed through the TEESlab UPRC's GitHub page.

To address the modelling needs of the work presented in this report and in order for the model to become capable of quantifying the potential of the different EEMs presented in **Section 3**, both in terms of evaluating their energy performance and analysing their cost-effectiveness, the model's original architecture and capacities, as originally introduced by Stavrakas & Flamos, 2020, have been expanded.

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[6] https://github.com/TEESlab-UPRC/DREEM

The updated modelling structure of DREEM is presented in **Figure 7**. Below, we provide a description of the new components and respective modules that have been developed and integrated into the original model's structure, along with the components and modules that have been used for the application at hand (**Table 2**).

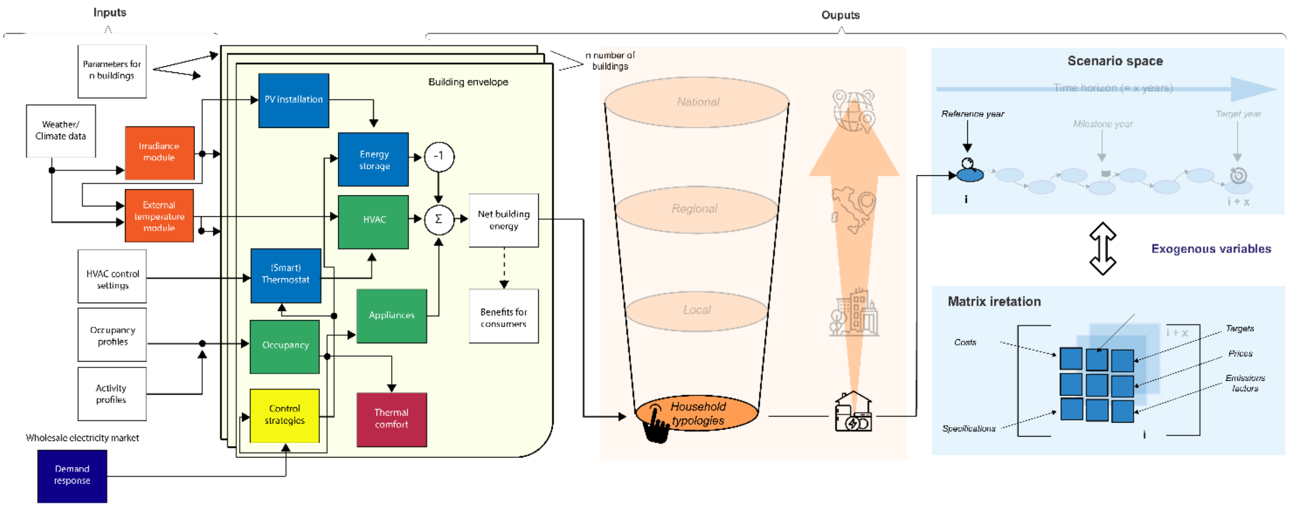

Figure 7. Expanded architecture of the DREEM model as further developed, modified, and adjusted in the context of the RENOVERTY project.

Table 2. Hierarchical structure of the expanded version of the DREEM model as used in this study: Short description of the main components and modules.

Components	Modules	Description	Developed
C_1: Weather/ Climate data	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.	Modelica
C_2: Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat conduction elements.	Modelica Python

C_3: Energy demand	*C_3M_1: Occupancy*	This module defines and sets the parameters for the behaviour and the activities of the occupants by generating and storing default patterns.	Modelica
	C_3M_2: Appliances	This module is responsible for generating energy demand profiles from appliances, using statistics describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles, based on occupancy patterns.	
	C_3M_3: Heating, ventilation, and air conditioning	This module is responsible for heating, ventilation, and air conditioning inside the building.	
C_4: Thermal comfort	-	This single-module component is responsible for determining, based on international standards, appropriate conditions and temperature ranges that result in occupants’ thermal satisfaction.	Modelica Python
C_5: Flexibility management	*C_5M_1: PV installation*	This module contains information about the orientation of the roof to determine the PV generation based on the position of the sun and recorded irradiation data for the location of interest.	Modelica
	C_5M_2: Energy storage	This module contains models that represent different energy	

		storages. It takes as an input the power that should be stored in/ extracted from the storage. The "C_7: Control strategies" component is responsible so that only a reasonable amount of power is exchanged, and that the state of charge remains between the appropriate ranges.	
	C_5M_3: (Smart) Thermostat	This module is responsible for the operation of the HVAC control system. By receiving the indoor temperature as a measured signal and based on the difference between set and measured temperature, it sends signals to the "*C_3M_3: Heating, ventilation, and air conditioning*" module to yield the heat and ventilation flows inside the building.	
C_6: Demand-Response	-	This single module component simulates Demand-Response mechanisms that motivate citizens to respond to real-time price signals.	Python
C_7: Control strategies	*C_7M_1: Momentary Control Algorithm*	This single module component is responsible for the energy management supervision strategy that, given the time-shifting events of demand and the citizen occupancy signals received, aims at achieving	Modelica Python

		energy savings and cost effectiveness.	
C_8: Multilevel upscaling	-	This single-module component is responsible for applying an upscaling approach to compute cumulative energy consumption patterns in the building sector, at the scale of interest, using parameters and statistics obtained from survey and/ or census data. It receives inputs from the "C_2: Building envelope" and the "C_3: Energy demand" components.	Python
C_9: Transition matrix	*C_9M_1: Scenario space*	This new module is responsible for designing the scenario space (in terms of different transition pathways and the respective exogenous variables) inside of which the transition matrix is initiated and updated, based on relevant policy documents' specifications and practical experts' feedback.	Python
	C_9M_2: Matrix iteration	This module is responsible for initialising the transition matrix and updating it at each time interval (i.e., iteration), following the scenario space's specifications (i.e., targets and constraints) derived from the "*C_9M_1: Scenario space*" module.	

4.1 C_1: Weather/ Climate data

Seasonal variability to reflect the changing level of demand between winter and summer is an important aspect, which is often omitted or addressed in an oversimplified manner by existing demand-side models in the field. In the DREEM model, we address this issue through the inclusion of a single module component dedicated to generating accurate climatic boundary conditions based on historical weather data.

To do so, the component uses Typical Meteorological Year (TMY) weather data format and particularly the TMY3 format, while it is then configured to provide a common set of irradiance and temperature data for the geography under study, with the respective irradiance and temperature profiles having appropriate time-diversity to enable higher resolution (Cebecauer & Suri, 2015; Wilcox & Marion, 2008).

4.2 C_2: Building envelope

The DREEM model builds on the concept of "reduced (low)-order" thermal network modelling, which represents a thermal zone by thermal resistances and capacities (resistor-capacitor network, RC) using the electrical circuit analogy, in which voltage is analogous to temperature and current is analogous to convective and radiative heat transfer (McKenna & Thomson, 2016; Harish & Kumar, 2016). The respective module represents all main thermal masses of the building under study as four elements, accompanied with supportive features for consideration of solar radiation (as visualised by Stavrakas & Flamos, 2020).

The parameters for heat transfer coefficients, as well as thermal resistances and capacities, are determined using either direct data, like in the case of the RENOVERTY energy audits data, or historical/statistical data and standards for the geographical context of interest. Below, we present the detailed mathematical representation and equations used to further develop the RC-network methodology in DREEM.

Thermal network models generally focus on one-dimensional heat transfer calculations, therefore a geometrically correct representation of all the walls of a thermal zone is not possible. To reduce simulation effort, walls were aggregated elements with similar thermal behaviour. The number of a wall's elements depends on the thermal properties of the walls and their excitation (e.g., through solar radiation), on the excitation frequencies.

The same applies to the number of RC-elements per wall. There is the option to choose between models with one to four wall elements, and to define the number of RC-elements per wall for each wall. The latter can be done by setting n_k, which is the length of the vectors for resistances R_k and capacities C_k. Each wall element uses reduced-order models to describe heat conduction and storage within the wall, depending on if the wall contributes to heat transfer to the outdoor environment (exterior walls), or if it can be considered as a simple heat storage element (interior walls). All of the exterior walls and windows provide a heat port to the outside, while all of the wall elements (exterior walls, windows, and interior walls) are connected.

This component's modelling architecture is defined in the German Guideline VDI 6007 Part 1, which describes a dynamic thermal building model for calculations of indoor air temperatures and heating/cooling power (German Association of Engineers, 2015). The important modelling parameters that are used to parameterize the "C_2: Building envelope" component in the DREEM model are as follows:

- n... defines the length of the chain of RC-elements per wall.
- R...[n] is the vector of resistances for the wall element. It moves from indoor to outdoor.
- C...[n] is the vector of capacities for the wall element. It moves from indoor to outdoor.
- R...$_{Rem}$ is the remaining resistance between C[end] and the outdoor surface of the wall element. This resistance can be used to ensure that the sum of all the resistances and coefficients of heat transfer is equal to the U-value. It represents the part of the wall that cannot be activated and thus does not take part in heat storage.

The thermal behaviour of a homogeneous wall layer *v* of arbitrary thickness *s*, for one-dimensional heat flow and periodic case problem, is illustrated by the following matrix notation (**Figure 8**).

$$\begin{pmatrix} \underline{\theta}(x=0) \\ \underline{q}(x=0) \end{pmatrix}_V = \boldsymbol{A_V} \cdot \begin{pmatrix} \underline{\theta}(x) \\ \underline{q}(x) \end{pmatrix}_V$$

where *x* is the coordination towards the normal wall.

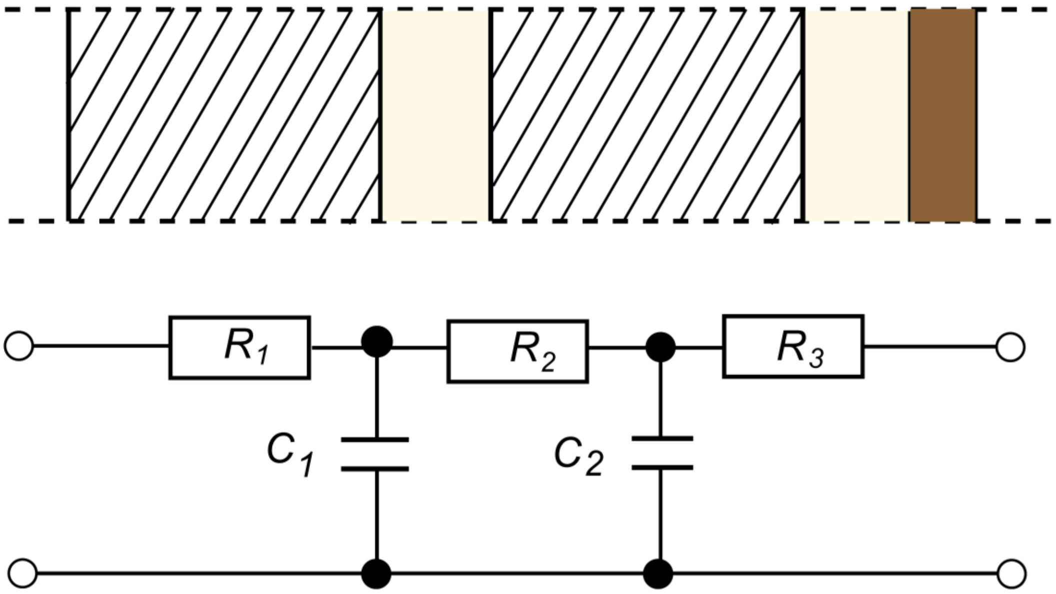

Figure 8. Graphical representation of the thermodynamic model used in DREEM for one wall element.

The chain matrix $\boldsymbol{A_V}$ for a wall layer can be written as:

$$\boldsymbol{A_V} = \begin{Vmatrix} \underline{a}_{11} & \underline{a}_{12} \\ \underline{a}_{21} & \underline{a}_{22} \end{Vmatrix}_V = \begin{Vmatrix} Re\underline{a}_{11} & Im\underline{a}_{11} & Re\underline{a}_{12} & Im\underline{a}_{12} \\ -Im\underline{a}_{21} & Re\underline{a}_{11} & -Im\underline{a}_{12} & Re\underline{a}_{12} \\ Re\underline{a}_{21} & Im\underline{a}_{21} & Re\underline{a}_{22} & Im\underline{a}_{22} \\ -Im\underline{a}_{21} & Re\underline{a}_{21} & -Im\underline{a}_{22} & Re\underline{a}_{22} \end{Vmatrix}_v$$

The elements of the chain matrix for a wall of layer ν are obtained as:

$$Re\underline{a}_{11} = Re\underline{a}_{22} = \cosh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \cos\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$Im\underline{a}_{11} = Im\underline{a}_{22} = \sinh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \sin\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$Re\underline{a}_{12} = \mathrm{R} \cdot \sqrt{\frac{1}{2\omega_{BT}RC}} \cdot \left(\cosh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \sin\sqrt{\frac{1}{2}\omega_{BT}RC} + \sinh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \cos\sqrt{\frac{1}{2}\omega_{BT}RC}\right)$$

$$Im\underline{a}_{12} = \mathrm{R} \cdot \sqrt{\frac{1}{2\omega_{BT}RC}} \cdot \left(\cosh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \sin\sqrt{\frac{1}{2}\omega_{BT}RC} - \sinh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \cos\sqrt{\frac{1}{2}\omega_{BT}RC}\right)$$

$$Re\underline{a}_{21} = \frac{-1}{R} \cdot \sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \left(\cosh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \sin\sqrt{\frac{1}{2}\omega_{BT}RC} - \sinh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \cos\sqrt{\frac{1}{2}\omega_{BT}RC}\right)$$

$$Im\underline{a}_{21} = \frac{-1}{R} \cdot \sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \left(\cosh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \sin\sqrt{\frac{1}{2}\omega_{BT}RC} + \sinh\sqrt{\frac{1}{2}\omega_{BT}RC} \cdot \cos\sqrt{\frac{1}{2}\omega_{BT}RC}\right)$$

where:

- R is the thermal resistance of the wall's layer per unit area in $\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$ with $\mathrm{R} = \frac{\mathrm{s}}{\lambda}$,
- C is the heat capacity of the wall's layer per unit area in $\frac{\mathrm{J}}{\mathrm{m^2 \cdot K}}$, $\mathrm{C} = \mathrm{c} \cdot \rho \cdot \mathrm{s}$,
- ω is the angular frequency in $\frac{1}{\mathrm{s}}$, $\omega = \frac{2 \cdot \pi}{86{,}400 \cdot \mathrm{T}}$,
- T is the period of the fundamental in days. For the calculations we select a period time of T=7 days, based on ISO 13786 - Thermal performance of building components - Dynamic thermal characteristics - Calculation methods,
- s is the thickness of the wall's layer in m,
- λ is the thermal conductivity of the wall's layer in $\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}$,
- $\mathrm{c} \cdot \rho$ is the heat storage capacity of the wall layer in $\frac{\mathrm{J}}{\mathrm{m^2 \cdot K}}$.

The chain matrix $A_{1,n}$ of the total wall is calculated by multiplying the matrices A_ν of the individual wall's layers (ν = 1,…, n). as:

$$\mathrm{A_{1,n} = A_1 \cdot A_2 \cdot A_3 \cdot \ldots \cdot A_{n-1} \cdot A_n}$$

Based on the chain matrix $A_{1,n}$ of the total wall, the resistances and capacities of the replacement model are estimated as:

$$R_1 = \frac{1}{A} \cdot \frac{(Re\underline{a}_{22} - 1) \cdot Re\underline{a}_{12} + Im\underline{a}_{22} \cdot Im\underline{a}_{12}}{(Re\underline{a}_{22} - 1)^2 + Im\underline{a}_{22}{}^2}$$

$$R_2 = \frac{1}{A} \cdot \frac{(Re\underline{a}_{11} - 1) \cdot Re\underline{a}_{12} + Im\underline{a}_{11} \cdot Im\underline{a}_{12}}{(Re\underline{a}_{11} - 1)^2 + Im\underline{a}_{11}{}^2}$$

$$C_1 = A \cdot \frac{1}{\omega_{BT}} \cdot \frac{(Re\underline{a}_{22} - 1)^2 + Im\underline{a}_{22}{}^2}{Re\underline{a}_{12} \cdot Im\underline{a}_{22} - (Re\underline{a}_{22} - 1) \cdot Im\underline{a}_{12}}$$

$$C_2 = A \cdot \frac{1}{\omega_{BT}} \cdot \frac{(Re\underline{a}_{11} - 1)^2 + Im\underline{a}_{11}{}^2}{Re\underline{a}_{12} \cdot Im\underline{a}_{11} - (Re\underline{a}_{11} - 1) \cdot Im\underline{a}_{12}}$$

Where A is the total area of the wall in m^2. The resistance $\mathrm{R_3}$ is then calculated as the difference between the total heat transfer resistance of the wall and the sum of the equivalent model resistors $\mathrm{R_2}$ and $\mathrm{R_1}$, as:

$$R_3 = \left(\frac{1}{A} \cdot \sum_{v=1}^{n} \frac{S_V}{\lambda_V} \right) - R_2 - R_1$$

The model can now be reduced to a simplified model (**Figure 9**) that comprises of a total resistance $\mathrm{R_w}$ and heat capacity $\mathrm{C_{1,korr}}$. For one-sided thermal stress, the replacement model simplifies the case of thermal load accordingly. The total resistance $\mathrm{R_w}$ is equal to:

$$R_w = R_3 + R_2 + R_1 = R_{REM} + R_1,$$

while the corrected heat storage capacity $C_{1,\mathrm{korr}}$ is equal to:

$$C_{1,korr} = A \cdot \frac{1}{R_1 \cdot \omega_{BT}} \cdot \frac{R_w - Rea_{12} \cdot Rea_{22} - Ima_{12} \cdot Ima_{22}}{Rea_{22} \cdot Ima_{12} - Rea_{12} \cdot Ima_{22}}$$

An external window is a special case of the replacement model and in this case, the heat storage capacity $C_{1,\mathrm{korr}}$ should practically be set to zero.

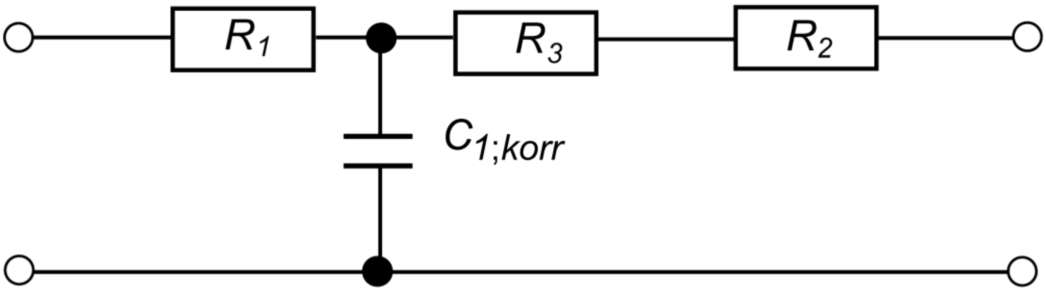

Figure 9. Graphical representation of a simplified model for the thermal behaviour of components under asymmetrical loading.

4.3 C_3: Energy demand

The DREEM model aims to generate accurate and realistic energy demand profiles, avoiding unnecessary computational complexity, by building on the concept of stochastic modelling and providing simulated data about households' energy demand, with statistics suitable for the task at hand. This component uses a bottom-up approach to simulate energy consumption considering households' occupancy, use of appliances, and heating, cooling, and ventilation options.

The component's individual modules use many simplified assumptions to simulate various aspects of energy demand (occupancy and citizens' activity/behaviour profiles, sharing of appliances, etc.) and focuses on parameters and statistics obtained from real-life, survey and/or census data.

4.4 C_4: Thermal comfort

The model focuses on addressing the aspect of occupants' thermal comfort, which is often overlooked by other models in the field, by utilising an individual component that aligns with international standards (DIN EN ISO 7730, ASHRAE 55, EN 15251). Built upon the Fanger approach, it employs the characteristic Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) indices (Shaw, 1972).

To determine optimal indoor thermal conditions for occupants, DREEM calculates PMV and PPD, by considering weather and other parameters, such as dynamic metabolic rates and clothing insulation, adjusted based on seasonal variations. By doing so, it offers a comprehensive approach to accurately model thermal comfort and to fill existing gaps. The acceptable ranges of the PMV and PPD indices are presented in **Table 3**.

Table 3. Expectation levels of the PMV and PPD indices according to the EN 15251 standard (CEN, 2012).

PPD (%)	PMV	Description
< 6	- 0.2 < PMV < + 0.2	Increased expectation level: recommended for spaces inhabited by highly vulnerable individuals with specific needs, like sick children, elderly persons, etc.
< 10	- 0.5 < PMV < + 0.5	Standard expectation level: new and renovated buildings.
< 15	- 0.7 < PMV < + 0.7	Moderate expectation level (acceptable range): existing buildings.
< 20	- 1 < PMV < + 1	Minimum expectation levels: values acceptable only for limited parts of the day.
> 20	PMV < -1 or PMV > + 1	Unacceptable expectation levels: values deviating acceptable criteria, deemed tolerable only for a very limited part of the year.

4.5 C_9: Transition matrix

The DREEM model has been developed to allow for the production of outputs at a high resolution (i.e., one minute), also accounting for seasonal variability to reflect the changing level of demand between winter and summer. Its modular structure provides the necessary computational efficiency to simulate large numbers of buildings for the long-term transition with the appropriate demand diversity and accuracy (due to its bottom-up structure), while also reducing the simulation complexity owing to the multidisciplinary nature of energy demand models and their input data requirements (Chatterjee et al., 2022; Süsser, Gaschnig, et al., 2022).

In this context, this newly developed component creates a "*scenario space*", based on the policy specifications of each application at hand. It is further updated based on the evolution of exogenous variables (e.g., costs, prices, technological specifications, etc.) and is stored in a matrix to provide detailed information for a building, a group of buildings, or the entire building sector of the area under study, for different time horizons, i.e., for the current year or upcoming decades (e.g., 2030, 2040, 2050, etc.), and the time interval (e.g., one hour, one year, five years) of interest.

Based on these parameters, "*C₉: Transition matrix*" is able to conduct technoeconomic assessments and identify the economic potential and viability of different combinations of interventions and policy measures. In this study, "*C₉: Transition matrix*" will assess the different EEMs using three key indicators: the investment's Net Present Value (NPV), payback period (PP), as well as its Levelised Cost of Saved Energy (LCSE).

- NPV is an absolute appraisal criterion that measures the increase in value resulting from a specific investment. The economic meaning of NPV can be directly derived from its definition: it represents the value or profitability realisable from the investment (Andersson & Science, 2000; Arnaboldi et al., 2015).
- PP is usually measured as the time required to recover the capital investment. More specifically, PP is the time taken for the cumulative net cash to equal the depreciable fixed capital investment (Reddy & Rangaiah, 2022).
- LCSE is defined as the total cost of saved energy, levelised over the average savings lifetime of the energy efficiency actions (Hoffman et al., 2017). As LCSE studies the levelised cost of an intervention per energy saved it is apparent that the lower the LCSE, the more cost-effective the intervention under study.

The formulas used in this component for each indicator are presented in **Box 1**, **Box 2**, and **Box 3**.

Box 1. Methodology for the calculation of the NPV.

NPV is calculated using the following formula:

$$NPV = \sum_{i=0}^{\tau} \left(\frac{CF_i}{(1+d)^i} \right)$$

Where:

- τ is the calculation period or the lifetime of the measure,
- d is the discount rate, and
- CF_i is the annual cash flow in the year i; $CF_i = \Delta cost_{energy,i} + \Delta cost_{om,i} - I_i$,

Where:

- $\Delta cost_{energy,i}$ is the energy cost savings in year I,
- $\Delta cost_{om,i}$ is the change of annual operation and maintenance cost in year I, and
- I_i is the investment cost in year i.

Box 2. Methodology for the calculation of the simple PP.

PP is calculated using the following formula:

$$PP = \frac{Initial\ investment}{Discounted\ energy\ savings} = \frac{I_0}{\sum_{i=0}^{\tau}\left(\frac{\Delta E}{(1+d)^i}\right)}$$

Box 3. Methodology for the calculation of the LCSE.

LCSE is calculated using the following formula:

$$LCSE = \frac{Discounted\ Cash\ Flow}{Discounted\ Energy\ Savings} = \frac{I_0 * CRF - \ \Delta cost_{energy} - \Delta cost_{om}}{\Delta E} = \frac{-NPV}{\sum_{i=0}^{\tau}\left(\frac{\Delta E}{(1+d)^i}\right)}$$

5. Model parameterisation

In this section, we present the parameterisation of the individual components and modules required for the application of the DREEM model, along with the main data inputs, the scenario design, and the assumptions made, in the RENOVERTY pilots. RENOVERTY pilots are located in rural areas in 7 EU countries located in CEE, SEE, and SE Europe, namely Osona in Spain, Parma in Italy, Bükk and SMB in Hungary, Sveta Nedelja and Žumberak in Croatia, Tartu in Estonia, Zasavje in Slovenia, and Coimbra in Portugal.

5.1 C_1: Weather/ Climate data

To configure the DREEM model, we use weather/ climate data from the database of the World Meteorological Organisation (WMO) (World Meteorological Organisation, 2021). The data is formatted as TMY3, accumulating a 14-year period (2007-2021) of data values, and including information on latitude, longitude, and time zone in relation to Greenwich Mean Time, as well as temperature, relative humidity, wind speed and direction, sun direction and radiation values, on an hourly basis. For each region under study, we select meteorological data available from the closest available locations. For the rural region of Osona in Spain, we use data from the region of Montseny, located around 50km away from Osona. For the rural region of Parma, we use data directly from the region, for the case of the rural region of Bükk in Hungary, we use data from the region of Miskolc, located around 27 km away, and for SMB, we use data from the region of Pápa, located around 13 km away. For the rural region of Sveta Nedelja and Žumberak in Slovenia, weather data from the region of Zagreb are used, located around 20km and 68km away, respectively. For Tartu in Estonia, data are used from the region of Jõgeva (around 50km away), for Zasavje in Slovenia from the region of Ljubljana (around 50km away), and for Coimbra in Portugal directly from the region.

5.2 C_2: Building envelope

For the needs of the next component of the model, data from the energy audits are used to parameterise and simulate the energy performance of the different dwellings across the pilots. To ensure the accurate application of the DREEM model in the existing situation (baseline scenario) that captures the specificities of the rural dwelling stock, parameterisation is based on the data collected from the energy audits.

For the parameterisation of the building envelope, in the case of the different building envelope upgrades foreseen in the different EEMs, we use data from the building database "TABULA", scientific literature, and national documents. Specifically, for each case study we used data related to the building characteristics after the upgrade of the building envelope (e.g., upgraded U-values).

In the following subsections a detailed presentation of the parameterisation inputs for "*C_2: Building Envelope*" in each pilot area is conducted.

5.2.1 The rural region of Osona in Spain

In the case of Osona (Spain), energy audits were conducted in both SFHs and MFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 4** and **Table 5**.

Table 4. Building specifications/characteristics for SFHs in the rural region of Osona (Spain) as derived from the energy audits.

Osona, Spain (SFH)	
Building characteristics	
Year of construction	1960-1980
Total floor area of the building	140 m^2
Total area of exterior walls of the buildings	72 m^2
Total roof area of the building	58 m^2
Total area of windows	11 m^2
Building envelope/construction features	
U_{wall}	2.40 $W/m^2/K$
U_{floor}	2.20 $W/m^2/K$
U_{roof}	2.60 $W/m^2/K$
U_{window}	3.60 $W/m^2/K$

Table 5. Building specifications/characteristics for MFHs in the rural region of Osona (Spain) as derived from the energy audits.

Osona, Spain (MFH)	
Building characteristics	
Year of construction	1960-1980
Total floor area of the building	98 m^2
Total area of exterior walls of the buildings:	48 m^2
Total roof area of the building:	78 m^2
Total area of windows:	12 m^2
Building envelope/construction features	
U_{wall}	1.90 $W/m^2/K$
U_{floor}	1.80 $W/m^2/K$
U_{roof}	1.40 $W/m^2/K$
U_{window}	3.50 $W/m^2/K$

For the parameterisation of "*C_2: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the building database "TABULA" (*EU TABULA WebTool*, 2017). Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 6**, and for MFHs in **Table 7**.

Table 6. Building specifications/characteristics for SFHs in the rural region of Osona (Spain) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.42 $W/m^2/K$
U_{roof}	0.85 $W/m^2/K$
U_{window}	1.84 $W/m^2/K$

Table 7. Building specifications/characteristics for MFHs in the rural region of Osona (Spain) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.45 W/m²/K
U_{window}	1.84 W/m²/K

5.2.2 The rural region of Parma in Italy

In the case of Parma (Italy), energy audits were conducted in both SFHs and MFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 8** and **Table 9**.

Table 8. Building specifications/characteristics for SFHs in the rural region of Parma (Italy) as derived from the energy audits.

Parma, Italy (SFH)	
Building characteristics	
Year of construction	before 1960
Total floor area of the building	113 m^2
Total area of exterior walls of the buildings	440 m^2
Total roof area of the building	110 m^2
Total area of windows	17 m^2
Building envelope/construction features	
U_{wall}	1.40 W/m²/K
U_{floor}	1.10 W/m²/K
U_{roof}	1.50 W/m²/K
U_{window}	2.40 W/m²/K

Table 9. Building specifications/characteristics for MFHs in the rural region of Parma (Italy) as derived from the energy audits.

Parma, Italy (MFH)	
Building characteristics	
Year of construction	1960-1975
Total floor area of the building	109 m^2
Total area of exterior walls of the buildings	378 m^2
Total roof area of the building	109 m^2
Total area of windows	18 m^2
Building envelope/construction features	
U_{wall}	1.30 $W/m^2/K$
U_{floor}	0.40 $W/m^2/K$
U_{roof}	1.70 $W/m^2/K$
U_{window}	4.10 $W/m^2/K$

For the parameterisation of "*C_2: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the building database ""TABULA" (*EU TABULA WebTool*, 2017). Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 10** and for MFHs in **Table 11**.

Table 10. Building specifications/characteristics for SFHs in the rural region of Parma (Italy) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.24 $W/m^2/K$
U_{roof}	0.23 $W/m^2/K$
U_{window}	1.70 $W/m^2/K$

Table 11. Building specifications/characteristics for MFHs in the rural region of Parma (Italy) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.24 W/m²/K
U_{window}	1.70 W/m²/K

5.2.3 The rural regions of Bükk and Somló-Marcalmente-Bakonyalja in Hungary

In the case of Bükk and SMB (Hungary), energy audits were conducted only in SFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 12** for the region of Bükk, and in **Table 13** for the region of SMB.

Table 12. Building specifications/characteristics for SFHs in the rural region of Bükk (Hungary) as derived from the energy audits.

Bükk, Hungary (SFH)	
Building characteristics	
Year of construction	1945-1980
Total floor area of the building	100 m^2
Total area of exterior walls of the buildings:	259 m^2
Total roof area of the building:	100 m^2
Total area of windows:	13 m^2
Building envelope/construction features	
U_{wall}	1.10 W/m²/K
U_{floor}	1.50 W/m²/K
U_{roof}	0.50 W/m²/K
U_{window}	1.80 W/m²/K

Table 13. Building specifications/characteristics for SFHs in the rural region of SMB (Hungary) as derived from the energy audits.

SMB, Hungary (SFH)	
Building characteristics	
Year of construction	1945-1980
Total floor area of the building	131 m^2
Total area of exterior walls of the buildings	356 m^2
Total roof area of the building	131 m^2
Total area of windows	19 m^2
Building envelope/construction features	
U_{wall}	1.30 $W/m^2/K$
U_{floor}	0.70 $W/m^2/K$
U_{roof}	1.00 $W/m^2/K$
U_{window}	2.50 $W/m^2/K$

For the parameterisation of "C_2*: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the building database "TABULA" (*EU TABULA WebTool*, 2017). Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 14**.

Table 14. Building specifications/characteristics for SFHs in the rural regions of Bükk and SMB (Hungary) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.17 $W/m^2/K$
U_{roof}	0.15 $W/m^2/K$
U_{window}	1.00 $W/m^2/K$

5.2.4 The rural regions of Sveta Nedelja and Žumberak in Croatia

In the case of Sveta Nedelja and Žumberak (Croatia), energy audits were conducted only in SFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 15**.

Table 15. Building specifications/characteristics for SFHs in the rural region of Sveta Nedelja and Žumberak (Croatia) as derived from the energy audits.

Sveta Nedelja and Žumberak, Croatia (SFH)	
Building characteristics	
Year of construction	1960-1980
Total floor area of the building	124 m^2
Total area of exterior walls of the buildings	139 m^2
Total roof area of the building	100 m^2
Total area of windows	20 m^2
Building envelope/construction features	
U_{wall}	1.50 W/m^2/K
U_{floor}	2.70 W/m^2/K
U_{roof}	1.90 W/m^2/K
U_{window}	2.80 W/m^2/K

For the parameterisation of "*C_2: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the Croatian "Long-term strategy for national building stock renovation by 2050" (Goverment of Croatia, 2020).

Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 16**.

Table 16. Building specifications/characteristics for SFHs in the rural regions of Sveta Nedelja and Žumberak (Croatia) after the building envelope upgrades as derived from the Croatian "Long-term strategy for national building stock renovation by 2050".

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.30 W/m²/K
U_{roof}	0.24 W/m²/K
U_{window}	1.70 W/m²/K

5.2.5 The rural region of Tartu in Estonia

In the case of Tartu (Estonia), energy audits were conducted only in MFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 17**.

Table 17. Building specifications/characteristics for the MFHs dwellings in the rural region of Tartu (Estonia) as derived from the energy audits.

Tartu, Estonia (MFH)	
Building characteristics	
Year of construction	1960-1980
Total floor area of the building	64 m^2
Total area of exterior walls of the buildings	63 m^2
Total roof area of the building	109 m^2
Total area of windows	11 m^2
Building envelope/construction features	
U_{wall}	0.90 W/m²/K
U_{floor}	0.70 W/m²/K
U_{roof}	0.80 W/m²/K
U_{window}	2.60 W/m²/K

For the parameterisation of "*C_2: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the building database "TABULA" (*EU TABULA WebTool*, 2017).

Building envelope characteristics after the building envelope upgrades for MFHs are presented in **Table 18**.

Table 18. Building specifications/characteristics for MFHs apartments in the rural region of Tartu (Estonia) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.17 W/m²/K
U_{window}	0.80 W/m²/K

5.2.6 The rural region of Zasavje in Slovenia

In the case of Zasavje (Slovenia), energy audits were conducted in both SFHs and MFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 19** and **Table 20**.

Table 19. Building specifications/characteristics for SFHs in the rural region of Zasavje (Slovenia) as derived from the energy audits.

Zasavje, Slovenia (SFH)	
Building characteristics	
Year of construction	before 1960
Total floor area of the building	90 m^2
Total area of exterior walls of the buildings	158 m^2
Total roof area of the building	108 m^2
Total area of windows	11 m^2
Building envelope/construction features	
U_{wall}	1.10 W/m²/K
U_{floor}	0.70 W/m²/K
U_{roof}	0.50 W/m²/K
U_{window}	1.30 W/m²/K

Table 20. Building specifications/characteristics for MFHs in the rural region of Zasavje (Slovenia) as derived from the energy audits.

Zasavje, Slovenia (MFH)	
Building characteristics	
Year of construction	1945-1970
Total floor area of the building	62 m^2
Total area of exterior walls of the buildings	51m^2
Total roof area of the building	61 m^2
Total area of windows	8 m^2
Building envelope/construction features	
U_{wall}	1.10 W/m^2/K
U_{floor}	1.40 W/m^2/K
U_{roof}	0.50 W/m^2/K
U_{window}	1.30 W/m^2/K

For the parameterisation of “*C_2: Building Envelope*” in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from the building database “TABULA” (*EU TABULA WebTool*, 2017). Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 21** and for MFHs in **Table 22**.

Table 21. Building specifications/characteristics for SFHs in the rural region of Zasavje (Slovenia) after the building envelope upgrades as derived from the “TABULA” platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.18 W/m^2/K
U_{roof}	0.16 W/m^2/K
U_{window}	0.75 W/m^2/K

Table 22. Building specifications/characteristics for MFHs in the rural region of Zasavje (Slovenia) after the building envelope upgrades as derived from the "TABULA" platform.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.18 W/m²/K
U_{window}	0.75 W/m²/K

5.2.7 The rural region of Coimbra in Portugal

In the case of Coimbra (Portugal), energy audits were conducted only in SFHs. The building specifications/characteristics, in the baseline situation, collected through the energy audits, are presented in **Table 23**.

Table 23. Building specifications/characteristics for SFHs typology in the rural region of Coimbra in Portugal as derived from the energy audits.

Coimbra, Portugal (SFH)	
Building characteristics	
Year of construction	1980-2006
Total floor area of the building	132 m^2
Total area of exterior walls of the buildings	114 m^2
Total roof area of the building	91 m^2
Total area of windows	20 m^2
Building envelope/construction features	
U_{wall}	1.20 W/m²/K
U_{floor}	2.20 W/m²/K
U_{roof}	2.70 W/m²/K
U_{window}	4.60 W/m²/K

For the parameterisation of "*C_2: Building Envelope*" in the case of the building envelope upgrades foreseen in the potential EEMs, i.e., EEM_1, EEM_2 and EEM_3 (EEM_3 is applied only in the case of SFH) we use data from scientific literature sources targeted in the Portuguese context (Reis et al., 2021). Building envelope characteristics after the building envelope upgrades for SFHs are presented in **Table 24**.

Table 24. Building specifications/characteristics for SFHs in the rural region of Coimbra (Portugal) after the building envelope upgrades as derived from relevant scientific sources.

Building envelope features after the building envelope upgrades (U-values)	
U_{wall}	0.36 W/m²/K
U_{roof}	0.33 W/m²/K
U_{window}	0.54 W/m²/K

5.3 C_3: Energy demand

For the parameterisation of the "*C_3: Energy demand*" component we use data derived from the energy audits coupled with statistical/historical data from each country context when needed.

For the parameterisation of the "*C_3M_1: Occupancy*" module, the household composition and occupancy patterns are based on the inputs gathered from the fieldwork conducted by the RENOVERTY pilot partners. The first key factor to properly configure this module concerns the number of members per household, while the second key factor concerns the time that occupants spend being active at their homes, which is strongly connected to their employment status and work schedules. The most prominent occupancy profiles for each case study are provided in **Table 25**.

Table 25. The most prominent occupancy profiles for each case study, as derived from the RENOVERTY energy audits process.

Pilot case	Members	Overall occupancy profiles
Osona, Spain (SFH)	1	1 unemployed person
Osona, Spain (MFH)	3	2 employed people & 1 unemployed person
Parma, Italy (SFH)	2	2 employed people
Parma, Italy (MFH)		
Bükk, Hungary (SFH)	2	2 employed people
SMB, Hungary (SFH)	2	2 employed people
Sveta Nedelja and Žumberak, Croatia (SFH)	3	2 employed people & 1 unemployed person
Tartu, Estonia (MFH)	2	2 employed people
Zasavje, Slovenia (SFH)	3	2 employed people & 1 unemployed person
Zasavje, Slovenia (MFH)		
Coimbra, Portugal (SFH)	3	2 employed people & 1 unemployed person

To configure the "*C_3M_2: Appliances*” and “*C_3M_3: Heating, Ventilation Air Conditioning (HVAC)*” modules data from the energy audit process, combined with historical and statistical data for each case study are used (Abdel-Salam & Simonson, 2016; Du et al., 2017; Jakob et al., 2019; Sala Lizarraga & Picallo-Perez, 2020). The most important information regarding the parameterisation of these two modules for each case study is presented in the following tables.

Table 26. HVAC and lighting systems in the case of Osona, Spain (SFH typology).

Osona, Spain (SFH)	
HVAC and lighting systems	
Heating system	Oil boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	16 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	230.1 kWh/m^2

Table 27. HVAC and lighting systems in the case of Osona, Spain (MFH typology).

Osona, Spain (MFH)	
HVAC and lighting systems	
Heating system	Oil boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	13 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	215.4 kWh/m^2

Table 28. HVAC and lighting systems in the case of Parma, Italy (SFH typology).

Parma, Italy (SFH)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	8 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	246.9 kWh/m^2

Table 29. HVAC and lighting systems in the case of Parma, Italy (MFH typology).

Parma, Italy (MFH)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	12 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	249.8 kWh/m^2

Table 30. HVAC and lighting systems in the case of Bükk, Hungary (SFH typology).

Bükk, Hungary (SFH)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	11 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	315.0 kWh/m^2

Table 31. HVAC and lighting systems in the case of SMB, Hungary (SFH typology).

SMB, Hungary (SFH)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	11 bulbs
Lighting equipment capacity	typical (not LED)
Estimated primary energy consumption	400.1 kWh/m^2

Table 32. HVAC and lighting systems in the case of Sveta Nedelja, Croatia (SFH typology - Natural gas boiler).

Sveta Nedelja, Croatia, (SFH, gas boiler)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	11 bulbs
Lighting equipment capacity	typical (not LED)
Estimated energy consumption	404.4 kWh/m^2

Table 33. HVAC and lighting systems in the case of Sveta Nedelja, Croatia (SFH typology - Wood stove).

Sveta Nedelja, Croatia, (SFH, Wood stove)	
HVAC and lighting systems	
Heating system	Wood stove
Nominal capacity	7 kW
COP	0.40
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	9 bulbs
Lighting equipment capacity	typical (not LED)
Estimated energy consumption	404.4 kWh/m^2

Table 34. HVAC and lighting systems in the case of Tartu, Estonia (MFH typology).

Tartu, Estonia (MFH)	
HVAC and lighting systems	
Heating system	District heating
COP	0.89
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	4 bulbs
Lighting equipment capacity	Typical/LED 50:50 (estimated)
Estimated energy consumption	308.1 kWh/m^2

Table 35. HVAC and lighting systems in the case of Zasavje, Slovenia (SFH typology).

Zasavje, Slovenia (SFH)	
HVAC and lighting systems	
Heating system	Wood stove
Nominal capacity	10 kW
COP	0.40
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	4 bulbs
Lighting equipment capacity	Typical/LED 50:50 (estimated)
Estimated energy consumption	346.6 kWh/m^2

Table 36. HVAC and lighting systems in the case of Zasavje, Slovenia (MFH typology).

Zasavje, Slovenia (MFH)	
HVAC and lighting systems	
Heating system	Gas boiler
Nominal capacity	24 kW
COP	0.85
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	4 bulbs
Lighting equipment capacity	Typical/LED 50:50 (estimated)
Estimated energy consumption	337.3 kWh/m^2

Table 37. HVAC and lighting systems in the case of Coimbra, Portugal (SFH typology).

Coimbra, Portugal (SFH)	
HVAC and lighting systems	
Heating system	Wood stove
Nominal capacity	10 kW
COP	0.40
Cooling system	non-existent
Nominal capacity	non-existent
EER (if available)	non-existent
Lighting equipment	average typologies
Lighting equipment capacity	average typologies
Estimated primary energy consumption	398.3 kWh/m^2

Finally, for the simulation of the EEMs that concern heating and lighting technology change, the following characteristics are used (Abdel-Salam & Simonson, 2016; Du et al., 2017;

"Energuide. Heating and Cooling With a Heat Pump," 2004; Jakob et al., 2019; Sala Lizarraga & Picallo-Perez, 2020):

- EEM_4: COP of the upgraded gas boiler: 1.05
- EEM_5: COP of the upgraded biomass boiler: 0.9
- EEM_6: COP of the heat pump: 3.5, EER of the heat pump: 12.0
- EEM_7: Nominal power of the LED lightings: 10W

5.4 C_9: Transition matrix

The last component parameterised for the needs of the DREEM application in the context of RENOVERTY project concerns "*C_9 Transition matrix*" and specifically, the module concerning the "*scenario space*". The "*scenario space*" is parameterised with data regarding useful exogenous variables to extract meaningful and policy-relevant conclusions on the socioeconomic and environmental implications of the EEMs under study.

To properly calculate the costs and benefits of the different EEMs and estimate the impacts for the vulnerable households under study, pilot partners were asked to provide information regarding investment and energy costs as well as economic and environmental parameters such as interest rates, and emission factors in the different country contexts.

The estimated costs for EEM_1, EEM_2, and EEM_3 in each pilot case are presented in **Table 38**, and for EEM_4, EEM_5, EEM_6, and EEM_7 in **Table 39**.

Table 38. Estimated costs for EEM_1, EEM_2, and EEM_3 in each pilot case (€/m^2) as derived from the pilot partners (Kuusk & Kalamees, 2016; Lakoss, 2024; REPUBLIKA HRVATSKA, 2024).

RENOVERTY pilot country	EEM_1: Exterior wall insulation (€/m^2)	EEM_2: Double-glazed windows (€/m^2)	EEM_3: Roof insulation (€/m^2)
Spain	50	100	50
Italy	50	250	25
Hungary	26	400	22
Croatia	60	350	48
Estonia	83	300	n/a[7]
Slovenia	40	300	18
Portugal	40	350	10

Table 39. Estimated costs for EEM_4, EEM_5, EEM_6, and EEM_7 in each pilot case (€/piece) as derived from the pilot partners.

RENOVERTY pilot country	EEM_4: Energy-efficient heating system (boiler upgrade-gas) (€/piece)	EEM_5: Energy-efficient heating system (boiler upgrade-biomass) (€/piece)	EEM_6: Energy-efficient heating system (heat pump) (€/piece)	EEM_7: Energy-efficient lighting (€/piece)
Spain	1,800	2,600	8,000	5
Italy	750	3,500	6,000	5
Hungary	540	980	400	5
Croatia	3,500	3,700	3,250	5
Estonia	1,000	2,500	5,000	5
Slovenia	2,750	3,500	1,500	5
Portugal	900	2,500	3,000	5

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[7] In the case of Estonia, where we focus only on MFH, EEM_3 is not applicable.

In addition, in order to properly proceed with the technoeconomic assessment of the different EEMs, data from EUROSTAT on the energy prices and interest rates for the different country contexts are utilised (*Electricity Price Statistics - Eurostat Statistics Explained*, 2024; *European Parliament, Discount Rates for Energy Efficiency Measures*, 2015; *Natural Gas Price Statistics - Eurostat Statistics Explained*, 2024). This information is presented in **Table 40**.

Table 40. Data on energy prices and interest rates for the different RENOVERTY country contexts.

RENOVERTY pilot country	Household electricity price (€/kWh)	Household natural gas price (€/kWh)	Household biomass price (€/kWh)	Interest rate (%)
Spain	0.212	0.095	0.031	4.00
Italy	0.290	0.043	0.075	
Hungary	0.090	0.027	0.061	
Croatia	0.117	0.043	0.060	
Estonia	0.175	0.075	0.040	
Slovenia	0.143	0.085	0.084	
Portugal	0.090	0.027	0.061	

Finally, for the analysis of the environmental impacts of each EEM we also took into account the emission factors (kg CO_2/kWh) of the different energy sources (i.e., oil, gas, electricity, and biomass) that are presented in **Table 41**.

Table 41. Data on the emission factors (kg CO_2/kWh) for the different energy sources in the RENOVERTY country contexts (Covenant of Mayors, 2024; Koffi et al., 2017).

RENOVERTY pilot country	Heating oil emission factor (kg CO_2/kWh)	Natural gas emission factor (kg CO_2/kWh)	Biomass emission factor (kg CO_2/kWh)	Electricity emission factor (kg CO_2/kWh)
Spain	0.267	0.202	0.007	0.273
Italy	0.267	0.202	0.007	0.285
Hungary	0.267	0.202	0.007	0.329
Croatia	0.267	0.202	0.007	0.376
Estonia	0.267	0.202	0.007	0.249
Slovenia	0.267	0.202	0.007	0.203
Portugal	0.267	0.202	0.007	0.179

6. Results

In this section, results from the application of the DREEM model to the case studies are presented. The application of the assessment framework required for the classification of the different EEMs regarding their effectiveness to address the needs of energy poor households in the RENOVERTY regions is based on two main assessment criteria, the maximisation of their energy-saving potential and their socioeconomic viability.

In this respect, in the following sections we present the energy profiles of each household typology identified in the current situation, along with quantifications of the impact of the different EEMs to their energy performance.

The analysis of the households' energy performance is complemented with quantifications on the environmental and thermal comfort impacts from the implementation of the different EEMs foreseen in this analysis.

For the quantification of the environmental impacts, kg of CO_2 emissions is used as an indicator based on the emission factors from the different energy sources, presented in **Section 5.4**.

Finally, our analysis is completed with the technoeconomic assessment of the different EEMs under study. The technoeconomic assessment was conducted based on the approach presented in **Section 4.5**, for a series of different subsidy levels.

6.1 Results for the rural region of Osona in Spain

For the case study of the rural region of Osona in Spain, the two household typologies explored concern a SFH equipped with an oil boiler and a typical apartment of a MFH equipped with an oil boiler to cover their heating needs. Detailed specifications of each household typology identified in the rural region of Osona are presented in **Sections 5.2.1**, **5.3 and 5.4**.

6.1.1 Energy performance in the current situation (baseline scenario)

SFH typology

In the baseline scenario, modelling results indicate that the SFH typology in Osona consumes around 31,194.6 kWh annually (almost 228.1kWh/m^2), which are divided into 29,867.0 kWh for its heating needs and 2,079.6 kWh for its cooling and appliances needs (**Figure 10**).

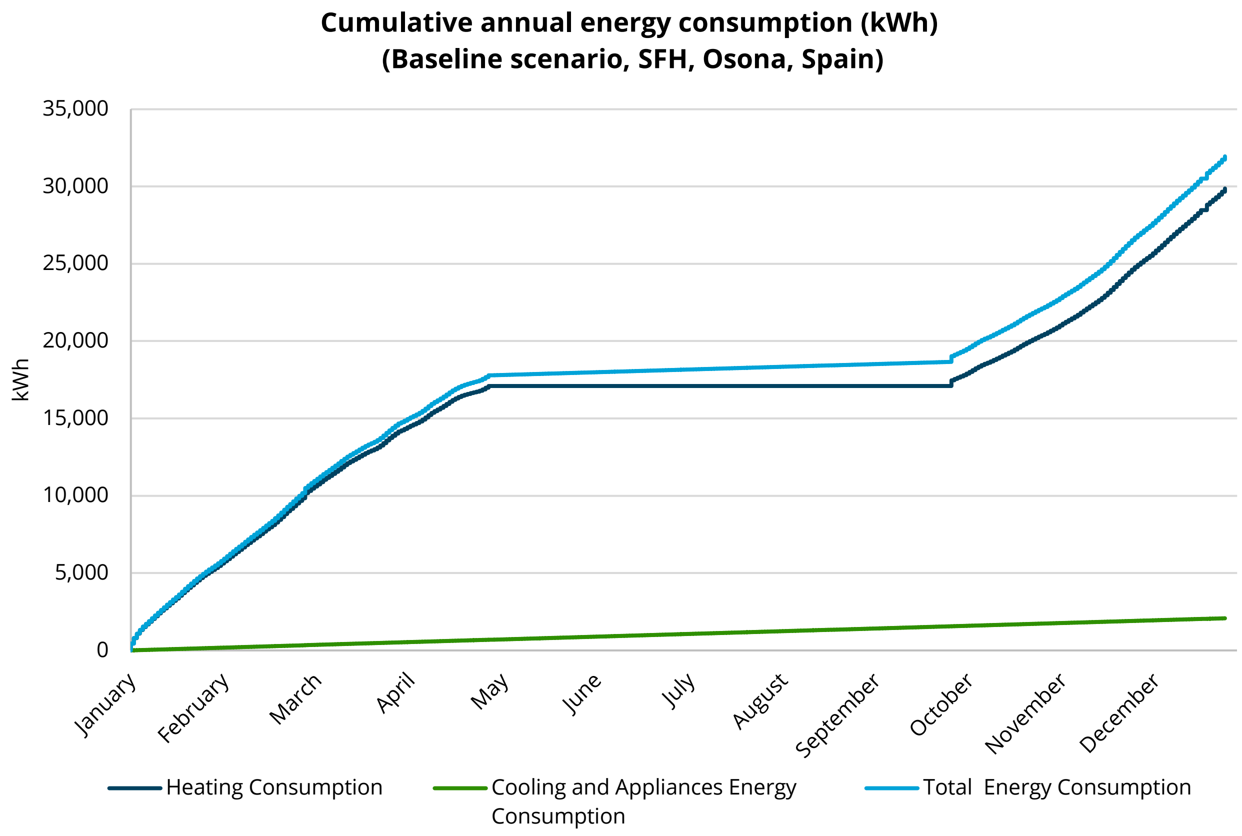

Figure 10. Cumulative annual consumption for the SFH typology in the rural region of Osona in Spain (baseline scenario).

MFH typology

In the baseline scenario, modelling results indicate that the MFH typology in Osona consumes around 20,580.7 kWh annually (almost 205.9 kWh/m^2), which is divided into 15,819.5 kWh for its heating needs and 4,761.3 kWh for its cooling and appliances needs (**Figure 11**).

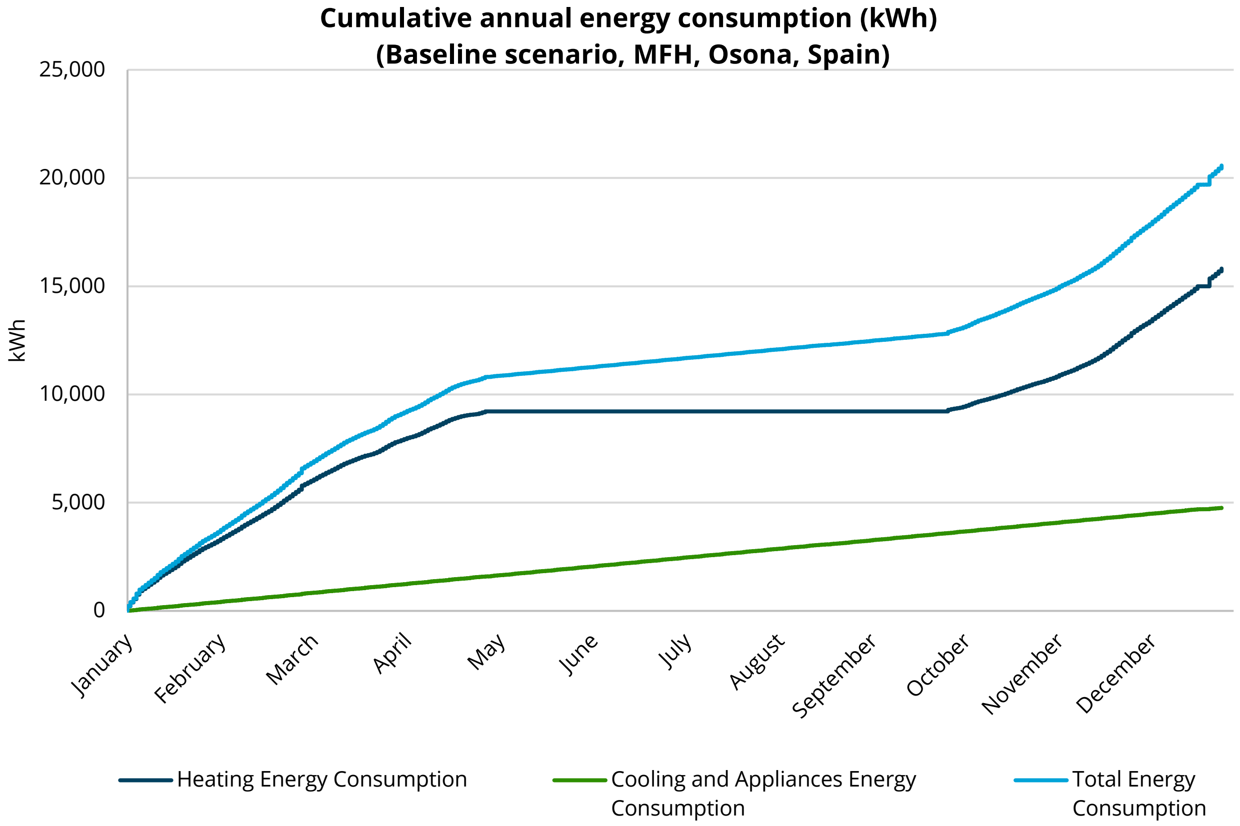

Figure 11. Cumulative annual consumption for the MFH typology in the rural region of Osona in Spain (baseline scenario).

6.1.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology

In the case of the SFH typology in Osona, **Figure 12** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3**. Simulation results indicate that EEM$_6$, which foresees the replacement of the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 8,874.4 kWh. This is followed by EEM$_4$, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 24,835.0 kWh, and EEM$_1$, which entails exterior wall insulation, leading to an annual consumption of 25,140.5 kWh.

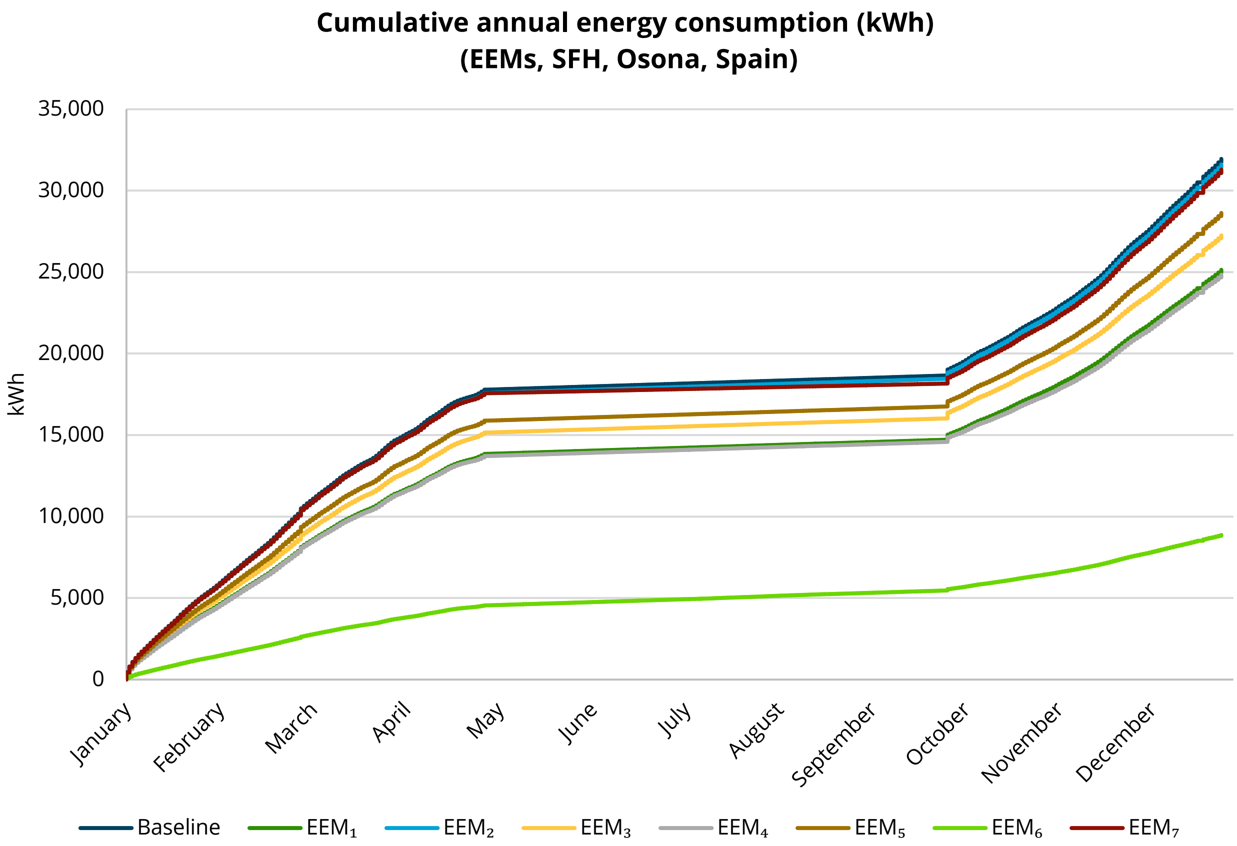

Figure 12. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of Osona in Spain.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 42**. As indicated in **Figure 13**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 23,072.2 kWh per year (72.2% reduction compared to the baseline scenario), while EEM$_4$ leads to 7,111.6 kWh saved annually (22.3% reduction) and EEM$_1$ leads to reducing energy consumption by 6,806.0 kWh per year (21.3%).

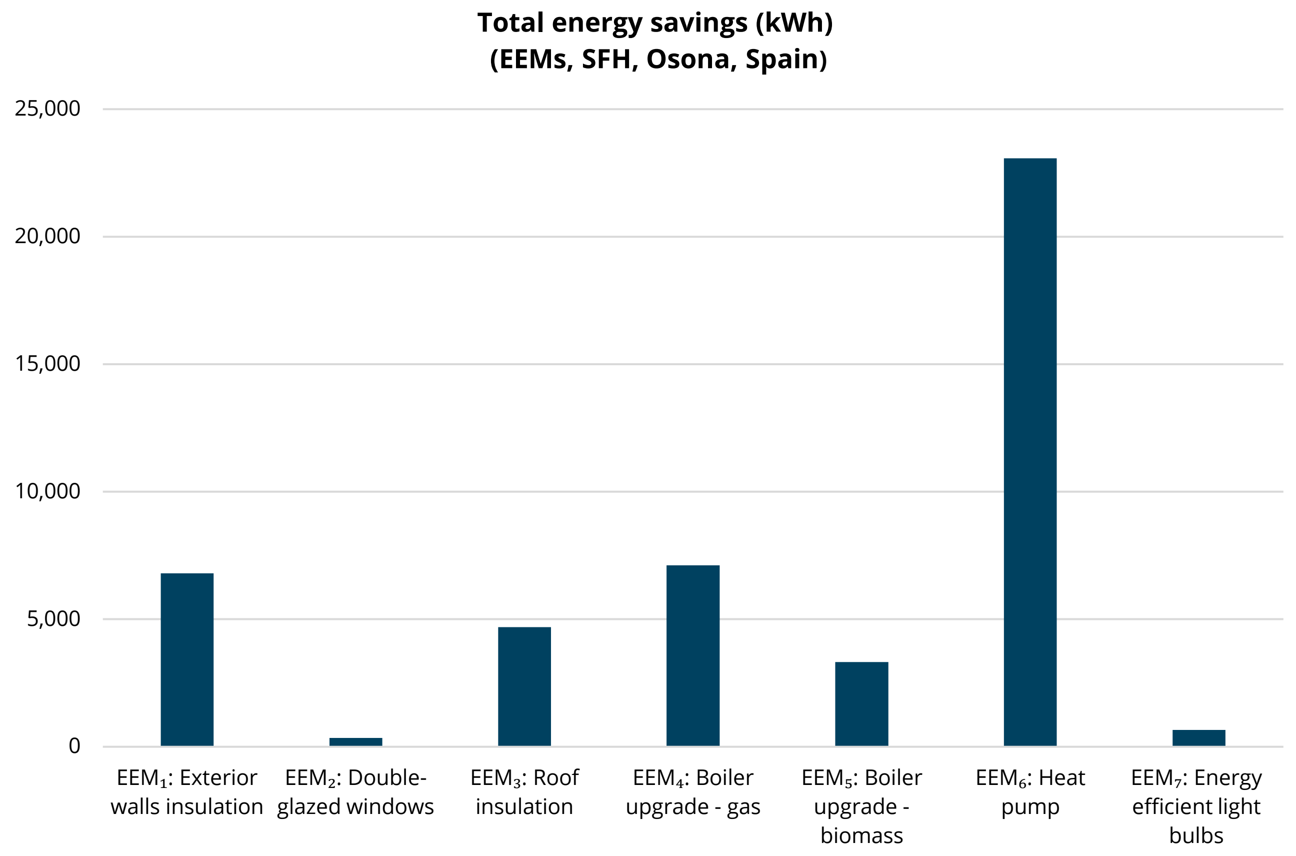

Figure 13. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Osona in Spain.

Table 42. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Osona in Spain.

Annual energy savings (in kWh) for the different EEMs (SFH, Osona, Spain)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	6,806.0	21.3
EEM$_2$: Double-glazed windows	340.8	1.1
EEM$_3$: Roof insulation	4,694.6	14.7
EEM$_4$: Boiler upgrade - gas	7,111.6	22.3
EEM$_5$: Boiler upgrade - biomass	3,318.6	10.4
EEM$_6$: Heat pump	23,072.2	72.2
EEM$_7$: Energy efficient light bulbs	658.2	2.1

MFH typology

In the case of the MFH typology in Osona, **Figure 14** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 8,336.1 kWh. This is followed by EEM$_1$, which entails exterior wall insulation, leading to an annual consumption of 15,466.5 kWh, and EEM$_4$, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 16,815.0 kWh.

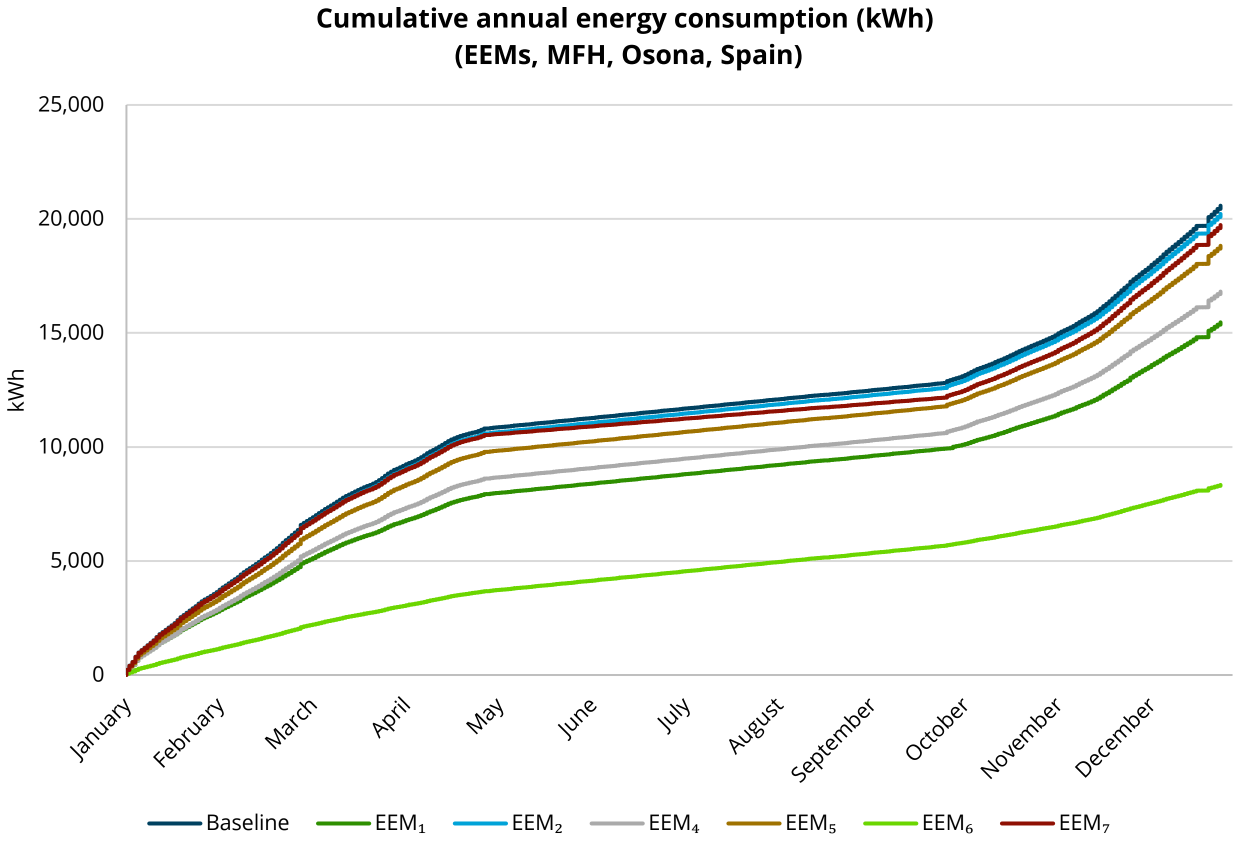

Figure 14. Cumulative annual energy consumption (in kWh) for the different EEMs in the MFH typology in the rural region of Osona in Spain.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 43**. As indicated in **Figure 15**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 12,244.6 kWh per year (59.5% reduction compared to the baseline scenario), while EEM$_1$ leads to 5,114.2 kWh saved annually (24.8% reduction) and EEM$_4$ leads to reducing energy consumption by 3,765.7 kWh per year (18.3%).

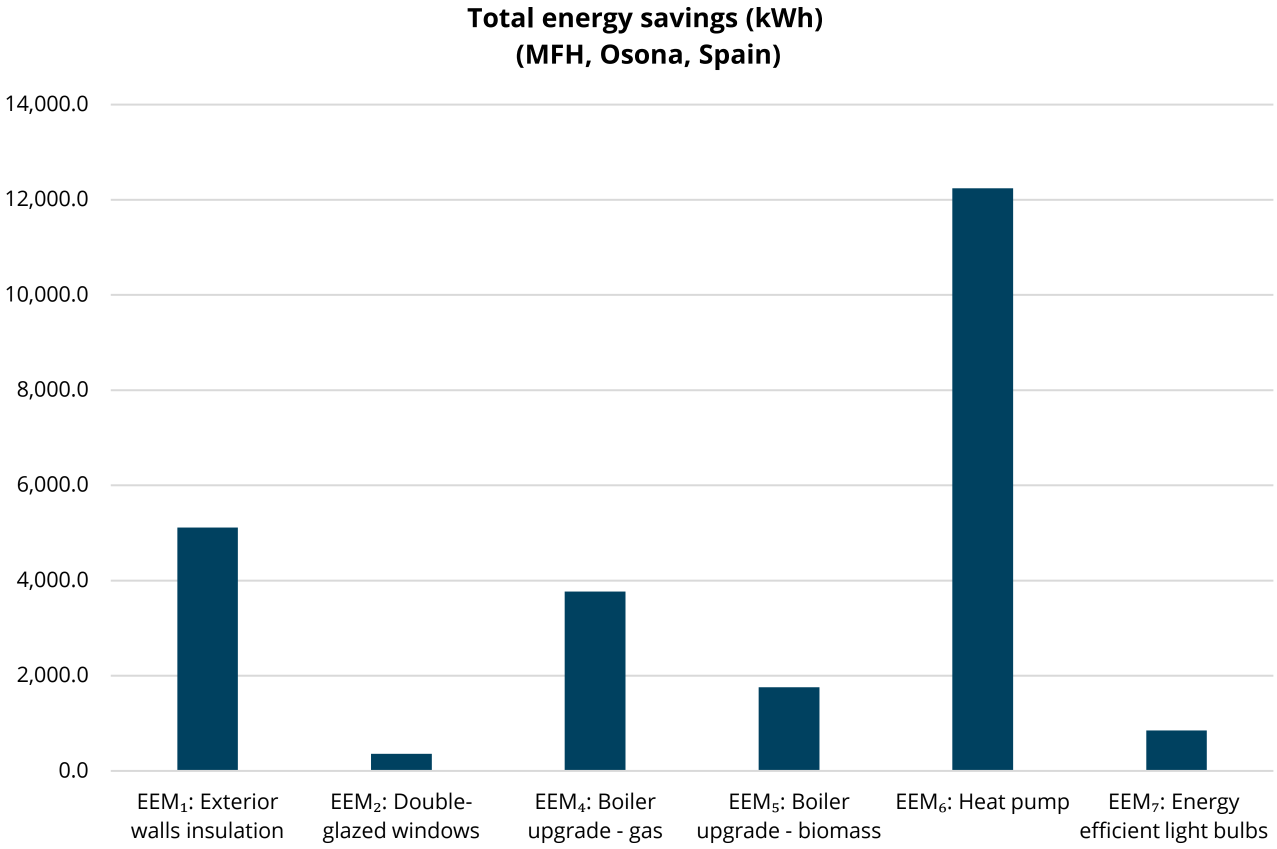

Figure 15. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Osona in Spain.

Table 43. Comparison of annual total energy savings (kWh) for all EEMs with baseline in Spain MFH typology.

Annual energy savings (kWh) (MFH, Osona, Spain)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	5,114.2	24.8
EEM$_2$: Double-glazed windows	360.6	1.8
EEM$_4$: Boiler upgrade - gas	3,765.7	18.3
EEM$_5$: Boiler upgrade - biomass	1,757.9	8.5
EEM$_6$: Heat pump	12,244.6	59.5
EEM$_7$: Energy efficient light bulbs	847.3	4.1

6.1.3 Environmental impact and thermal comfort analysis

SFH typology

CO_2 footprint

Figure 16 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of Osona in Spain for the SFH typology. We can observe that EEM_6 leads to the highest emissions reduction, leading to the avoidance of almost 6,221.5 kg CO_2 per year, followed by EEM_5 and EEM_4 which lead to an avoidance of around 4,898.2 and 3,968.1 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 44**.

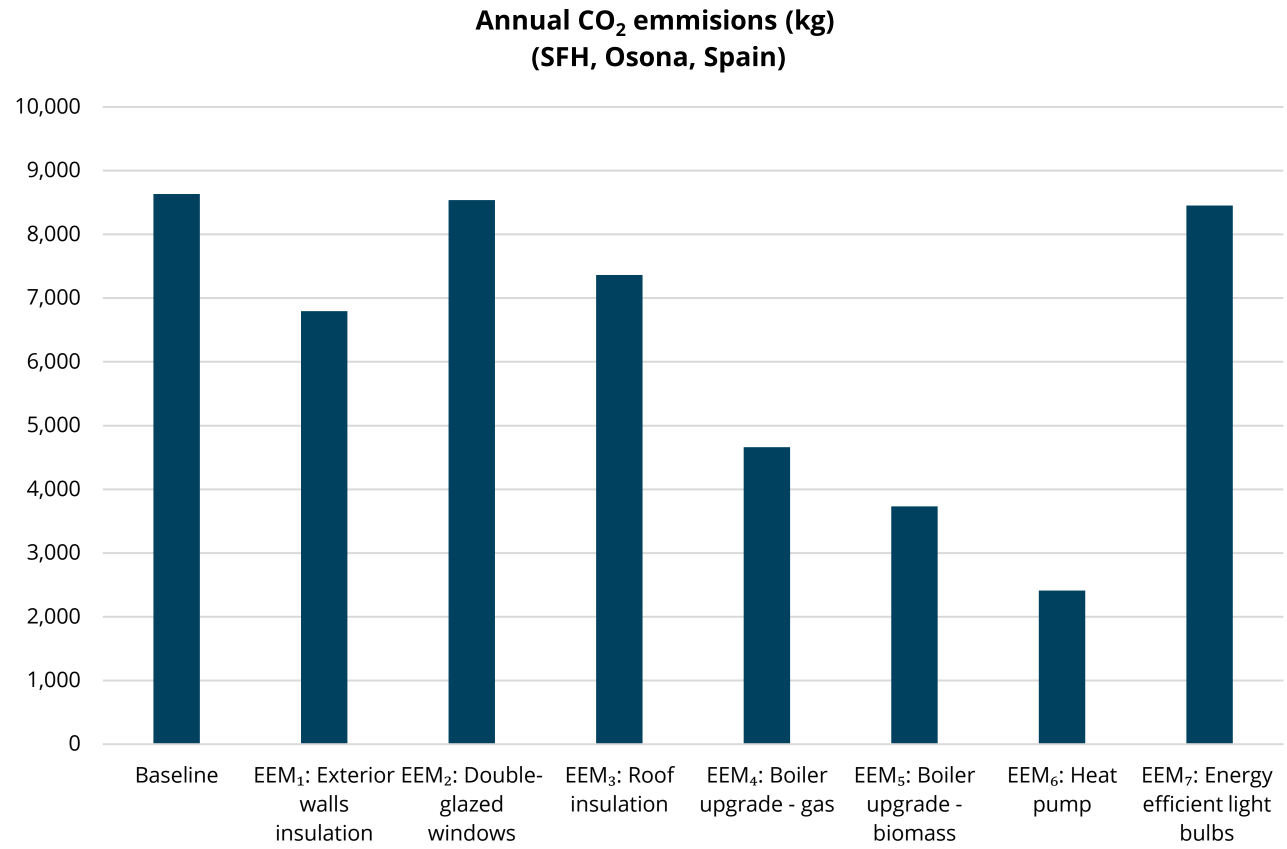

Figure 16. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of Osona in Spain.

Table 44. Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of Osona in Spain.

Annual CO_2 emissions avoided (SFH, Osona, Spain)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,837.6	21.3
EEM_2: Double-glazed windows	92.0	1.1
EEM_3: Roof insulation	1,267.5	14.7
EEM_4: Boiler upgrade - gas	3,968.1	46.0
EEM_5: Boiler upgrade - biomass	4,898.2	56.7
EEM_6: Heat pump	6,221.5	72.1
EEM_7: Energy efficient light bulbs	177.7	2.1

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 17** indicate that the heating needs of the households are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs on energy use can be examined while maintaining consistent thermal comfort levels.

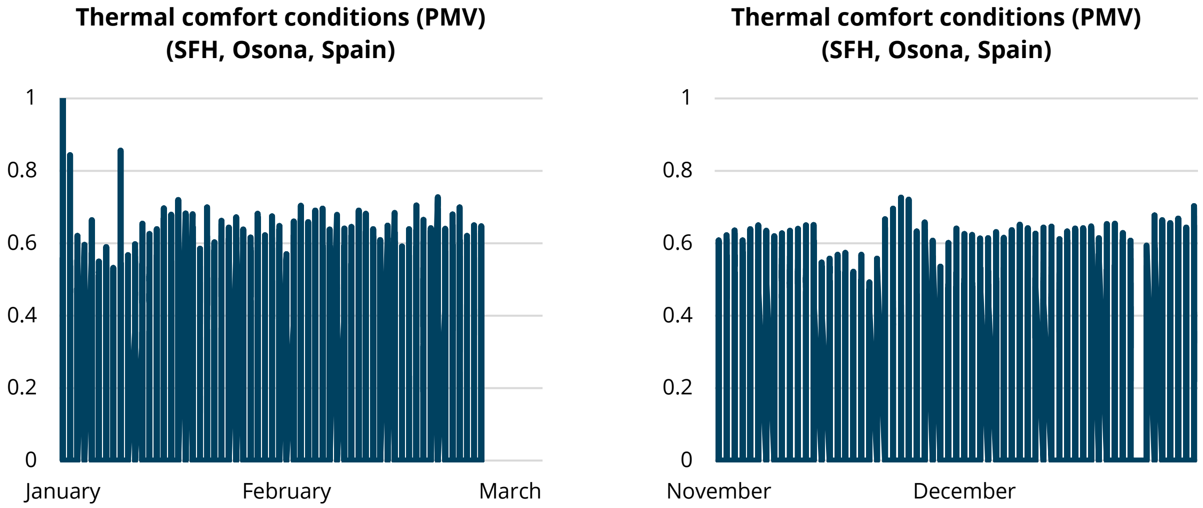

Figure 17. Thermal comfort as indicated by the PMV indicator during the winter for all the scenarios under study in the SFH typology in the rural region of Osona in Spain.

MFH typology

CO_2 footprint

Figure 18 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of Osona in Spain for the MFH typology. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 4,018.1 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 3,295.3 and 2,101.6 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 45**.

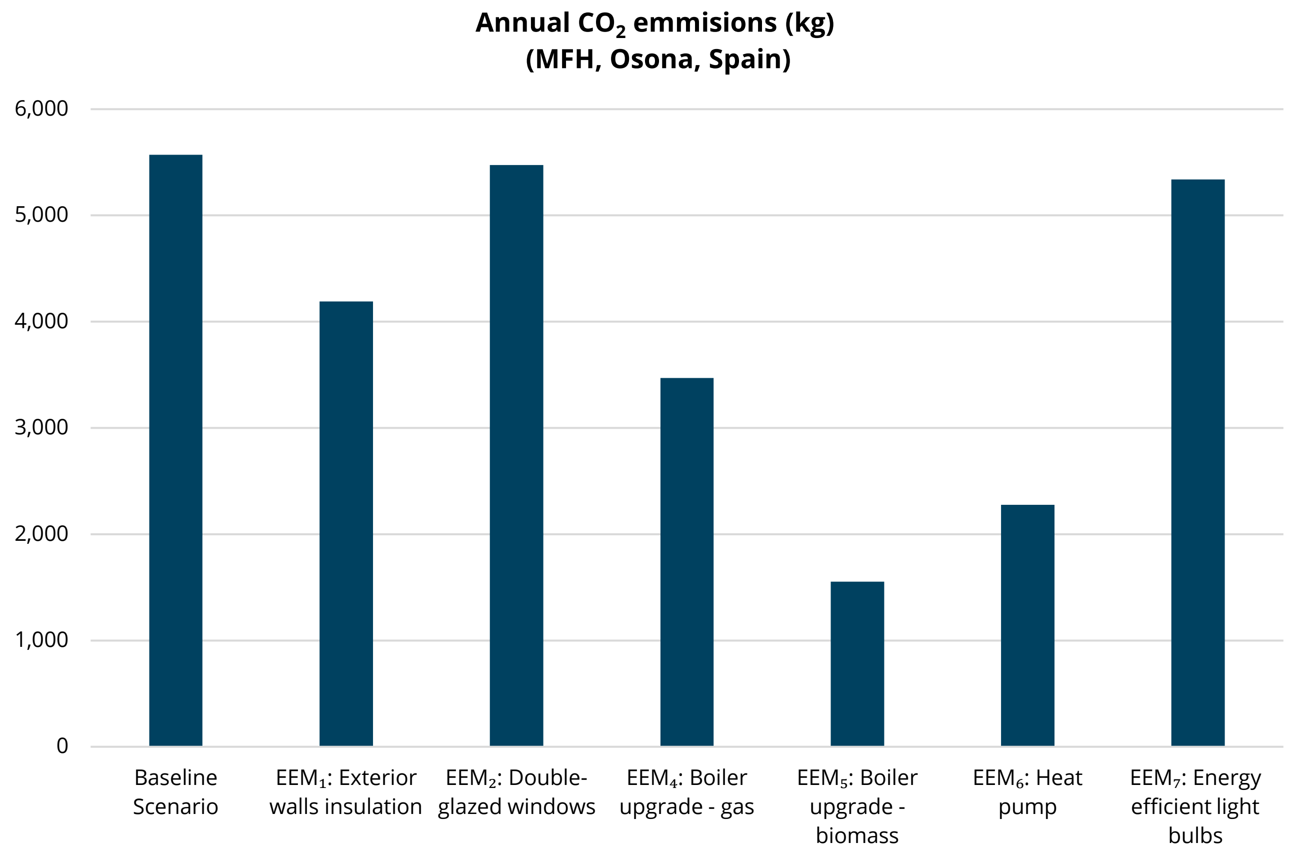

Figure 18. Annual CO_2 emissions (kg) in all scenarios in the MFH typology in the rural region of Osona in Spain.

Table 45. Annual CO_2 emissions avoided (kg) for the different EEMs in the MFH typology in the rural region of Osona in Spain.

Annual emissions avoided (kg CO_2) **(MFH, Osona, Spain)**		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,380.8	24.8
EEM_2: Double-glazed windows	97.4	1.7
EEM_4: Boiler upgrade - gas	2,101.6	37.7
EEM_5: Boiler upgrade - biomass	4,0181.1	72.1
EEM_6: Heat pump	3,295.3	59.2
EEM_7: Energy efficient light bulbs	231.3	4.2

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 19** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEM scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

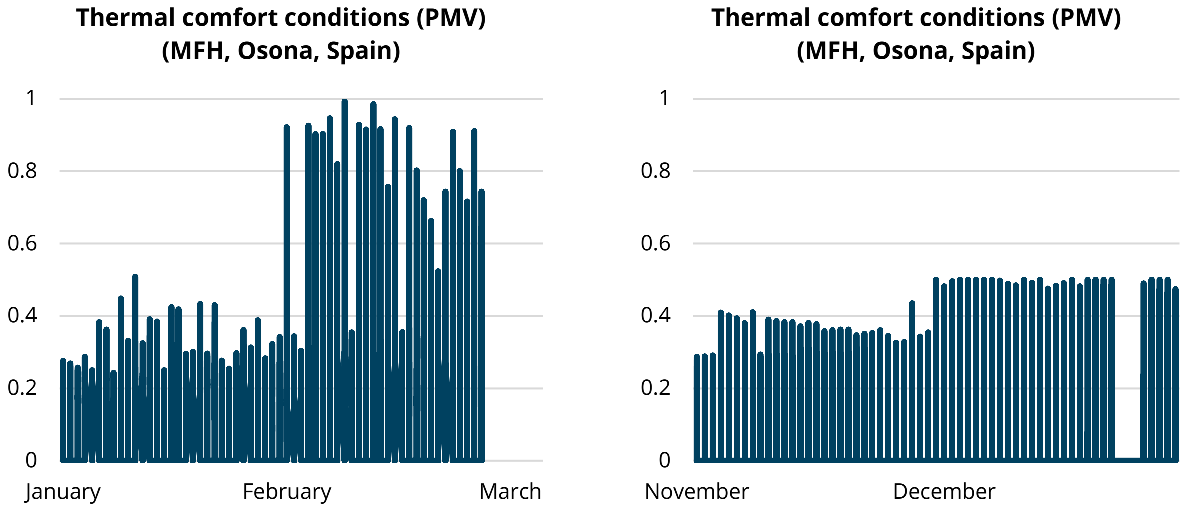

Figure 19. Thermal comfort as indicated by the PMV indicator during the winter for all the scenarios under study in the MFH typology in the rural region of Osona in Spain.

6.1.4 Technoeconomic assessment

SFH typology

The results of the technoeconomic assessment of the different EEMs for the SFH typology in the rural region of Osona in Spain, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 46**.

According to the analysis, EEM$_5$ (Boiler upgrade- biomass) and EEM$_6$ (Heat pump) demonstrate the best performance in terms of NPV, with NPVs of 42,646.2€ and 28,600.1€, respectively. EEM$_7$ (Energy efficient light bulbs) and EEM$_4$ (Boiler upgrade - gas) result in the lowest LCSE, at 0.007€/kWh and 0.019€/kWh, respectively. Additionally, EEM$_7$ and EEM$_5$ exhibit the best performance in PP, with 0.5 and 0.8 years, respectively.

The substantial profitability provided of all EEMs highlights the poor performance of the current energy situation and underscores the urgent need for rural households in Osona to implement energy efficiency interventions. In addition, the higher profitability of EEMs that focus on changing to a more energy efficient heating technology indicates the urgent need for the building stock of Osona to transition from oil to other energy sources. This shift is crucial not only for improving energy performance but also for enhancing environmental sustainability. By adopting alternative energy sources, households can benefit from both reduced energy consumption and a lower environmental impact, leading to overall improved efficiency and ecological health.

Table 46. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Osona in Spain (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	9,583	30	4.00%	6,705.8	13.3	0.081
EEM_2	553	30	4.00%	262.7	16.1	0.094
EEM_3	2,917	30	4.00%	8,318.8	5.0	0.036
EEM_4	1,800	20	4.00%	24,997.8	0.9	0.019
EEM_5	2,600	20	4.00%	42,646.2	0.8	0.058
EEM_6	8,000	20	4.00%	28,600.1	3.2	0.026
EEM_7	65	23	4.00%	2,008.1	0.5	0.007

Table 47, **Table 48**, and **Table 49** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs.

Table 47. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Osona in Spain (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	9,583	25%	30	4.00%	9,101.4	9.3	0.061
EEM_2	553		30	4.00%	400.9	11.1	0.070
EEM_3	2,917		30	4.00%	9,047.9	3.7	0.027
EEM_4	1,800		20	4.00%	25,447.8	0.7	0.014
EEM_5	2,600		20	4.00%	43,114.2	0.6	0.043
EEM_6	8,000		20	4.00%	30,600.1	2.4	0.019
EEM_7	65		23	4.00%	2,024.4	0.4	0.005

Table 48. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Osona in Spain (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	9,583	50%	30	4.00%	11,497.1	5.8	0.041
EEM_2	553		30	4.00%	539.2	6.8	0.047
EEM_3	2,917		30	4.00%	9,777.0	2.4	0.018
EEM_4	1,800		20	4.00%	25,597.9	0.5	0.009
EEM_5	2,600		20	4.00%	43,764.2	0.4	0.029
EEM_6	8,000		20	4.00%	32,600.1	1.6	0.013
EEM_7	65		23	4.00%	2,040.6	0.2	0.003

Table 49. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Osona in Spain (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	9,583	75%	30	4.00%	13,892.69	2.7	0.020
EEM$_2$	553		30	4.00%	677.44	3.2	0.023
EEM$_3$	2,917		30	4.00%	10,506.14	1.2	0.009
EEM$_4$	1,800		20	4.00%	26,347.83	0.2	0.005
EEM$_5$	2,600		20	4.00%	44,414.17	0.2	0.014
EEM$_6$	8,000		20	4.00%	34,600.13	0.8	0.006
EEM$_7$	65		23	4.00%	2,056.896	0.1	0.002

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 20**, the replacement of the current heating system with an energy-efficient heat pump (EEM$_6$) is the most cost-effective measure (energy savings: 23,072.2 kWh/year, LCSE: 0.026 €/kWh). On the contrary, EEM$_2$ (Double-glazed windows) is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings.

Overall, EEM$_6$, EEM$_4$, and EEM$_3$ are indicated as the most cost-effective measures, as they combine a significant energy-saving potential with lower investment costs, while EEM$_1$ and EEM$_2$, are the ones that are ranked lower in terms of cost-effectiveness, mainly because of the higher investment costs, indicating the need for relevant incentives and initiatives aiming to lower the investments costs and increase their cost-effectiveness.

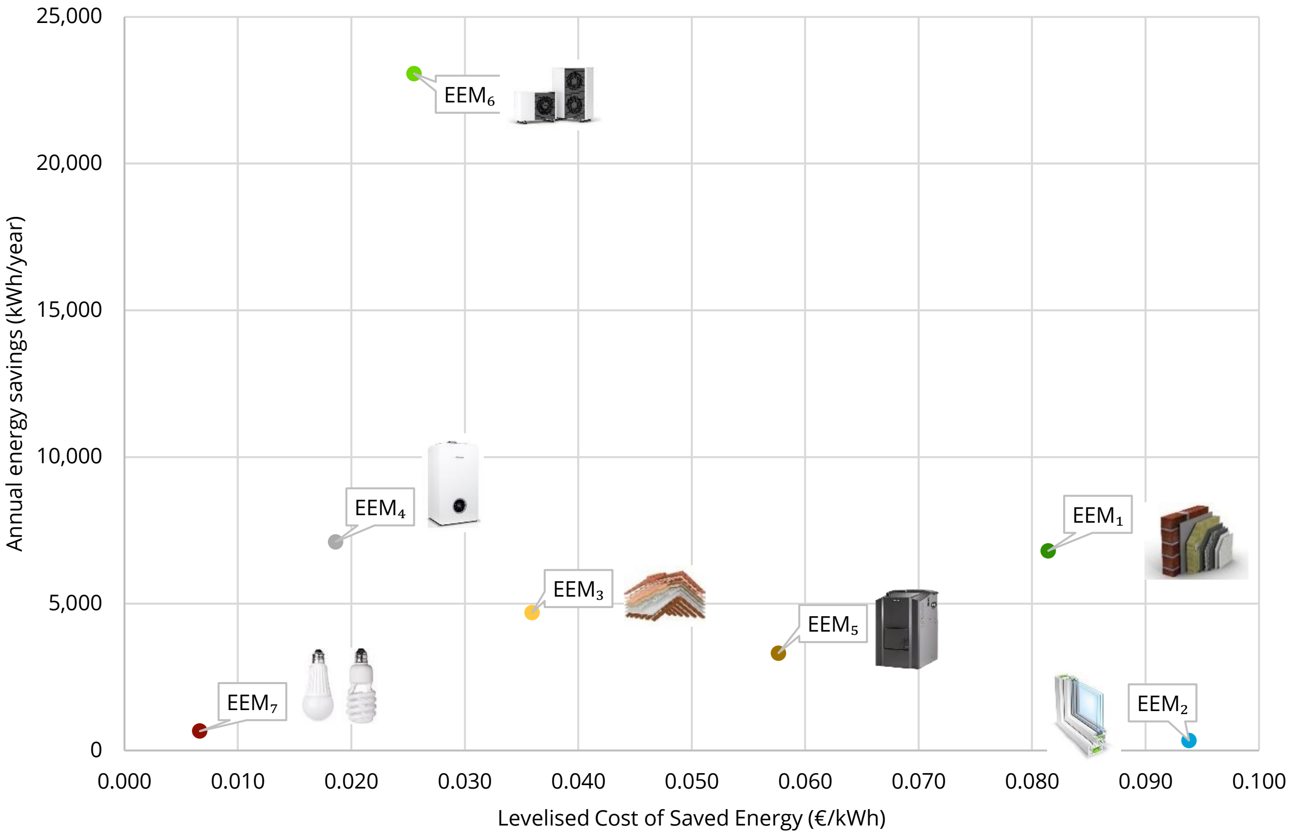

Figure 20. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Osona in Spain.

Additionally, we seek to analyse the correlation between profitability and cost-effectiveness of the different EEMs under study. **Figure 21** indicates that EEM_5 (Boiler upgrade- biomass) and EEM_6 (Heat pump) rank highest, offering substantial profitability with NPVs of 42,646€ and 28,600€, respectively, and demonstrating strong cost-efficiency in energy savings. The strong effect of local economic dynamics regarding fuel pricing is evident, as EEM_5 despite having significantly lower energy-saving potential and cost-effectiveness than EEM_6, it performs better in terms of profitability. This highlights the need for subsidisation of heat pumps to incentivise households to electrify their dwelling. In contrast, EEM_1 and EEM_2 rank lowest, with lower NPVs and higher LCSEs, indicating less attractive investments, and highlighting the need for their subsidisation. Notably, EEM7 (Energy-efficient light bulbs) has the lowest LCSE of 0.007€/kWh, highlighting its exceptional cost-efficiency despite a modest NPV.

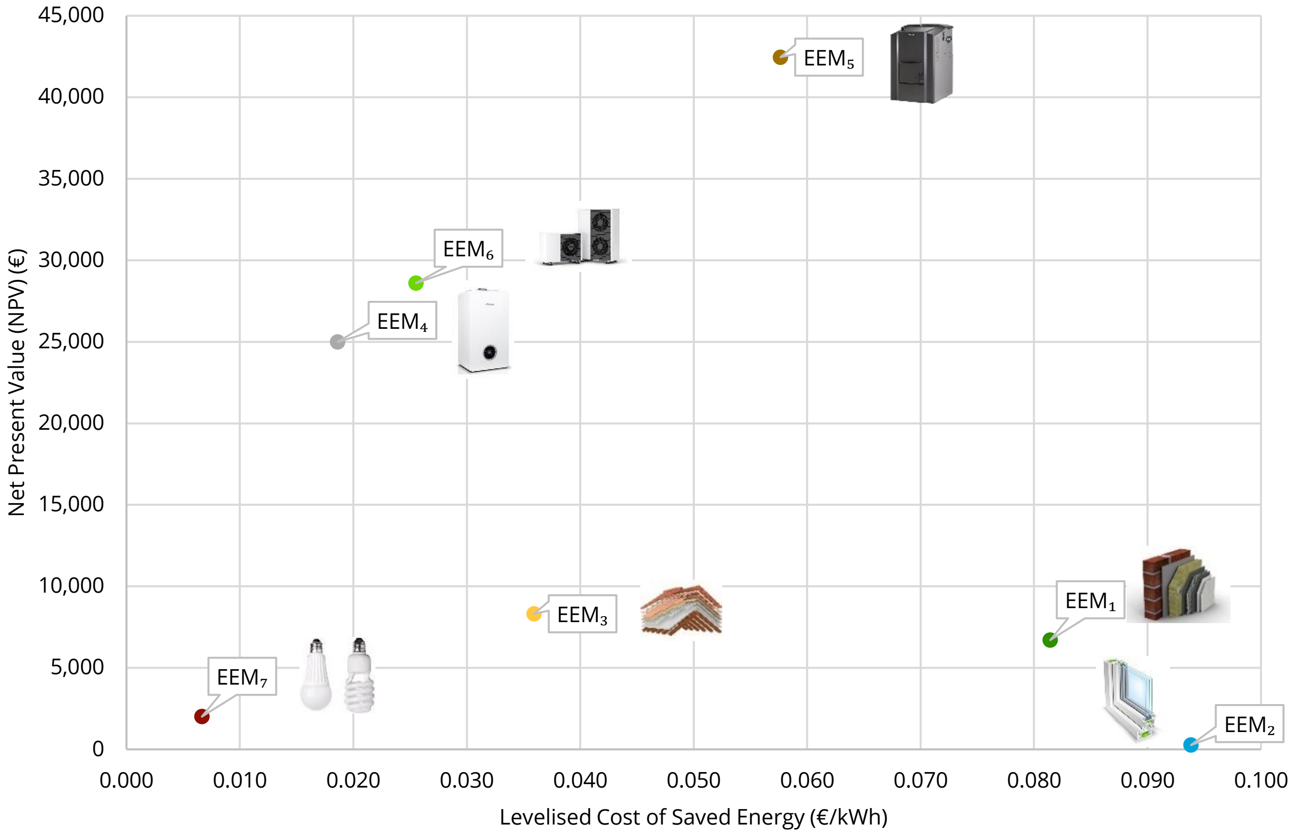

Figure 21. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Osona in Spain.

The same ranking among the different EEMs is observed in the case of the various of subsidisation levels (i.e., 25%, 50%, and 75%) leading to increased economic viability, due to the lower LCSEs and the higher NPVs, for the same amount of energy savings achieved.

MFH typology

The results of the technoeconomic assessment of the different EEMs for the MFH typology in the rural region of Osona in Spain, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 50**.

According to the analysis, EEM$_5$ (Boiler upgrade- biomass) and EEM$_4$ (Boiler upgrade- gas) demonstrate the best performance in terms of NPV, with NPVs of 21,269.0€ and 16,258.2€, respectively. EEM$_7$ (Energy efficient light bulbs) and EEM$_1$ (Exterior wall insulation) result in the lowest LCSE, at 0.007€/kWh and 0.027€/kWh, respectively. Additionally, EEM$_7$ and EEM$_5$ exhibit the best performance in PP, with 0.5 and 1.6 years, respectively.

The substantial economic benefits provided by all EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Osona to implement energy efficiency interventions. As in the case of the SFH typology, the higher profitability of EEMs that focus on changing to a more energy efficient heating technology indicates the urgent need for the building stock of Osona to transit from oil to other energy sources. This shift is crucial not only for improving energy performance but also for enhancing environmental sustainability. By adopting alternative energy sources, households can benefit from both reduced energy consumption and a lower environmental impact, leading to overall improved efficiency and ecological health.

Table 50. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Osona in Spain (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	2,387	30	4.00%	9,852.4	3.7	0.027
EEM_2	612	30	4.00%	251.0	17.2	0.098
EEM_4	1,800	20	4.00%	16,258.2	1.8	0.028
EEM_5	2,600	20	4.00%	21,269.0	1.6	0.109
EEM_6	8,000	20	4.00%	11,455.2	6.5	0.048
EEM_7	80	23	4.00%	2,361.1	0.5	0.007

Table 51, **Table 52**, and **Table 53** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs.

Table 51. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Osona in Spain (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	1,790	25%	30	4.00%	10,449.2	2.7	0.020
EEM$_2$	459		30	4.00%	404.0	11.7	0.074
EEM$_4$	1,350		20	4.00%	16,708.2	1.4	0.021
EEM$_5$	1,950		20	4.00%	21,918.9	1.2	0.082
EEM$_6$	6,000		20	4.00%	13,455.2	4.7	0.036
EEM$_7$	60		23	4.00%	2,381.1	0.3	0.005

Table 52. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Osona in Spain (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	1,790	50%	30	4.00%	11,045.9	1.7	0.013
EEM$_2$	459		30	4.00%	557.0	6.1	0.049
EEM$_4$	1,350		20	4.00%	17,158.2	0.9	0.014
EEM$_5$	1,950		20	4.00%	22,269.0	0.7	0.054
EEM$_6$	6,000		20	4.00%	15,455.2	3.0	0.024
EEM$_7$	60		23	4.00%	2,401.1	0.2	0.003

Table 53. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Osona in Spain (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	1,790	75%	30	4.00%	11,642.7	0.9	0.007
EEM_2	459		30	4.00%	710.0	3.3	0.025
EEM_4	1,350		20	4.00%	17,608.2	0.4	0.007
EEM_5	1,950		20	4.00%	23,219.0	0.4	0.027
EEM_6	6,000		20	4.00%	17,455.2	1.5	0.012
EEM_7	60		23	4.00%	2,421.1	0.1	0.002

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 22**, the replacement of the current heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 12,244.6 kWh/year, LCSE: 0.048 €/kWh). On the contrary, EEM_2 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall, EEM_6, EEM_1, and EEM_4 are identified as the most cost-effective measures, indicating the importance of focusing on relevant investments, while EEM_5 and EEM_2 are the ones that are ranked lower in terms of cost-effectiveness, indicating the need for incentives and initiatives that can increase their cost-effectiveness.

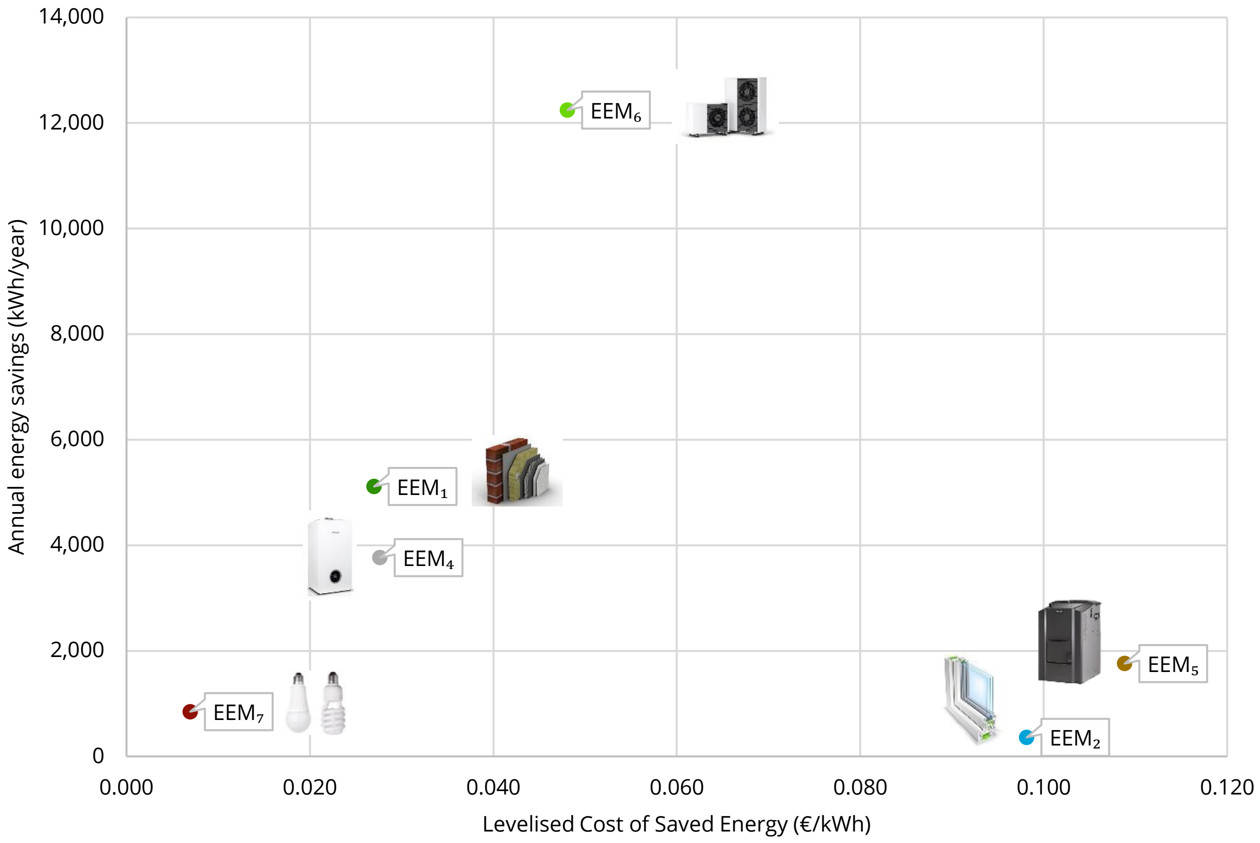

Figure 22. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Osona in Spain.

Additionally, we seek to identify the correlation between NPV and cost-effectiveness of the different EEMs under study. **Figure 23** indicates that EEM$_4$ (Boiler upgrade- gas) and EEM$_6$ (Heat pump) rank highest, offering substantial profitability with NPVs of 16,258€ and 11,455€ respectively, while demonstrating strong cost-effectiveness in energy savings. As in the case of the SFH typology, this highlights the strong effect of local economic dynamics regarding fuel pricing, as despite having significantly lower energy-saving potential and higher LCSE than EEM$_6$, EEM$_5$ performs better in terms of profitability. In contrast, EEM$_2$ ranks lowest, with lower NPVs and higher LCSE, indicating less attractive investment. Notably, EEM$_5$ (Boiler upgrade- biomass) presents high NPV and high LCSE, while EEM$_7$ (Energy efficient light bulbs) has the lowest LCSE of 0.007€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV. These results underscore the varying economic impacts and energy-saving potential of the EEMs under consideration.

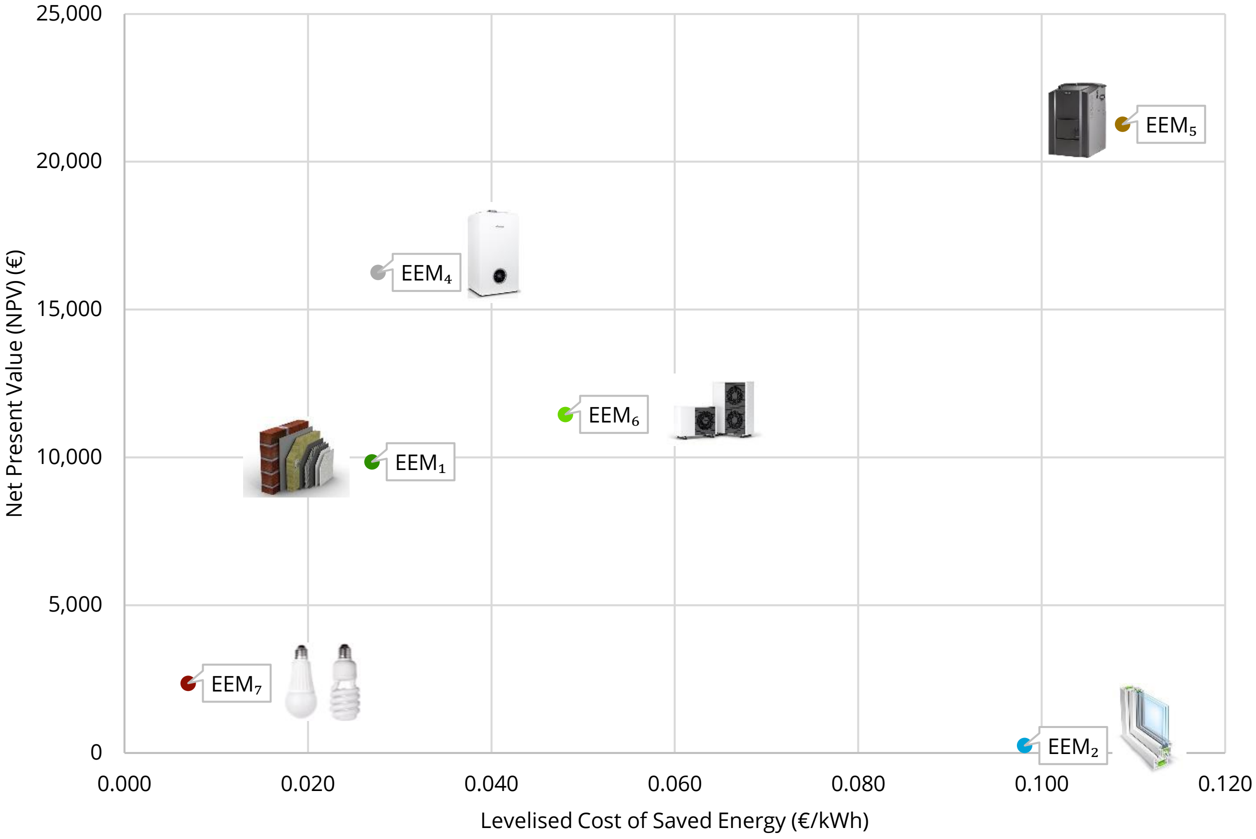

Figure 23. Profitability and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Osona in Spain.

The same ranking is observed in the case of the different of subsidisation levels leading to increased cost-effectiveness, due to the lower LCSEs and the higher NPVs, for the same amount of energy savings achieved.

6.2 Results for the rural region of Parma in Italy

For the case study of the rural region of Parma in Italy, the two household typologies explored concern a SFH equipped with a gas boiler and a typical apartment of a MFH equipped with a gas boiler to cover their heating needs. Detailed specifications of each household typology identified in the rural region of Parma are presented in **Sections 5.2.2**, **5.3**, and **5.4**.

6.2.1 Energy performance in the current situation (baseline scenario)

SFH typology

In the baseline scenario, modelling results indicate that the SFH typology in Parma consumes around 27,930.8 kWh annually (almost 247.4 kWh/m^2), which are divided into 23,763.0 kWh for its heating needs and 4,167.8 kWh for its cooling and appliances needs (**Figure 24**).

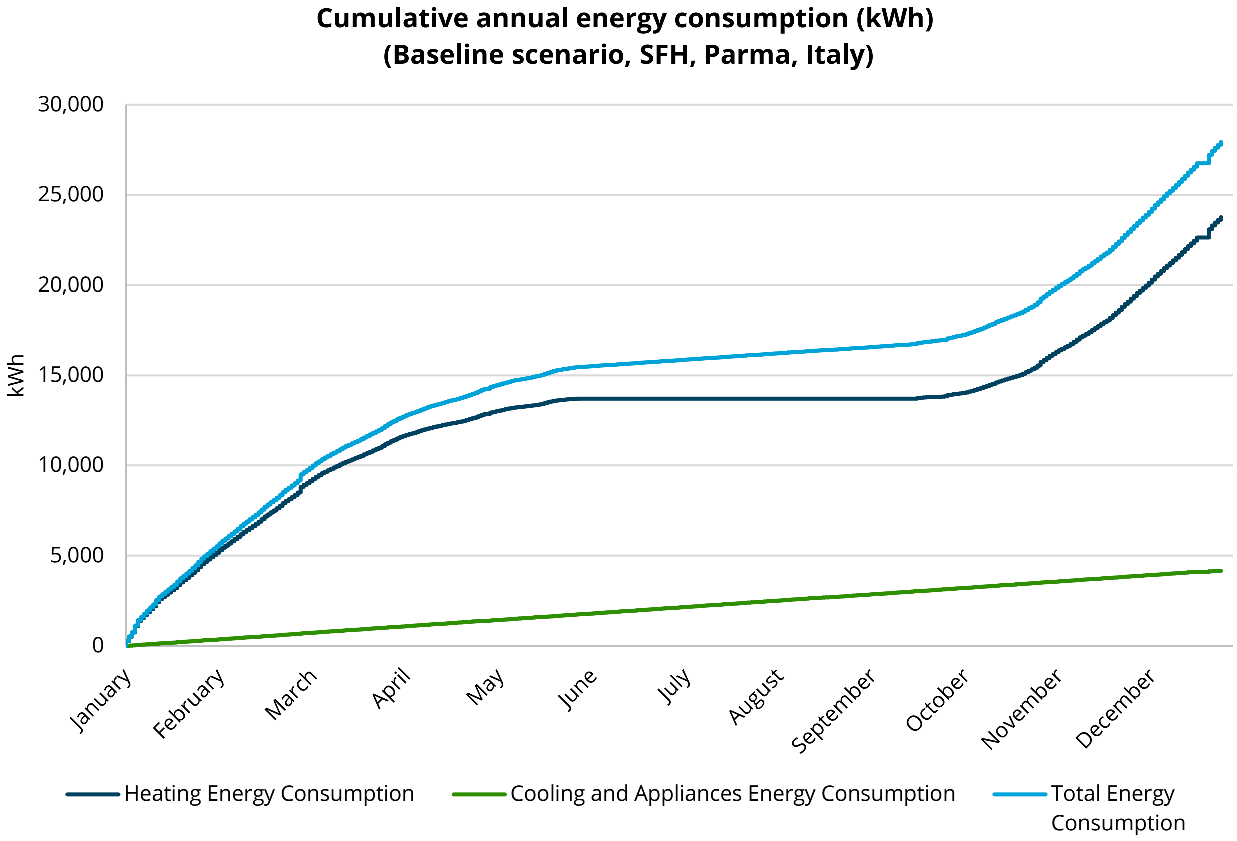

Figure 24. Cumulative annual consumption for the SFH typology in the rural region of Parma in Italy (baseline scenario).

MFH typology

In the baseline scenario, modelling results indicate that the MFH typology in Parma consumes around 25,855.8 kWh annually (almost 236.6 kWh/m^2), which is divided into 21,420.4 kWh for its heating needs and 4,435.3 kWh for its cooling and appliances needs (**Figure 25**).

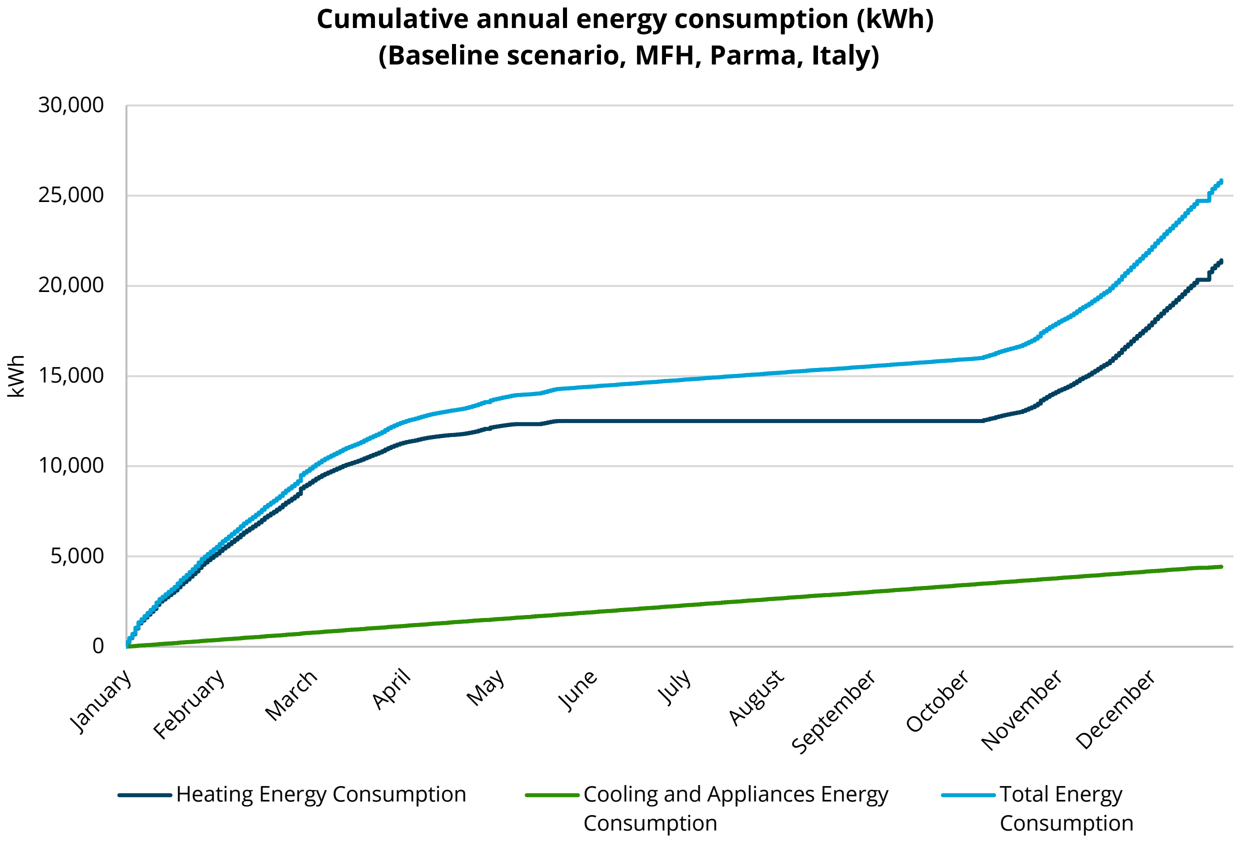

Figure 25. Cumulative annual consumption for the MFH typology in the rural region of Parma in Italy (baseline scenario).

6.2.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology

In the case of the SFH typology in Parma, **Figure 26** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 10,172.8 kWh. This is followed by EEM$_3$, the insulation of the roof, with an annual energy consumption of 17,114.4 kWh, and EEM$_1$, which entails external walls' insulation, leading to an annual consumption of 23,219.7 kWh.

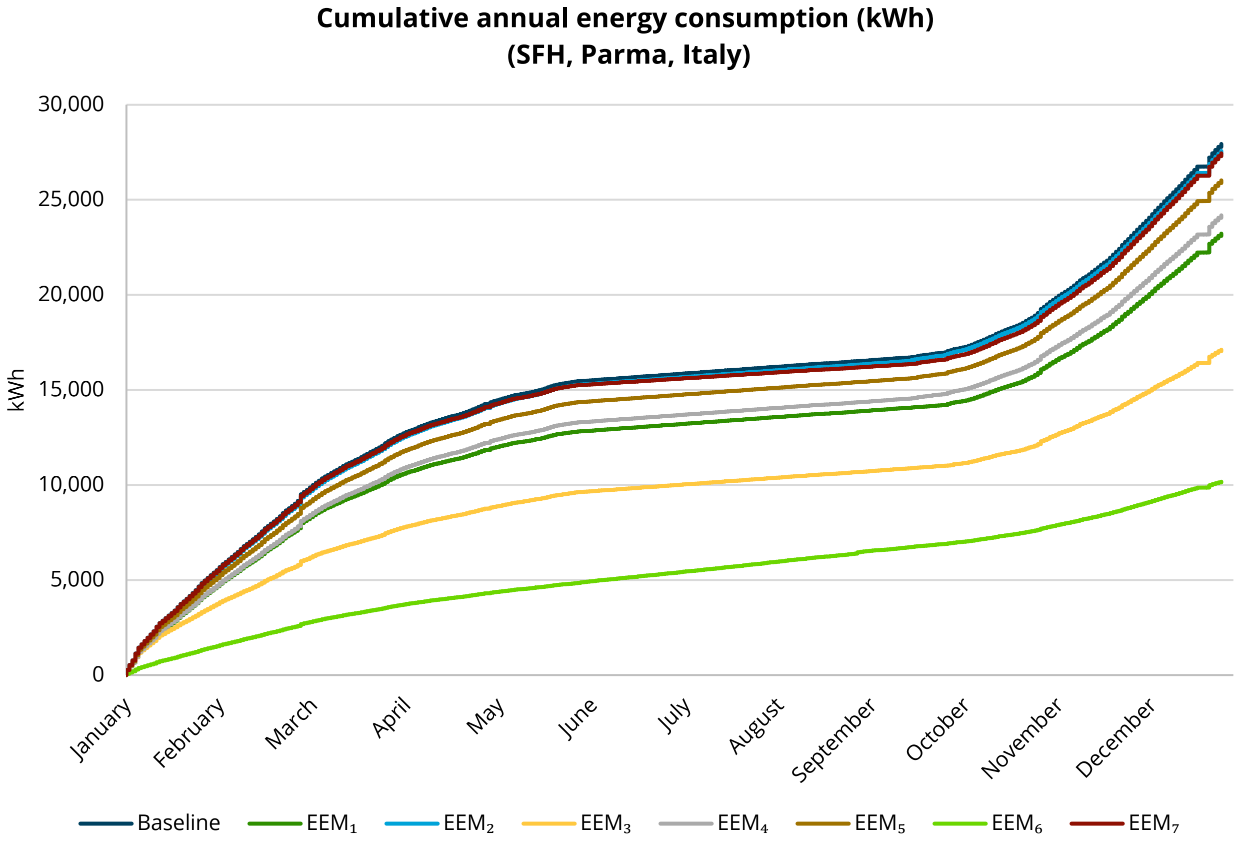

Figure 26. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of Parma in Italy.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 54**. As indicated in **Figure 27**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 17,758.0 kWh per year (63.6% reduction compared to the baseline scenario), while EEM$_3$ leads to 10,816.4 kWh saved annually (38.7% reduction) and EEM$_1$ leads to reducing energy consumption by 4,711.1 kWh per year (16.9% reduction).

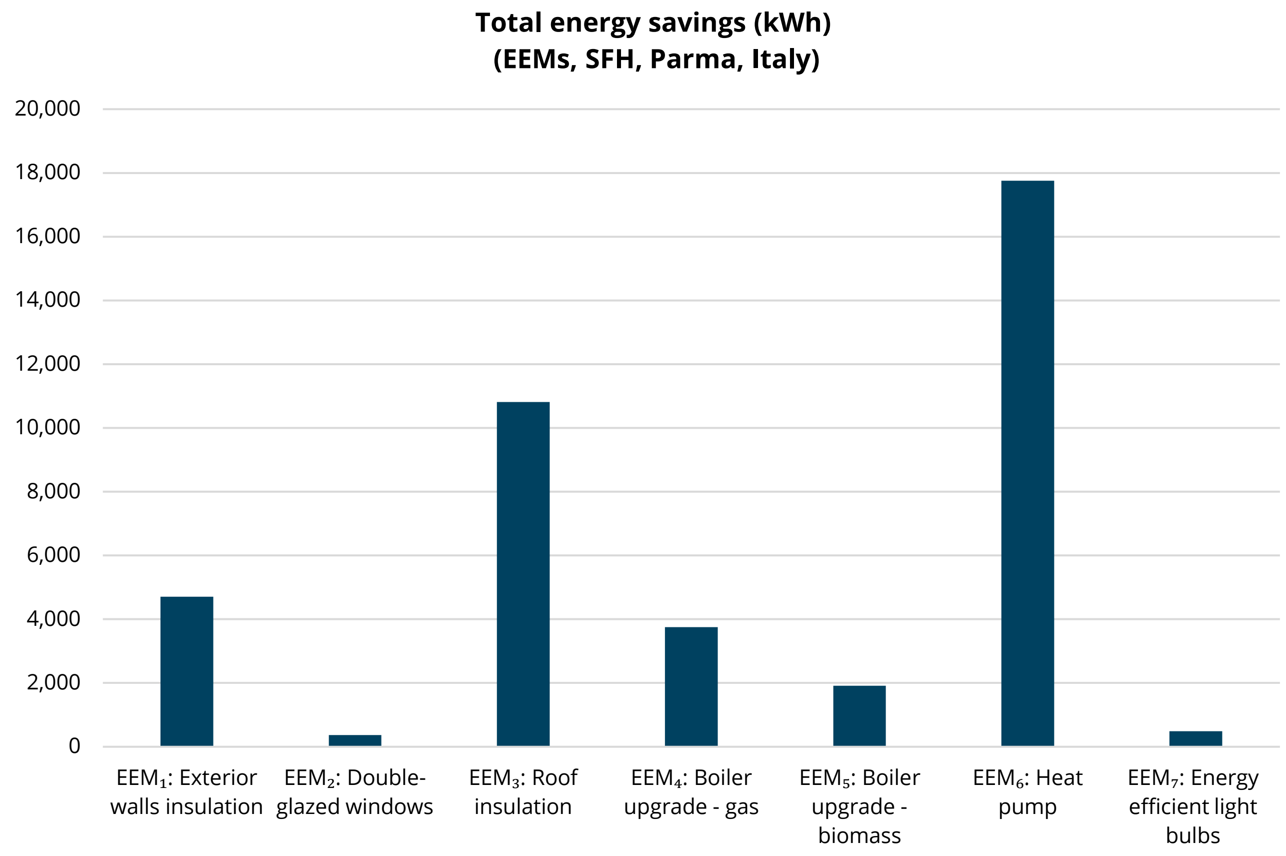

Figure 27. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Parma in Italy.

Table 54. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Parma in Italy.

Annual energy savings (in kWh) for the different EEMs (SFH, Parma, Italy)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	4,711.1	16.9
EEM$_2$: Double-glazed windows	367.5	1.3
EEM$_3$: Roof insulation	10,816.4	38.7
EEM$_4$: Boiler upgrade - gas	3,751.0	13.4
EEM$_5$: Boiler upgrade - biomass	1,912.1	6.8
EEM$_6$: Heat pump	17,758.0	63.6
EEM$_7$: Energy efficient light bulbs	490.5	1.8

MFH typology

In the case of the MFH typology in Parma, **Figure 28** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, resulting in the lowest annual cumulative consumption of 10,159.1 kWh. This is followed by EEM$_1$, which entails exterior wall insulation, leading to an annual consumption of 17,432.6 kWh, and EEM$_4$, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 22,179.9 kWh.

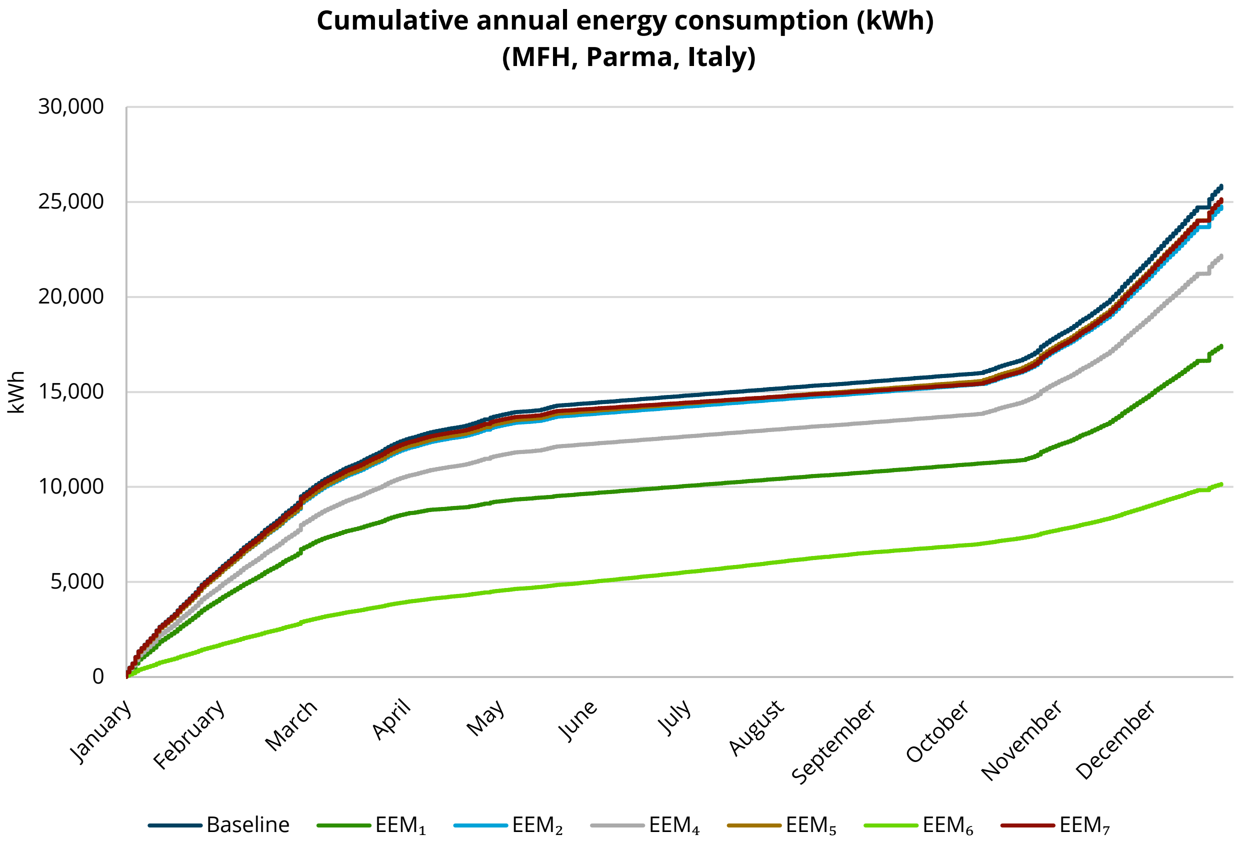

Figure 28. Cumulative annual energy consumption (in kWh) for the different EEMs in the MFH typology in the rural region of Parma in Italy.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 55**. As indicated in **Figure 29**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 15,696.7 kWh per year (60.7% reduction compared to the baseline scenario), while EEM$_1$ leads to 8,426.2 kWh saved annually (32.6% reduction) and EEM$_4$ leads to reducing energy consumption by 3,675.8 kWh per year (14.2%).

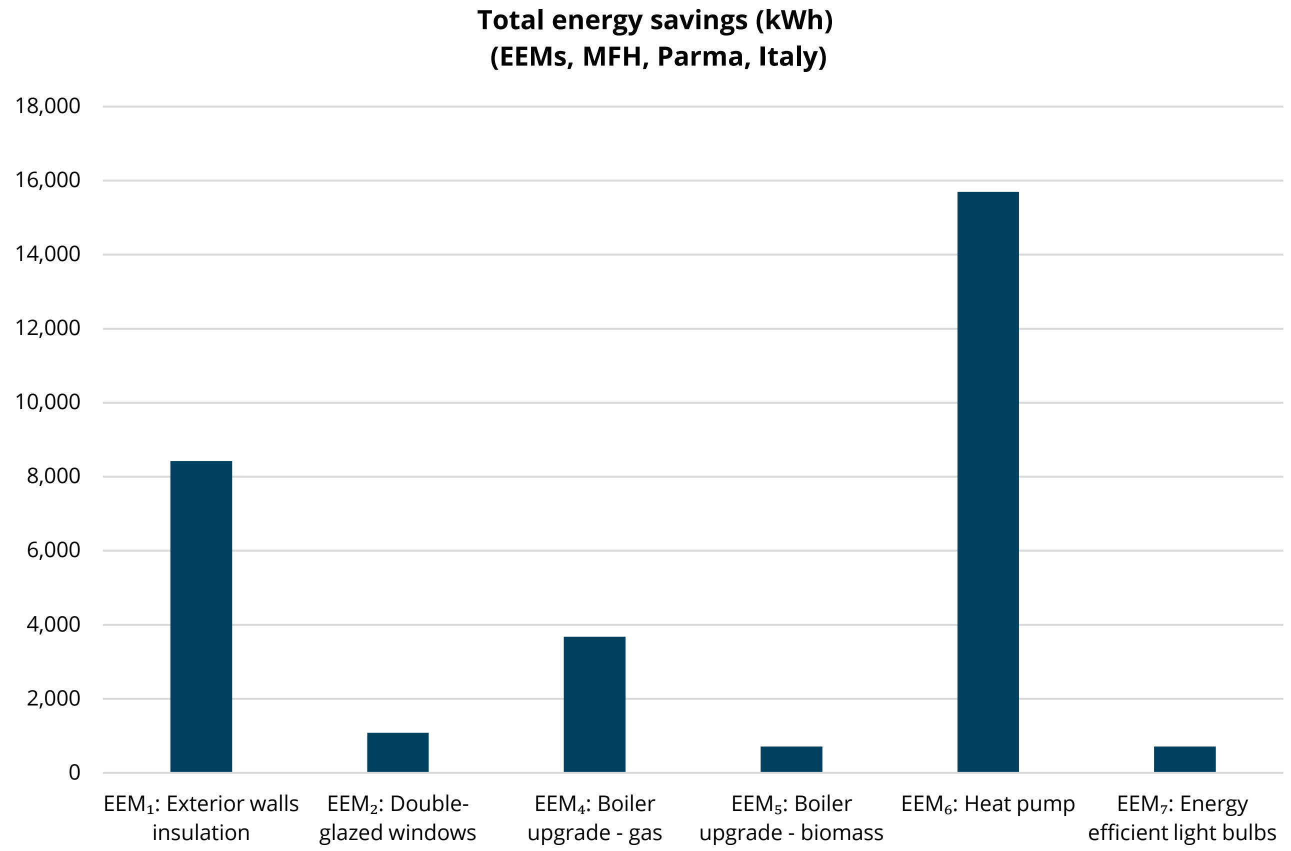

Figure 29. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Parma in Italy.

Table 55. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Parma in Italy.

Annual energy savings (in kWh) for the different EEMs (MFH, Parma, Italy)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	8,423.2	32.6
EEM$_2$: Double-glazed windows	1,085.4	4.2
EEM$_4$: Boiler upgrade - gas	3,675.8	14.2
EEM$_5$: Boiler upgrade - biomass	716.3	2.8
EEM$_6$: Heat pump	15,696.7	60.7
EEM$_7$: Energy efficient light bulbs	713.5	2.8

6.2.3 Environmental impact and thermal comfort analysis

SFH typology

CO_2 footprint

Figure 30 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of Parma in Italy for the SFH typology. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 4,647.2 kg CO_2 per year, followed by EEM_6 and EEM_3 which lead to an avoidance of around 3,229.3 and 2,184.9 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 56**.

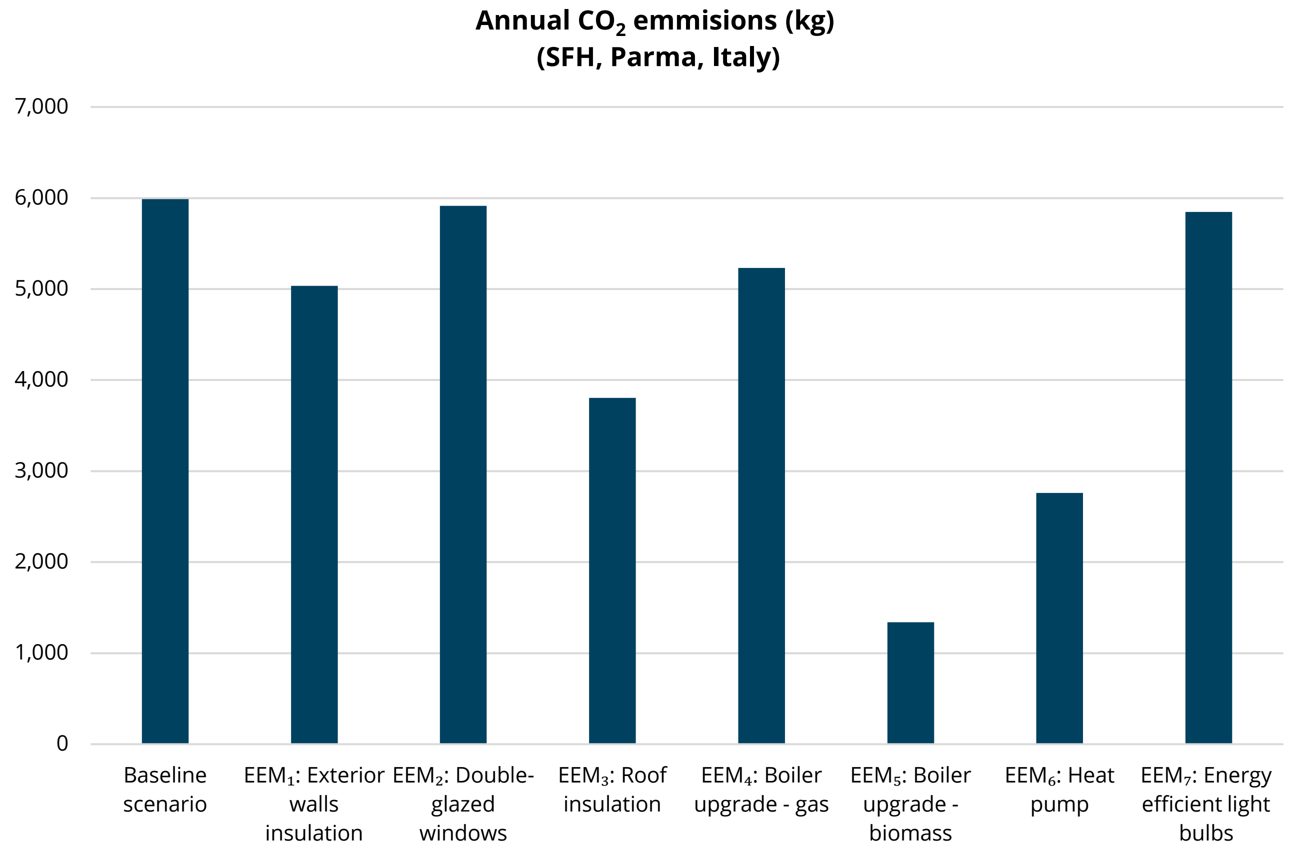

Figure 30. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of Parma in Italy.

Table 56 Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of Parma in Italy.

Annual CO_2 emissions avoided (SFH, Parma, Italy)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	951.6	15.9
EEM_2: Double-glazed windows	74.2	1.2
EEM_3: Roof insulation	2,184.9	36.5
EEM_4: Boiler upgrade - gas	757.7	12.7
EEM_5: Boiler upgrade - biomass	4,647.2	77.6
EEM_6: Heat pump	3,229.3	53.9
EEM_7: Energy efficient light bulbs	139.8	2.3

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 31** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). It is important to note that thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

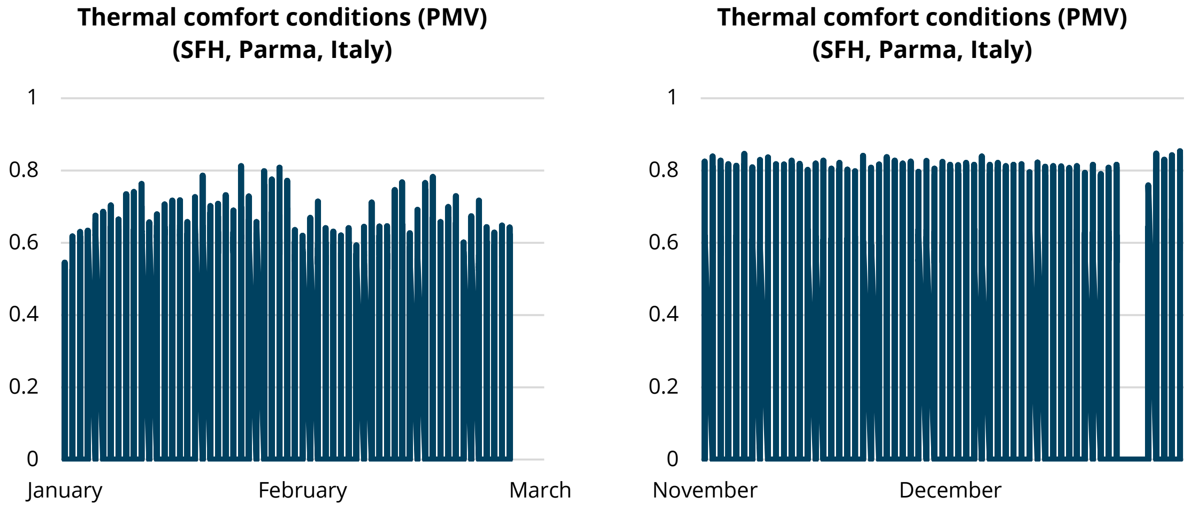

Figure 31. Thermal comfort (PMV indicator) for the SFH typology in the rural region of Parma in Italy during the winter for all the scenarios under study.

MFH typology

CO_2 footprint

Figure 32 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of Parma in Italy for the MFH typology. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 4,182.0 kg CO_2 per year, followed by EEM_6 and EEM_1 which lead to an avoidance of around 2,965.5 and 1,701.5 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 57**.

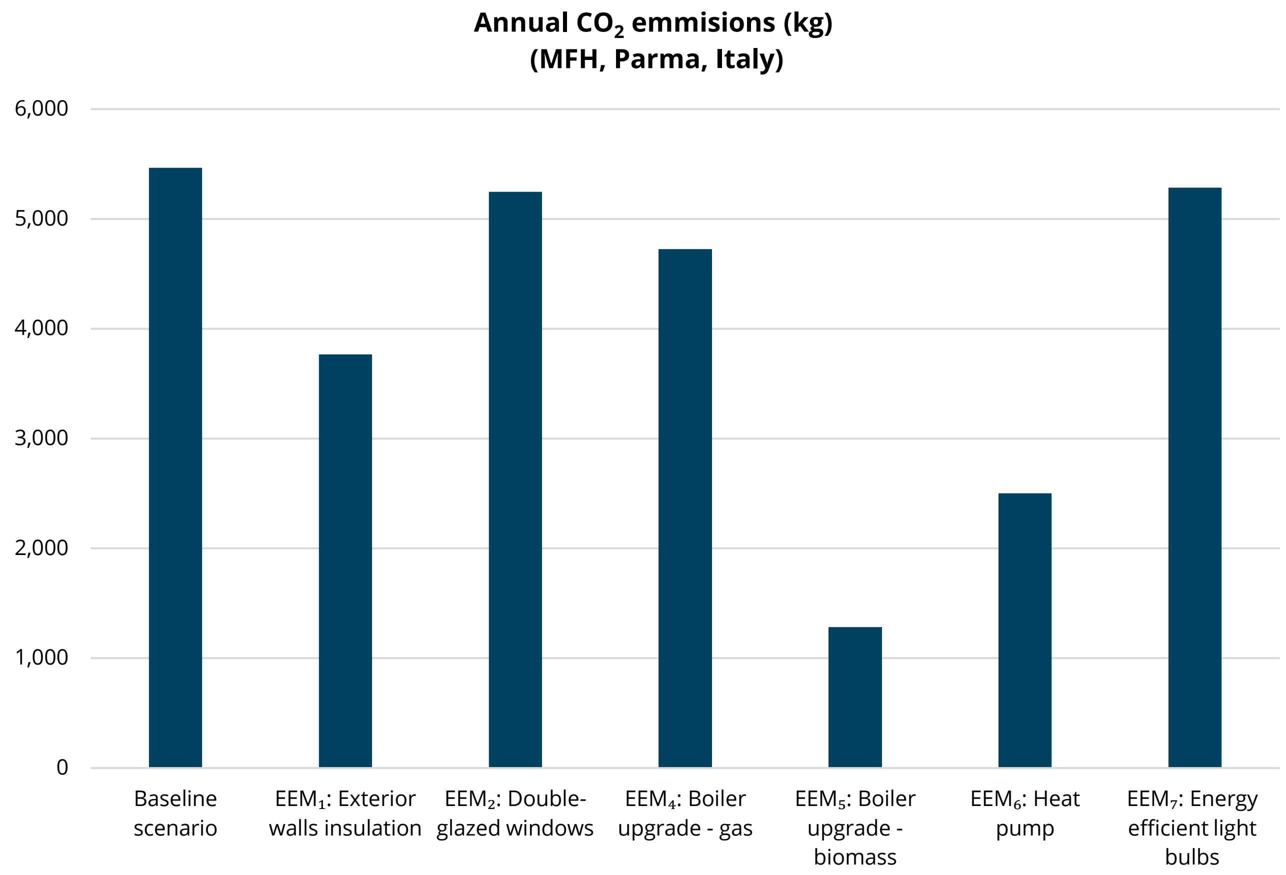

Figure 32. Annual CO_2 emissions (kg) in all scenarios in the MFH typology in the rural region of Parma in Italy.

Table 57. Annual CO_2 emissions avoided (kg) for the different EEMs in the MFH typology in the rural region of Parma in Italy.

Annual emissions avoided (kg CO_2) (MFH, Parma, Italy)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,701.5	31.1
EEM_2: Double-glazed windows	219.2	4.0
EEM_4: Boiler upgrade - gas	745.5	13.6
EEM_5: Boiler upgrade - biomass	4,182.0	76.5
EEM_6: Heat pump	2,965.5	54.2
EEM_7: Energy efficient light bulbs	183.4	3.4

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 33** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

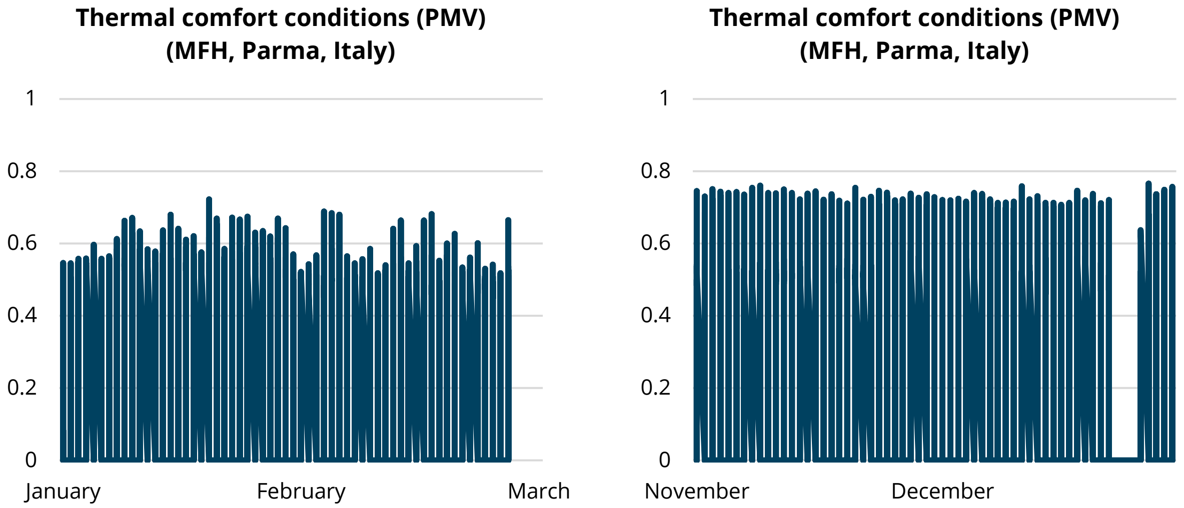

Figure 33. Thermal comfort (PMV indicator) for the MFH typology in the rural region of Parma in Italy during the winter for all the scenarios under study.

6.2.4 Technoeconomic assessment

SFH typology

The results of the technoeconomic assessment of the different EEMs for the SFH typology in the rural region of Parma in Italy, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 58**.

According to the analysis, EEM_3 (Roof insulation) and EEM_5 (Boiler upgrade- biomass) demonstrate the best performance in terms of NPV, with NPVs of 17,765.9€ and 7,568.6€, respectively. EEM_1 (Exterior wall insulations) and EEM_2 (Double-glazed windows) demonstrate negative NPV and thus are not profitable investments, without any subsidy rate. EEM_7 (Energy efficient light bulbs) and EEM_3 (Roof insulation) result in the lowest LCSE, at 0.009€/kWh and

0.015€/kWh, respectively. Additionally, EEM_7 and EEM_3 exhibit the best performance in PP, with 0.4 and 2.4 years, respectively.

The economic benefits provided by the majority of EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Parma to implement energy efficiency interventions, while also highlighting the need for subsidisation when it comes to EEMs with higher investment costs like the exterior wall insulations. In addition, the profitability of EEMs that change the heating technology of the household suggest that there is an urgent need for the building stock of Parma to migrate to more efficient heating systems.

Table 58. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Parma in Italy (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	22,013	30	4.00%	-13,072.3	>lifetime	0.270
EEM_2	4,313	30	4.00%	-3,615.0	>lifetime	0.679
EEM_3	2,762	30	4.00%	17,765.9	2.5	0.015
EEM_4	735	20	4.00%	3,364.8	2.6	0.044
EEM_5	3,500	20	4.00%	7,568.6	4.8	0.233
EEM_6	6,000	20	4.00%	3,078.9	11.4	0.036
EEM_7	60	23	4.00%	1,871.6	0.4	0.009

Table 59, **Table 60**, and **Table 61** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for energy-poor households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the economic viability of EEMs, especially those with higher upfront costs, negative NPVs and longer PPs. In addition, for high subsidy rates (75%) EEM_1 (Exterior wall insulation) becomes economically viable, highlighting the importance of incentives to enhance the uptake of energy efficiency interventions like this.

Table 59. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Parma in Italy (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	22,013	25%	30	4.00%	-7,569.0	>lifetime	0.203
EEM$_2$	4,313		30	4.00%	-2,536.9	>lifetime	0.509
EEM$_3$	2,762		30	4.00%	18,456.3	1.8	0.011
EEM$_4$	735		20	4.00%	3,548.6	1.9	0.040
EEM$_5$	3,500		20	4.00%	8,443.6	3.5	0.199
EEM$_6$	6,000		20	4.00%	4,578.9	8	0.030
EEM$_7$	60		23	4.00%	1,886.6	0.3	0.007

Table 60. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Parma in Italy (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	22,013	50%	30	4.00%	-2,065.8	>lifetime	0.135
EEM$_2$	4,313		30	4.00%	-1,458.8	>lifetime	0.339
EEM$_3$	2,762		30	4.00%	19,146.6	1.2	0.007
EEM$_4$	735		20	4.00%	3,732.3	1.3	0.037
EEM$_5$	3,500		20	4.00%	9,318.6	2.3	0.165
EEM$_6$	6,000		20	4.00%	6,078.9	5.1	0.024
EEM$_7$	60		23	4.00%	1,901.6	0.2	0.005

Table 61. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Parma in Italy (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	22,013	75%	30	4.00%	3,437.5	14.1	0.068
EEM$_2$	4,313		30	4.00%	-380.6	>lifetime	0.170
EEM$_3$	2,762		30	4.00%	19,837.0	0.6	0.004
EEM$_4$	735		20	4.00%	3,916.0	0.6	0.033
EEM$_5$	3,500		20	4.00%	10,193.6	1.1	0.132
EEM$_6$	6,000		20	4.00%	7,578.9	2.4	0.017
EEM$_7$	60		23	4.00%	1,916.6	0.1	0.002

The energy-saving potential and the LCSE indicator differ between the different EEMs countries under study. As indicated by **Figure 34**, the replacement of the current heating system with an energy-efficient heat pump (EEM$_6$) is the most cost-effective measure (energy savings: 17,758.0 kWh/year, LCSE: 0,036 €/kWh). On the contrary, EEM$_2$ is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall, EEM$_6$, EEM$_3$, and EEM$_4$ are identified as the most cost-effective measures, indicating the importance of focusing on relevant investments, while EEM$_2$, EEM$_1$, and EEM$_5$ are the ones that are ranked lower in terms of cost-effectiveness, indicating the need for incentives and initiatives that can increase it.

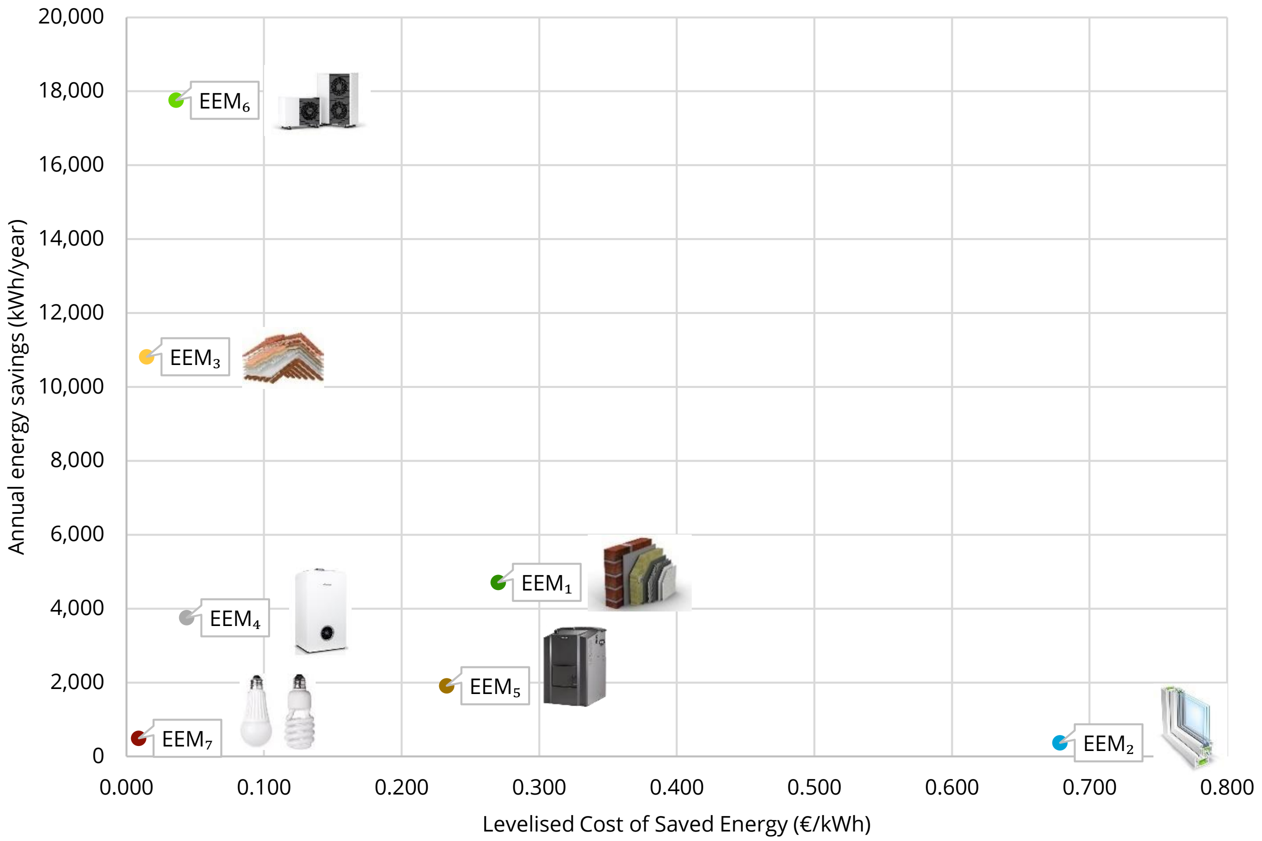

Figure 34. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Parma in Italy.

Additionally, we seek to analyse the correlation between NPV and cost-effectiveness of the different EEMs under study. **Figure 35** indicates that EEM$_3$ (Roof insulation) and EEM$_5$ (Boiler upgrade- biomass) rank highest, offering substantial profitability with NPVs of 17,765.9€ and 7,568.6€ respectively. This highlights the strong effect of local economic dynamics regarding fuel pricing, as EEM$_5$ despite not having exceptional energy-saving potential performs better in terms of profitability. Additionally, EEM$_6$, EEM$_4$, and EEM$_7$ demonstrate attractive combinations of NPV and LCSE. In contrast, EEM$_1$ and EEM$_2$ rank lowest, with negative NPVs and higher LCSEs, indicating less attractive investments, if not subsidised. Notably, EEM$_7$

(Energy-efficient light bulbs) has the lowest LCSE of 0.009€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV.

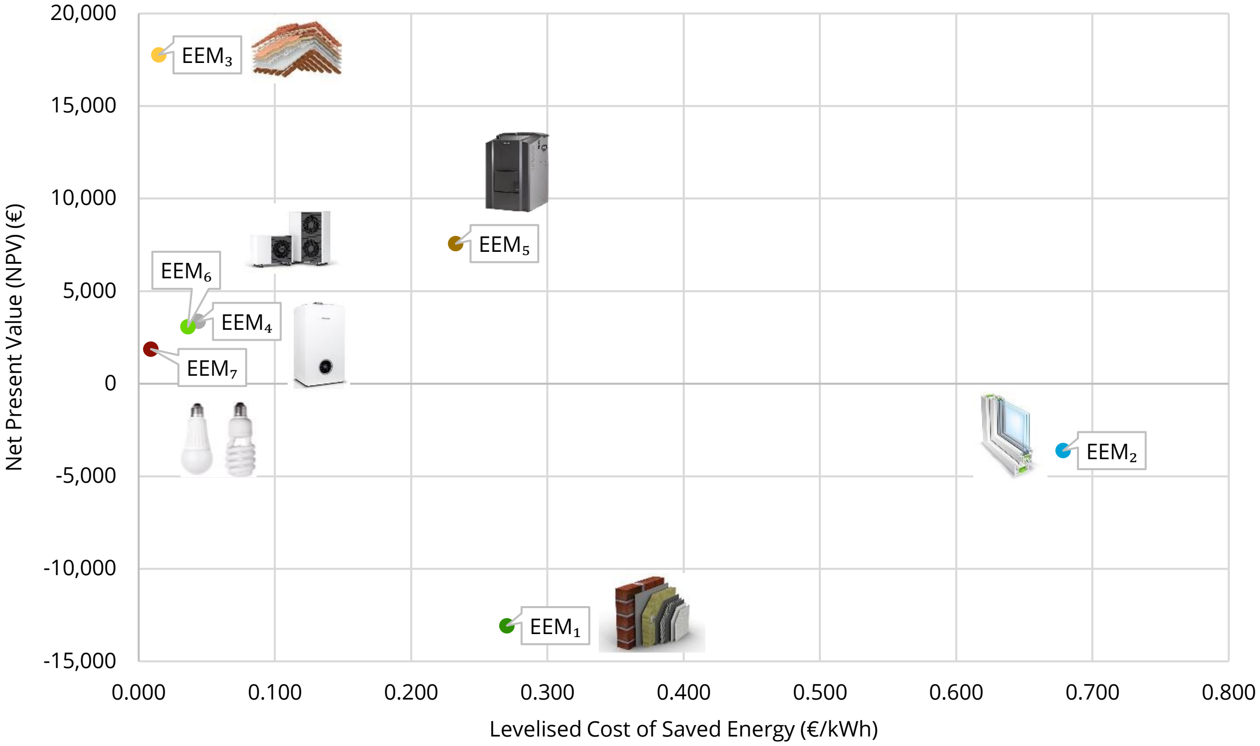

Figure 35. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Parma in Italy.

The ranking remains consistent when examining various subsidy levels, which lead to increased cost-effectiveness and profitability due to lower LCSEs and higher NPVs for the same amount of energy savings. Moreover, subsidy levels of at least 50% result in positive NPVs for EEM$_1$, while the NPV of EEM$_2$ remains negative at all subsidy levels (i.e., 25%, 50%, and 75%).

MFH typology

The results of the technoeconomic assessment of the different EEMs for the MFH typology in the rural region of Parma in Italy, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 62**.

According to the analysis, EEM$_5$ (Boiler upgrade- biomass) and EEM$_6$ (Heat pump) demonstrate the best performance in terms of NPV, with NPVs of 6,777.5€ and 4,836.3€, respectively. Furthermore, EEM$_7$ (Energy efficient light bulbs) and EEM$_6$ result in the lowest LCSE, at 0.007€/kWh and 0.041€/kWh, respectively. Additionally, EEM$_7$ and EEM$_4$ exhibit the best performance in PP, with 0.4 and 2.5 years, respectively. EEM$_1$ (Exterior wall insulation) and EEM_2 (Double-glazed windows) are not economically viable investments, in the case of no subsidy granted, as they demonstrate negative NPVs.

The substantial economic benefits provided by all EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Parma to implement energy efficiency interventions. These findings underscore the effectiveness of a diverse range of EEMs in delivering significant economic returns and improving household energy sustainability.

Table 62. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Parma in Italy (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	18,943	30	4.00%	-2,177.8	>lifetime	0.130
EEM_2	2,200	30	4.00%	-552.2	>lifetime	0.151
EEM_4	735	20	4.00%	3,789.5	2.5	0.044
EEM_5	3,500	20	4.00%	6,777.5	5.2	0.621
EEM_6	6,000	20	4.00%	4,836.3	9.1	0.041
EEM_7	75	23	4.00%	2,643.9	0.4	0.007

Table 63, **Table 64**, and **Table 65** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs. In addition, EEM_1 (Exterior wall insulation) and EEM_2 (Double-glazed windows) become viable investments only in the case of granting subsidies, highlighting the importance of such for the uptake of such energy efficiency interventions.

Table 63. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Parma in Italy (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	18,943	25%	30	4.00%	2,557.9	22.5	0.098
EEM$_2$	2,200		30	4.00%	32.8	19.4	0.113
EEM$_4$	735		20	4.00%	3,973.2	1.9	0.040
EEM$_5$	3,500		20	4.00%	7,652.5	3.8	0.531
EEM$_6$	6,000		20	4.00%	6,336.3	6.5	0.034
EEM$_7$	75		23	4.00%	2,662.7	0.3	0.005

Table 64. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Parma in Italy (50% subsidy).

EEM	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	18,943	50%	30	4.00%	7,293.5	12.6	0.065
EEM$_2$	2,200		30	4.00%	587.8	11.2	0.075
EEM$_4$	735		20	4.00%	4,157.0	1.2	0.037
EEM$_5$	3,500		20	4.00%	8,527.5	2.5	0.442
EEM$_6$	6,000		20	4.00%	7,836.3	4.2	0.027
EEM$_7$	75		23	4.00%	2,681.4	0.2	0.004

Table 65. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Parma in Italy (75% subsidy).

EEM	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	18,943	75%	30	4.00%	12,023.1	5.4	0.033
EEM_2	2,200		30	4.00%	1,142.8	5.0	0.038
EEM_4	735		20	4.00%	4,340.7	0.6	0.033
EEM_5	3,500		20	4.00%	9,402.5	1.2	0.352
EEM_6	6,000		20	4.00%	9.336.3	2.0	0.020
EEM_7	75		23	4.00%	2,700.2	0.1	0.002

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 36**, the replacement of the current heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 15,696.7 kWh/year, LCSE: 0.041€/kWh). On the contrary, EEM_5 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall, EEM_6, EEM_4 and EEM_1 are indicated as the most cost-effective measures as they combine a significant energy-saving potential with lower investment costs, while EEM_5 and EEM_2 are ranked lower in terms of cost-effectiveness, mainly because of their higher investment costs.

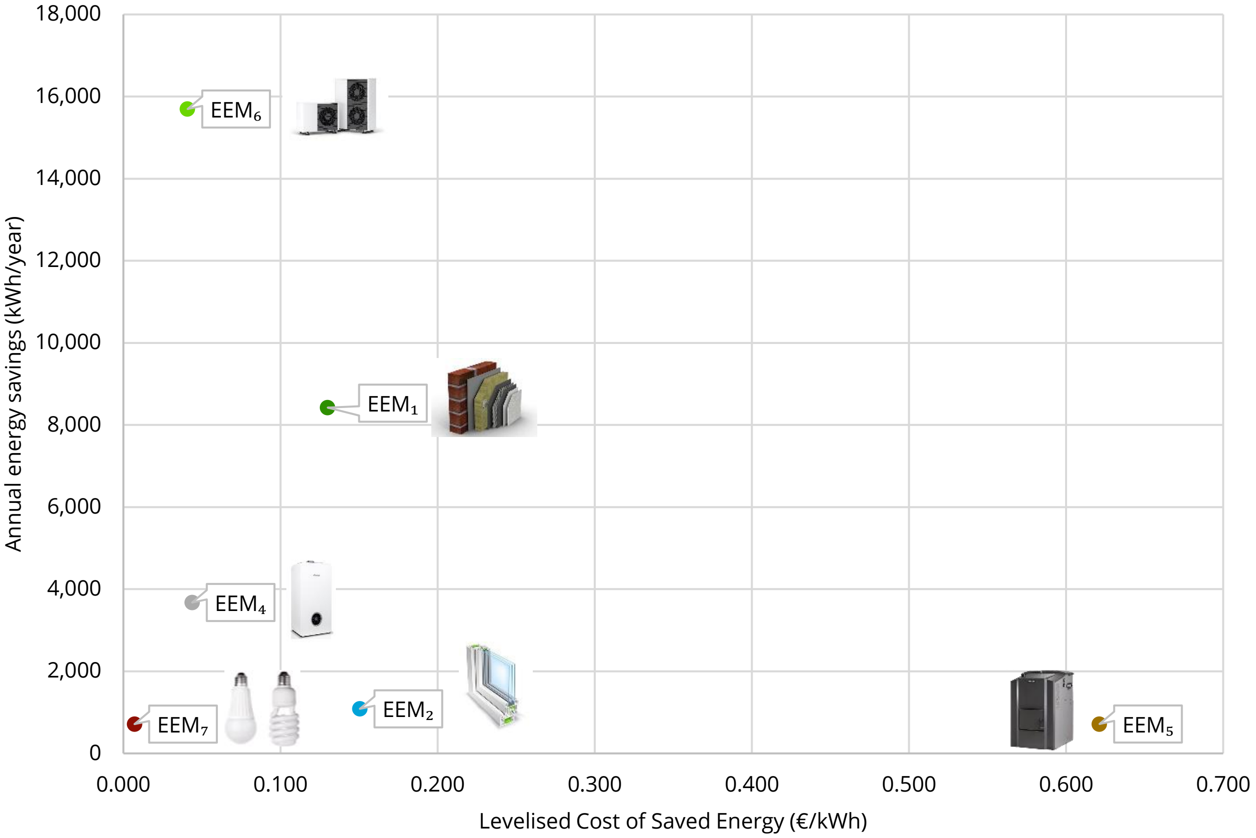

Figure 36. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Parma in Italy.

Additionally, we seek to identify the correlation between profitability and cost-effectiveness of the different EEMs under study. **Figure 37** indicates that EEM_5 (Boiler upgrade- biomass) and EEM_6 (Heat pump) rank highest in NPV, offering substantial profitability with NPVs of 6,777.5€ and 4,836.3€, respectively, while EEM_6 demonstrates strong cost-effectiveness. This highlights the strong effect of local economic dynamics regarding fuel pricing, as EEM_5 despite having significantly lower energy-saving potential and cost-effectiveness than EEM_6, it performs better in terms of profitability.In contrast, EEM_1 and EEM_2 rank lowest, with negative NPVs and higher LCSEs, indicating unattractive investments. Notably, EEM_7 (Energy efficient light bulbs) has the lowest LCSE of 0.007€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV. These results underscore the varying economic impacts and energy-saving potentials of the EEMs under consideration.

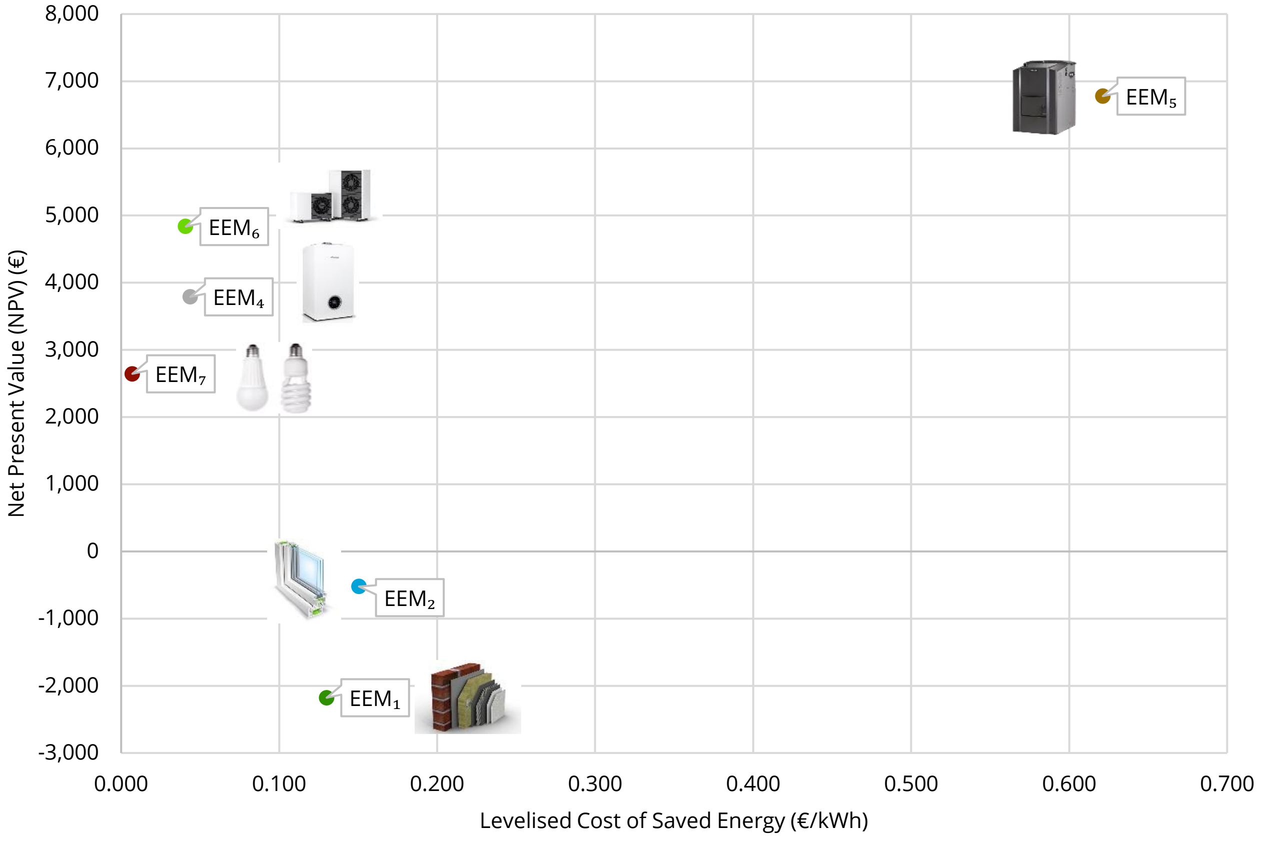

Figure 37. Profitability and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Parma in Italy.

The same ranking is observed across different subsidy levels, leading to increased cost-effectiveness due to lower LCSEs and higher NPVs for the same amount of energy savings. Additionally, sufficient subsidy levels (at least 25%) can result in positive NPVs for both EEM$_1$ and EEM$_2$.

6.3 The rural regions of Bükk-Mak and Somló-Marcalmente-Bakonyalja in Hungary

For the case study of the rural regions of Bükk-Mak and SMB in Hungary, the two household typologies explored concern a SFH equipped with a gas boiler, based in Bükk-Mak region, and a SFH equipped with a gas boiler, based in SMB. Detailed specifications of each household typology identified in the rural regions of Hungary are presented in **Sections 5.2.3**, **5.3**, and **5.4**.

6.3.1 Energy performance in the current situation (baseline scenario)

SFH typology (rural region of Bükk-Mak)

In the baseline scenario, modelling results indicate that the SFH typology in the rural region of Bükk-Mak consumes around 30,365.4 kWh annually (almost 303.7 kWh/m^2), which are divided into 27,725.3 kWh for its heating needs and 2,640.1 kWh for its cooling and appliances needs (**Figure 38**).

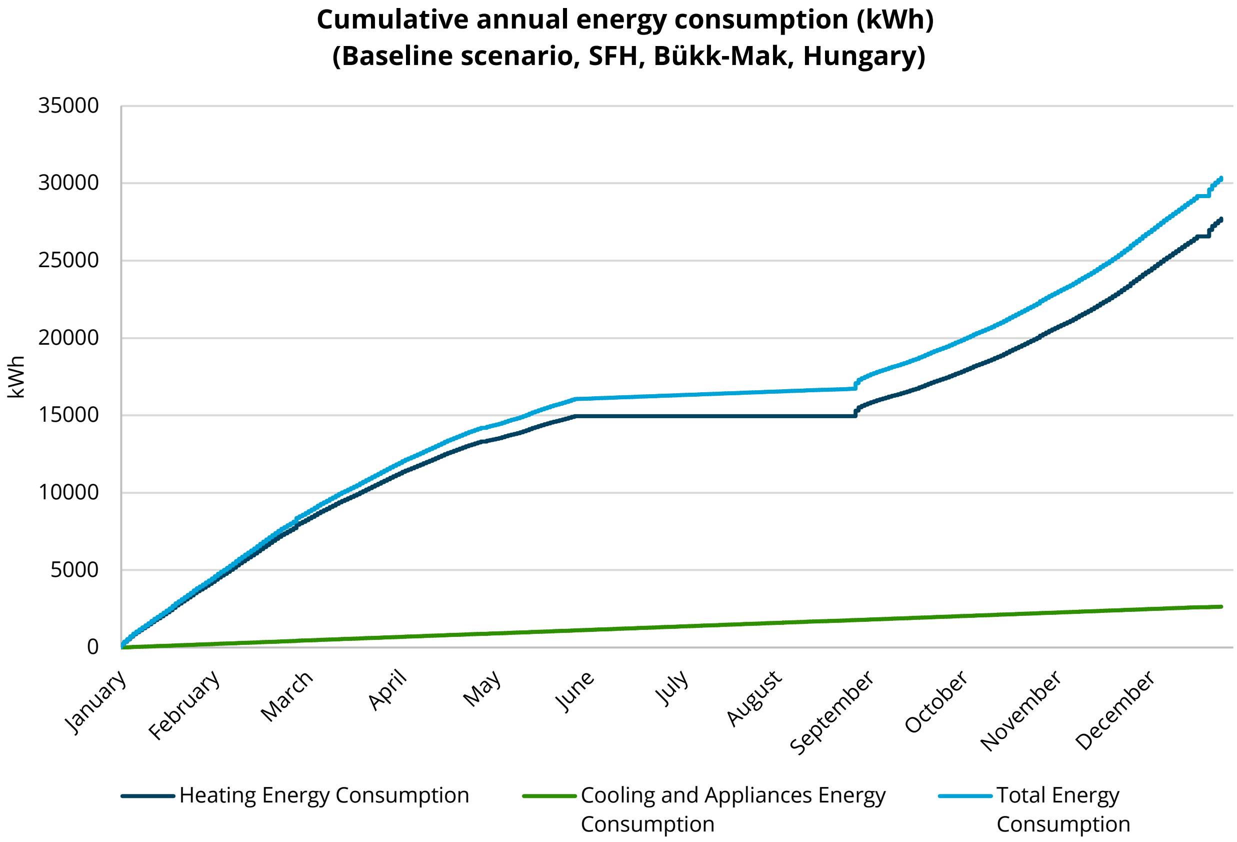

Figure 38. Cumulative annual consumption for the SFH typology in the rural region of Bükk-Mak in Hungary (baseline scenario).

SFH typology (rural region of Somló-Marcalmente-Bakonyalja)

In the baseline scenario, modelling results indicate that the SFH typology in the rural region of SMB consumes around 40,965.9 kWh annually (almost 409.8 kWh/m^2), which is divided into 36,664.5 kWh for its heating needs and 4,301.4 kWh for its cooling and appliances needs (**Figure 39**).

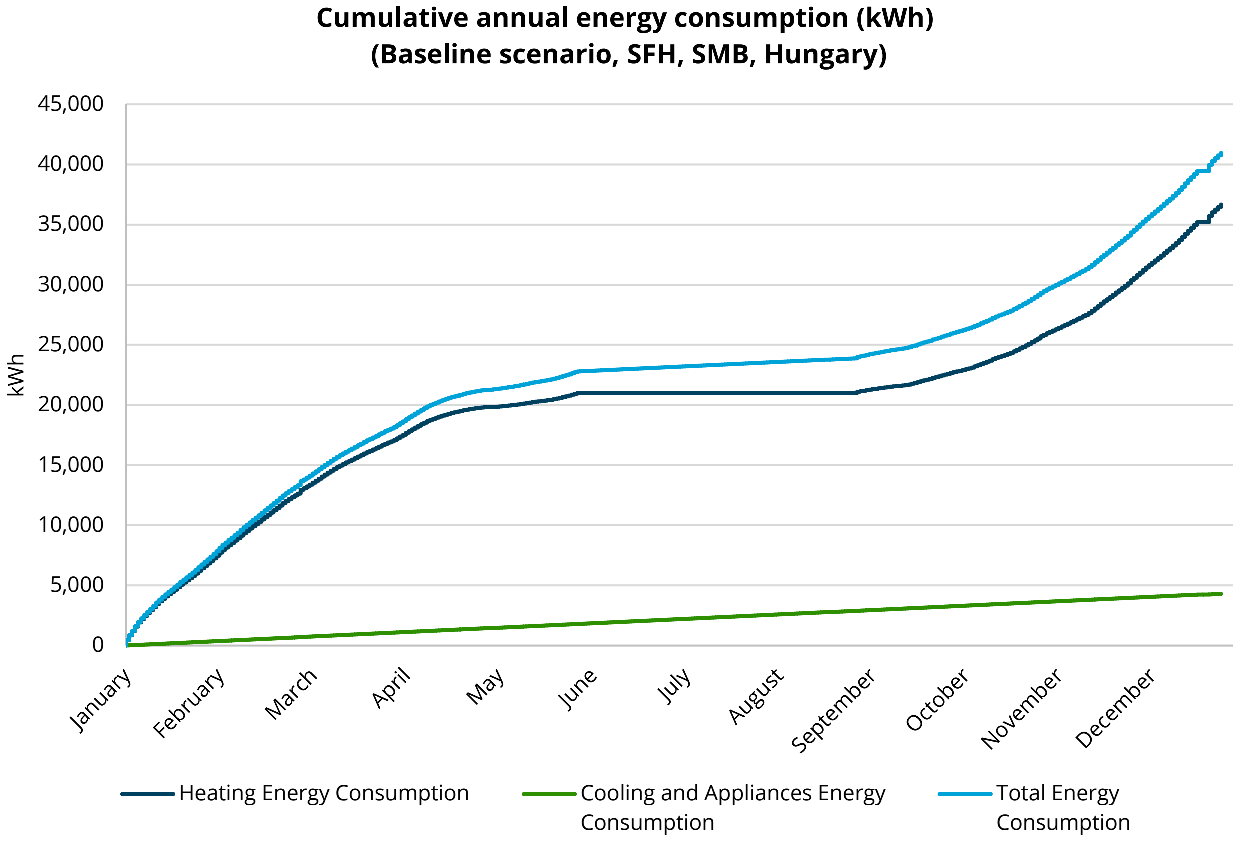

Figure 39. Cumulative annual consumption for the SFH typology in the rural region of SMB in Hungary (baseline scenario).

6.3.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology (rural region of Bükk-Mak)

In the case of the SFH typology in Bükk-Mak, **Figure 40** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which foresees the replacement of the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 9,454.1kWh per year. This is followed by EEM$_1$, which entails exterior wall insulation, leading to an annual energy consumption of 21,818.3 kWh, and EEM_4 (Boiler upgrade- gas) with an annual energy consumption of 25,613.2 kWh.

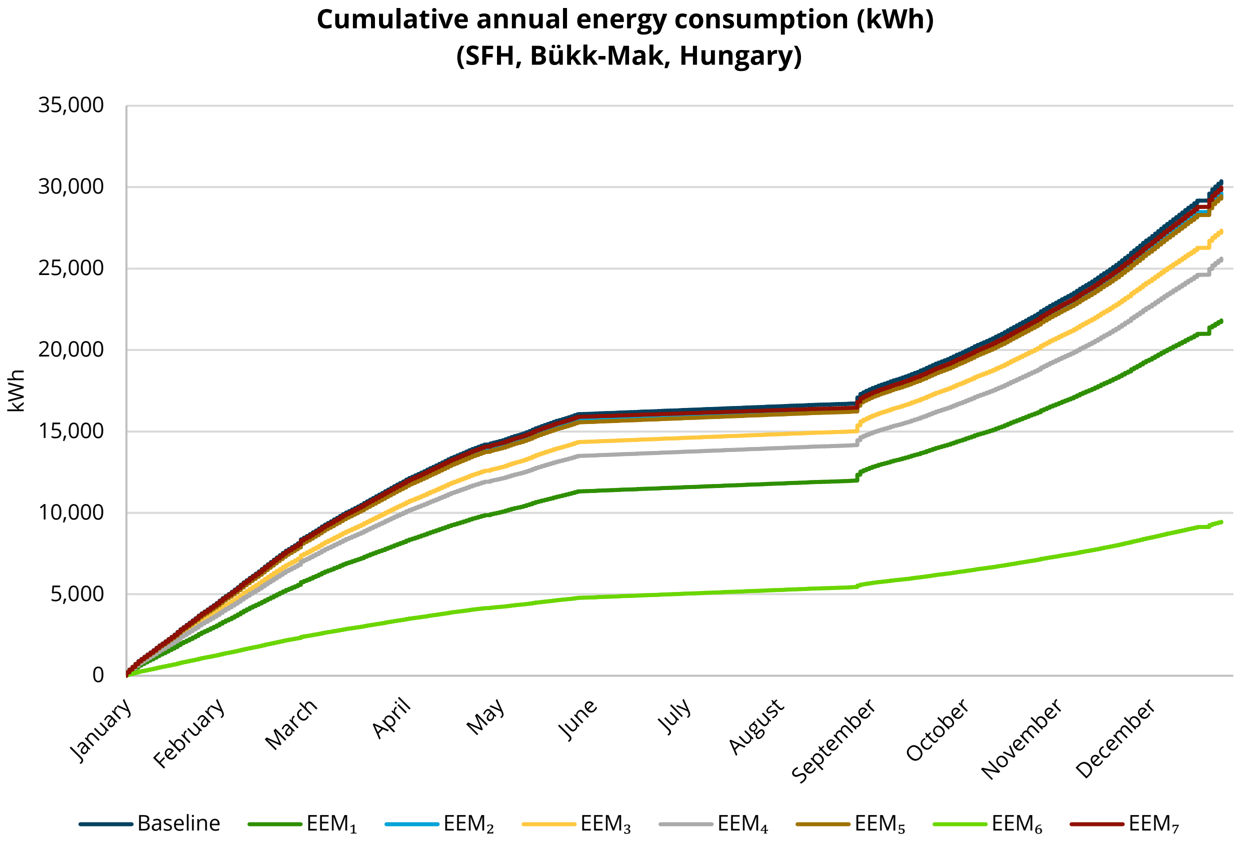

Figure 40. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 66**. As indicated in **Figure 41**, we identify that EEM_6 leads to the highest amount of energy savings, namely 20,911.3 kWh per year (68.9% reduction compared to the baseline scenario), while EEM_1 leads to 8,547.1 kWh saved annually (28.1% reduction) and EEM_4 leads to reducing energy consumption by 4,752.2 kWh per year (15.6%).

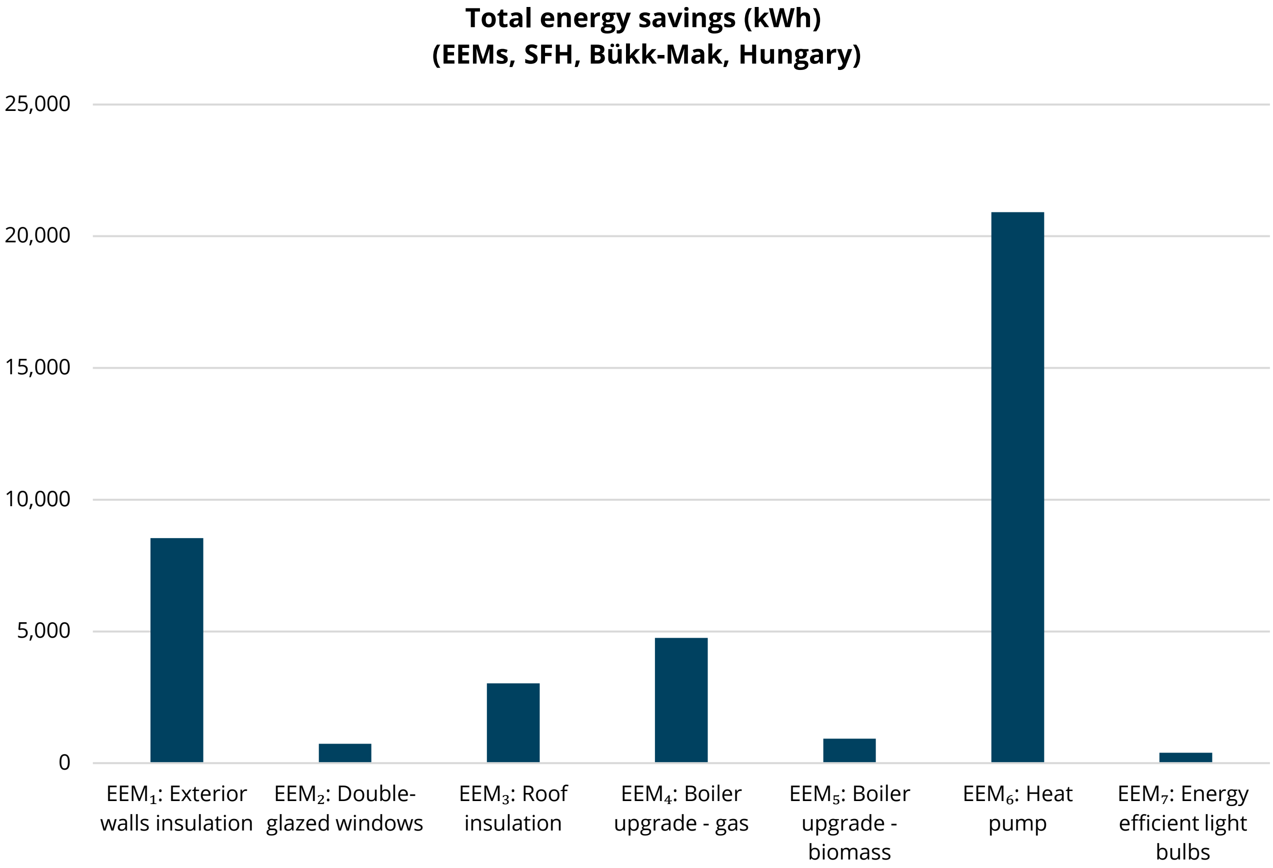

Figure 41. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary.

Table 66. Comparison of annual total energy savings (kWh) for all EEMs with baseline in Bükk-Mak in Hungary.

Annual energy savings (in kWh) for the different EEMs (SFH, Bükk-Mak Hungary)		
	Energy savings (kWh)	**Reduction (%)**
EEM_1: Exterior wall insulation	8,547.1	28.1
EEM_2: Double-glazed windows	731.8	2.4
EEM_3: Roof insulation	3,032.6	10.0
EEM_4: Boiler upgrade - gas	4,752.2	15.6
EEM_5: Boiler upgrade - biomass	923.5	3.0
EEM_6: Heat pump	20,911.3	68.9
EEM_7: Energy efficient light bulbs	390.7	1.3

SFH typology (rural region of Somló-Marcalmente-Bakonyalja)

In the case of the SFH typology in the rural region of SMB, **Figure 42** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 11,550.6 kWh. This is followed by EEM$_1$ (Exterior wall insulation) which leads to an annual energy consumption of 24,769.5 kWh, and EEM$_3$, which foresees the insulation of the roof, with an annual energy consumption of 27,690.4 kWh.

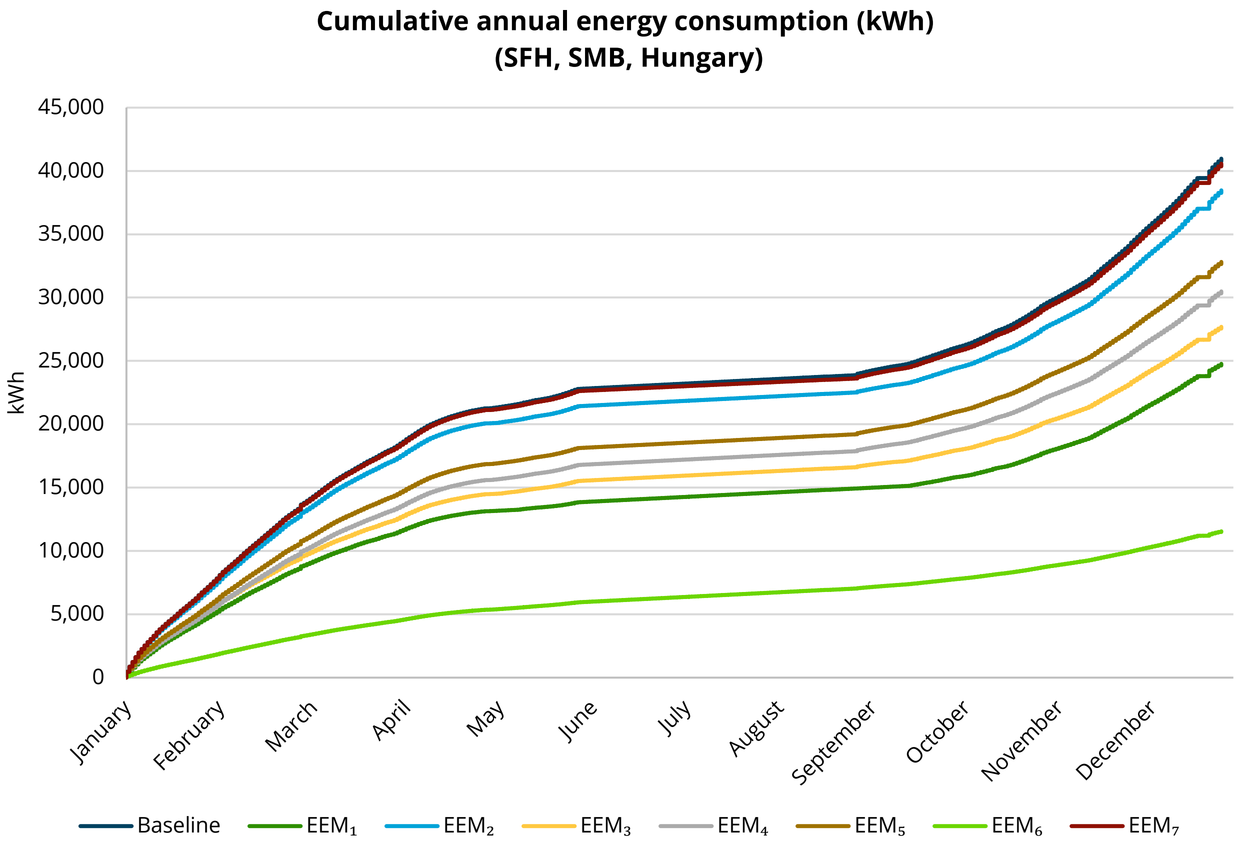

Figure 42. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of SMB in Hungary.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 67**. As indicated in **Figure 43**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 29,415.3 kWh per year (71.8% reduction compared to the baseline scenario), while EEM$_1$ leads to 16,196.4 kWh saved annually (39.5% reduction) and EEM$_3$ leads to reducing energy consumption by 13,275.5 kWh per year (32.4% reduction).

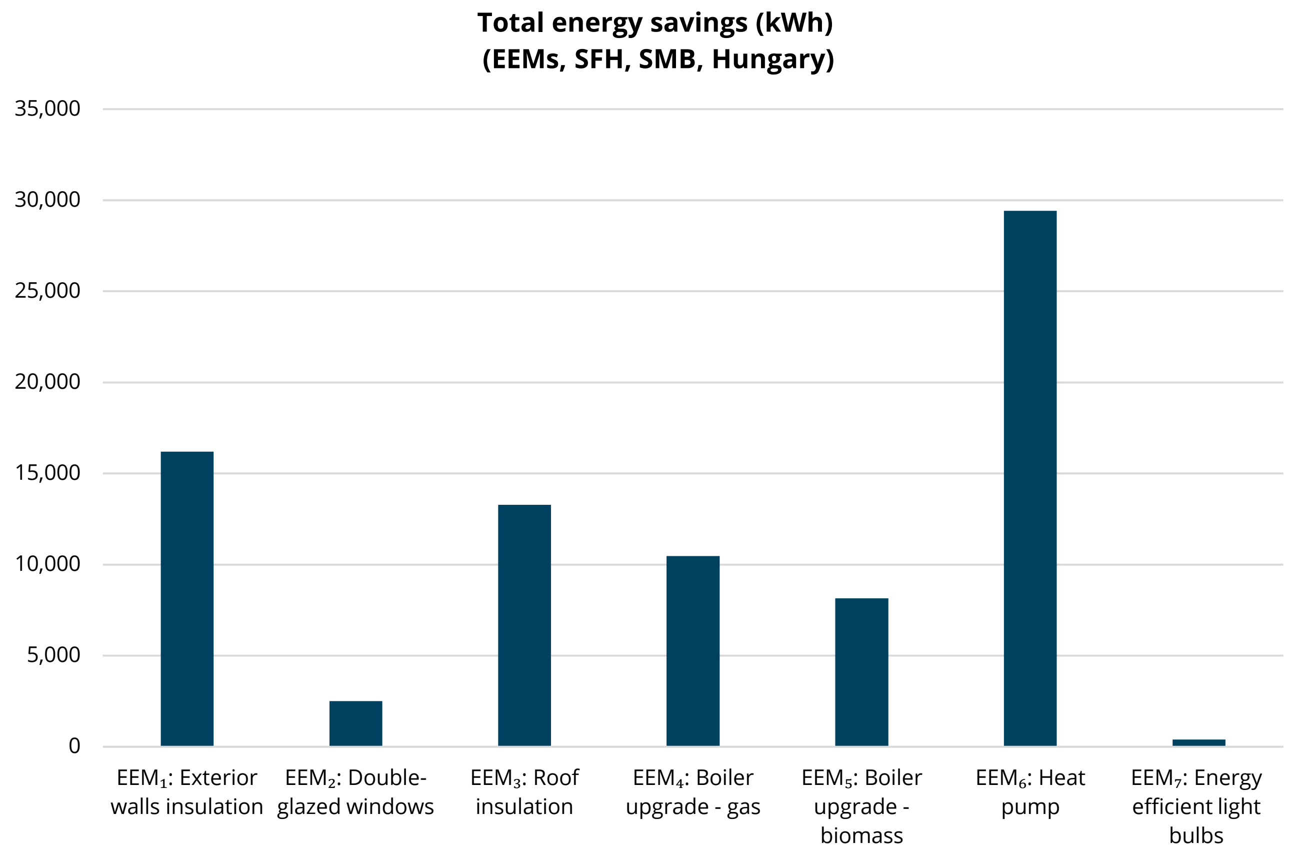

Figure 43. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of SMB in Hungary.

Table 67. Comparison of annual total energy savings (kWh) for all EEMs with baseline in SMB in Hungary.

Annual energy savings (kWh) (EEMs, SFH, SMB, Hungary)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	16,196.4	39.5
EEM$_2$: Double-glazed windows	2,503.0	6.1
EEM$_3$: Roof insulation	13,275.5	32.4
EEM$_4$: Boiler upgrade - gas	10,477.1	25.6
EEM$_5$: Boiler upgrade - biomass	8,149.7	19.9
EEM$_6$: Heat pump	29,415.3	71.8
EEM$_7$: Energy efficient light bulbs	390.4	1.0

6.3.3 Environmental impact and thermal comfort analysis

SFH typology (the rural region of Bükk-Mak)

CO_2 footprint

Figure 44 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) for the SFH typology in the rural region of Bükk-Mak in Hungary. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 5,412.9 kg CO_2 per year, followed by EEM_6 and EEM_1 which lead to an avoidance of around 3,358.7 and 1,726.5 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 68**.

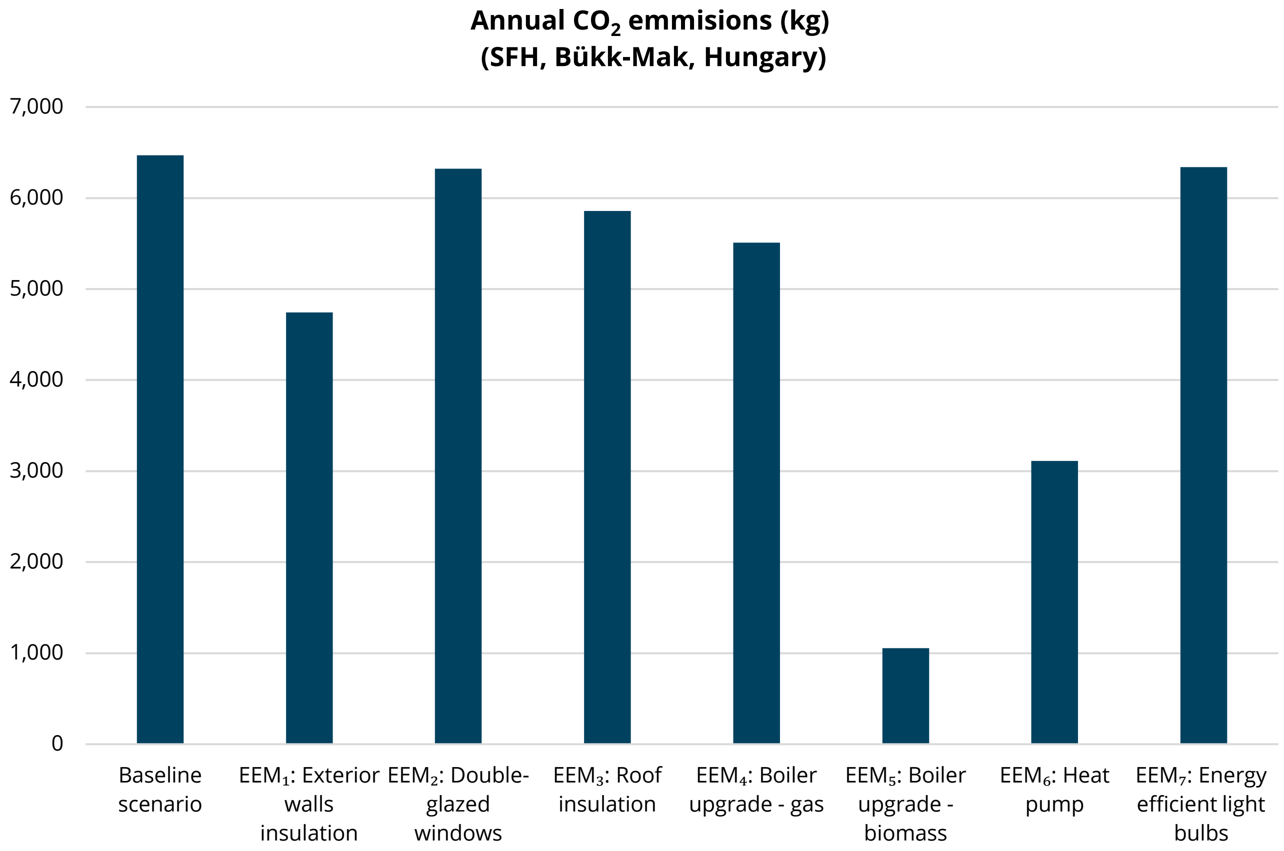

Figure 44. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of Bükk-Mak in Hungary.

Table 68 Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary.

Annual CO_2 emissions avoided (SFH, Bükk-Mak, Hungary)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,726.5	26.7
EEM_2: Double-glazed windows	147.8	2.3
EEM_3: Roof insulation	612.6	9.5
EEM_4: Boiler upgrade - gas	959.9	14.8
EEM_5: Boiler upgrade - biomass	5,412.9	83.7
EEM_6: Heat pump	3,358.7	51.9
EEM_7: Energy efficient light bulbs	128.5	2.0

PMV indicator

In regards with the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 45** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

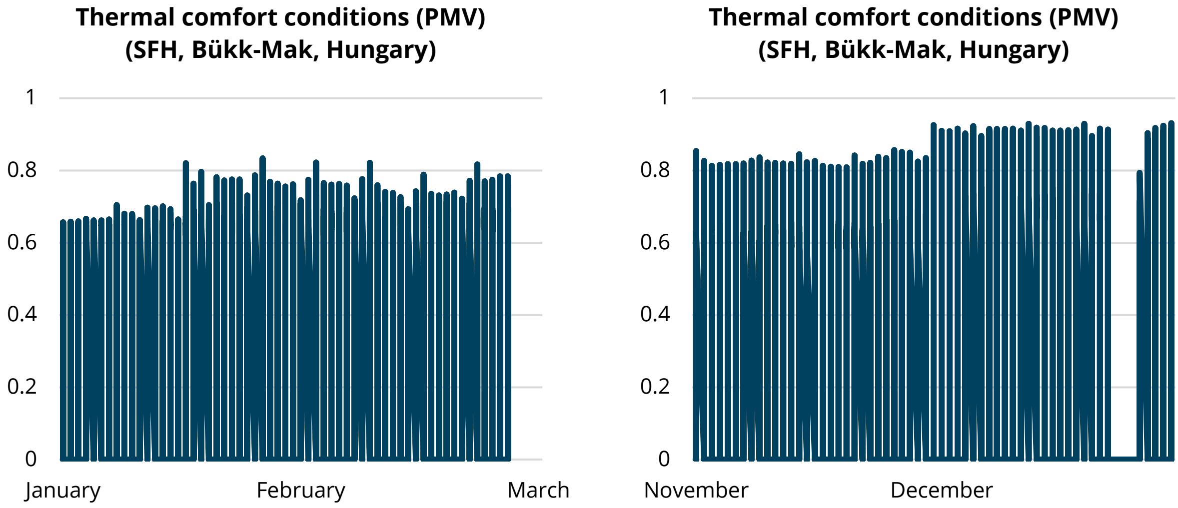

Figure 45. Thermal comfort (PMV indicator) for the SFH typology in the rural region of Bükk-Mak in Hungary during the winter for all the scenarios under study.

SFH typology (rural region of Somló-Marcalmente-Bakonyalja)

CO_2 footprint

Figure 46 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of SMB, in Hungary. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 7,206.6 kg CO_2 per year, followed by EEM_6 and EEM_1 which lead to an avoidance of around 5,021.3 and 3,271.6 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 69**.

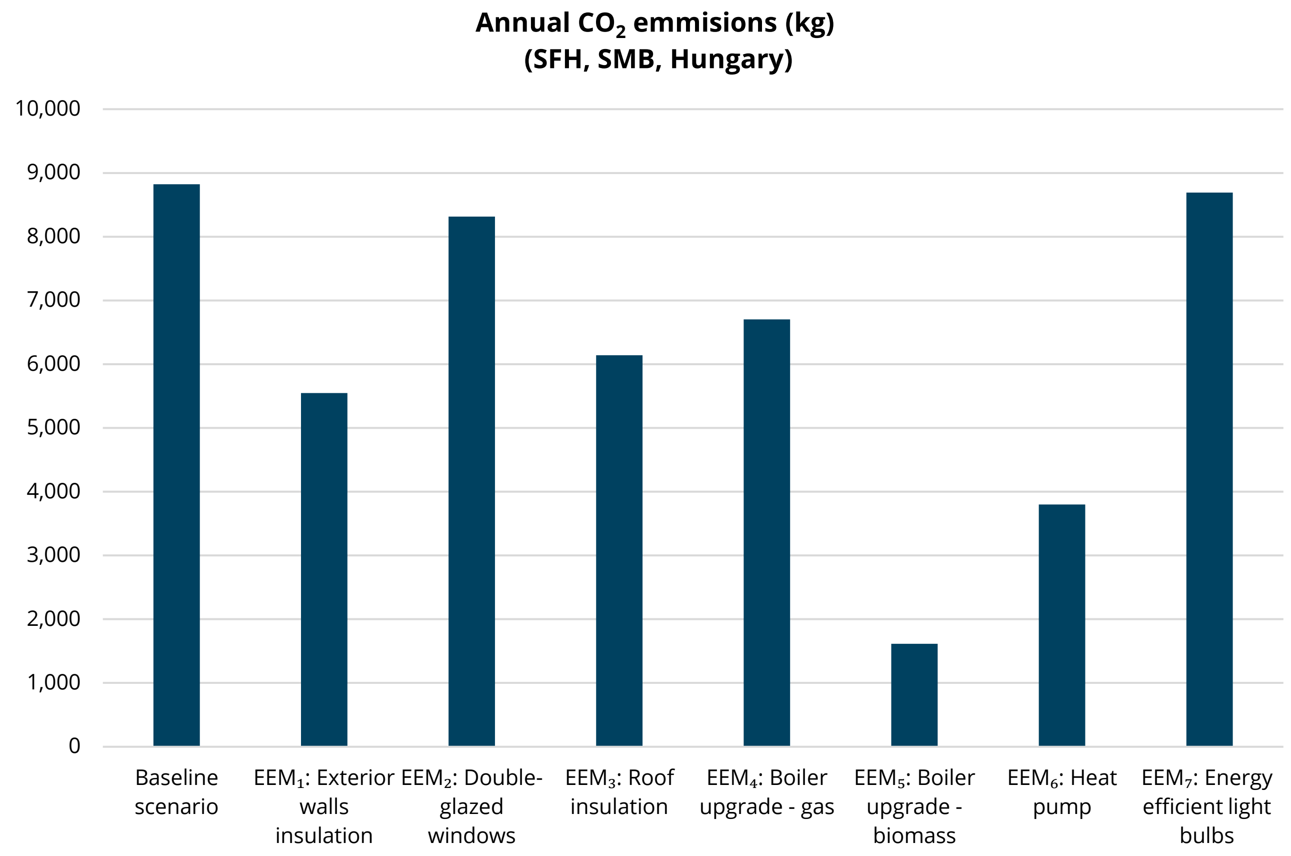

Figure 46. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of SMB in Hungary.

Table 69. Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of SMB in Hungary.

Annual emissions avoided (kg CO_2) (SFH, SMB, Hungary)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	3,271.7	37.1
EEM_2: Double-glazed windows	505.6	5.7
EEM_3: Roof insulation	2,681.6	30.4
EEM_4: Boiler upgrade - gas	2,116.4	24.0
EEM_5: Boiler upgrade - biomass	7,206.6	81.7
EEM_6: Heat pump	5,021.3	59.2
EEM_7: Energy efficient light bulbs	128.5	1.5

PMV indicator

In regards with the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 47** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

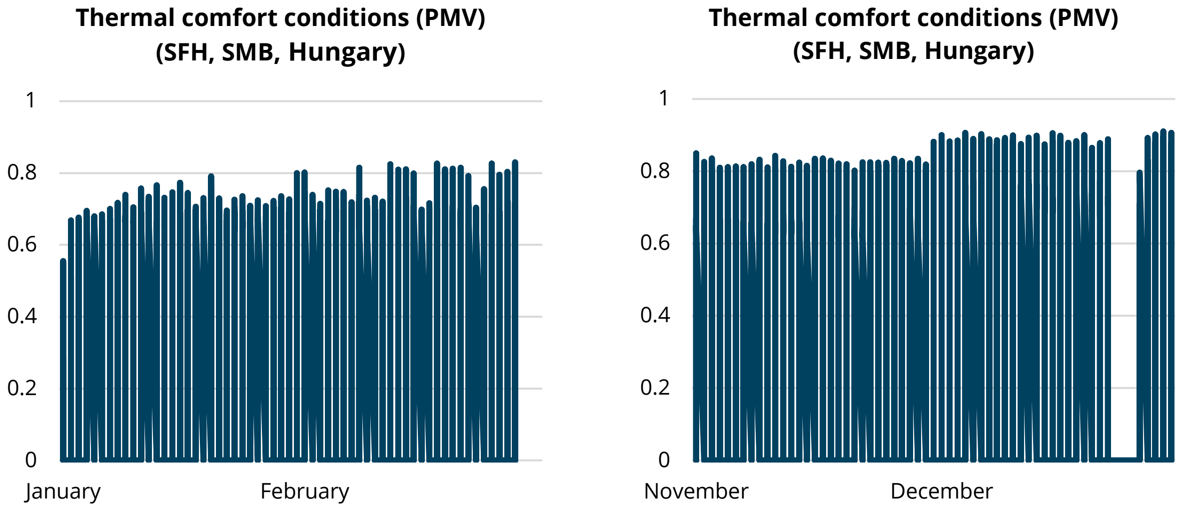

Figure 47. Thermal comfort (PMV indicator) for the SFH typology in the rural region of SMB in Hungary during the winter for all the scenarios under study.

6.3.4 Technoeconomic assessment

SFH typology (rural region of Bükk-Mak)

The results of the technoeconomic assessment of the different EEMs for the SFH typology in the rural region of Bükk-Mak in Hungary, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 70**. In the rural region of Bükk-Mak in Hungary, despite achieving substantial energy savings, the majority of the EEMs are not economically viable. This lack of viability is primarily due to the current low prices of natural gas for domestic users in Hungary. Consequently, there is a pressing need for subsidisation to promote the adoption of EEMs and to prevent future reliance on natural gas, especially in the face of potential price increases like the ones during the latest 2022 energy crisis.

More specifically, our analysis indicates that all EEMs, except for EEM_4 (Boiler upgrade- gas) and EEM_7 (Energy efficient light bulbs), are not economically viable investments, as they demonstrate negative NPVs. In regard to EEM_4 and EEM_7, their NPVs are 1,165.0€ and 462.9€, respectively, while they also result in the lowest LCSE at 0.008€/kWh and 0.003€/kWh, respectively. Additionally, they exhibit the best performance in PP, with 0.5 and 4.3 years, respectively. Notably, according to the modelling results EEM_5 (Boiler upgrade- biomass) does not provide any annual profit for the household under study.

Table 70. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	7,618	30	4.00%	-3,716.2	>lifetime	0.052
EEM_2	6,500	30	4.00%	-6,165.9	>lifetime	0.514
EEM_3	2,189	30	4.00%	-804.6	>lifetime	0.042
EEM_4	540	20	4.00%	1,165.0	4.3	0.008
EEM_5	980	20	4.00%	-13,251.5	-	0.078
EEM_6	3,250	20	4.00%	-1,664.8	>lifetime	0.011
EEM_7	17	23	4.00%	462.9	0.5	0.003

Table 71, **Table 72**, and **Table 73** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking among the various EEMs remains consistent; however, the economic benefits for energy-poor households increase significantly in terms of NPV (NPV becomes positive) and LCSE, while the PP is significantly reduced. The latter demonstrates that subsidies in this case are substantial in enhancing the financial viability of EEMs, especially for those with higher investment costs. More specifically, EEM_1 (Exterior wall insulation) and EEM_3 (Roof insulation) start to become attractive investments with a minimum of 50% subsidy rate, while EEM_6 (Heat pump) with a minimum of a 75% subsidy rate.

Table 71. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	7,618	25%	30	4.00%	-1,811.68	>lifetime	0.039
EEM$_2$	6,500		30	4.00%	-4,540.9	>lifetime	0.385
EEM$_3$	2,189		30	4.00%	-257.3	>lifetime	0.031
EEM$_4$	540		20	4.00%	1,300.0	3.5	0.006
EEM$_5$	980		20	4.00%	-13,006.5	-	0.059
EEM$_6$	3,250		20	4.00%	-852.3	>lifetime	0.009
EEM$_7$	17		23	4.00%	467.1	0.4	0.002

Table 72. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	7,618	50%	30	4.00%	92.8	28.7	0.026
EEM$_2$	6,500		30	4.00%	-2,951.9	>lifetime	0.257
EEM$_3$	2,189		30	4.00%	289.9	20.2	0.021
EEM$_4$	540		20	4.00%	1,435	2.3	0.004
EEM$_5$	980		20	4.00%	-12,761.5	-	0.039
EEM$_6$	3,250		20	4.00%	-39.79	>lifetime	0.006
EEM$_7$	17		23	4.00%	471.2	0.2	0.002

Table 73. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Bükk-Mak in Hungary (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	7,618	75%	30	4.00%	1,997.3	10.5	0.013
EEM_2	6,500		30	4.00%	-1,290.9	>lifetime	0.128
EEM_3	2,189		30	4.00%	837.0	8.1	0.010
EEM_4	540		20	4.00%	1,570.0	1.1	0.002
EEM_5	980		20	4.00%	-12,516.5	-	0.020
EEM_6	3,250		20	4.00%	772.7	8.3	0.003
EEM_7	17		23	4.00%	475.3	0.1	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 48**, the replacement of the current heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 20,911.3 kWh/year, LCSE: 0.011€/kWh). On the contrary, EEM_2 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall EEM_2 and EEM_5 are ranked lower in terms of cost-effectiveness, mainly because of the high investment costs, and for the case of EEM_5 the lower price of natural gas compared to biomass.

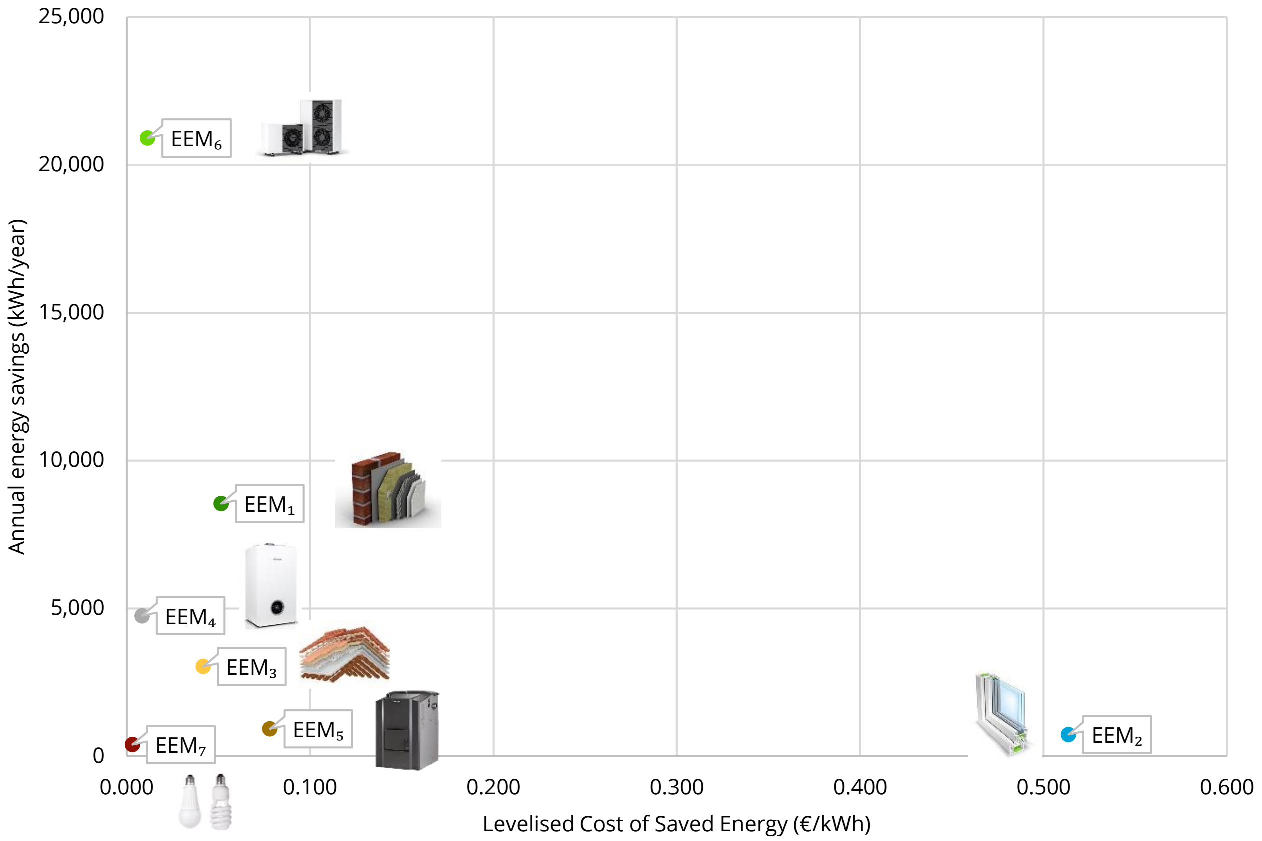

Figure 48. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of region of Bükk-Mak in Hungary.

Additionally, we seek to investigate the correlation between NPV and cost effectiveness of the different EEMs under study. **Figure 49** indicates that EEM_4 (Boiler upgrade- gas) and EEM_7 (Energy efficient light bulbs) rank highest, offering profitability with NPVs of 1,165.0€ and 462.9€ respectively, and demonstrating strong cost-effectiveness in energy savings. In contrast, EEM_2 and $EEM5_2$ rank lowest, with negative NPVs and higher LCSEs, indicating less attractive investments. Notably, EEM_7 (Energy efficient light bulbs) has the lowest LCSE of 0.009€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV. These results underscore the varying economic impacts and energy-saving potentials of the EEMs under consideration.

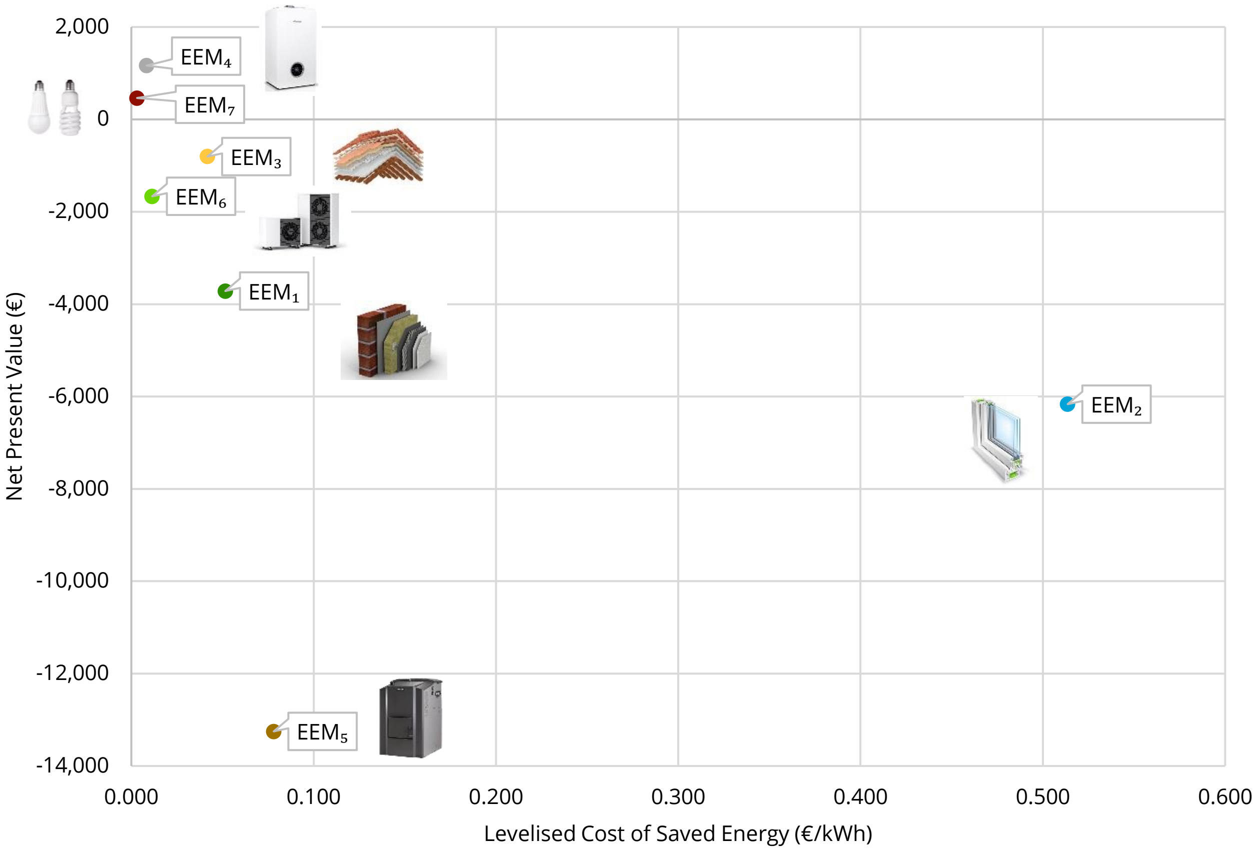

Figure 49. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of region of Bükk-Mak in Hungary.

The observed ranking remains consistent across various subsidisation levels, leading to increased cost-effectiveness and profitability of the investments. This is due to the lower LCSE and higher NPVs for the same amount of energy savings achieved. In most cases, subsidies of at least 50% to 75% ensure positive NPVs. It is important to note that the NPVs for measures such as EEM_5 and EEM_6 is negative, despite their significant impact on reducing energy consumption, mainly due to the low natural gas prices in Hungary. However, this situation is susceptible to future changes, as indicated by the recent substantial natural gas price increases during the latest energy crisis.

SFH typology (Somló-Marcalmente-Bakonyalja)

The results of the technoeconomic assessment of the different EEMs for the MFH typology in the rural region of SMB in Hungary, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 74**.

According to the analysis, EEM_4 (Boiler upgrade- gas) and EEM_3 (Roof insulation) demonstrate the best performance in terms of NPV, with NPVs of 3,219.0€ and 3,167.4€, respectively. EEM_7

(Energy efficient light bulbs) and EEM$_4$ (Boiler upgrade- gas) result in the lowest LCSE, at 0.003€/kWh and 0.004€/kWh, respectively. Additionally, EEM$_7$ and EEM$_4$ exhibit the best performance in PP, with 0.5 and 2.1 years, respectively. EEM$_1$ (Exterior wall insulation), EEM$_2$ (Double-glazed windows) and EEM$_5$ (Boiler upgrade- biomass) are not economically viable investments, without any subsidy rate, as they demonstrate negative NPVs.

The achieved energy savings from the different EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in SMB in Hungary to implement energy efficiency interventions. Moreover, the mixed picture in terms of the profitability of each EEM underscores the necessity of financial incentives/subsidisation. This financial support is crucial to enable energy-poor households to achieve energy savings while also realising tangible economic benefits. Without subsidies, these households might not be able to afford the initial investments required for energy efficiency improvements, despite the potential long-term savings. Therefore, subsidies play a vital role in making these measures accessible and economically viable for all, especially those exposed to energy poverty.

Table 74. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of SMB in Hungary (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	9,230	30	4.00%	-1,836.2	>lifetime	0.033
EEM$_2$	6,500	30	4.00%	-5,357.4	>lifetime	0.150
EEM$_3$	2,893	30	4.00%	3,167,4	10.2	0.013
EEM$_4$	540	20	4.00%	3,219.0	2.1	0.004
EEM$_5$	980	20	4.00%	-11,464.4	-	0.009
EEM$_6$	3,250	20	4.00%	1,008.5	13.7	0.008
EEM$_7$	17	23	4.00%	462.7	0.5	0.003

Table 75, **Table 76**, and **Table 77** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher

PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs.

Table 75. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region SMB in Hungary (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	9,230	25%	30	4.00%	471.3	26.6	0.025
EEM$_2$	6,500		30	4.00%	-3,732.4	>lifetime	0.113
EEM$_3$	2,893		30	4.00%	3,890.6	7.3	0.009
EEM$_4$	540		20	4.00%	3,354.0	1.5	0.003
EEM$_5$	980		20	4.00%	-11,219.4	-	0.007
EEM$_6$	3,250		20	4.00%	1,821.0	9.5	0.006
EEM$_7$	17		23	4.00%	466.8	0.4	0.002

Table 76. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of SMB in Hungary (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	9,230	50%	30	4.00%	2,778.8	14.4	0.016
EEM$_2$	6,500		30	4.00%	-2,107.4	>lifetime	0.075
EEM$_3$	2,893		30	4.00%	4,613.9	4.6	0.006
EEM$_4$	540		20	4.00%	3,489.0	1.0	0.002
EEM$_5$	980		20	4.00%	-10,974.4	-	0.004
EEM$_6$	3,250		20	4.00%	2,633.5	5.9	0.004
EEM$_7$	17		23	4.00%	470.9	0.2	0.002

Table 77. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of SMB in Hungary (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	9,230	75%	30	4.00%	5,086.3	6.2	0.008
EEM_2	6,500		30	4.00%	-482.4	>lifetime	0.038
EEM_3	2,893		30	4.00%	5,337.1	2.2	0.003
EEM_4	540		20	4.00%	3,624.0	0.5	0.001
EEM_5	980		20	4.00%	-10,729.4	-	0.002
EEM_6	3,250		20	4.00%	3,446.0	2.8	0.002
EEM_7	17		23	4.00%	475.0	0.1	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 50**, the replacement of the current heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 29,415.3 kWh/year, LCSE: 0.008€/kWh), followed by EEM_3 and EEM_1. On the contrary, EEM_2 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall, EEM_2 is ranked lower in terms of cost-effectiveness, mainly because of the high investment cost combined with its performance in terms of energy savings.

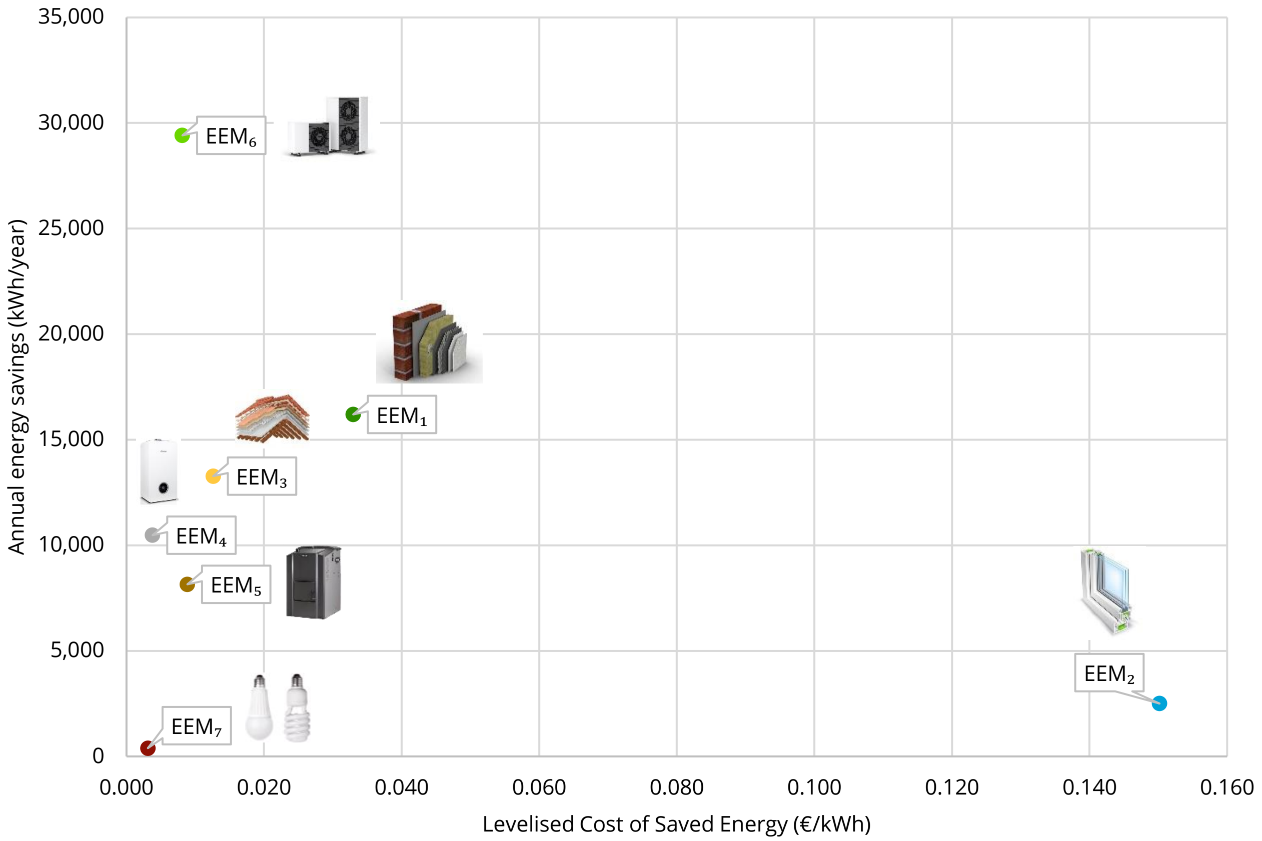

Figure 50. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of SMB in Hungary.

Additionally, we seek to identify the correlation between the NPV and cost effectiveness of the different EEMs under study. **Figure 51** indicates that EEM_4 (Boiler upgrade-gas) and EEM_3 (Roof Insulation) rank highest in NPV, offering higher profitability with NPVs of 3,219.0€ and 3,167.4€ respectively, while EEM_6 demonstrates strong cost-effectiveness. In contrast, EEM_1 and EEM_2 rank lowest, with lower NPVs and higher LCSEs, indicating less attractive investments in case no subsidy is granted. Notably, EEM_7 (Energy efficient light bulbs) has the lowest LCSE of 0.003€/kWh, highlighting its exceptional cost-effectiveness despite a modest

NPV. These results underscore the varying economic impacts and energy-saving potentials of the EEMs under consideration.

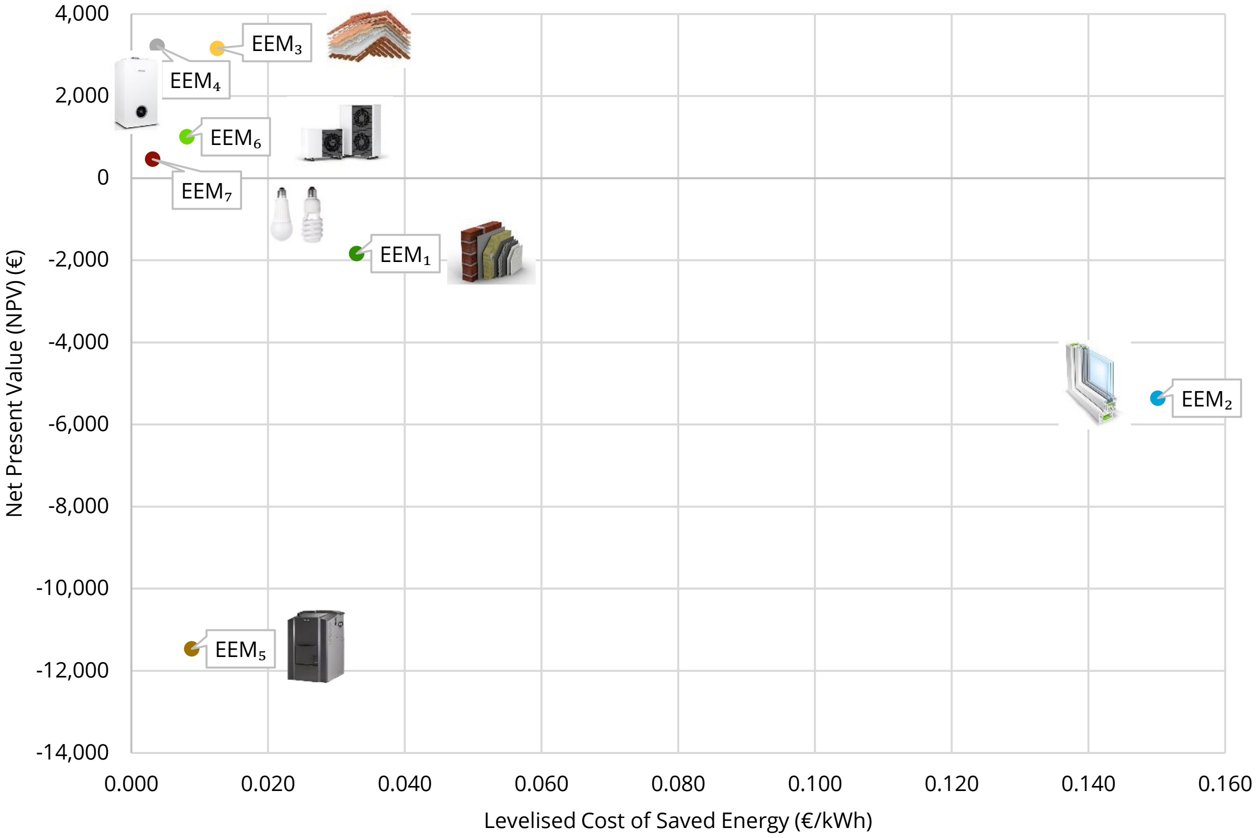

Figure 51. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of SMB in Hungary.

The observed ranking among the EEMs remains consistent across various subsidisation levels, leading to increased cost-effectiveness and profitability. This is due to the lower LCSE and higher NPVs for the same amount of energy savings achieved. In most cases, subsidies of at least 50% to 75% ensure positive NPVs for the majority of the EEMs. It is important to note that the NPVs for measures such as EEM_5 and EEM_6 is negative, despite their significant impact on reducing energy consumption, mainly due to the low natural gas prices in Hungary. However, this situation is susceptible to future changes, as indicated by the recent substantial natural gas price increases in during the latest energy crisis.

6.4 Results for the rural region of Sveta Nedelja and Žumberak in Croatia

For the case study of the rural regions of Sveta Nedelja and Žumberak in Croatia, the two household typologies explored concern a SFH equipped with a wood stove, and a SFH equipped with a gas boiler to cover their heating needs. Detailed specifications of each household typology identified in the rural region of Parma are presented in **Sections 5.2.4**, **5.3**, and **5.4**.

6.4.1 Energy performance in the current situation (baseline scenario)

SFH typology (wood stove)

In the baseline scenario, modelling results indicate that the SFH typology equipped with a wood stove consumes around 57,484.6 kWh annually (almost 575.0 kWh/m^2), which are divided into 54,719.5 kWh for its heating needs and 2,765.0 kWh for its cooling and appliances needs (**Figure 52**).

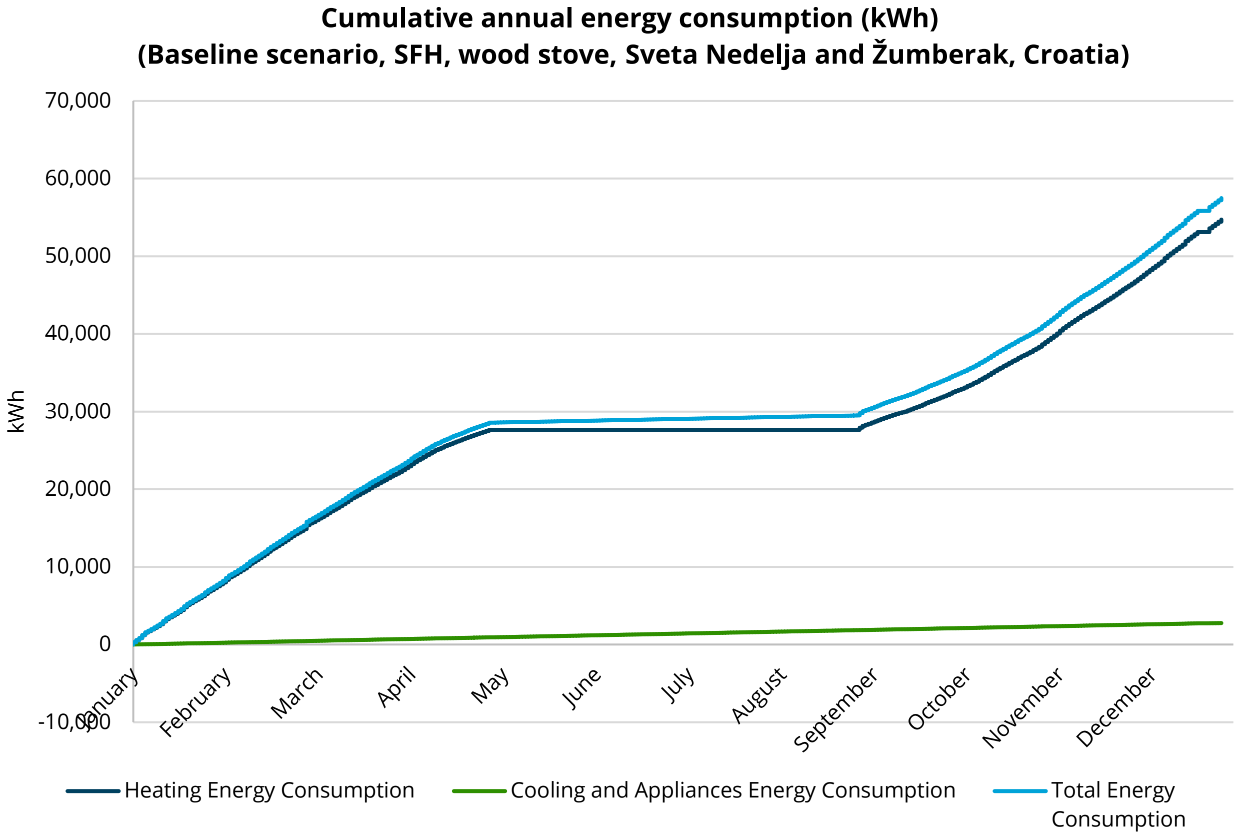

Figure 52. Cumulative annual consumption for the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia (baseline scenario).

SFH typology (gas boiler)

In the baseline scenario, modelling results indicate that the SFH typology equipped with a gas boiler consumes around 39,291.0 kWh annually (almost 315.8 kWh/m^2), which is divided into 36,526.0 kWh for its heating needs and 2,765.0 kWh for its cooling and appliances needs (**Figure 53**).

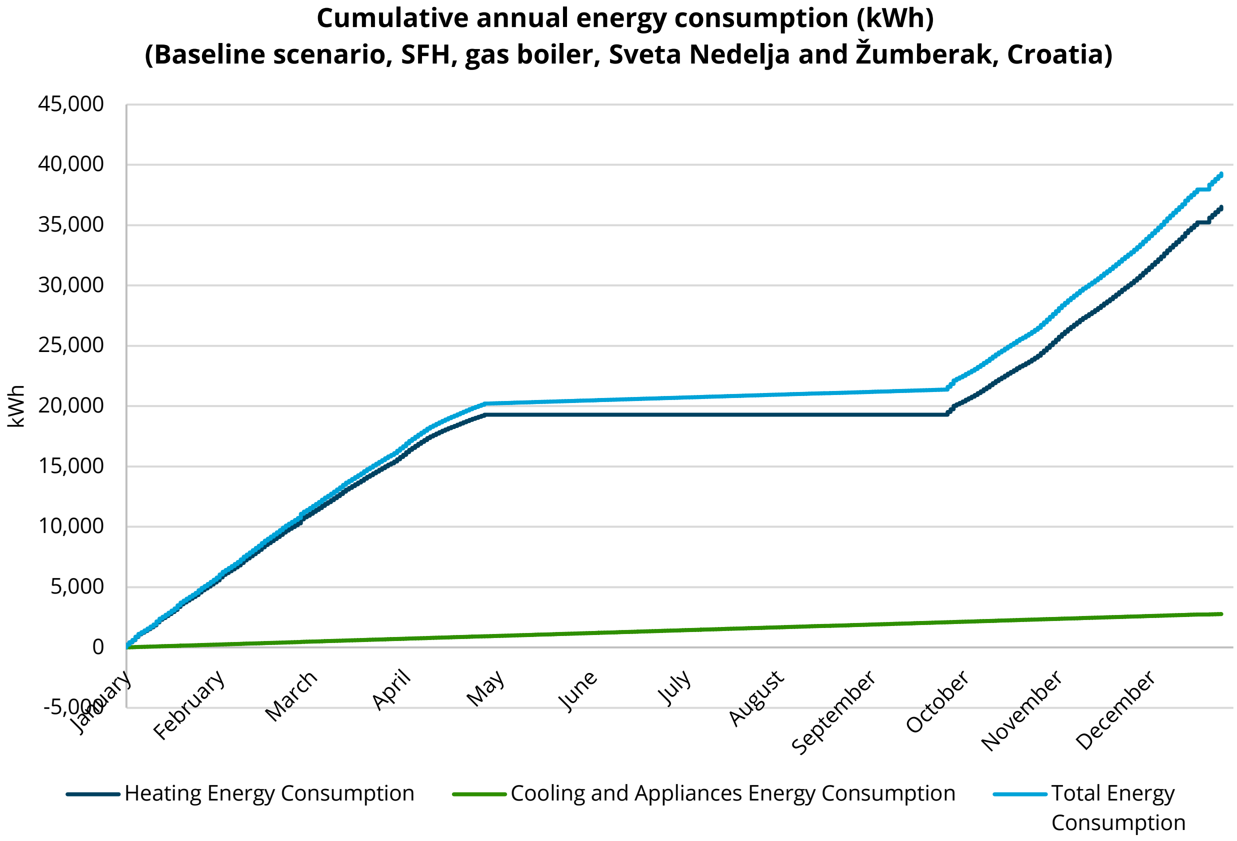

Figure 53. Cumulative annual consumption for the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia (baseline scenario).

6.4.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology (wood stove)

In the case of the SFH typology equipped with a wood stove, **Figure 54** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 14,204.2 kWh. This is followed by EEM$_4$, which involves the installation of an upgraded gas boiler, leading to an annual consumption of 42,467.5 kWh and EEM$_4$ (Roof insulation), with an annual energy consumption of 43,173.4 kWh.

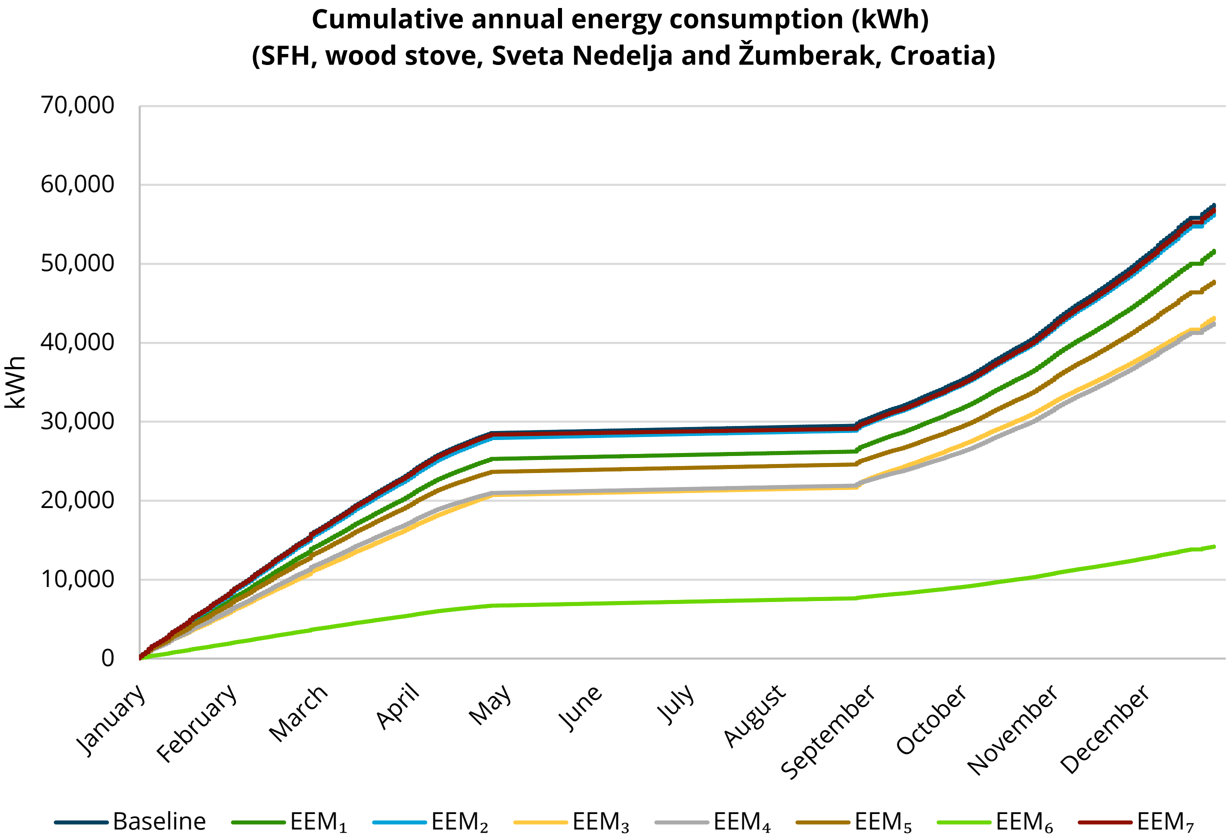

Figure 54. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 78**. As indicated in **Figure 55**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 43,280.4 kWh per year (75.3% reduction compared to the baseline scenario), while EEM$_4$ leads to 15,017.0 kWh saved annually (26.1% reduction) and EEM$_3$ leads to reducing energy consumption by 14,311.2 kWh per year (24.9% reduction).

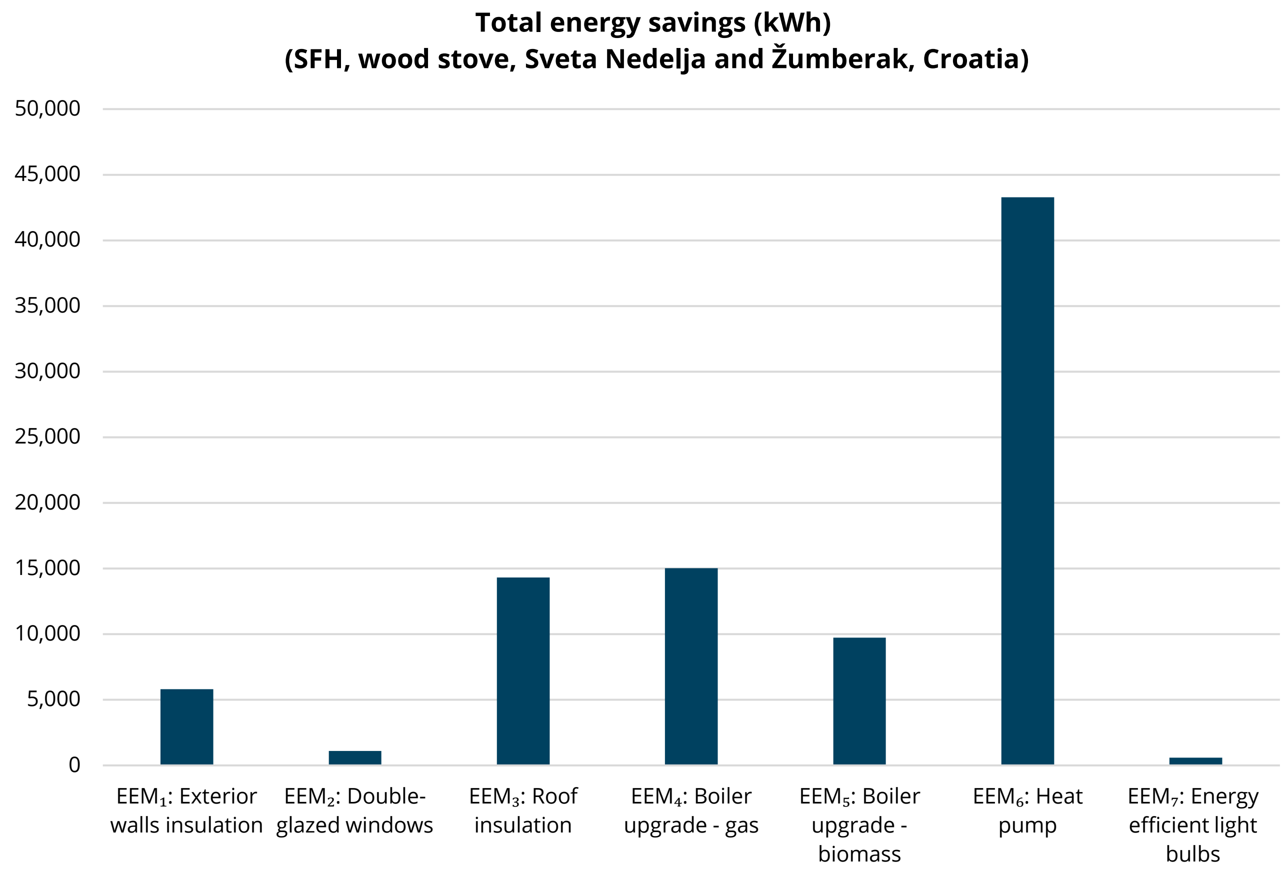

Figure 55. Annual total energy savings (in kWh) for the different EEMs in the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Table 78. Comparison of annual total energy savings (kWh) for all EEMs with baseline (wood Stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Annual energy savings (kWh) (SFH, wood stove, Sveta Nedelja and Žumberak, Croatia)		
	Energy savings (kWh)	**Reduction (%)**
EEM_1: Exterior wall insulation	5,814.1	10.1
EEM_2: Double-glazed windows	1,100.1	1.9
EEM_3: Roof insulation	14,311.2	24.9
EEM_4: Boiler upgrade – gas	15,017.0	26.1
EEM_5: Boiler upgrade – biomass	9,724.8	16.9
EEM_6: Heat pump	43,280.4	75.3
EEM_7: Energy efficient light bulbs	579.7	1.0

SFH typology (gas boiler)

In the case of the SFH typology equipped with a gas boiler, **Figure 56** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 11,294.2 kWh. This is followed by EEM$_3$, which entails roof insulation, leading to an annual consumption of 28,673.0 kWh and EEM$_4$, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 34,770.7 kWh.

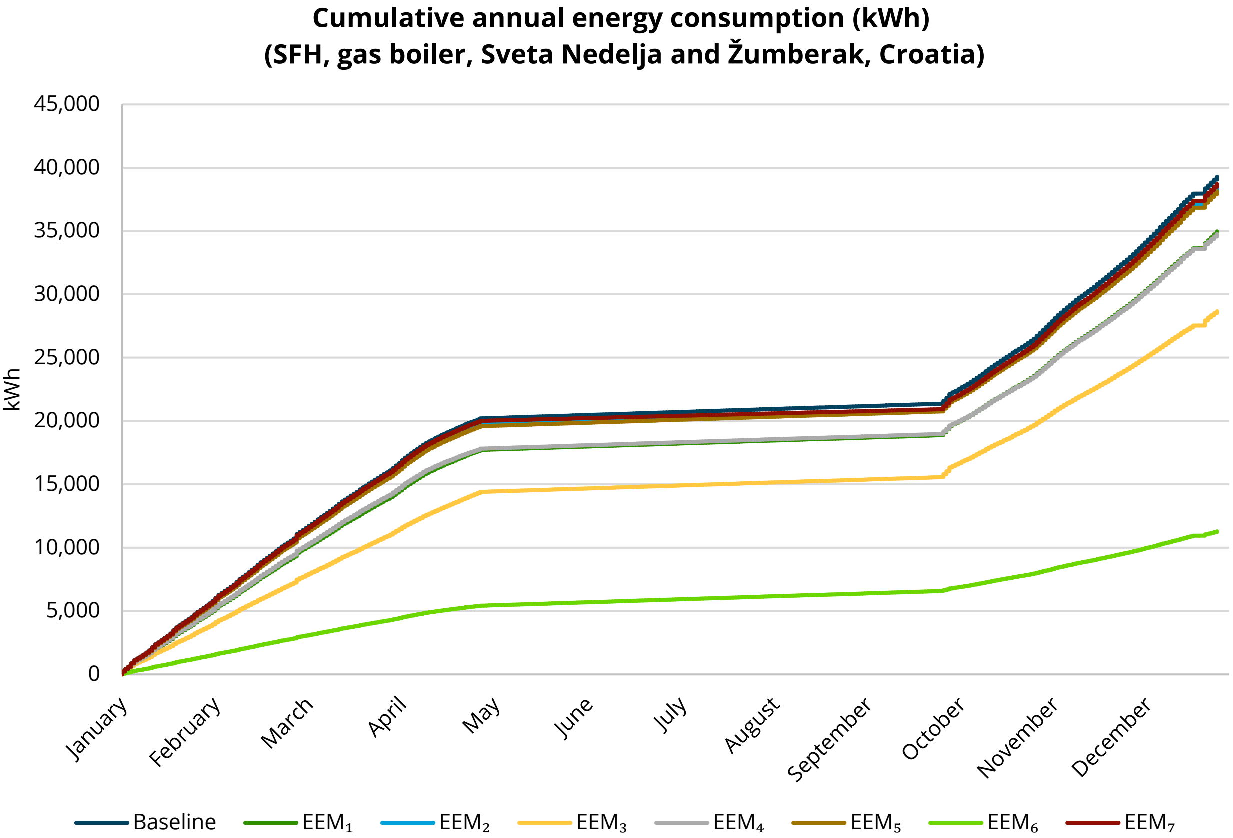

Figure 56. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 79**. As indicated in **Figure 57**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 27,996.8 kWh per year (71.3% reduction compared to the baseline scenario), while EEM$_3$ leads to 10,618.0 kWh saved annually (27.0% reduction) and EEM$_3$ leads to reducing energy consumption by 4,520.4 kWh per year (11.5% reduction).

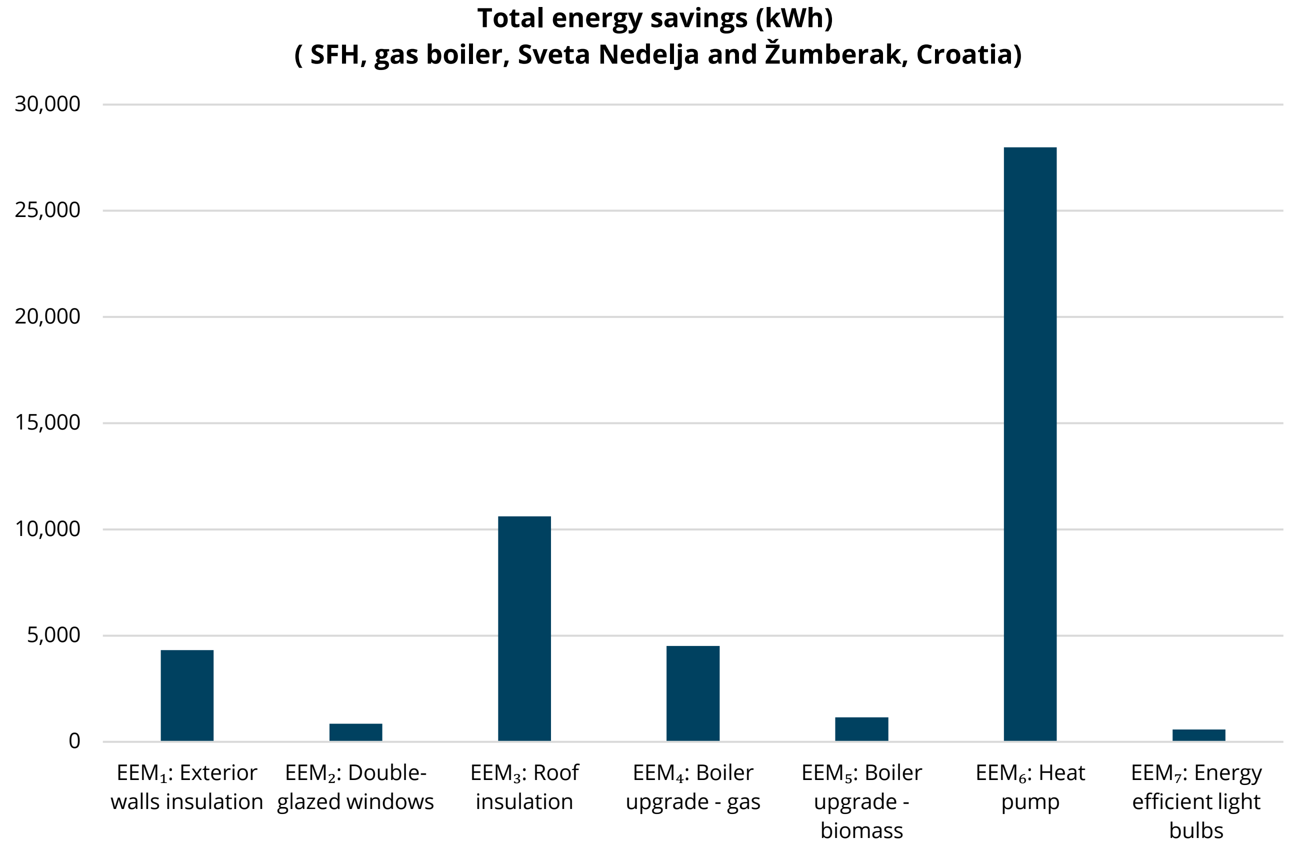

Figure 57. Annual total energy savings (in kWh) for the different EEMs in the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Table 79. Comparison of annual total energy savings (kWh) for all EEMs with baseline (gas boiler) in Sveta Nedelja and Žumberak in Croatia.

Annual energy savings (kWh) (SFH, gas boiler, Sveta Nedelja and Žumberak Croatia)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	4,322.0	11.0
EEM$_2$: Double-glazed windows	857.5	2.2
EEM$_3$: Roof insulation	10,618.0	27.0
EEM$_4$: Boiler upgrade – gas	4,520.4	11.5
EEM$_5$: Boiler upgrade – biomass	1,154.0	2.9
EEM$_6$: Heat pump	27,996.8	71.3
EEM$_7$: Energy efficient light bulbs	597.7	1.5

6.4.3 Environmental impact and thermal comfort analysis

SFH typology (wood stove)

CO_2 footprint

Figure 58 presents the annual CO_2 emissions (in kg) for both all the scenarios under study (i.e., baseline and EEMs) in the rural region of Sveta Nedelja and Žumberak in Croatia for the SFH typology. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 16,757.5 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 12,771.4 and 9,052.6 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 80**. The emission factor for the use of wood stove in the baseline situation is derived from sources in the scientific literature (Bhattacharya et al., 2002).

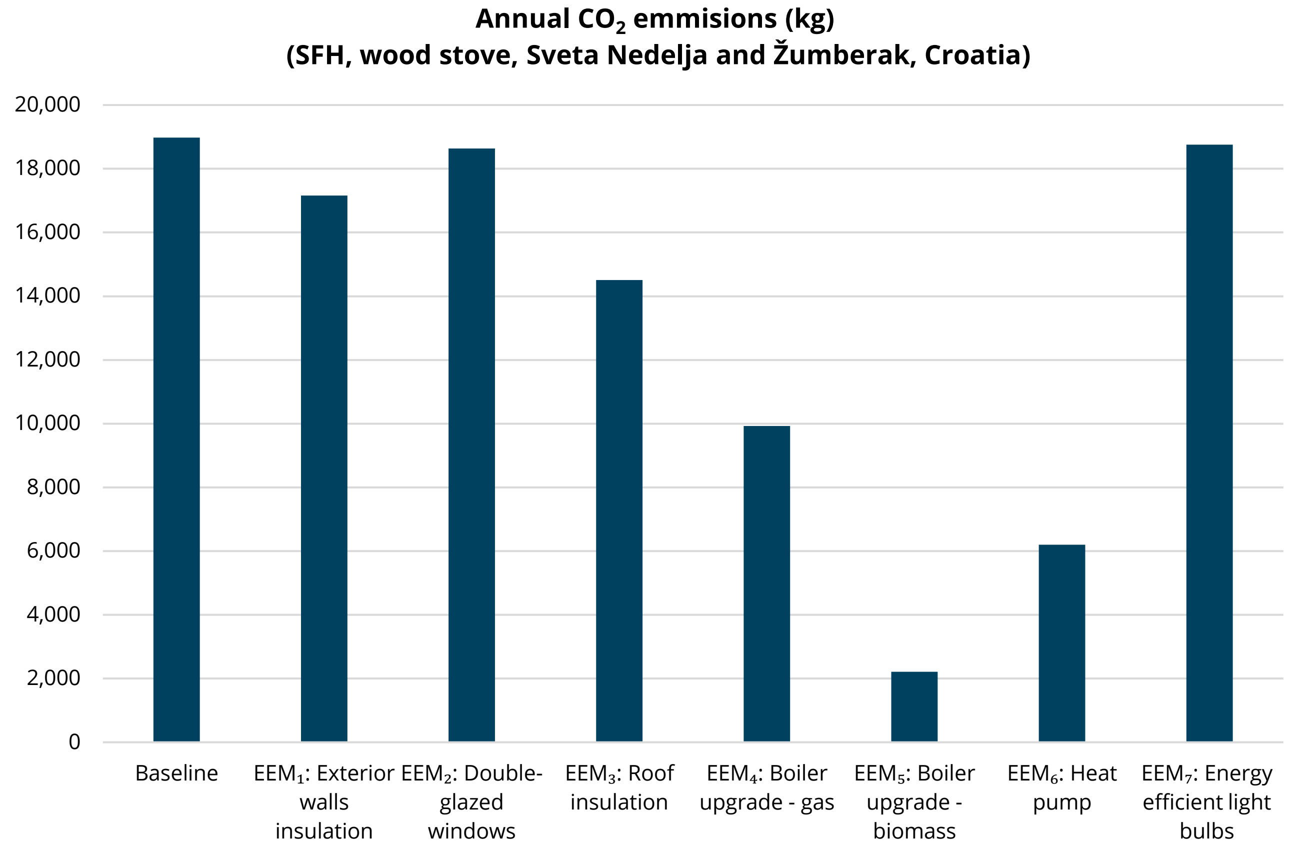

Figure 58. Annual CO_2 emissions (kg) in all scenarios in the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Table 80 Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology (wood stove) in the rural region of Sveta Nedelja and Žumberak in Croatia.

Annual CO_2 emissions avoided (SFH, wood stove, Sveta Nedelja and Žumberak, Croatia)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,814.0	9.6
EEM_2: Double-glazed windows	343.2	1.8
EEM_3: Roof insulation	4,465.1	23.5
EEM_4: Boiler upgrade – gas	9,052.6	47.7
EEM_5: Boiler upgrade – biomass	16,757.5	88.3
EEM_6: Heat pump	12,771.4	67.3
EEM_7: Energy efficient light bulbs	218.0	1.1

PMV indicator

In regards with the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 59** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

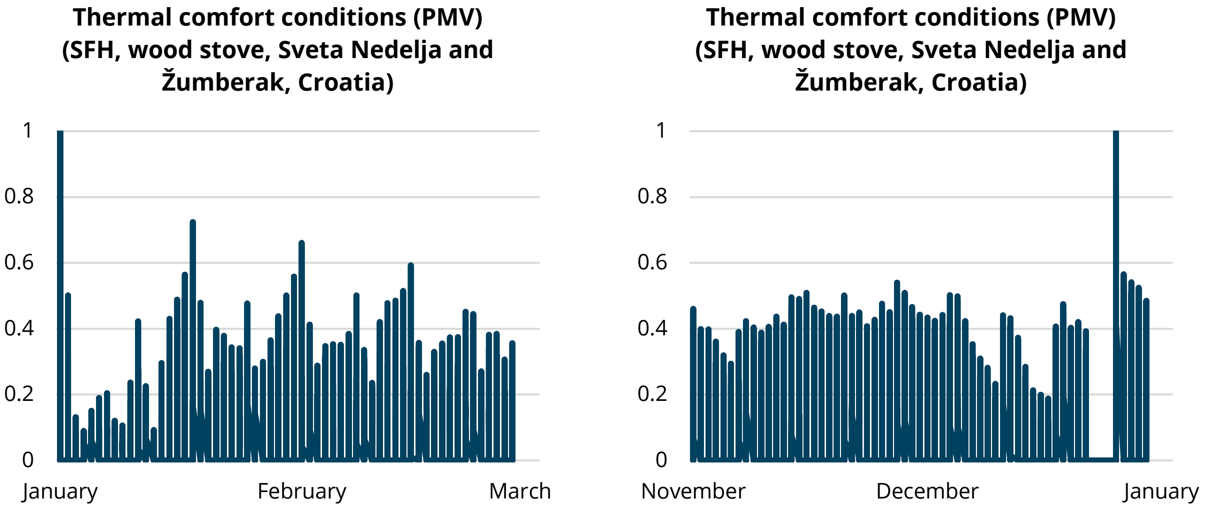

Figure 59. Thermal comfort (PMV indicator) for the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia during the winter for all the scenarios under study.

SFH typology (gas boiler)

CO$_2$ footprint

Figure 60 presents the annual CO$_2$ emissions (in kg) for both all the scenarios under study (i.e., baseline and EEMs) in the case of the SFH equipped with gas boiler in the rural regions of Sveta Nedelja and Žumberak in Croatia. We can observe that EEM$_5$ leads to the highest emissions reduction, leading to the avoidance of almost 7,130.6 kg CO$_2$ per year, followed by EEM$_6$ and EEM$_3$ which lead to an avoidance of around 4,171.3 and 2,144.8 kg CO$_2$, respectively. More details on the total kg CO$_2$ avoided and the reduction percentage for each EEM can be found in **Table 81**.

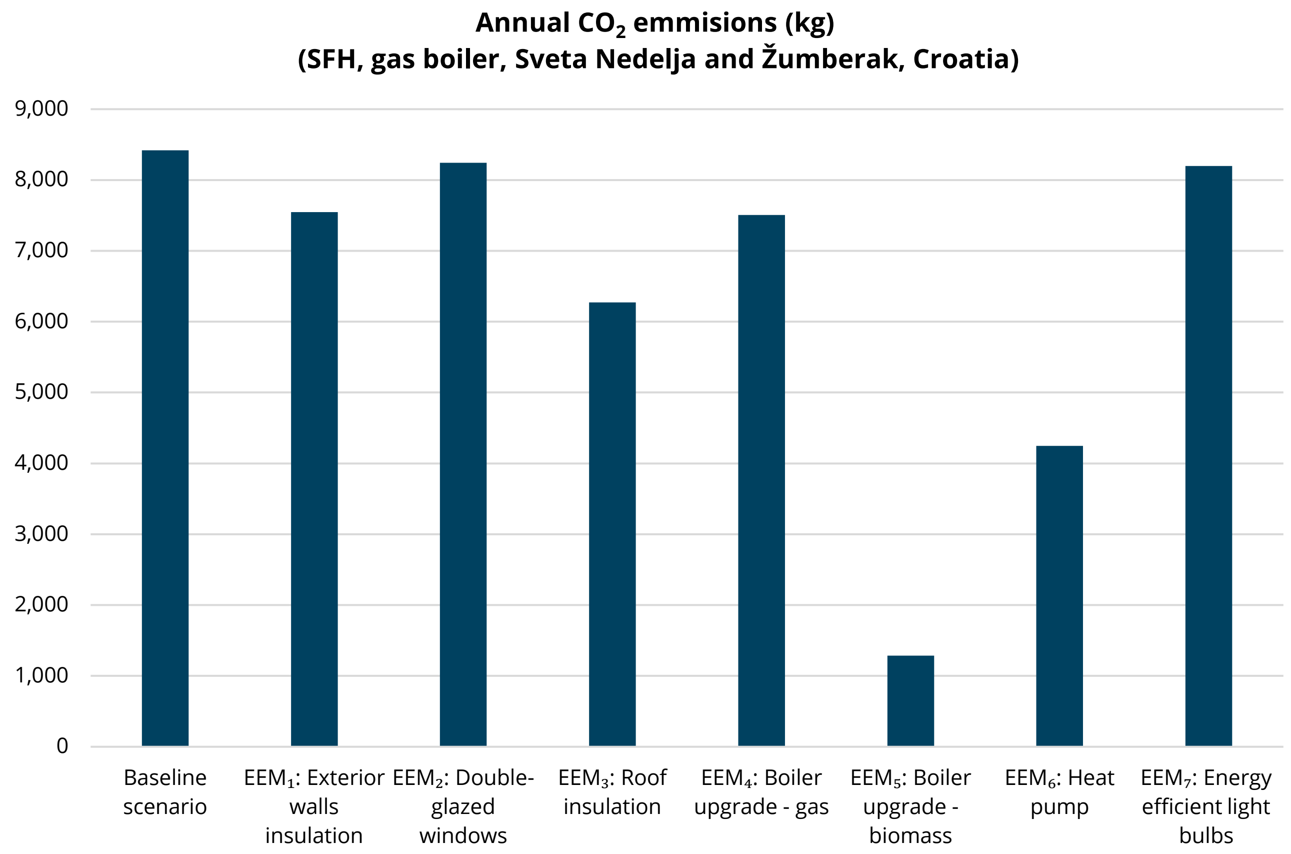

Figure 60. Annual CO_2 emissions (kg) in all scenarios in the SFH typology equipped with gas boiler in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Table 81. Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology equipped with gas boiler in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Annual emissions avoided (kg CO_2) (EEMs, SFH, gas boiler, Sveta Nedelja and Žumberak, Croatia)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	873.0	10.4
EEM_2: Double-glazed windows	173.2	2.1
EEM_3: Roof insulation	2,144.8	25.5
EEM_4: Boiler upgrade – gas	913.1	10.8
EEM_5: Boiler upgrade – biomass	7,130.6	84.7
EEM_6: Heat pump	4,171.3	49.6
EEM_7: Energy efficient light bulbs	218.0	2.6

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 61** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

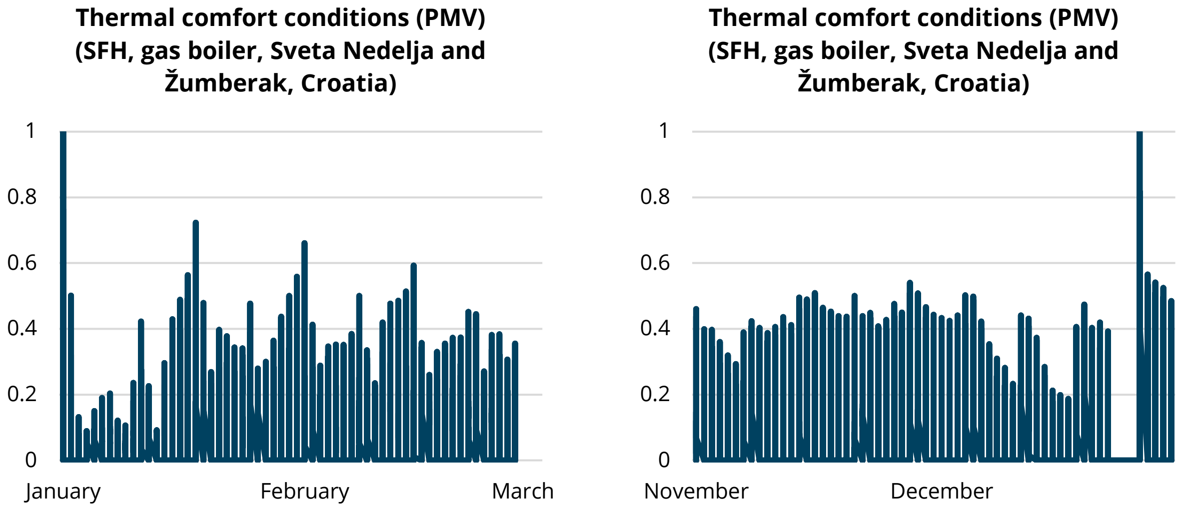

Figure 61. Thermal comfort (PMV indicator) for the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia during the winter for all the scenarios under study.

6.4.4 Technoeconomic assessment

SFH typology (wood stove)

The results of the technoeconomic assessment of the different EEMs for the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 82**.

According to the analysis, EEM_4 (Boiler upgrade– gas) and EEM_3 (Roof insulation) demonstrate the best performance in terms of NPV, with NPVs of 18,583.9€ and 10,060.6€, respectively. EEM_7 (Energy efficient light bulbs) and EEM_6 (heat pump) result in the lowest LCSE, at 0.005€/kWh and 0.018€/kWh, respectively. Additionally, EEM_7 and EEM_4 exhibit the best performance in PP, with 0.7 and 2.4 years, respectively. EEM_2 (Double-glazed windows) is not an economically viable investment, without any subsidy rate, as it demonstrates negative NPV.

The substantial economic benefits provided by all EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Sveta Nedelja and Žumberak to implement energy efficiency interventions. In addition, the profitability of EEMs that change the heating technology of the household suggest that there is an urgent need for the housing stock of Sveta Nedelja and Žumberak to migrate to more efficient heating systems without the utilisation of wood but rather move to other more efficient solutions.

Table 82. Technoeconomic assessment of the different EEMs in the SFH (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	4,847	30	4.00%	1,185.1	20.7	0.048
EEM_2	3,584	30	4.00%	-2,687.0	>lifetime	0.240
EEM_3	4,788	30	4.00%	10,060.6	6.4	0.019
EEM_4	3,468	20	4.00%	18,583.9	2.4	0.019
EEM_5	3,657	20	4.00%	3,593.3	8.2	0.033
EEM_6	10,000	20	4.00%	3,108.6	13.7	0.018
EEM_7	45	23	4.00%	962.7	0.7	0.005

Table 83, **Table 84**, and **Table 85** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs.

Table 83. Technoeconomic assessment of the different EEMs in the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,847	25%	30	4.00%	2,396.9	13.8	0.036
EEM$_2$	3,584		30	4.00%	-1,791.0	>lifetime	0.180
EEM$_3$	4,788		30	4.00%	11,257.5	4.7	0.015
EEM$_4$	3,468		20	4.00%	19,450.9	1.8	0.015
EEM$_5$	3,657		20	4.00%	4,507.5	5.9	0.026
EEM$_6$	10,000		20	4.00%	5,608.6	9.5	0.014
EEM$_7$	45		23	4.00%	973.9	0.5	0.004

Table 84. Technoeconomic assessment of the different EEMs in the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,847	50%	30	4.00%	3,608.7	8.3	0.024
EEM$_2$	3,584		30	4.00%	-895.0	>lifetime	0.120
EEM$_3$	4,788		30	4.00%	12,454.4	3.0	0.010
EEM$_4$	3,468		20	4.00%	20,317.9	1.2	0.011
EEM$_5$	3,657		20	4.00%	5,421.8	3.8	0.019
EEM$_6$	10,000		20	4.00%	8,108.7	5.9	0.010
EEM$_7$	45		23	4.00%	985.2	0.3	0.003

Table 85. Technoeconomic assessment of the different EEMs in the SFH (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	4,847	75%	30	4.00%	4,820.5	3.8	0.012
EEM_2	3,584		30	4.00%	1.0	20.0	0.060
EEM_3	4,788		30	4.00%	13,651.3	1.5	0.005
EEM_4	3,468		20	4.00%	21,184.9	0.6	0.007
EEM_5	3,657		20	4.00%	6,336.0	1.8	0.012
EEM_6	10,000		20	4.00%	10,608.6	2.8	0.005
EEM_7	45		23	4.00%	996.4	0.2	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 62**, the replacement of the current heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 43,280.4 kWh/year, LCSE: 0.018€/kWh), followed by EEM_4 and EEM_3. On the contrary, EEM_2 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the lower values of expected annual savings, followed by EEM_1, indicating the need for incentives and initiatives aiming to increase the cost-effectiveness of those measures and to lower their investment costs.

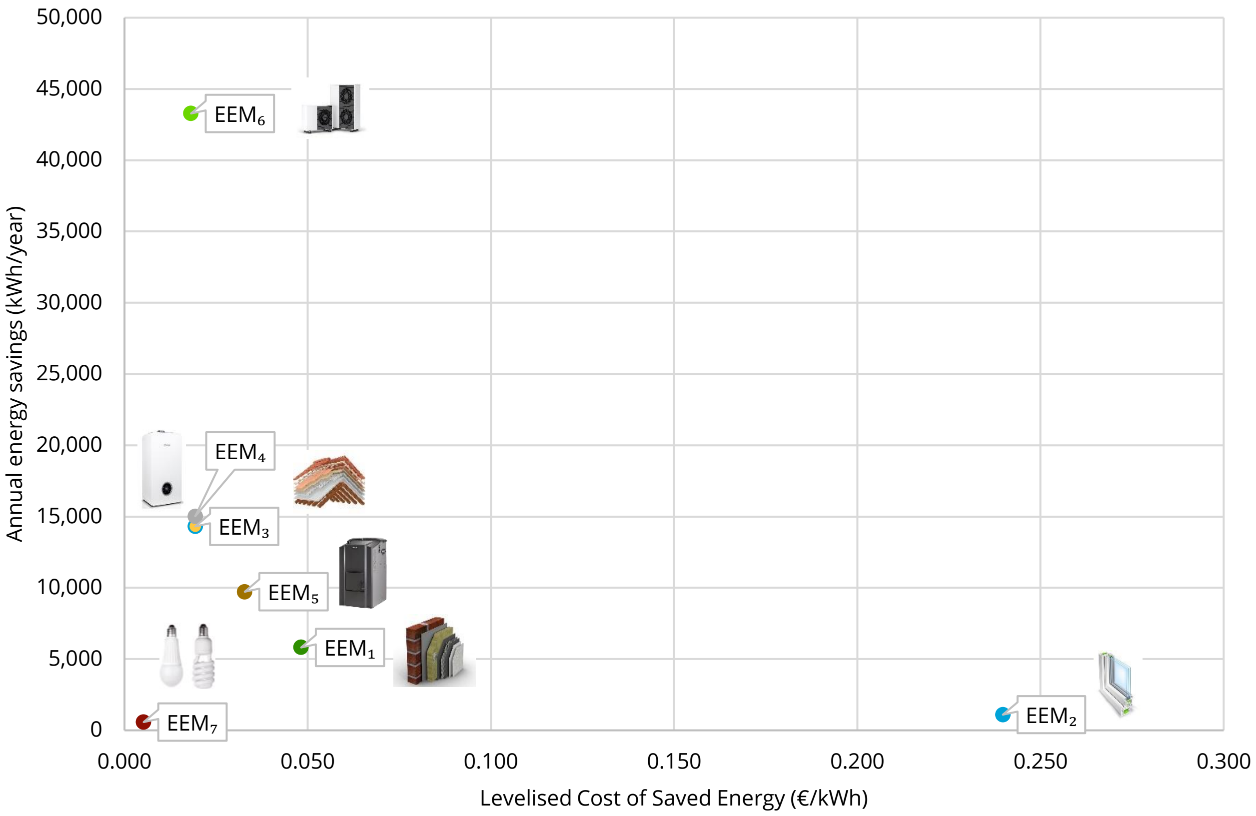

Figure 62. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Additionally, we seek to identify the correlation between profitability and cost-effectiveness of the different EEMs under study. **Figure 63** indicates that EEM_4 (Boiler upgrade– gas), EEM_3 (Roof insulation), EEM_6 (Heat pump), EEM_5 (Boiler upgrade- biomass), EEM_1 (External walls insulation) and EEM_7 (Energy efficient light bulbs) offer valuable combinations of NPV and LCSE. In contrast, EEM_2 ranks lowest, with negative NPV and higher LCSE, indicating a less attractive investment.

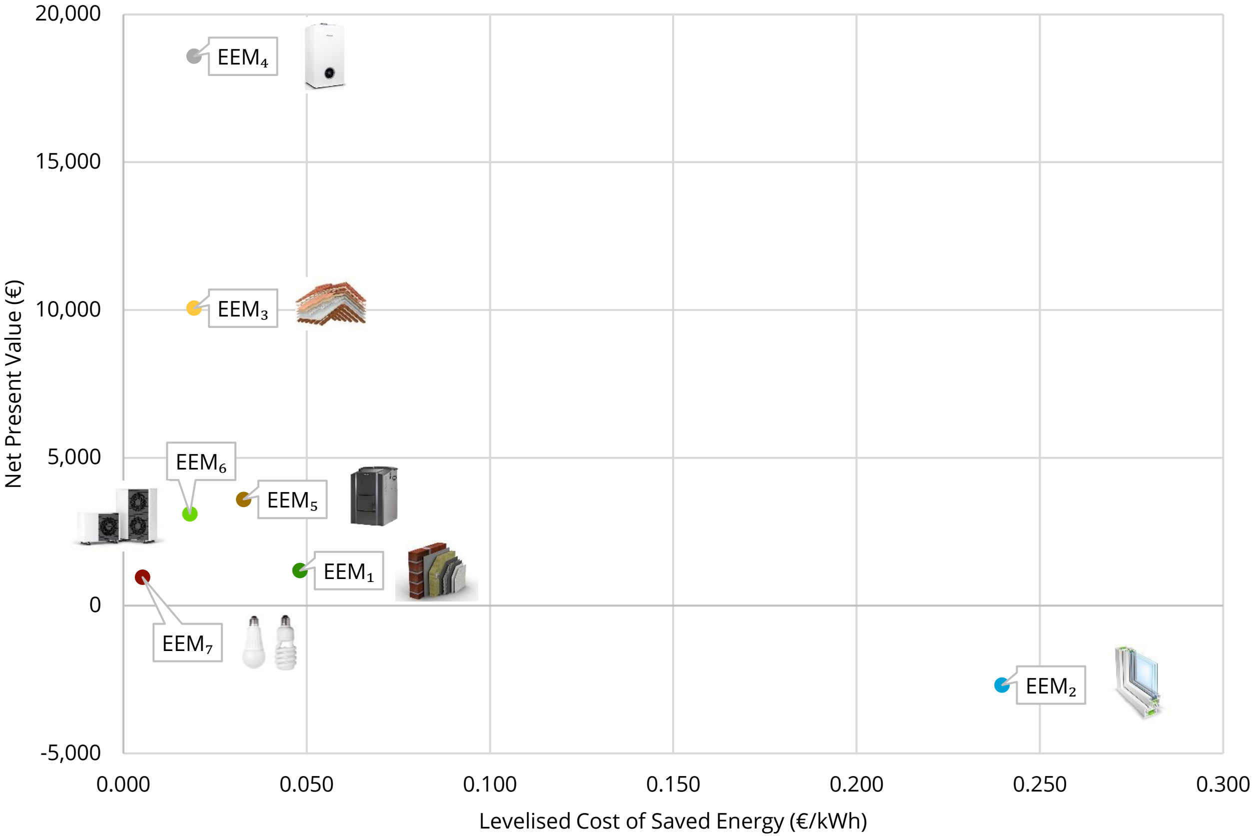

Figure 63. Economic benefits and cost-effectiveness of the EEMs under study in the case of the SFH typology (wood stove) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

The same ranking is observed in the case of the different subsidisation levels leading to increased cost-effectiveness, due to the lower LCSEs and the higher NPVs, for the same amount of energy savings achieved. Moreover, the NPV of EEM_2 becomes positive for subsidy levels of at least 75%.

SFH typology (gas boiler)

The results of the technoeconomic assessment of the different EEMs for the SFH typology equipped with a gas boiler for the rural regions of Sveta Nedelja and Žumberak in Croatia, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 86**. In the case of Sveta Nedelja and Žumberak in Croatia, this is not reflected in the technoeconomic analysis, due to the low price of gas for domestic uses in Croatia.

According to the analysis, EEM_3 (Roof Insulation) and EEM_7 (Energy efficient light bulbs) demonstrate the best performance in terms of NPV, with NPVs of 3,107.6€ and 957.7€, respectively. The rest of the EEMs are not economically viable investments, without any subsidy rate, as they demonstrate negative NPVs. EEM_7 (Energy efficient light bulbs) and EEM_4 (Boiler upgrade– gas) result in the lowest LCSE, at 0.006€/kWh and 0.026€/kWh, respectively.

Additionally, EEM_7 and EEM_4 exhibit the best performance in PP, with 0.8 and 13.9 years, respectively. EEM_1 (Exterior wall insulation), EEM_2 (Double-glazed windows), EEM_4 (Boiler upgrade– gas) and EEM_5 (Boiler upgrade– biomass) are not economically viable investments, without any subsidy rate, as they demonstrate negative NPVs.

Table 86. Technoeconomic assessment of the different EEMs in the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	4,847	30	4.00%	-1,633.5	>lifetime	0.065
EEM_2	3,584	30	4.00%	-3,082.9	>lifetime	0.308
EEM_3	4,788	30	4.00%	3,107,6	13.9	0.026
EEM_4	3,468	20	4.00%	-1,381.6	>lifetime	0.064
EEM_5	3,657	20	4.00%	-11,834.3	-	0.277
EEM_6	10,000	20	4.00%	-2,896.4	>lifetime	0.028
EEM_7	45	23	4.00%	957.7	0.8	0.006

Table 87, **Table 88**, and **Table 89** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. In addition, several EEMs become economically viable, highlighting the importance of incentives created by governments for the uptake of energy efficiency interventions. More specifically, EEM_1 (Exterior wall insulation), EEM_4 (Boiler upgrade– gas) and EEM_6 (heat pump) become economically viable investments for a subsidy rate of at least 50%.

Table 87. Technoeconomic assessment of the different EEMs in the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,847	25%	30	4.00%	-421.7	>lifetime	0.049
EEM$_2$	3,584		30	4.00%	-2,186.9	>lifetime	0.231
EEM$_3$	4,788		30	4.00%	4,304.5	9.6	0.020
EEM$_4$	3,468		20	4.00%	-514.6	>lifetime	0.051
EEM$_5$	3,657		20	4.00%	-10,920.1	-	0.218
EEM$_6$	10,000		20	4.00%	-396.2	>lifetime	0.021
EEM$_7$	45		23	4.00%	970.2	0.6	0.004

Table 88. Technoeconomic assessment of the different EEMs in the SFH typology (gas boiler) in the rural region of Sveta Nedelja and Žumberak in Croatia (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,847	50%	30	4.00%	790.1	18.8	0.032
EEM$_2$	3,584		30	4.00%	-1,290.9	>lifetime	0.154
EEM$_3$	4,788		30	4.00%	5,5501.4	6.0	0.013
EEM$_4$	3,468		20	4.00%	352.4	12.0	0.038
EEM$_5$	3,657		20	4.00%	-10,005.8	-	0.160
EEM$_6$	10,000		20	4.00%	2,103.8	12.3	0.015
EEM$_7$	45		23	4.00%	982.7	0.4	0.003

Table 89. Technoeconomic assessment of the different EEMs in the SFH typology (gas boiler) in the rural region of SMB in Hungary (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,847	75%	30	4.00%	2,001.9	7.7	0.016
EEM$_2$	3,584		30	4.00%	-394.9	>lifetime	0.077
EEM$_3$	4,788		30	4.00%	6,698.2	2.8	0.007
EEM$_4$	3,468		20	4.00%	1,219.4	7.0	0.024
EEM$_5$	3,657		20	4.00%	-9,091.6	-	0.102
EEM$_6$	10,000		20	4.00%	4,603.8	5.4	0.008
EEM$_7$	45		23	4.00%	995.2	0.2	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 64**, the replacement of the current heating system with an energy-efficient heat pump (EEM$_6$) is the most cost-effective measure (energy savings: 27,996.8 kWh/year, LCSE: 0.028€/kWh), followed by EEM$_3$. On the contrary, EEM$_5$ and EEM$_2$ are shown to be the least cost-effective energy-efficient measures due to their higher LCSEs and the lower values of expected annual savings.

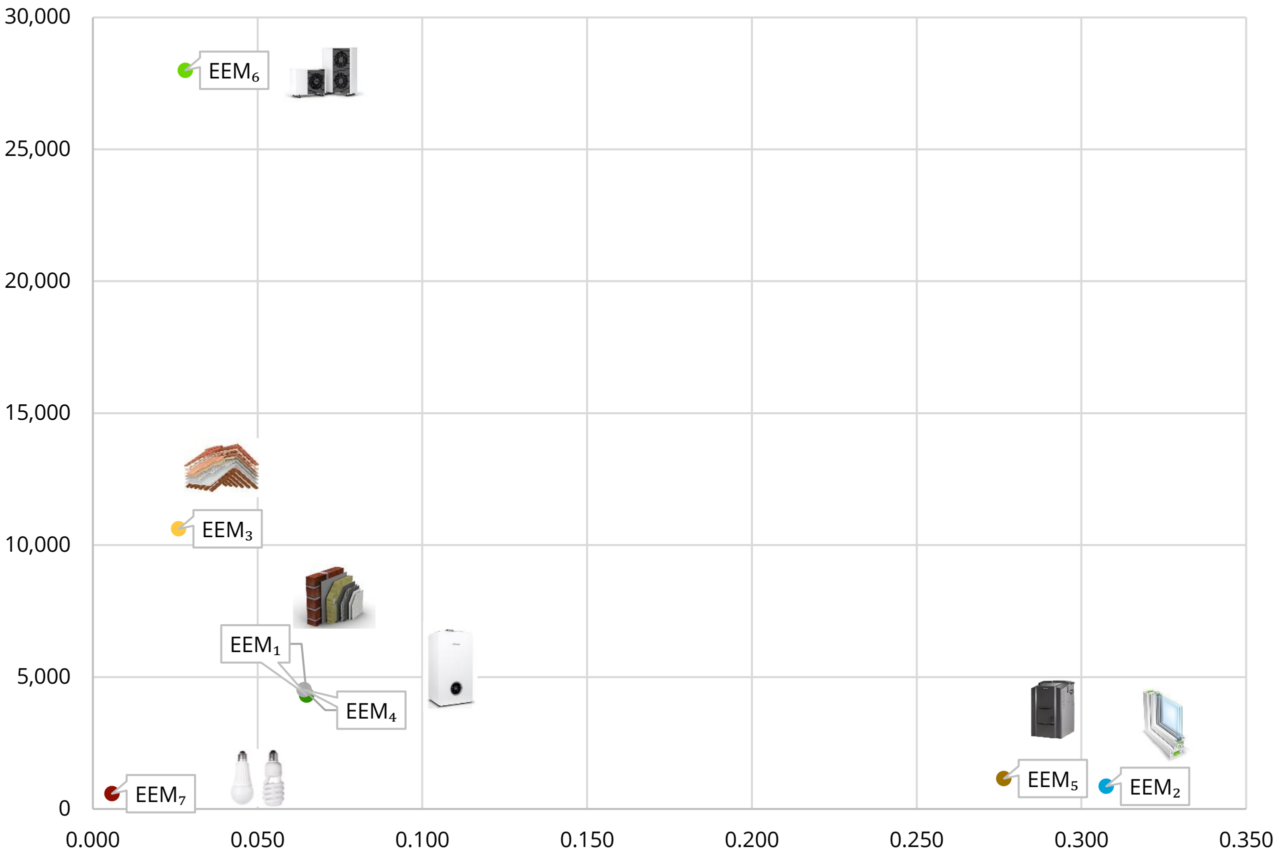

Figure 64. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

Additionally, we seek to identify the correlation between profitability and cost-effectiveness of the different EEMs under study. **Figure 65**, indicates that EEM_3 (Roof Insulation) and EEM_7 (Energy efficient light bulbs) have the best combinations of NPV and LCSE, offering profitability with NPVs of 3,107.6€ and 957.7€, while their LCSEs are lower than 0.020€/kWh.

In contrast, EEM$_5$, EEM$_2$, EEM$_4$, and EEM$_1$ rank lowest, with negative NPVs and higher LCSEs, indicating less attractive investments.

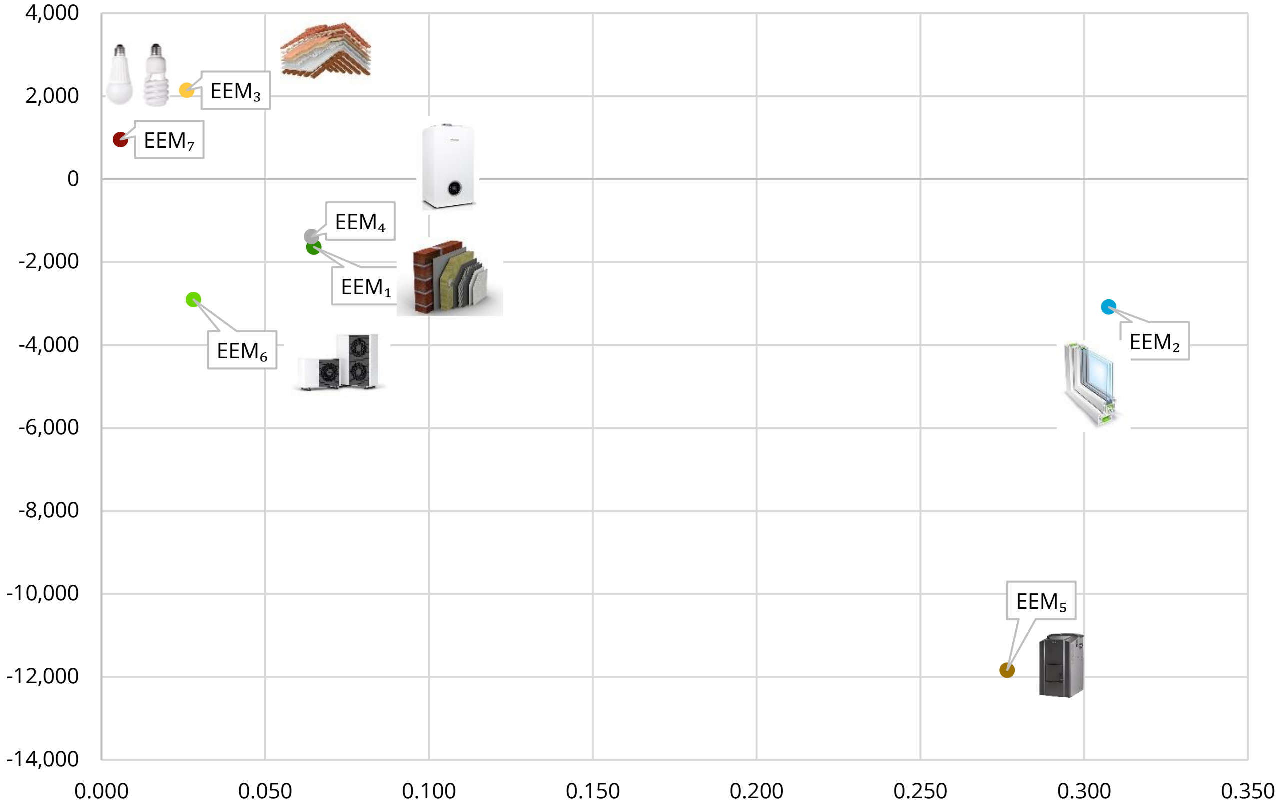

Figure 65. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology (gas boiler) in the rural regions of Sveta Nedelja and Žumberak in Croatia.

The status of profitability among the majority of EEMs in the case of the SFH typology (gas boiler) in Sveta Nedelja and Žumberak in Croatia, highlight the urgent need for subsidisation of the different actions. Among the different subisidisation levels, the observed ranking among the different EEMs remains consistent. As indicated in **Table 88** and **Table 89**, subsidies of at least 50% to 75% ensure positive NPVs for all EEMs, except for EEM$_5$ and EEM$_2$.

6.5 Results for the rural region of Tartu in Estonia

For the case study of the rural region of Tartu in Estonia, the household typology explored concerns a MFH equipped using district heating to cover heating needs. Detailed specifications of the household typology identified in the rural region of Tartu are presented in **Sections 5.2.5**, **5.3**, and **5.4**.

6.5.1 Energy performance in the current situation (baseline scenario)

MFH typology

In the baseline scenario, modelling results indicate that the MFH typology in Tartu consumes around 19,621.2 kWh annually (almost 305.9 kWh/m^2), which are divided into 17,008.2 kWh for its heating needs and 2,613.0 kWh for its cooling and appliances needs Figure **73**).

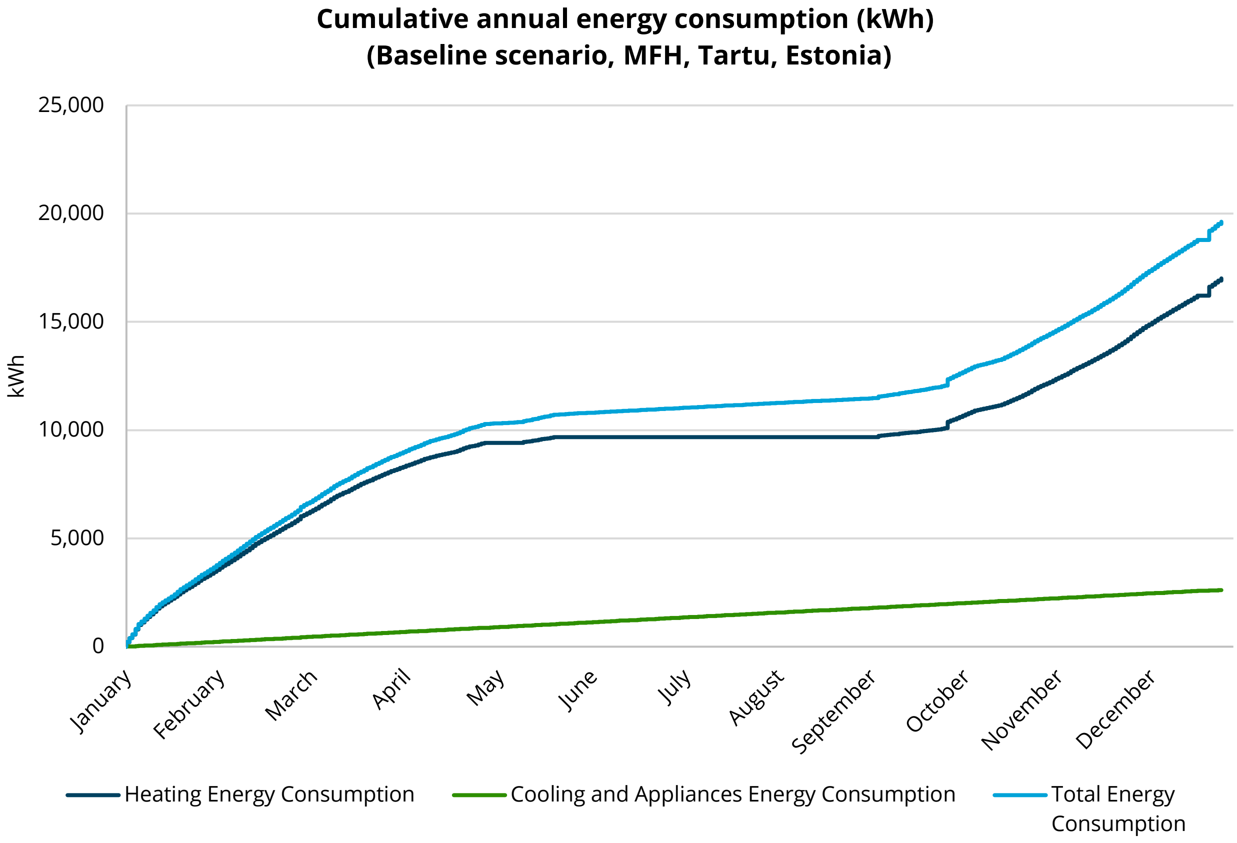

Figure 66. Cumulative annual consumption for the MFH typology in the rural region of Tartu in Estonia (baseline scenario).

6.5.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

MFH typology

In the case of the MFH typology in Tartu, **Figure 67** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM_6, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 8,784.0 kWh. This is followed by EEM_1, which entails exterior wall insulation, leading to an annual consumption of 14,099.1 kWh, and EEM_4, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 16,019.1 kWh.

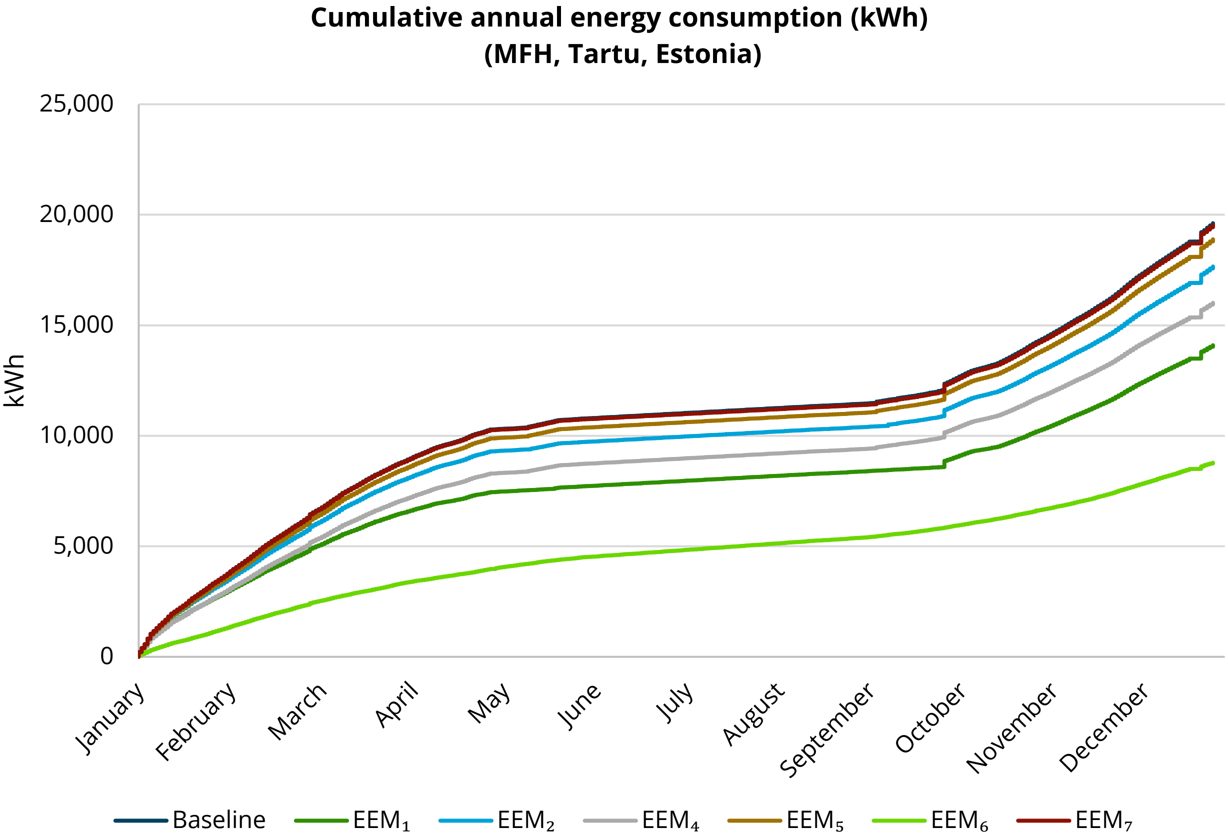

Figure 67. Cumulative annual energy consumption (in kWh) for the different EEMs in the MFH typology in the rural region of Tartu in Estonia.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 90**. As indicated in **Figure 75**, we identify that EEM_6 leads to the highest amount of energy savings, namely 10,837.2 kWh per year (55.2% reduction compared to the baseline scenario), while EEM_1 leads to 5,522.1 kWh saved annually (28.1% reduction) and EEM_4 leads to reducing energy consumption by 3,602.1 kWh per year (18.4%).

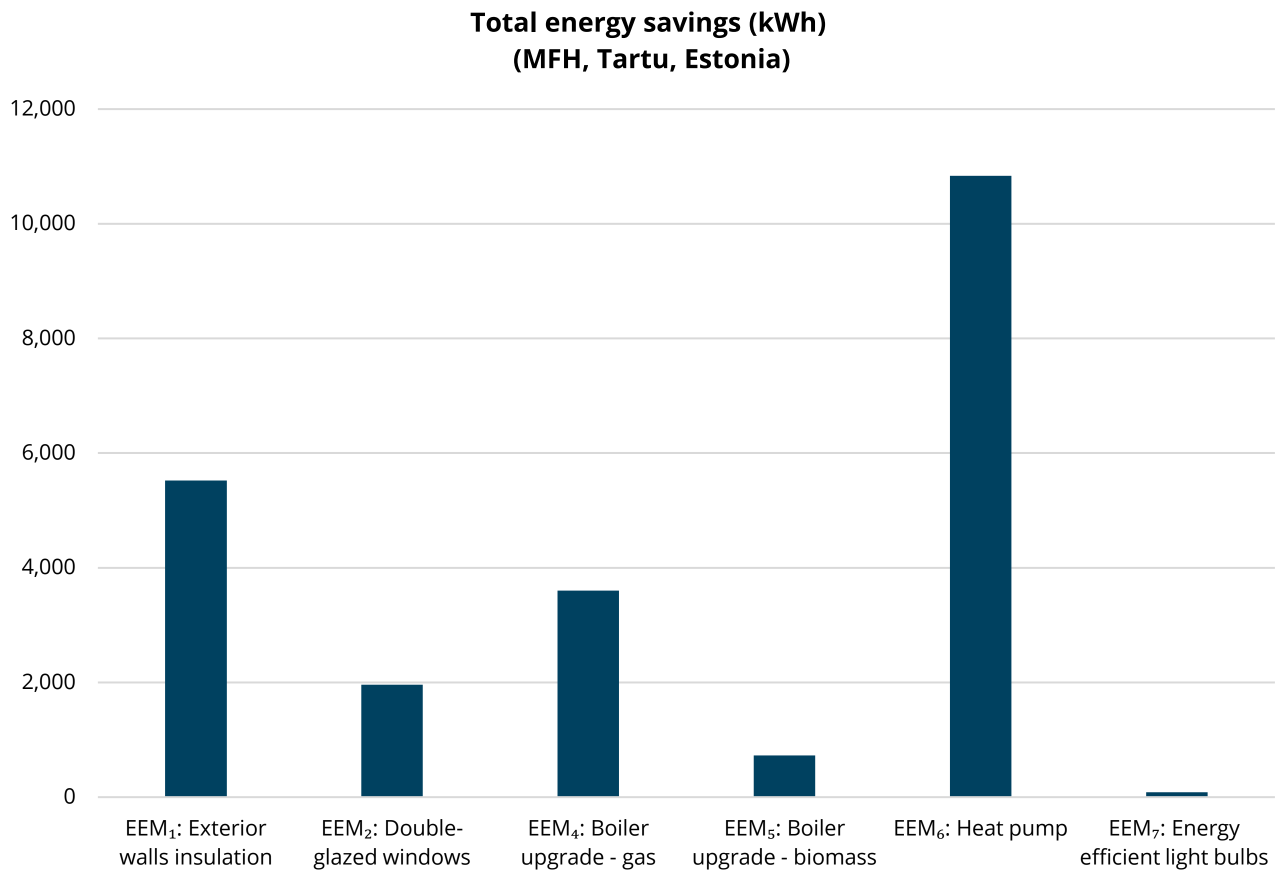

Figure 68. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Tartu in Estonia.

Table 90. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Tartu in Estonia.

Annual energy savings (kWh) (MFH, Tartu, Estonia)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	5,522.1	28.1
EEM$_2$: Double-glazed windows	1,959.7	10.0
EEM$_4$: Boiler upgrade - gas	3,602.1	18.4
EEM$_5$: Boiler upgrade - biomass	728.4	3.7
EEM$_6$: Heat pump	10,837.2	55.2
EEM$_7$: Energy efficient light bulbs	85.4	0.4

6.5.3 Environmental impact and thermal comfort analysis

MFH typology

CO_2 footprint

Figure 69 presents the annual CO_2 emissions (in kg) for all scenarios under study (i.e., baseline and EEMs) in the rural region of Tartu in Estonia for the MFH typology. We observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 3,985.0 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 2,770.9 and 1,390.0 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 91**.

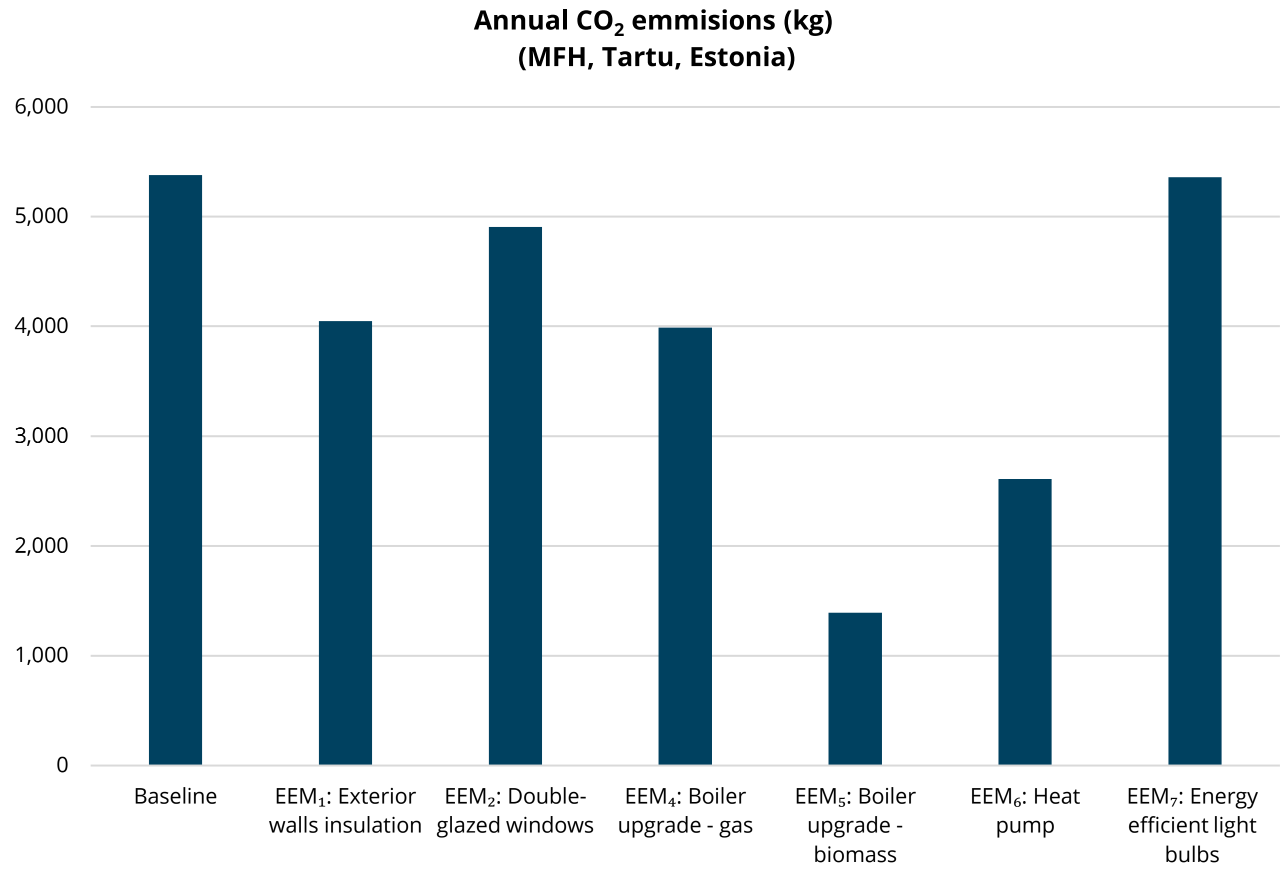

Figure 69. Annual CO_2 emissions (kg) in all scenarios in the MFH typology in the rural region of Tartu in Estonia.

Table 91. Annual CO_2 emissions avoided (kg) for the different EEMs in the MFH typology in the rural region of Tartu in Estonia.

Annual emissions avoided (kg CO_2) (MFH, Tartu Estonia)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	1,330.8	24.7
EEM_2: Double-glazed windows	472.3	8.8
EEM_4: Boiler upgrade - gas	1,390.9	25.9
EEM_5: Boiler upgrade - biomass	3,985.0	74.1
EEM_6: Heat pump	2,770.1	51.5
EEM_7: Energy efficient light bulbs	21.3	0.4

PMV indicator

In regard to the analysis of the indoor condition of the household typology under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 77** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor condition (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the different EEM scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

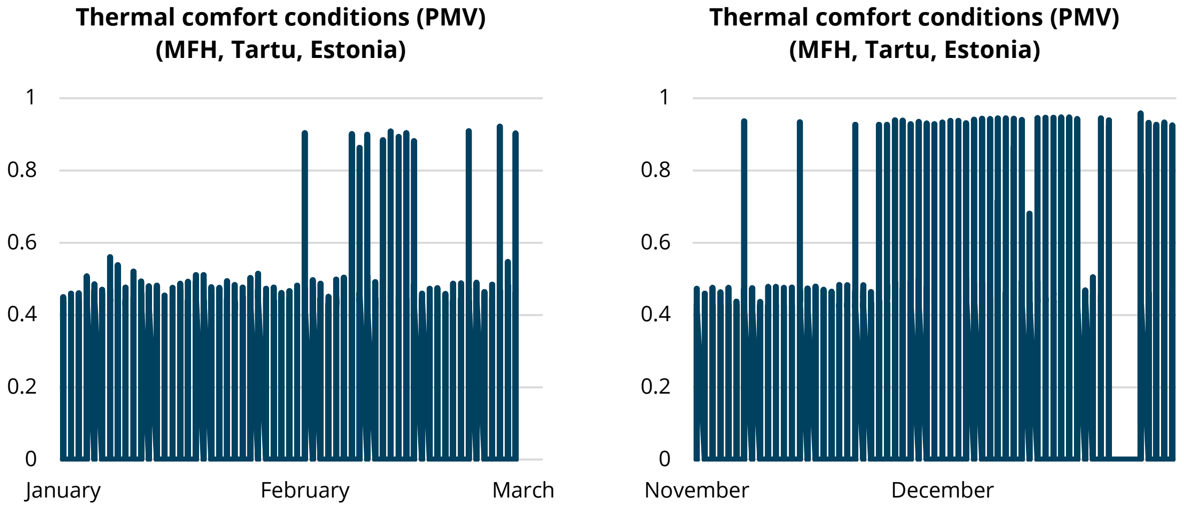

Figure 70. Thermal comfort (PMV indicator) for the MFH typology in the rural region of Tartu in Estonia during the winter for all the scenarios under study.

6.5.4 Technoeconomic assessment

MFH typology

The results of the technoeconomic assessment of the different EEMs for the MFH typology in the rural region of Tartu in Estonia, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 92**.

According to the analysis, EEM_5 (Boiler upgrade- biomass) and EEM_4 (Boiler upgrade- gas) demonstrate the best performance in terms of NPV, with NPVs of 9,236.1€ and 6,359.9€, respectively. EEM_4 (Boiler upgrade- gas), EEM_7 (Energy efficient light bulbs) and EEM_6 (Heat pump) result in the lowest LCSE, at 0.033€/kWh, 0.039€/kWh, and 0.039€/kWh respectively. Additionally, EEM_7 and EEM_4 exhibit the best performance in PP, with 1.4 and 2.1 years, respectively.

The substantial economic benefits provided by all EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Tartu to implement energy efficiency interventions. These findings underscore the effectiveness of a diverse range of EEMs in delivering significant economic returns and improving household energy sustainability.

Table 92. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Tartu in Estonia (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	5,221	30	4.00%	3,573.9	13.5	0.055
EEM_2	1,674	30	4.00%	776.2	11.8	0.063
EEM_4	1,000	20	4.00%	6,359.9	2.1	0.033
EEM_5	2,500	20	4.00%	9,236.1	3.1	0.321
EEM_6	5,000	20	4.00%	943.0	15.6	0.039
EEM_7	20	23	4.00%	171.4	3.7	0.039

Table 93, **Table 94**, and **Table 95** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with higher investment costs leading also to higher PP and LCSE, and lower NPV, indicating their importance when it comes to energy poor rural households.

Table 93. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Tartu in Estonia (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM_1	5,221	25%	30	4.00%	4,876.6	9.4	0.041
EEM_2	1,674		30	4.00%	1,194.7	8.3	0.047
EEM_4	1,000		20	4.00%	6,609.9	1.5	0.028
EEM_5	2,500		20	4.00%	9,861.1	2.3	0.258
EEM_6	5,000		20	4.00%	2,193.0	10.7	0.030
EEM_7	20		23	4.00%	183.9	2.7	0.030

Table 94. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Tartu in Estonia (50% subsidy).

EEM	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	5,221	50%	30	4.00%	6,179.4	5.9	0.027
EEM$_2$	1,674		30	4.00%	1,613.2	5.2	0.031
EEM$_4$	1,000		20	4.00%	6,859.9	1.0	0.023
EEM$_5$	2,500		20	4.00%	10,486.1	1.5	0.195
EEM$_6$	5,000		20	4.00%	3,443.0	6.6	0.022
EEM$_7$	20		23	4.00%	196.4	1.8	0.020

Table 95. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Tartu in Estonia (75% subsidy).

EEM	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP	LCSE (€/kWh)
EEM$_1$	5,221	75%	30	4.00%	7,482.2	2.8	0.014
EEM$_2$	1,674		30	4.00%	2,031.7	2.5	0.016
EEM$_4$	1,000		20	4.00%	7,109.9	0.5	0.019
EEM$_5$	2,500		20	4.00%	11,111.1	0.7	0.132
EEM$_6$	5,000		20	4.00%	4,693.0	3.1	0.013
EEM$_7$	20		23	4.00%	208.9	0.9	0.010

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 71**, the replacement of the current heating system with an energy-efficient heat pump (EEM$_6$) is the most cost-effective measure (energy savings: 10,837.2 kWh/year, LCSE: 0.039€/kWh), followed by EEM$_1$ and EEM$_4$. On the contrary, EEM$_5$ is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings, followed by EEM$_2$. The latter indicates the need for incentives and initiatives aiming to increase the cost-effectiveness of those measures and to lower their investment costs.

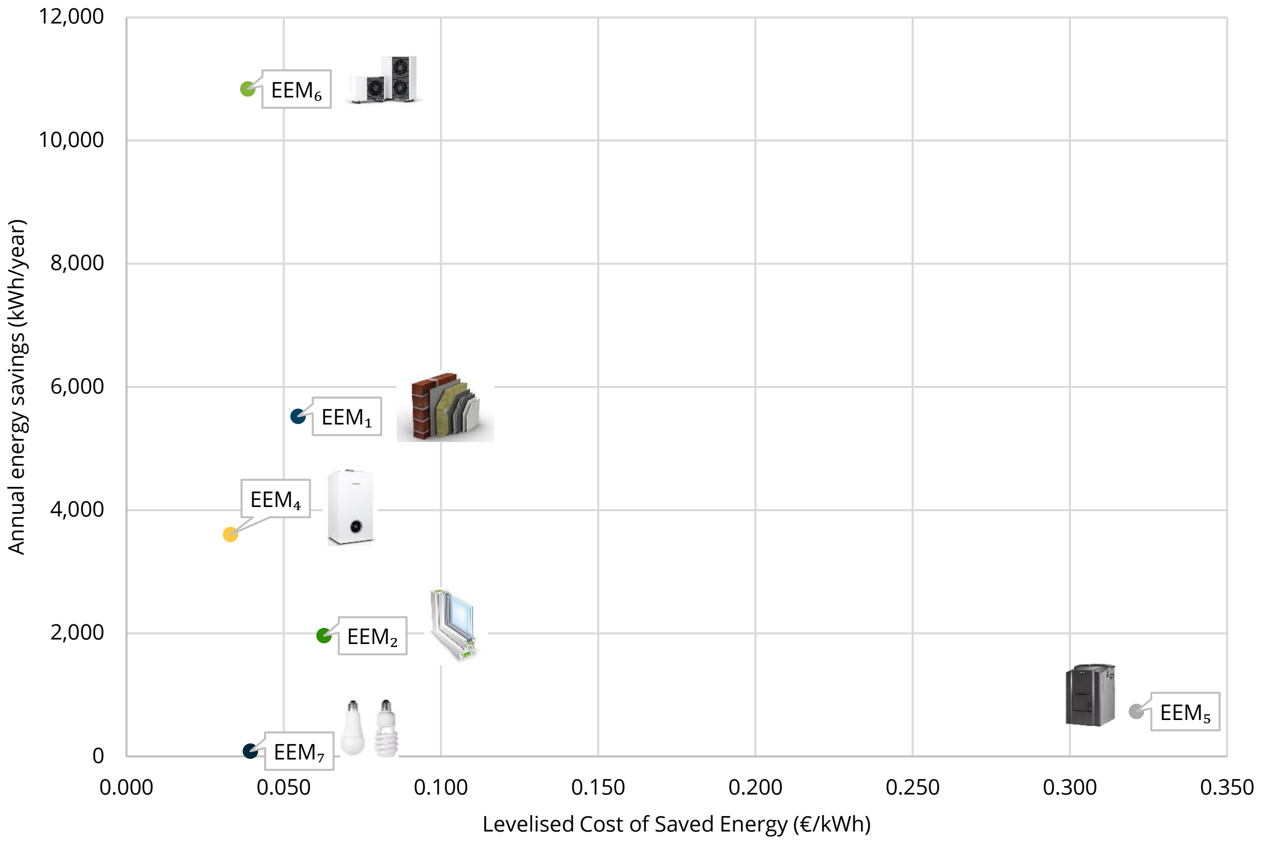

Figure 71. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Tartu in Estonia.

Additionaly, we seek to analyse the corellation between NPV and cost effectiveness of the different EEMs under study. **Figure 72** indicates that EEM$_5$ (Boiler upgrade- biomass) and EEM$_4$ (Boiler upgrade- gas) rank highest in terms of NPV, offering higher profitability with NPVs of 9,236.1€ and 6,359.9€ respectively, while their performance in terms of LCSE varies. EEM$_5$ offers the highest LCSE (0.321€/kWh), while EEM$_4$ is deemed to have the second lowest LCSE (0.033€/kWh). EEM$_1$ and EEM$_6$ also demonstrate valuable combinations of profitability and cost-effectiveness, (EEM$_1$: 3,573.9 € and 0.055€/kWh, EEM$_6$: 943.0€ and 0.039€/kWh). The low profitability of EEM$_6$, despite its high cost-effectiveness, highlights the need for financial incentives towards to incentivise energy-poor households electrify their heating and gain the relevant financial benefits (e.g., reduced consumption, energy expenses, etc.). Notably, EEM$_7$ (Energy efficient light bulbs) has the lowest LCSE of 0.016€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV.

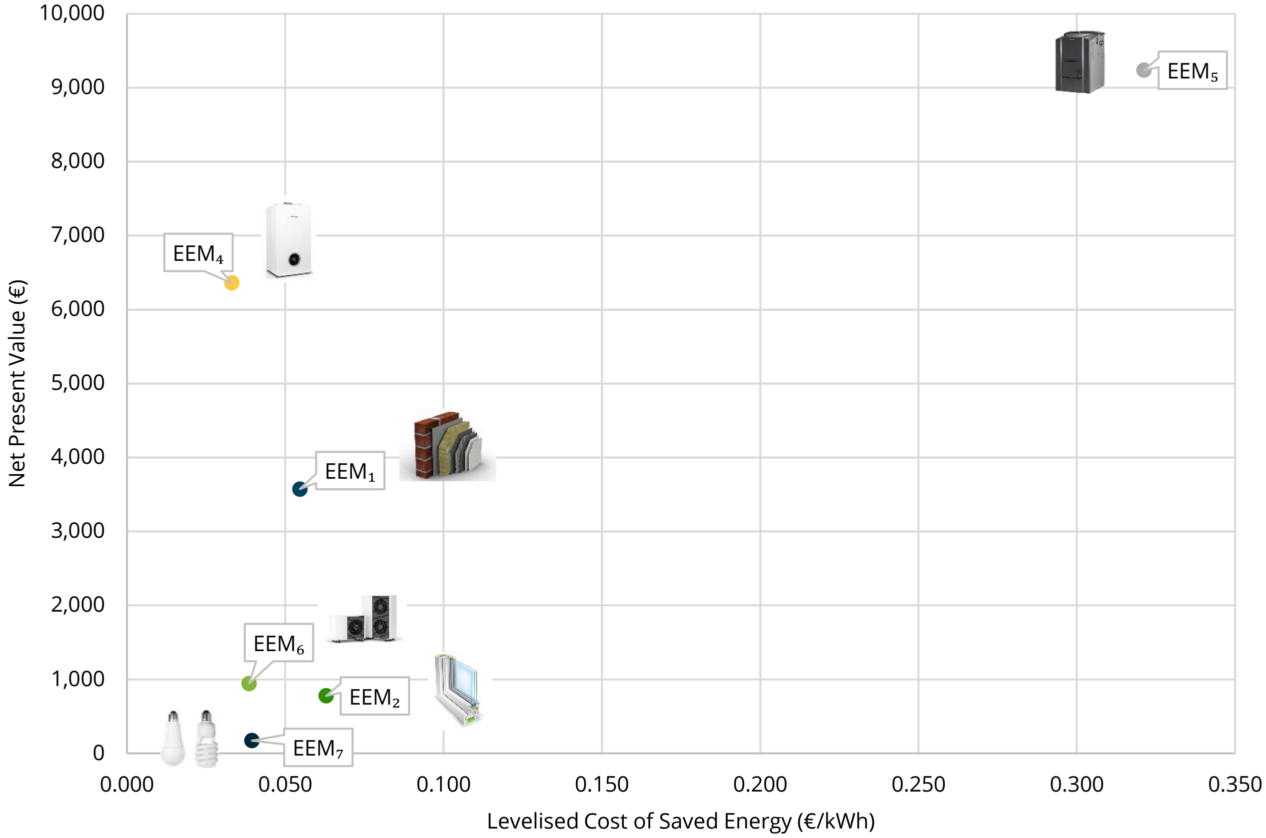

Figure 72. Profitability and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Tartu in Estonia.

The same ranking among the EEMs is observed in the case of the different of subsidisation levels leading to increased cost-effectiveness and profitability, due to the lower LCSEs and the higher NPVs, for the same amount of energy savings achieved.

6.6 Results for the rural region of Zasavje in Slovenia

For the case study of the rural region of Zasavje in Slovenia, the two household typologies explored concern a SFH equipped with a wood stove, and a MFH in Zasavje equipped with a gas boiler to cover heating needs. Detailed specifications of each household typology identified in the rural region of Zasavje are presented in **Sections 5.2.6**, **5.3**, and **5.4**.

6.6.1 Energy performance in the current situation (baseline scenario)

SFH typology

In the baseline scenario, modelling results indicate that the SFH typology equipped with a wood stove in the rural region of Zasavje in Slovenia consumes around 27,053.8 kWh annually (almost 301.7 kWh/m^2), which are divided into 23,603.5 kWh for its heating needs and 3,450.3 kWh for its cooling and appliances needs (**Figure 73**).

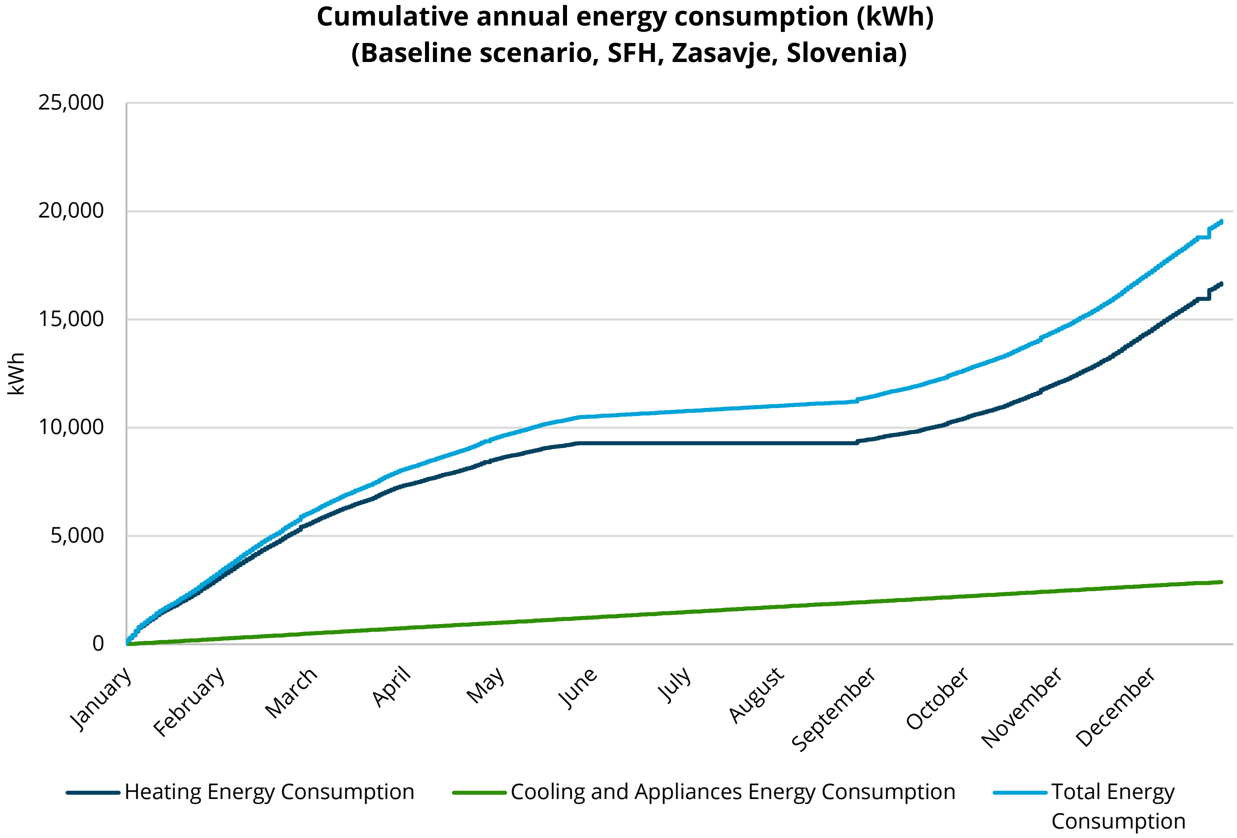

Figure 73. Cumulative annual consumption for the SFH typology in the rural region of Zasavje in Slovenia (baseline scenario).

MFH typology

In the baseline scenario, modelling results indicate that the MFH typology equipped with a gas boiler in the rural region of Zasavje in Slovenia consumes around 19,551.2 kWh annually (almost 317.4 kWh/m^2), which is divided into 16,682.1 kWh for its heating needs and 2,869.0 kWh for its cooling and appliances needs (**Figure 74**).

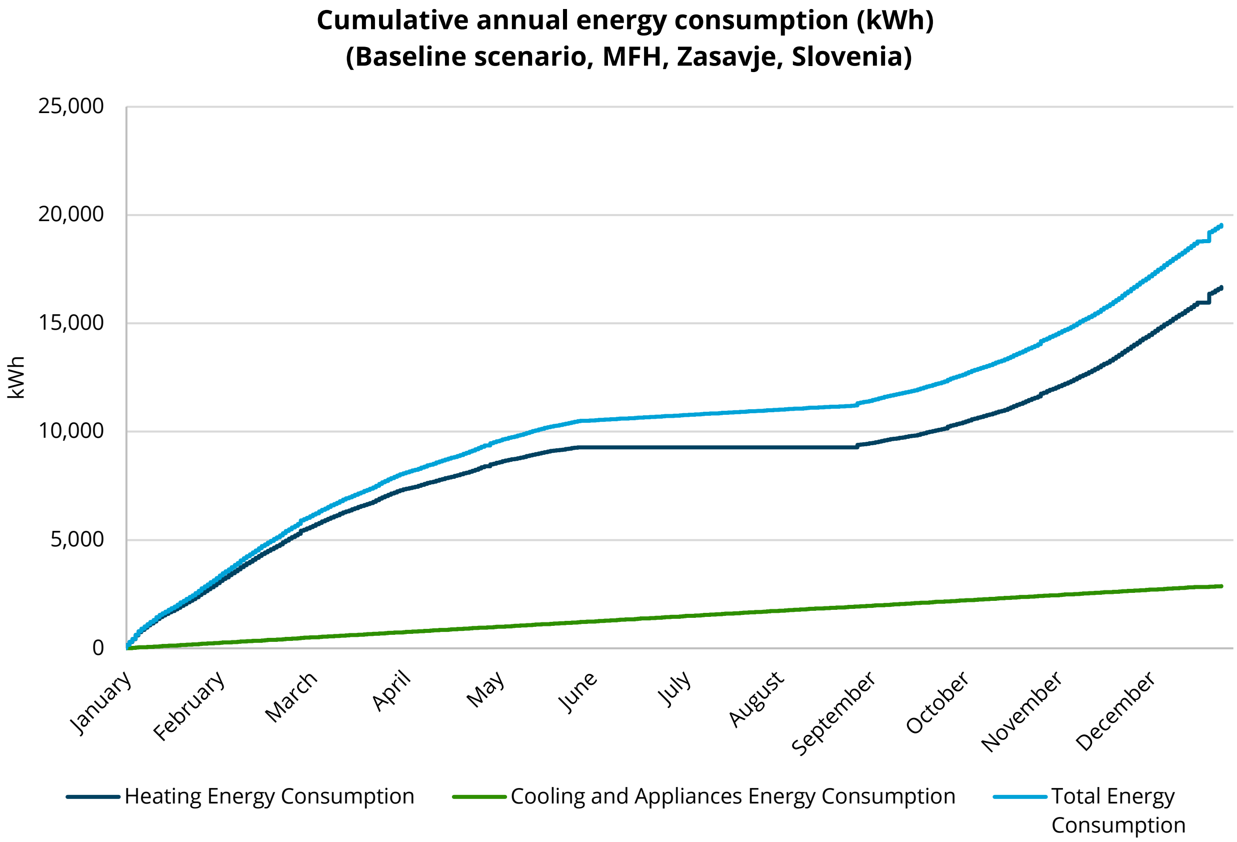

Figure 74. Cumulative annual consumption for the MFH typology in the rural region of Zasavje in Slovenia (baseline scenario).

6.6.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology

In the case of the SFH typology in the rural region of Zasavje in Slovenia, **Figure 75** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM_6, which involves replacing the existing heating system with a heat pump, results in the lowest annual cumulative consumption of 8,784.0 kWh. This is followed by EEM_3, which concerns roof installation, leading to an annual consumption of 14,829.3 kWh and EEM_4, which involves replacing the existing heating system with a high-efficiency gas boiler, with an annual energy consumption of 21,434.0 kWh.

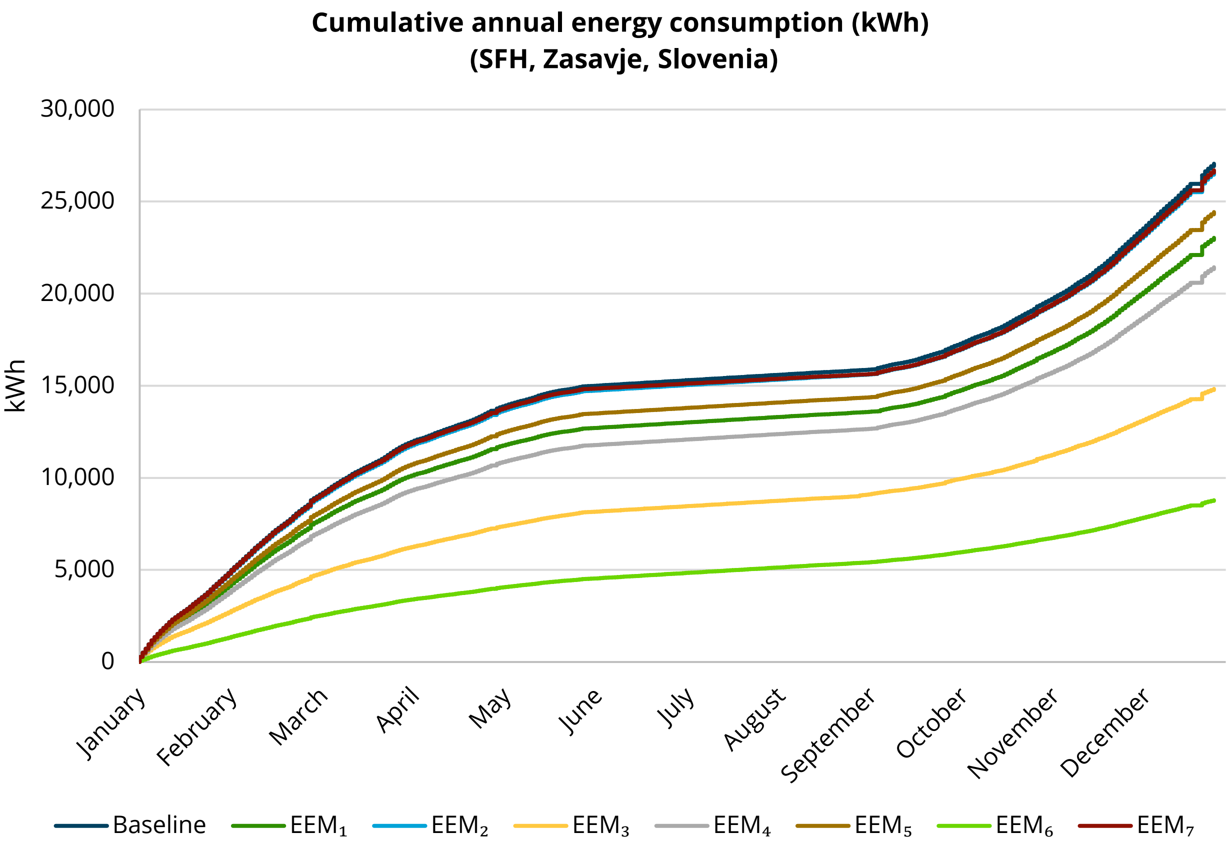

Figure 75. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 96**. As indicated in **Figure 76**, we identify that EEM_6 leads to the highest amount of energy savings, namely 18,269.8 kWh per year (67.5% reduction compared to the baseline scenario), while EEM_3 leads to 12,224.5 kWh saved annually (45.2% reduction) and EEM_4 leads to reducing energy consumption by 5,619.8 kWh per year (20.8% reduction).

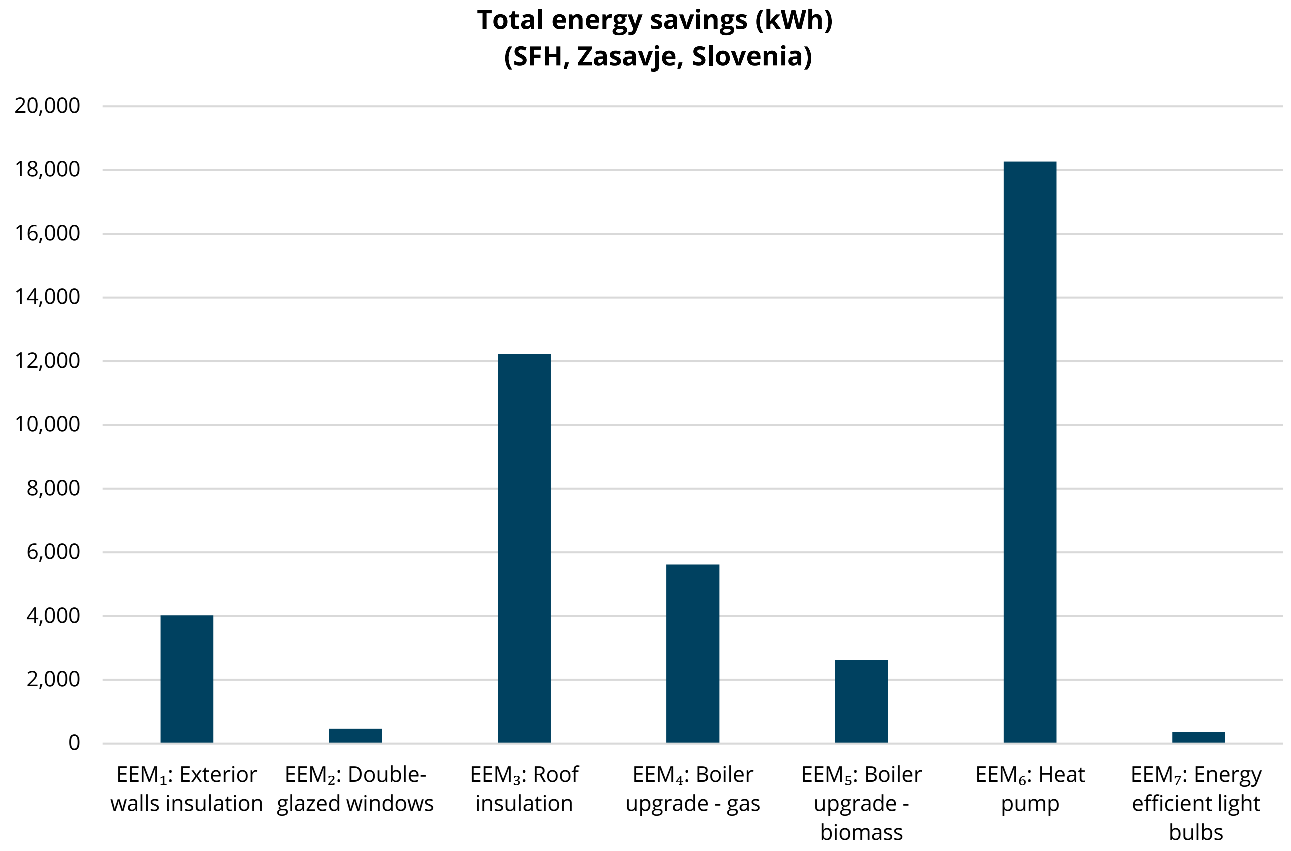

Figure 76. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia.

Table 96. Comparison of annual total energy savings (kWh) for all EEMs with baseline in the SFH typology in the rural region of Zasavje in Slovenia.

Annual energy savings (kWh) (SFH, Zasavje Slovenia)		
	Energy savings (kWh)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	4,024.0	14.9
EEM$_2$: Double-glazed windows	464.3	1.7
EEM$_3$: Roof insulation	12,224.5	45.2
EEM$_4$: Boiler upgrade - gas	5,619.8	20.8
EEM$_5$: Boiler upgrade - biomass	2,625.0	9.7
EEM$_6$: Heat pump	18,269.8	67.5
EEM$_7$: Energy efficient light bulbs	353.6	1.3

MFH typology

In the case of the MFH typology in the rural region of Zasavje in Slovenia, **Figure 77** presents the cumulative annual energy consumption profiles for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, resulting in the lowest annual cumulative consumption of 6,638.5 kWh. This is followed by EEM$_4$, which involves the installation of an upgraded gas boiler, leading to an annual consumption of 16,917.1 kWh and EEM$_1$, which entails exterior wall insulation, with an annual energy consumption of 17,454.4 kWh.

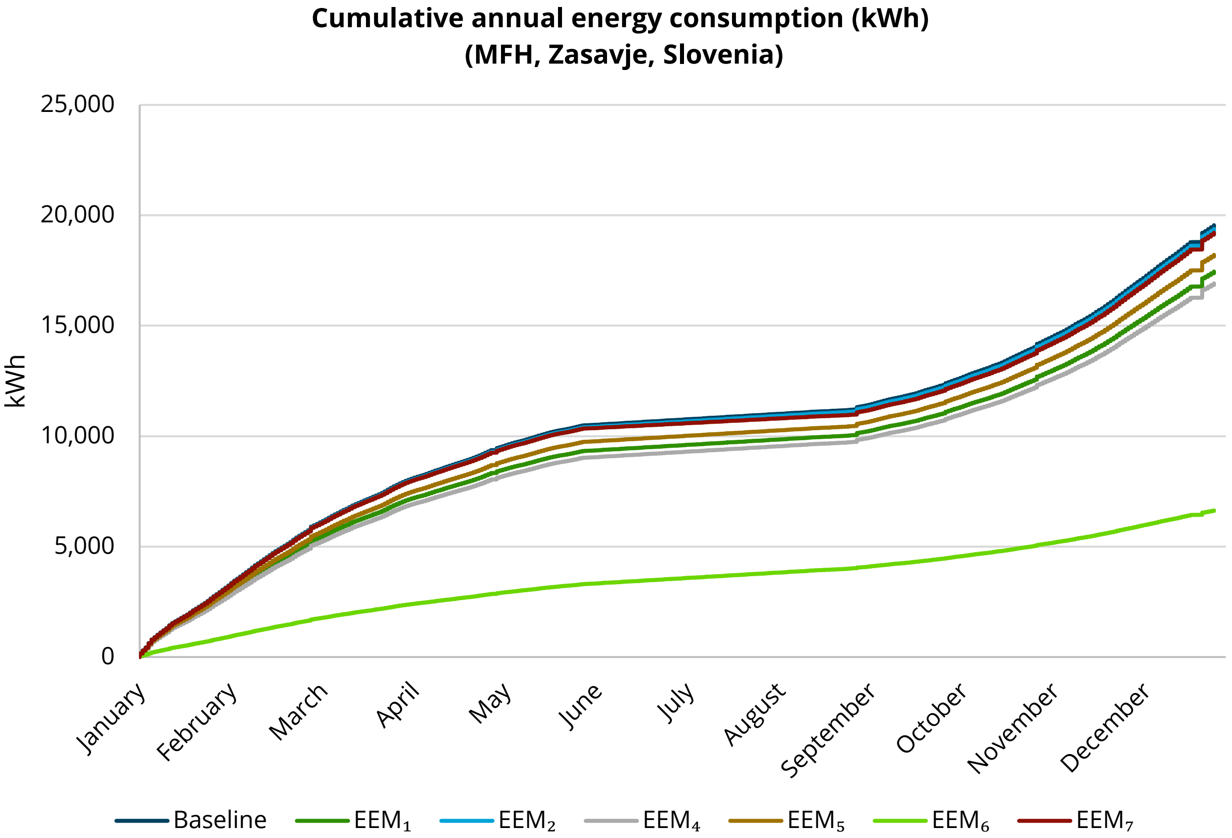

Figure 77. Cumulative annual energy consumption (in kWh) for the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 97**. As indicated in **Figure 78**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 12,912.7 kWh per year (66.0% reduction compared to the baseline scenario), while EEM$_4$ leads to 2,634.0 kWh saved annually (13.5% reduction) and EEM$_1$ leads to reducing energy consumption by 2,096.8 kWh per year (10.7% reduction).

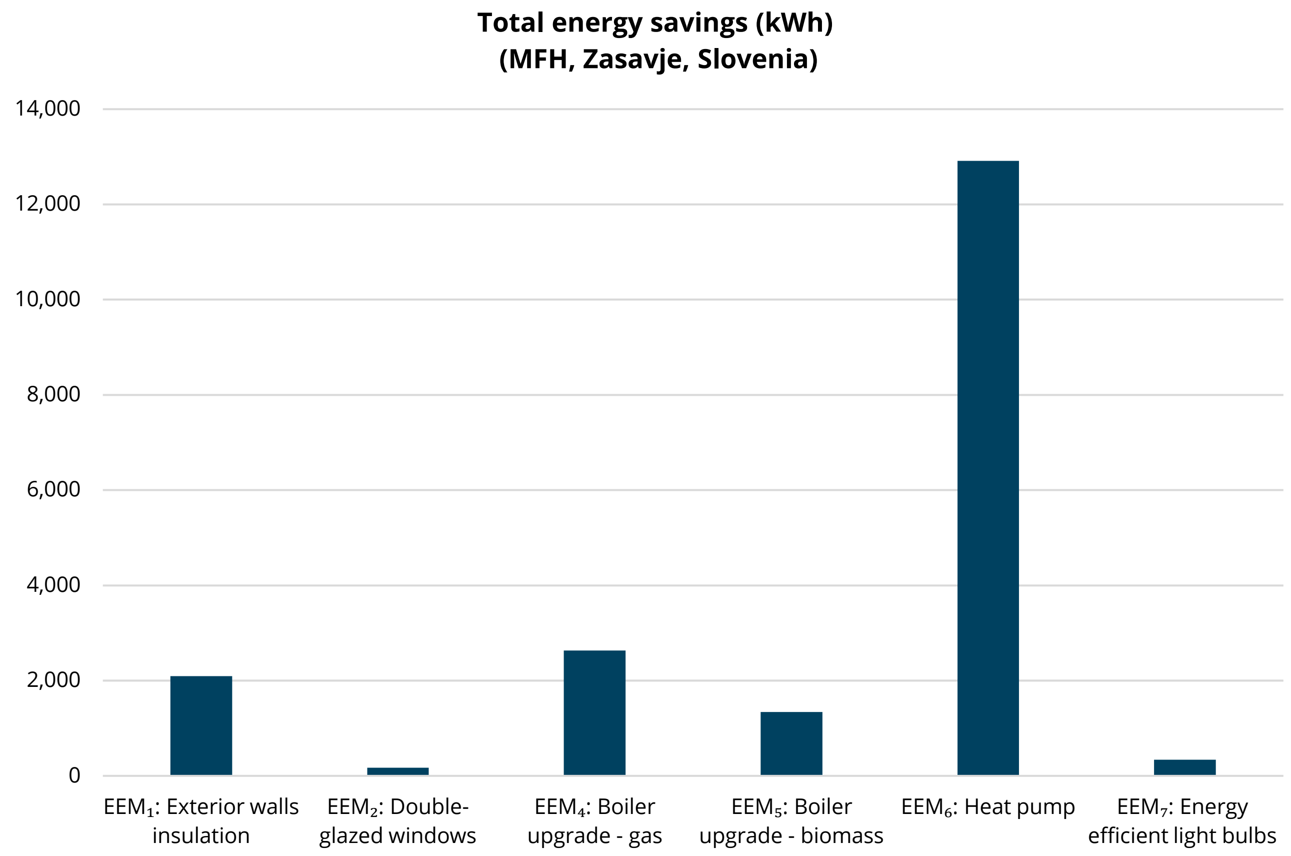

Figure 78. Annual total energy savings (in kWh) for the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia.

Table 97. Comparison of annual total energy savings (kWh) for all EEMs with baseline in the MFH typology Zasavje in Slovenia.

Annual energy savings (kWh) (MFH, Zasavje, Slovenia)		
	Energy savings (kWh)	**Percentage (%)**
EEM$_1$: Exterior wall insulation	2,096.8	10.7
EEM$_2$: Double-glazed windows	170.1	0.9
EEM$_4$: Boiler upgrade - gas	2,634.0	13.5
EEM$_5$: Boiler upgrade - biomass	1,341.7	6.9
EEM$_6$: Heat pump	12,912.7	66.0
EEM$_7$: Energy efficient light bulbs	314.4	1.7

6.6.3 Environmental impact and thermal comfort analysis

SFH typology

CO_2 footprint

Figure 79 presents the annual CO_2 emissions (in kg) for all of the scenarios under study (i.e., baseline and EEMs) in the rural region of Zasavje in Slovenia for the SFH typology. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 7,217.4 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 6,281.6 and 3,814.1 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 98**. The emission factor for the use of wood stove in the baseline situation is derived from sources in the scientific literature (Bhattacharya et al., 2002).

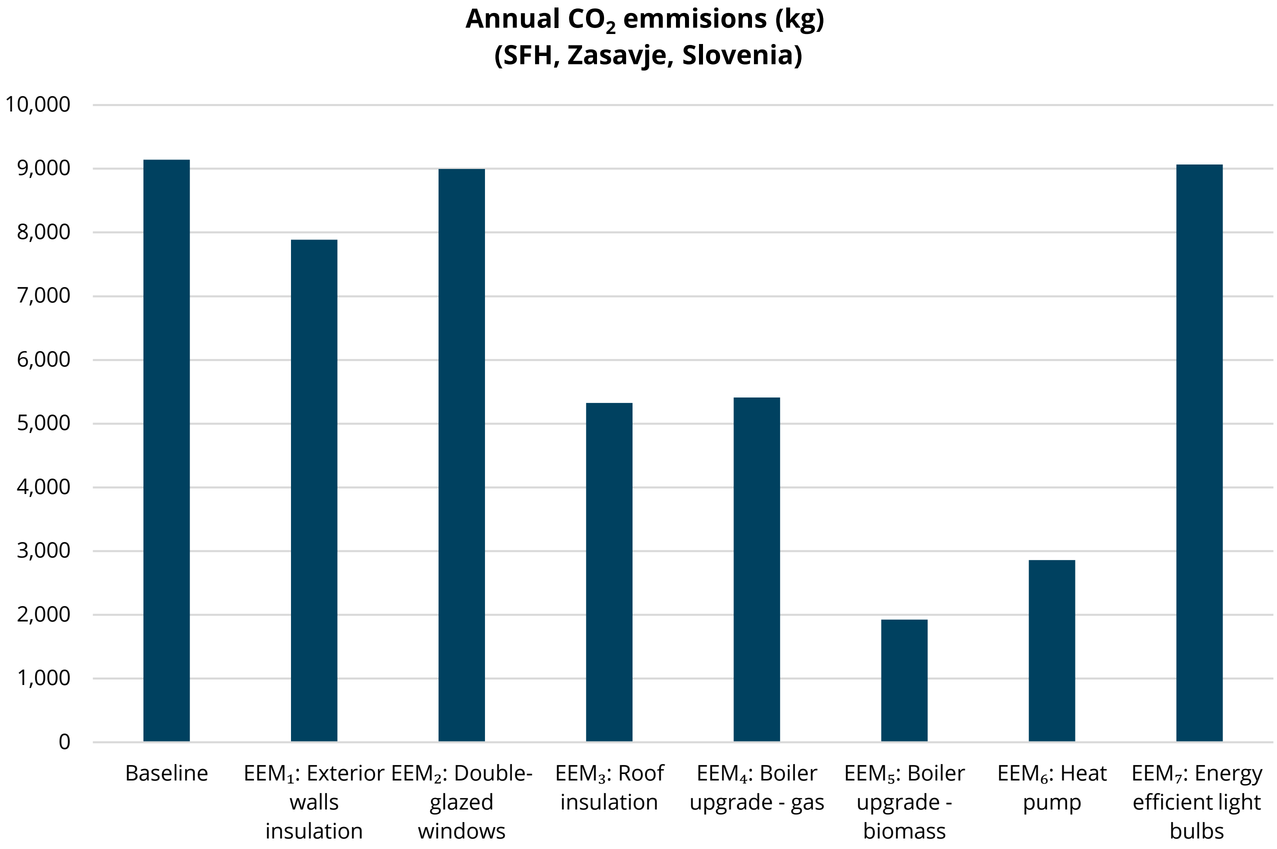

Figure 79. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of Zasavje in Slovenia.

Table 98. Annual CO$_2$ emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia.

Annual CO$_2$ emissions avoided (SFH, Zasavje, Slovenia)		
	Emissions avoided (kg CO$_2$)	**Reduction (%)**
EEM$_1$: Exterior wall insulation	1,255.5	13.7
EEM$_2$: Double-glazed windows	144.9	1.6
EEM$_3$: Roof insulation	3,814.1	41.7
EEM$_4$: Boiler upgrade - gas	3,731.6.9	40.8
EEM$_5$: Boiler upgrade - biomass	7,217.4	79.0
EEM$_6$: Heat pump	6,281.6	68.7
EEM$_7$: Energy efficient light bulbs	71.8	0.8

PMV indicator

In regards, to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 80** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

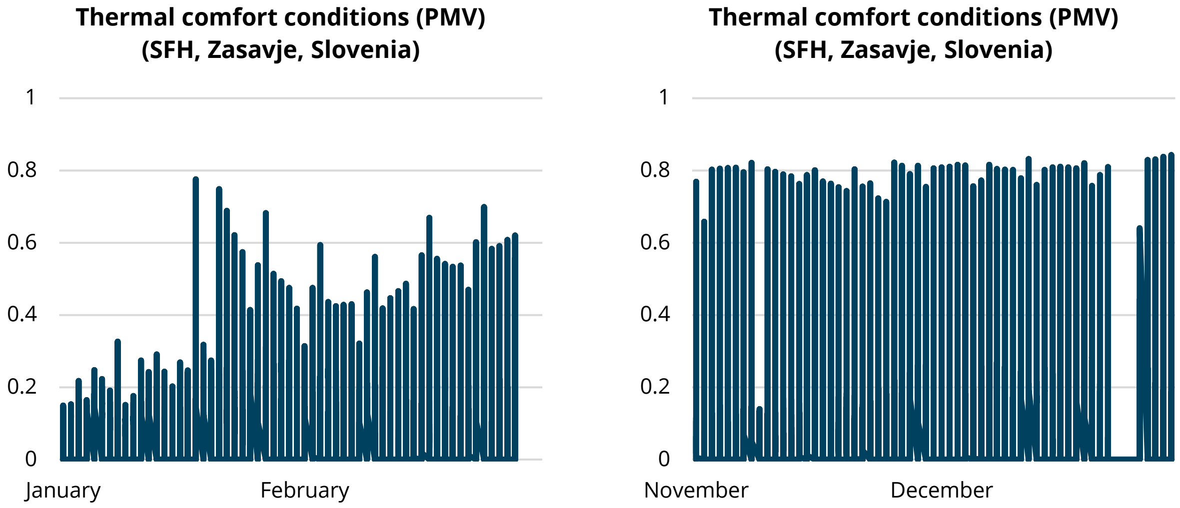

Figure 80. Thermal comfort (PMV indicator) for the SFH typology in the rural region of Zasavje in Slovenia during the winter for all the scenarios under study.

MFH typology

CO_2 footprint

Figure 81 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) in the rural region of Zasavje in Slovenia. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 3,262.4 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 2,604.6 and 532.1 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 99**.

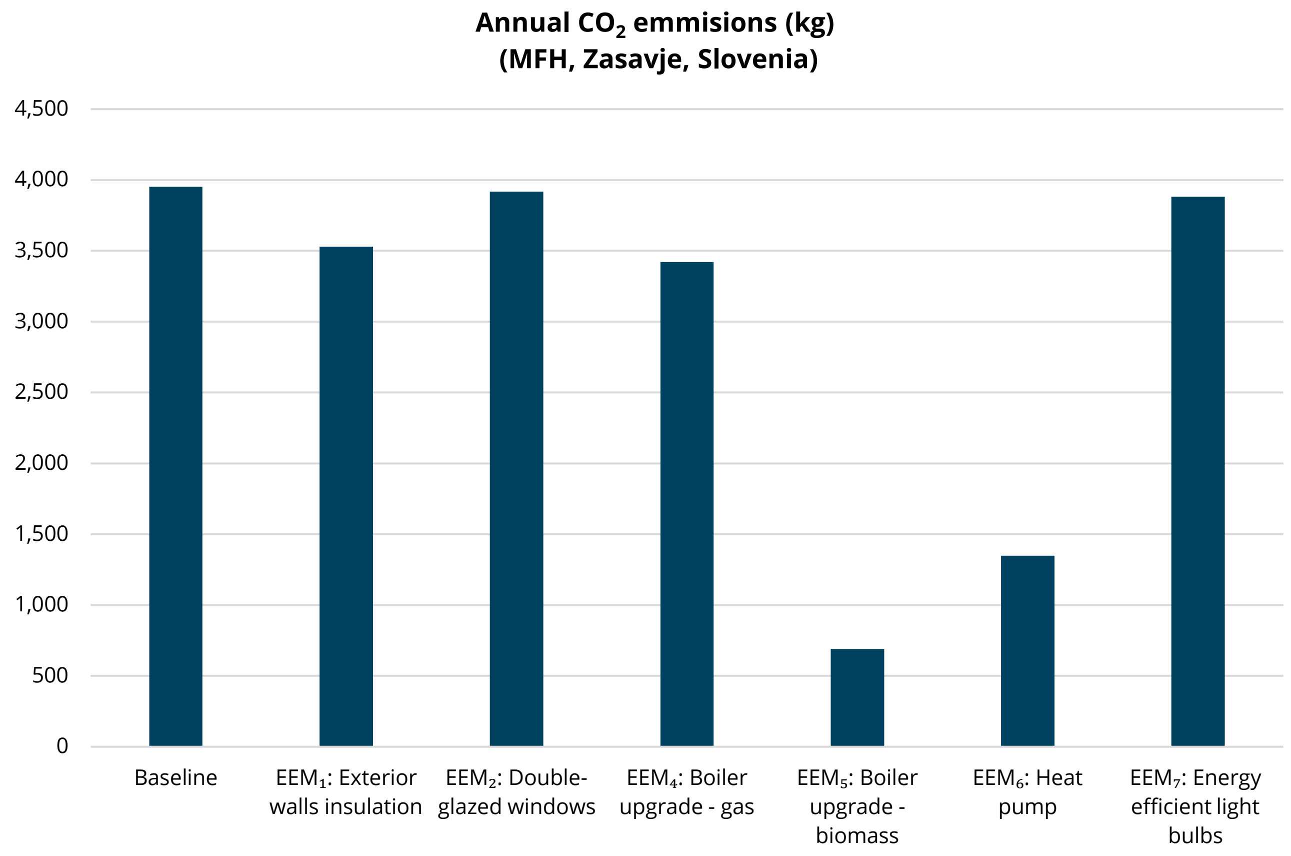

Figure 81. Annual CO_2 emissions (kg) in all scenarios in the MFH typology in the rural region of Zasavje in Slovenia.

Table 99. Annual CO_2 emissions avoided (kg) for the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia.

Annual emissions avoided (kg CO_2) (MFH, Zasavje, Slovenia)		
	Emissions avoided (kg CO_2)	**Reduction (%)**
EEM_1: Exterior wall insulation	423.6	10.7
EEM_2: Double-glazed windows	34.4	0.9
EEM_4: Boiler upgrade - gas	532.1	13.5
EEM_5: Boiler upgrade - biomass	3,262.4	82.5
EEM_6: Heat pump	2,604.6	65.9
EEM_7: Energy efficient light bulbs	69.3	1.8

PMV indicator

In regard to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 82** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

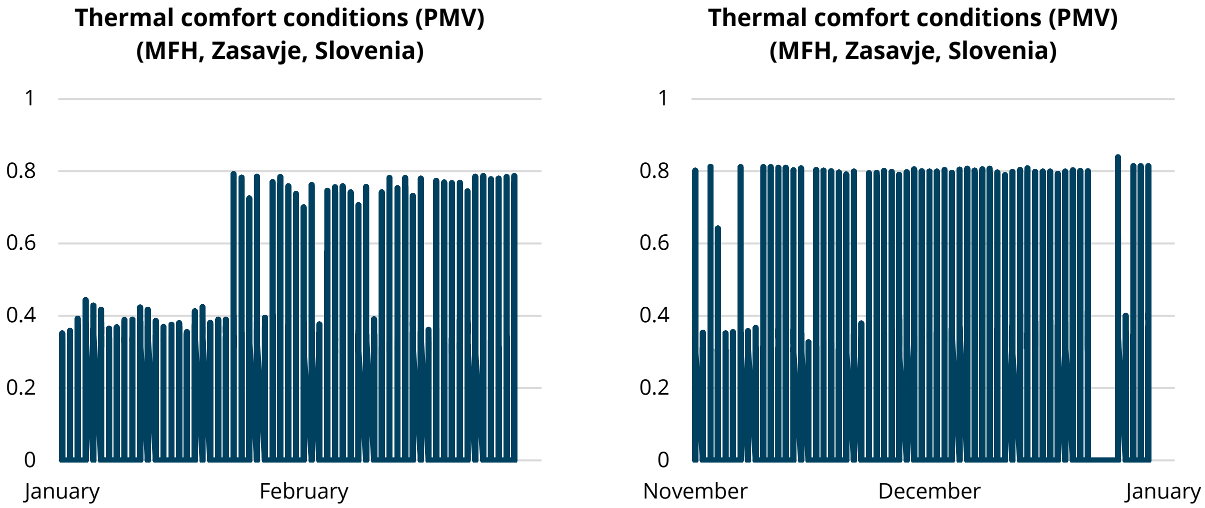

Figure 82. Thermal comfort (PMV indicator) for the MFH typology in the rural region of Zasavje in Slovenia during the winter for all the scenarios under study.

6.6.4 Technoeconomic assessment

SFH typology

The results of the technoeconomic assessment of the different EEMs for the SFH typology in the rural region of Zasavje in Slovenia, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 100**.

According to the analysis, EEM_3 (Roof insulation) and EEM_4 (Boiler upgrade- gas) demonstrate the best performance in terms of NPV, with NPVs of 15,812.5€ and 3,089.4€, respectively. EEM_7 (Energy efficient light bulbs) and EEM_3 (Roof insulation) result in the lowest LCSE, at 0.005€/kWh and 0.009€/kWh, respectively. Additionally, EEM_7 and EEM_3 exhibit the best performance in PP, with 0.5 and 2.0 years, respectively. EEM_1 (Exterior wall insulation), EEM_5

(Boiler upgrade- biomass) and EEM_2 (Double-glazed windows) are not an economically viable investment, without any subsidy rate, as they demonstrate negative NPV.

The economic benefits provided by some EEMs highlight the poor performance of the current energy situation and underscore the urgent need for rural households in Zasavje to implement energy efficiency interventions. In addition, the profitability of most of the EEMs that change the heating technology of the household suggests that there is an urgent need for the housing stock of Zasavje to migrate to more efficient heating systems avoiding the use of inefficient heating sources, like wood.

Table 100. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	6,304	30	4.00%	-459.0	>lifetime	0.091
EEM_2	1,704	30	4.00%	-1,173.9	>lifetime	0.270
EEM_3	1,944	30	4.00%	15,812.5	2.0	0.009
EEM_4	2,750	20	4.00%	3,089.4	8.1	0.043
EEM_5	3,500	20	4.00%	-1,182.8	>lifetime	0.117
EEM_6	12,500	20	4.00%	2,416.4	15.5	0.053
EEM_7	27	23	4.00%	818.7	0.5	0.005

Table 101, **Table 102** and **Table 103** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPVs. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially of those with higher upfront costs and longer PPs. In addition, EEM_1, EEM_2 and EEM_5 become economically viable for a subsidy rate of at least 25%, 75% and 50%, respectively, highlighting the importance of subsidy grants to increase energy efficiency in vulnerable rural areas in Slovenia.

Table 101. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	6,304	25%	30	4.00%	1,117.0	13.8	0.068
EEM$_2$	1,704		30	4.00%	-747.9	>lifetime	0.203
EEM$_3$	1,944		30	4.00%	16,298.5	4.7	0.007
EEM$_4$	2,750		20	4.00%	3,776.9	1.8	0.034
EEM$_5$	3,500		20	4.00%	-307.8	>lifetime	0.093
EEM$_6$	12,500		20	4.00%	5,541.4	9.5	0.040
EEM$_7$	27		23	4.00%	8250.5	0.5	0.004

Table 102. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	6,304	50%	30	4.00%	2,693.0	11.9	0.045
EEM$_2$	1,704		30	4.00%	-321.93	>lifetime	0.135
EEM$_3$	1,944		30	4.00%	16,784.5	1.0	0.005
EEM$_4$	2,750		20	4.00%	4,464.4	3.7	0.026
EEM$_5$	3,500		20	4.00%	567.2	13.5	0.068
EEM$_6$	12,500		20	4.00%	8,666.4	6.6	0.028
EEM$_7$	27		23	4.00%	832.2	0.2	0.003

Table 103. Technoeconomic assessment of the different EEMs in the SFH typology in the rural region of Zasavje in Slovenia (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	6,304	75%	30	4.00%	4,269.0	5.3	0.023
EEM_2	1,704		30	4.00%	104.1	14.6	0.068
EEM_3	1,944		30	4.00%	17,270.5	0.5	0.002
EEM_4	2,750		20	4.00%	5,151.9	1.8	0.017
EEM_5	3,500		20	4.00%	1,442.2	5.9	0.044
EEM_6	12,500		20	4.00%	11,791.4	3.1	0.015
EEM_7	27		23	4.00%	839.0	0.1	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs countries under study. As indicated by **Figure 83**, the replacement of the existing heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 18,269.8 kWh/year, LCSE: 0,015€/kWh), followed by EEM_3. On the contrary, EEM_2 is shown to be the least cost-effective energy-efficient measure due to its high LCSE and the low values of expected annual savings. Overall, EEM_2 and EEM_5 are the ones ranked lower in terms of cost-effectiveness, mainly because of the high investment cost of this intervention, indicating the need for incentives and initiatives aiming to increase their cost-effectiveness and lower their investment costs.

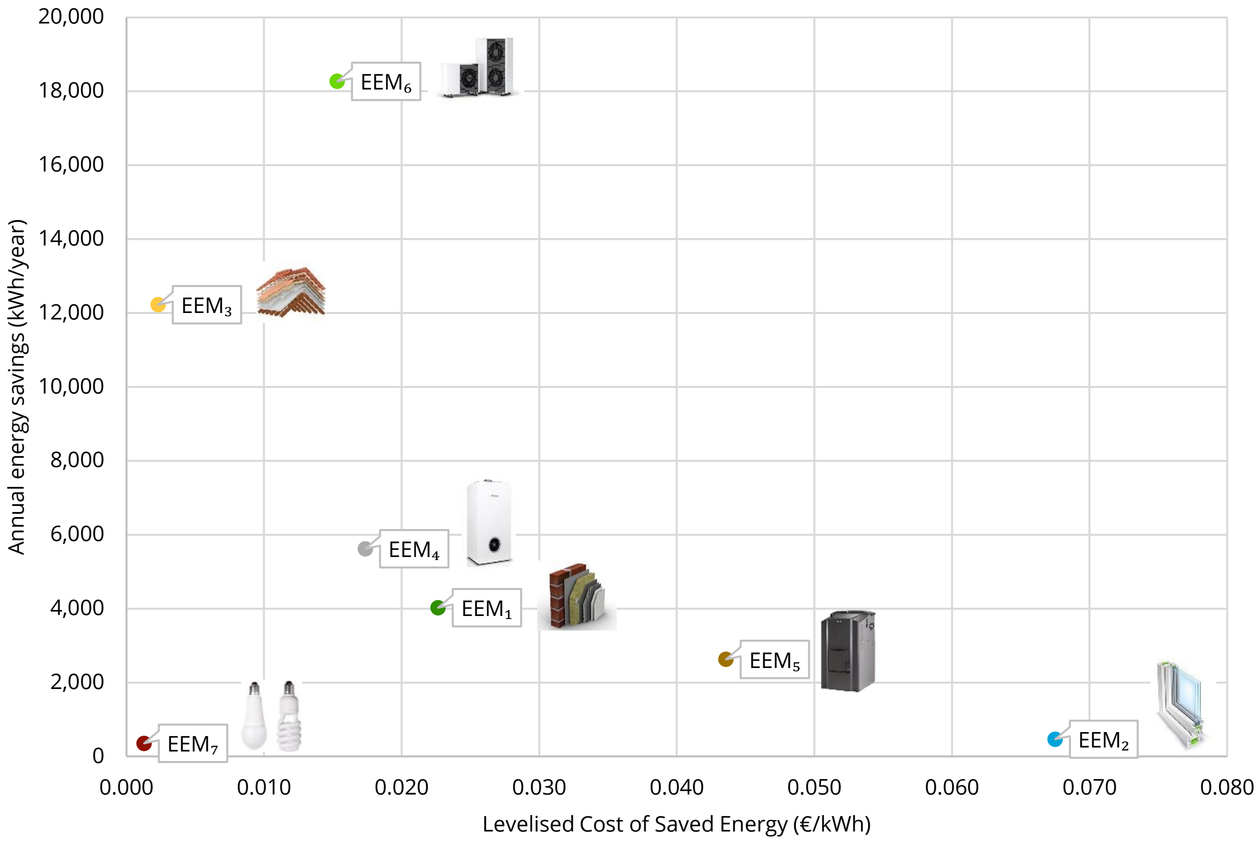

Figure 83. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Zasavje in Slovenia.

Additionally, we seek to investigate the correlation between NPV and cost effectiveness of the different EEMs under study. **Figure 84,** indicated that EEM_3 (Roof insulation), EEM_4 (Boiler upgrade- gas) and EEM_6 (Heat pump) rank highest, offering higher profitability with NPVs of 15,812.5€, 3,289.4€ and 2,416.0€ respectively, while demonstrating strong cost-effectiveness (LCSEs of 0.009€/kWh, 0.043€/kWh, and 0.053€/kWh, respectively). In contrast, EEM_1, EEM_2, and EEM_5 lead to poorer NPV-LCSE combinations (negative NPVs and higher LCSEs), indicating less attractive investments. Notably, EEM_7 (Energy efficient light bulbs) has the lowest LCSE of €0.005/kWh, highlighting its exceptional cost-effecrtiveness despite a modest NPV.

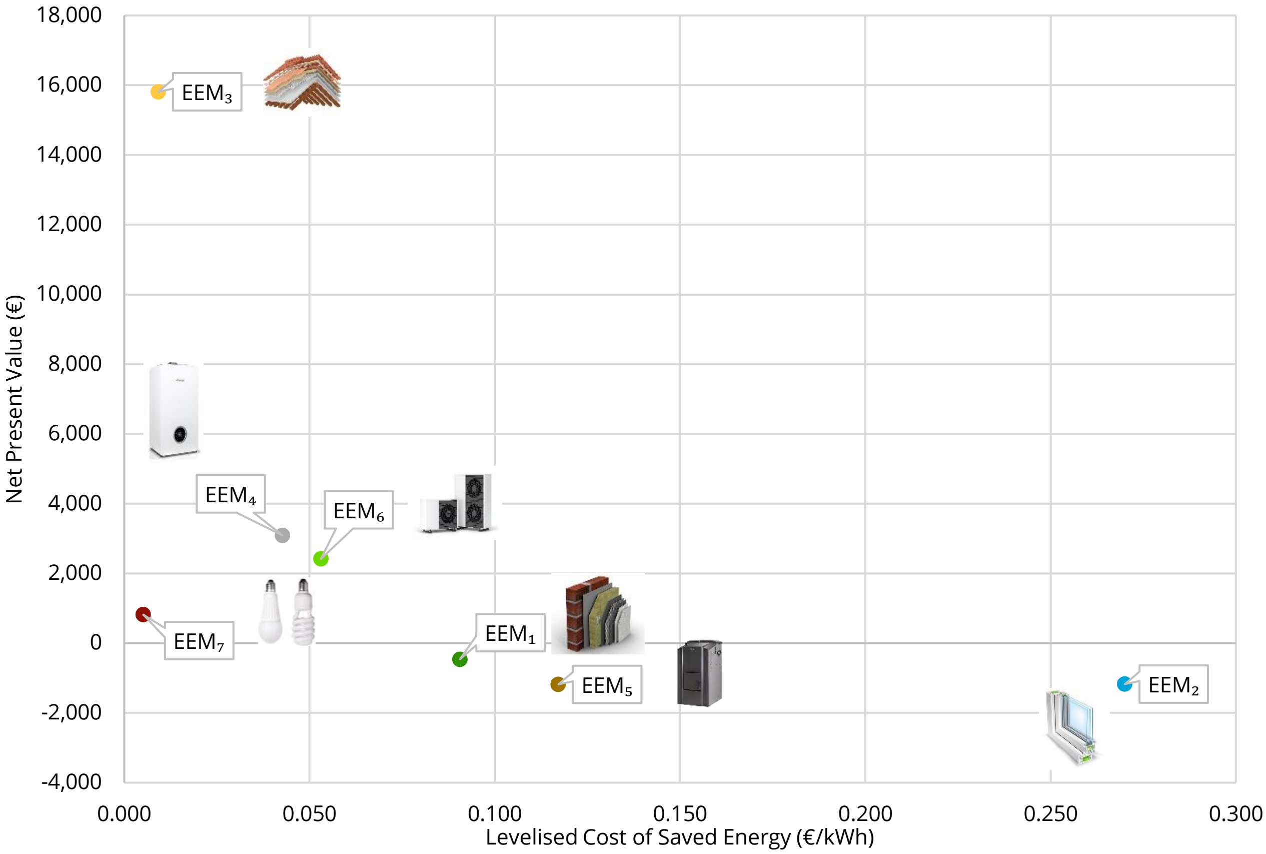

Figure 84. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Zasavje in Slovenia.

The observed ranking remains consistent across various subsidisation levels, leading to increased cost-effectiveness and profitability. This is due to the lower LCSE and higher NPVs for the same amount of energy savings achieved. Subsidies of at least 50% ensure positive NPVs for EEM_1 and EEM_5, while EEM_2 needs subsidisation of at least 75%.

MFH typology

The results of the technoeconomic assessment of the different EEMs for the MFH typology in the rural region of Zasavje in Slovenia, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 104**.

According to the analysis, EEM_1 (Exterior wall insulation) and EEM_7 (Energy efficient light bulbs) demonstrate the best performance in terms of NPV, with NPVs of 1,018.5€ and 766.6€, respectively. EEM_2 (Roof insulation), EEM_4 (Boiler upgrade- gas) and EEM_5 (Boiler upgrade-biomass) are not economically viable investments, without any subsidy rate, as they demonstrate negative NPV. EEM_7 (Energy efficient light bulbs) and EEM_1 (Exterior wall insulation) result in the lowest LCSE, at 0.005€/kWh and 0.056€/kWh, respectively.

Additionally, EEM_7 and EEM_1 exhibit the best performance in PP, with 0.5 and 15.4 years, respectively.

Table 104. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	2,024	30	4.00%	1058.3	15.4	0.056
EEM_2	1,215	30	4.00%	-1,018.5	>lifetime	0.525
EEM_4	2,750	20	4.00%	-237.1	>lifetime	0.091
EEM_5	3,500	20	4.00%	-2,421.1	>lifetime	0.229
EEM_6	10,000	20	4.00%	343.5	19.0	0.061
EEM_7	27	23	4.00%	789.6	0.5	0.005

Table 105, **Table 106**, and **Table 107** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. In addition, several EEMs, become economically viable, highlighting the importance of such incentives for the uptake of energy efficiency interventions. More specifically, EEM_4 (Boiler upgrade- gas) becomes an attractive investment for a subsidy rate of at least 25%.

Table 105. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	2,024	25%	30	4.00%	1,528.0	8.6	0.042
EEM_2	1,215		30	4.00%	-717.0	>lifetime	0.394
EEM_4	2,750		20	4.00%	209.4	13.1	0.073
EEM_5	3,500		20	4.00%	-1,772.9	>lifetime	0.181
EEM_6	10,000		20	4.00%	2,843.5	12.8	0.047
EEM_7	27		23	4.00%	796.4	0.4	0.004

Table 106. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	2,024	50%	30	4.00%	2,033.9	6.7	0.028
EEM_2	1,215		30	4.00%	-413.3	>lifetime	0.263
EEM_4	2,750		20	4.00%	896.9	11.0	0.055
EEM_5	3,500		20	4.00%	-897.9	>lifetime	0.133
EEM_6	10,000		20	4.00%	5,343.5	7.8	0.032
EEM_7	27		23	4.00%	803.1	0.3	0.003

Table 107. Technoeconomic assessment of the different EEMs in the MFH typology in the rural region of Zasavje in Slovenia (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	2,024	75%	30	4.00%	2,539.8	3.1	0.014
EEM_2	1,215		30	4.00%	-109.5	>lifetime	0.131
EEM_4	2,750		20	4.00%	1,584.4	4.9	0.037
EEM_5	3,500		20	4.00%	-22.9	>lifetime	0.085
EEM_6	10,000		20	4.00%	7,843.5	3.6	0.018
EEM_7	27		23	4.00%	809.9	0.1	0.001

The energy-saving potential and the LCSE indicator differ between the different EEMs under study. As indicated by **Figure 85**, the replacement of the existing heating system with an energy-efficient heat pump (EEM_6) is the most cost-effective measure (energy savings: 12,912.7 kWh/year, LCSE: 0.061€/kWh), followed by EEM_4 and EEM_1. On the contrary, EEM_5 and EEM_2 are shown to be the least cost-effective energy-efficient measures due to their high LCSE and the low values of expected annual savings, indicating the need for incentives and initiatives aiming to increase their cost-effectiveness and lower their investment costs.

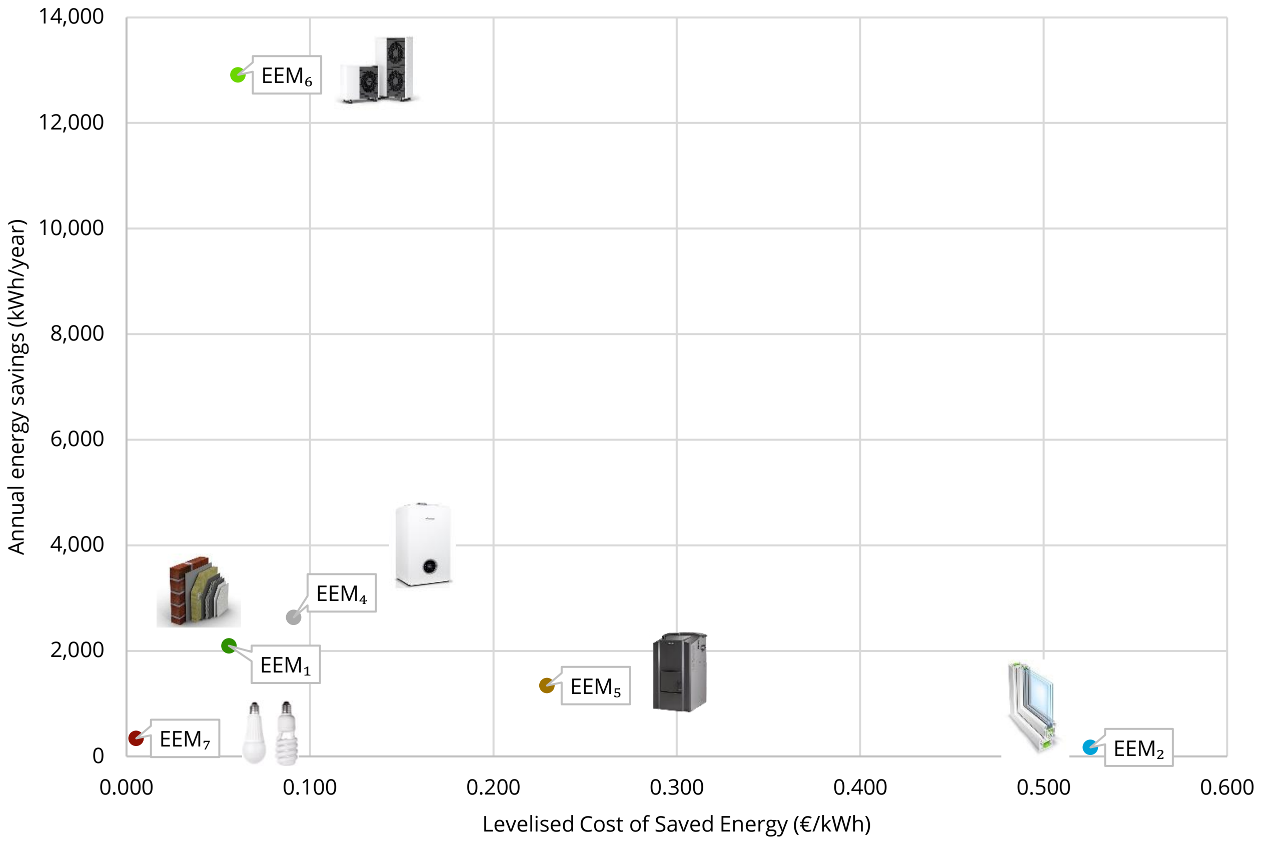

Figure 85. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the MFH typology (gas boiler) in the rural region of Zasavje in Slovenia.

Additionally, we seek to identify the correlation between profitability and cost-effectiveness of the different EEMs under study. **Figure 86**, indicates that EEM$_1$ (External wall insulation), EEM$_6$ (Heat Pump) and EEM$_7$ (Energy efficient light bulbs) offer the most valuable combinations of NPVs and LCSEs (1058.3€- 0.056€/kWh), (343.5€- 0.061€/kWh), and (789.6€- 0.005€/kWh), respectively). Notably, EEM$_7$ (Energy efficient light bulbs) has the lowest LCSE of 0.006€/kWh, highlighting its exceptional cost-effectiveness despite a modest NPV. On the other hand, EEM$_2$, EEM$_5$ and EEM$_4$ lead to the least attractive combinations leading to negative NPVs while also offering the higher LCSEs.

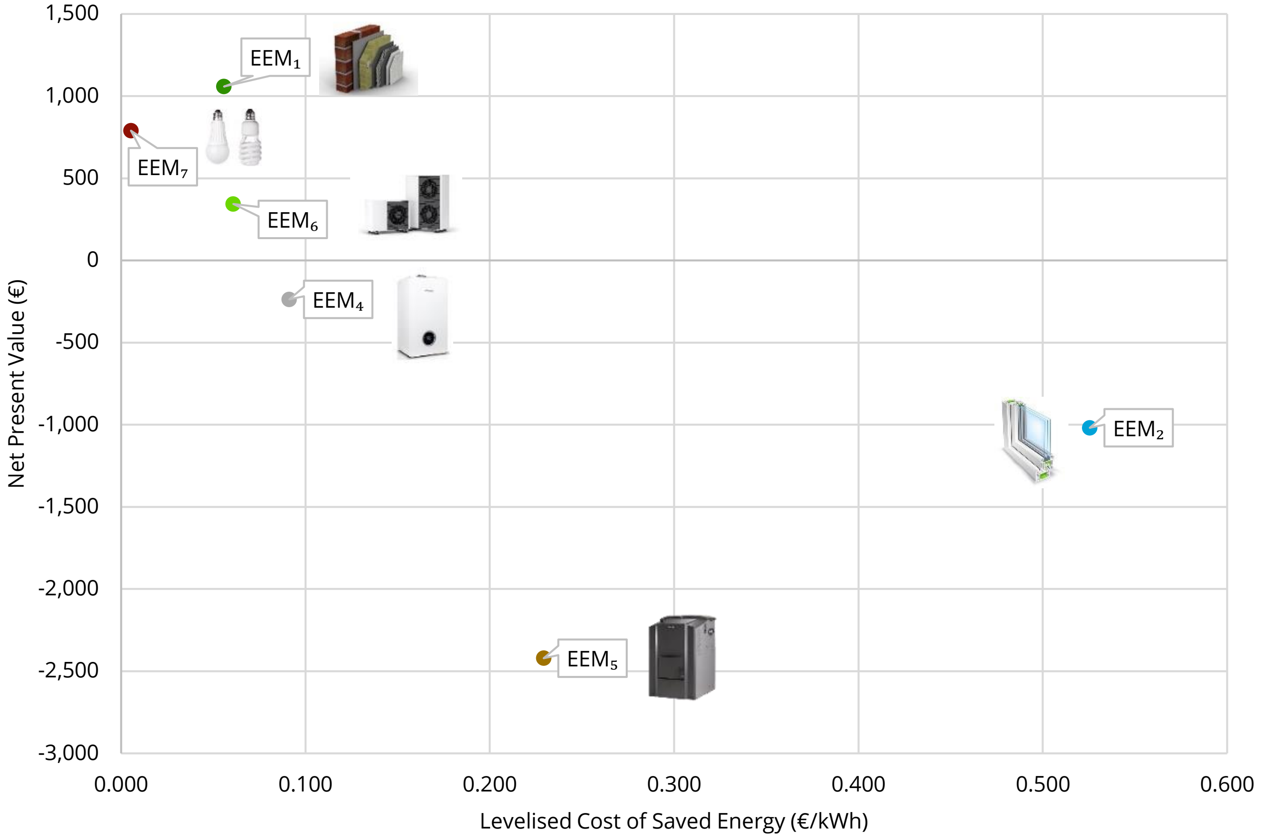

Figure 86. Profitability and cost-effectiveness of the EEMs under study in the case of the MFH typology in the rural region of Zasavje in Slovenia.

The observed ranking remains consistent across various subsidisation levels, leading to increased cost-effectiveness and profitability. This is due to the lower LCSE and higher NPVs for the same amount of energy savings achieved. EEM_4 offers positive NPV for a subsidy level of at least 25% while the NPVs of EEM_2 and EEM_5 remain negative at all subsidy levels (i.e., 25%, 50%, and 75%).

6.7 Results for the rural region of Coimbra in Portugal

For the case study of the rural region of Coimbra in Portugal, the household typology explored, concerns a SFH typology equipped with a wood stove, to cover its heating needs. Detailed specifications of each household typology identified in the rural region of Parma are presented in **Sections 5.2.7**, **5.3**, and **5.4**.

6.7.1 Energy performance in the current situation (baseline scenario)

SFH typology (wood stove)

In the baseline scenario, modelling results indicate that the SFH typology equipped with a wood stove in Coimbra consumes around 51,018.2 kWh annually (almost 390.0 kWh/m^2), which are divided into 49,162.2 kWh for its heating needs and 1,856.0 kWh for its cooling and appliances needs (**Figure 87**).

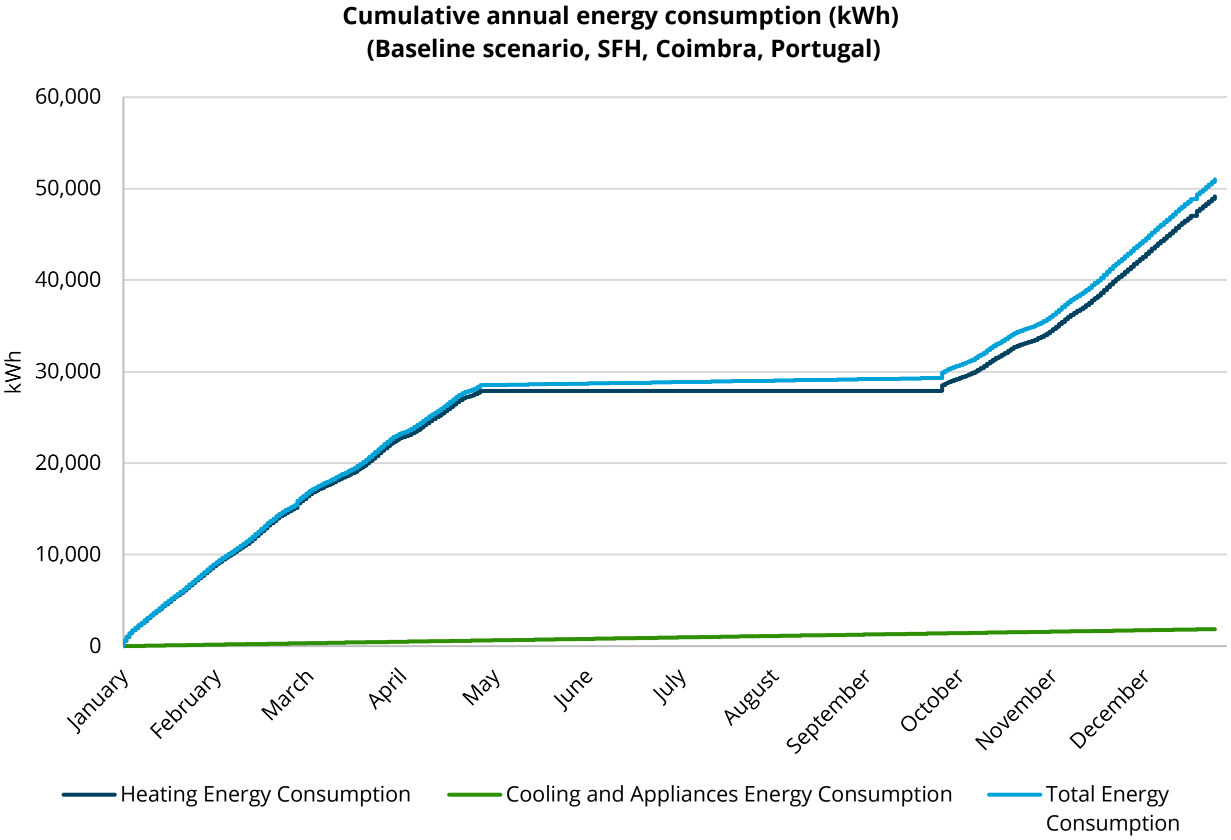

Figure 87. Cumulative annual consumption for the SFH typology in the rural region of Coimbra in Portugal (baseline scenario).

6.7.2 Energy-saving potential

DREEM simulations also lead to concrete quantifications regarding the impact of the different EEMs on the household typologies' energy performance.

SFH typology

In the case of the SFH typology equipped with a wood stove in the rural region of Coimbra in Portugal, **Figure 88** presents the cumulative annual energy consumption profile for the different EEMs presented in **Section 3.8**. Simulation results indicate that EEM$_6$, which involves replacing the existing heating system with a heat pump, resulting in the lowest annual cumulative consumption of 10,496.8 kWh. This is followed by EEM$_3$, which involves roof installation, leading to an annual consumption of 27,863.2 kWh and EEM$_4$, which involves the installation of an upgraded gas boiler, with an annual energy consumption of 32,904.1 kWh.

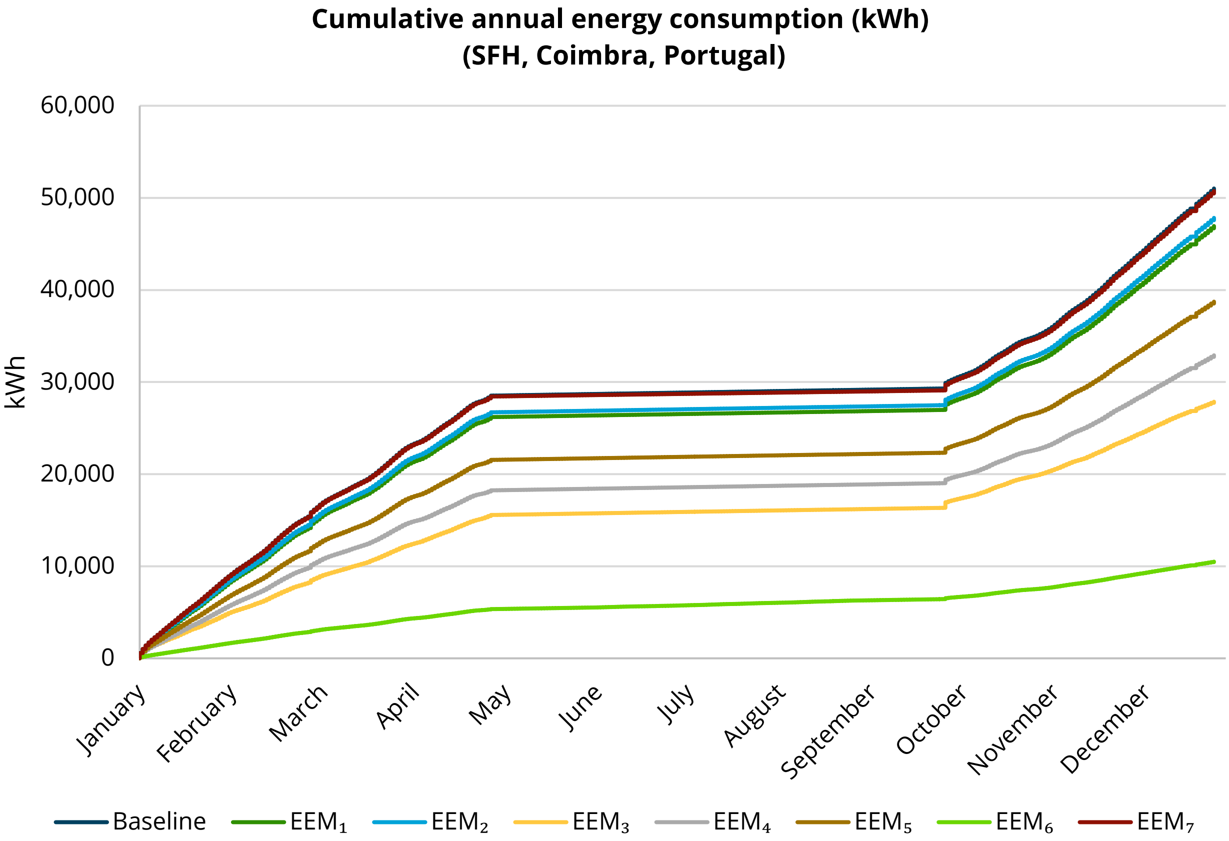

Figure 88. Cumulative annual energy consumption (in kWh) for the different EEMs in the SFH typology in the rural region of Coimbra in Portugal.

To gain a better overview of the impact of each EEM, the annual energy savings achieved from the different interventions are presented in **Table 108**. As indicated in **Figure 89**, we identify that EEM$_6$ leads to the highest amount of energy savings, namely 40,521.4 kWh per year (79.4% reduction compared to the baseline scenario), while EEM$_3$ leads to 23,155.0 kWh saved annually (45.4% reduction) and EEM$_3$ leads to reducing energy consumption by 18,114.1 kWh per year (35.5% reduction).

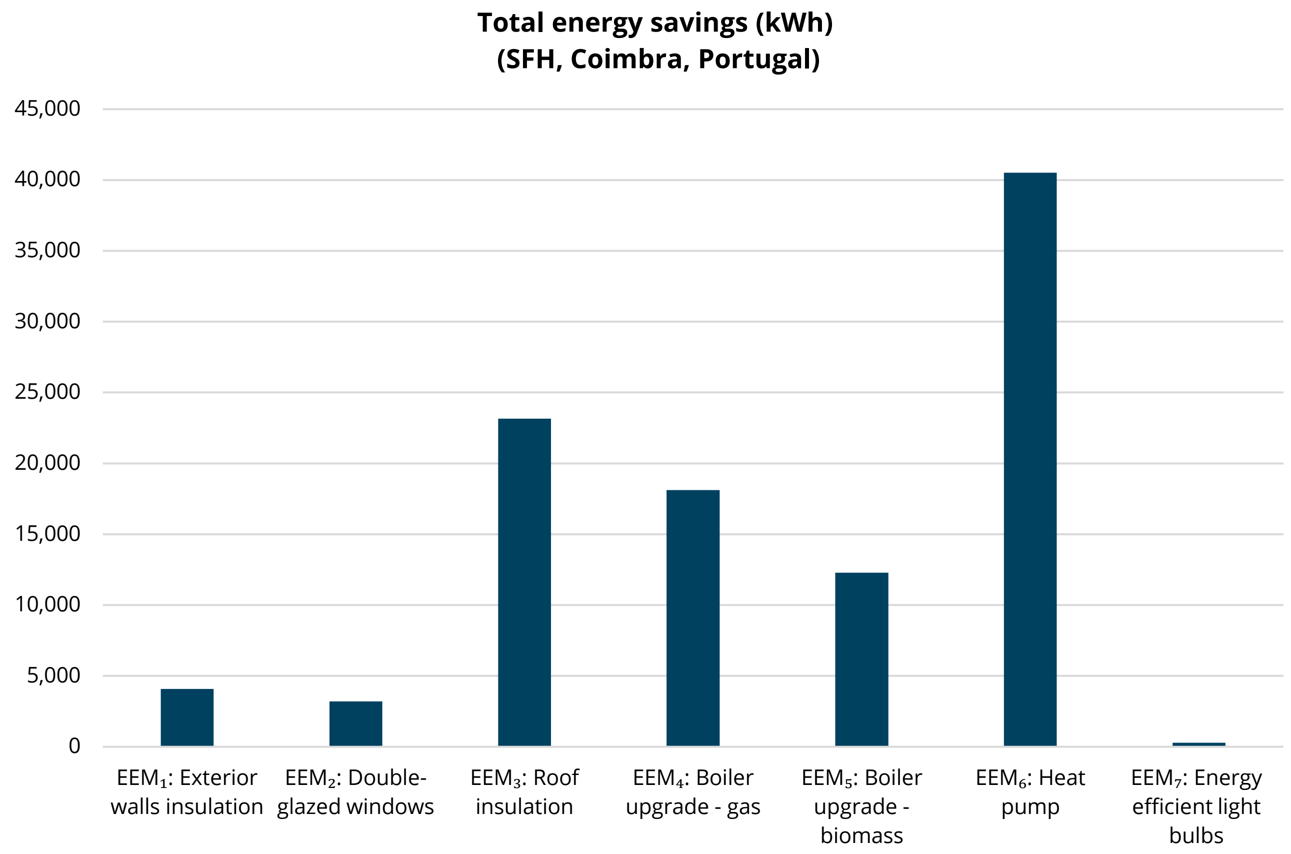

Figure 89. Annual total energy savings (in kWh) for the different EEMs in the SFH typology in the rural region of Coimbra in Portugal.

Table 108. Comparison of annual total energy savings (kWh) for all EEMs with baseline in the rural region of Coimbra in Portugal.

Annual energy savings (in kWh) (SFH, Coimbra, Portugal)		
	Energy savings (kWh)	**Reduction (%)**
EEM_1: Exterior wall insulation	4,079.6	8.0
EEM_2: Double-glazed windows	3,192.2	6.3
EEM_3: Roof insulation	23,155.0	45.4
EEM_4: Boiler upgrade - gas	18,114.1	35.5
EEM_5: Boiler upgrade -biomass	12,289.6	24.1
EEM_6: Heat pump	40,521.4	79.4
EEM_7: Energy efficient light bulbs	277.1	0.5

6.7.3 Environmental impact and thermal comfort analysis

SFH typology

CO_2 footprint

Figure 90 presents the annual CO_2 emissions (in kg) for all the scenarios under study (i.e., baseline and EEMs) for the SFH typology in the rural region of Coimbra in Portugal. We can observe that EEM_5 leads to the highest emissions reduction, leading to the avoidance of almost 15,080.5 kg CO_2 per year, followed by EEM_6 and EEM_4 which lead to an avoidance of around 13,846.8 and 9,066.9 kg CO_2, respectively. More details on the total kg CO_2 avoided and the reduction percentage for each EEM can be found in **Table 109**. The emission factor for the use of a wood stove in the baseline situation is derived from sources in the scientific literature (Bhattacharya et al., 2002).

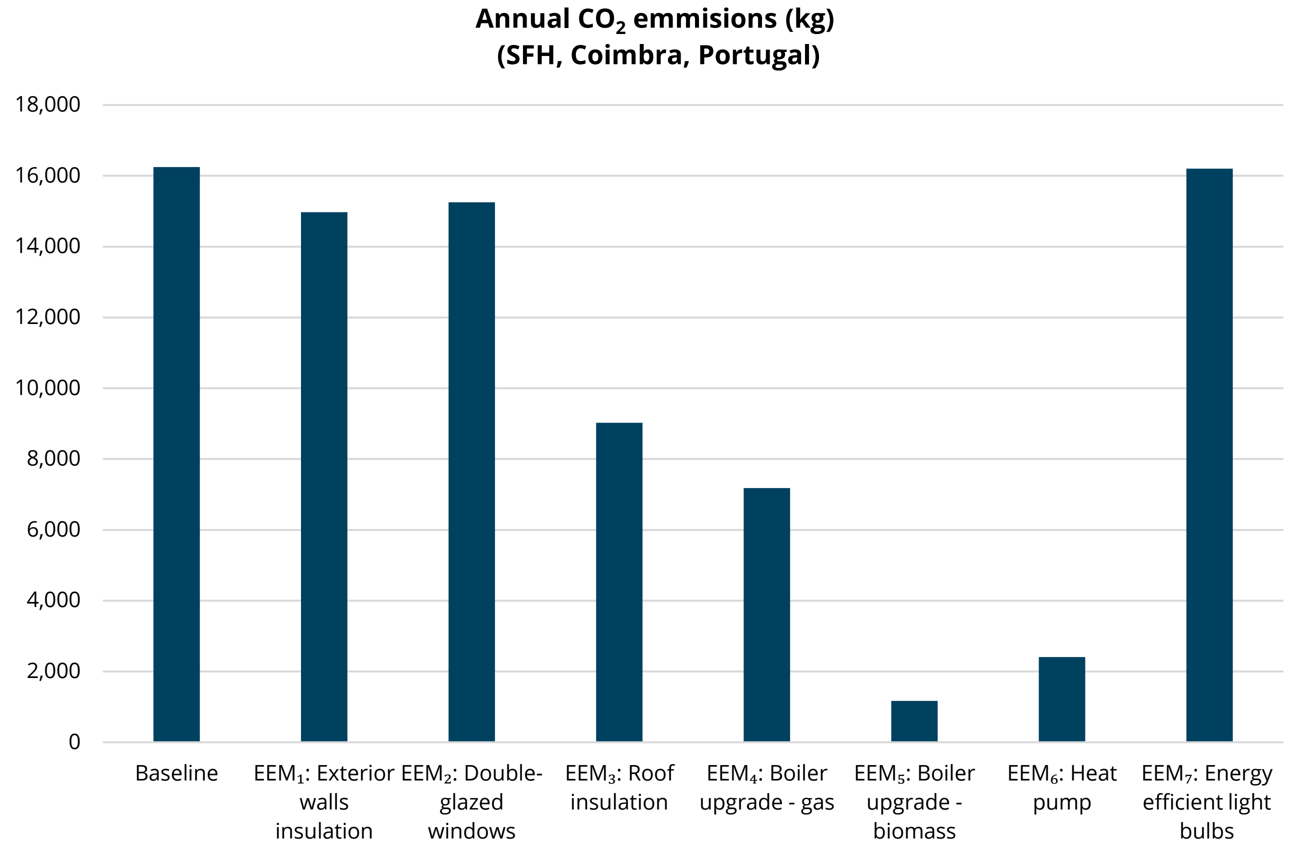

Figure 90. Annual CO_2 emissions (kg) in all scenarios in the SFH typology in the rural region of Coimbra in Portugal.

Table 109 Annual CO_2 emissions avoided (kg) for the different EEMs in the SFH typology in the rural region of Coimbra in Portugal.

Annual CO_2 emissions avoided (SFH, Coimbra, Portugal)		
	Emissions avoided (kg CO_2)	Reduction (%)
EEM_1: Exterior wall insulation	1,272.8	7.8
EEM_2: Double-glazed windows	996.0	6.1
EEM_3: Roof insulation	7,224.4	44.5
EEM_4: Boiler upgrade - gas	9,066.9	55.8
EEM_5: Boiler upgrade - biomass	15,080.5	92.8
EEM_6: Heat pump	13,846.8	85.2
EEM_7: Energy efficient light bulbs	49.6	0.3

PMV indicator

In regards to the analysis of the indoor condition of the households under study, the PMV indicator is used to determine their thermal comfort based on the principles presented in **Section 4.4**. The levels of thermal comfort presented in **Figure 91** indicate that the heating needs of the household are sufficiently met during the winter, as the PMV values fall within the acceptable range of 0 to 1, indicating warm indoor conditions (in Winter PMV values outside this range indicate unacceptable expectation levels, deemed tolerable only for a very limited part of the year). Thermal comfort is not differentiated among the various EEMs scenarios and the baseline scenario, as the same indoor temperature setpoints are used in all cases. This approach ensures that the impact of the different EEMs can be examined while maintaining consistent thermal comfort levels.

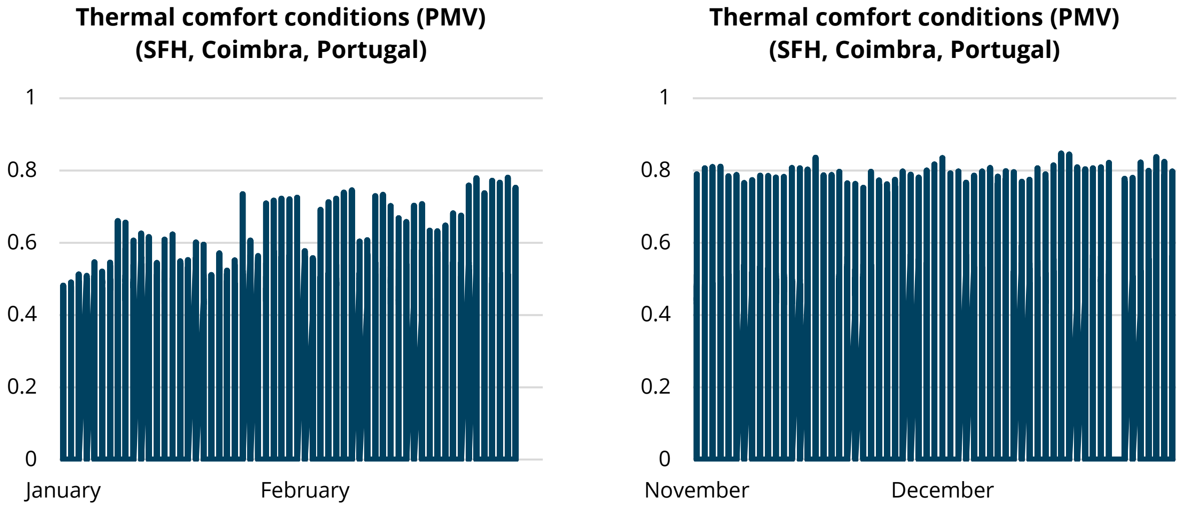

Figure 91. Thermal comfort (PMV indicator) for the SFH typology in the rural region of Coimbra in Portugal during the winter for all the scenarios under study.

6.7.4 Technoeconomic assessment

SFH typology

The results of the technoeconomic assessment of the different EEMs for the SFH typology in the rural region of Coimbra in Portugal, based on the three key indicators analysed in **Section 4.5**, are presented in **Table 110Table 110**.

According to the analysis, EEM$_3$ (Roof insulation) and EEM$_6$ (Heat pump) demonstrate the best performance in terms of NPV, with NPVs of €16,850.5 and €13,584.7, respectively. EEM$_3$ (Roof insulation) and EEM$_4$ (Boiler upgrade- gas) result in the lowest LCSE, at €0.002/kWh and €0.006/kWh, respectively. Additionally, EEM$_3$ and EEM$_7$ exhibit the best performance in PP, with 0.8 and 1.8 years, respectively. Furthermore, EEM$_1$ (Exterior wall insulation), EEM$_2$ (Double-glazed windows) and EEM$_4$ are not economically viable investments, without any subsidy, as they demonstrate negative NPVs, indicating the need for incentives and initiatives aiming to increase their cost-effectiveness of those measures and lower their investment costs.

Table 110. Technoeconomic assessment of the different EEMs in the SFH in the rural region of Coimbra in Portugal (no subsidy).

	Investment Costs (€)	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM_1	4,209	30	4.00%	-1,095.6	>lifetime	0.060
EEM_2	3,357	30	4.00%	-1,441.7	>lifetime	0.077
EEM_3	822	30	4.00%	16,850.5	0.8	0.002
EEM_4	900	20	4.00%	-16,367.7	-	0.006
EEM_5	2,500	20	4.00%	4,192.1	5.8	0.019
EEM_6	3,000	20	4.00%	13,584.7	2.6	0.007
EEM_7	50	23	4.00%	378.6	1.8	0.012

Table 111, **Table 112**, and **Table 113** present the technoeconomic assessment of the EEMs for different subsidy rates (25%, 50%, and 75%, respectively). In all three scenarios, the ranking of the various EEMs remains consistent; however, the economic benefits for vulnerable households increase significantly in terms of NPV and LCSE, while the PP is reduced. Notably, the impact of the different subsidy rates is more pronounced for EEMs with initially higher PP and LCSE, and lower NPV. This demonstrates that subsidies can substantially enhance the financial viability of EEMs, especially those with higher upfront costs and longer PPs. More specifically, EEM_1 and EEM_2 become economically viable with a subsidy rate of at least 50%, while EEM_5 presents a negative NPV for all the different subsidy levels.

Table 111. Technoeconomic assessment of the different EEMs in the SFH (Wood stove) in the rural region of Coimbra in Portugal (25% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,209	25%	30	4.00%	-43.3	>lifetime	0.045
EEM$_2$	3,357		30	4.00%	-602.6	>lifetime	0.058
EEM$_3$	822		30	4.00%	17,055.9	0.6	0.002
EEM$_4$	900		20	4.00%	-16,142.7	-	0.005
EEM$_5$	2,500		20	4.00%	4,817.1	4.2	0.015
EEM$_6$	3,000		20	4.00%	14,334.7	2.0	0.005
EEM$_7$	50		23	4.00%	391.1	1.4	0.009

Table 112. Technoeconomic assessment of the different EEMs in the SFH (Wood stove) in the rural region of Coimbra in Portugal (50% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,209	50%	30	4.00%	1,009.0	16.1	0.030
EEM$_2$	3,357		30	4.00%	236.5	16.5	0.039
EEM$_3$	822		30	4.00%	17,261.3	0.4	0.001
EEM$_4$	900		20	4.00%	-15,917.7	-	0.004
EEM$_5$	2,500		20	4.00%	5,442.1	2.7	0.012
EEM$_6$	3,000		20	4.00%	15,084.7	1.3	0.004
EEM$_7$	50		23	4.00%	403.6	0.9	0.006

Table 113. Technoeconomic assessment of the different EEMs in the SFH (Wood stove) in the rural region of Coimbra in Portugal (75% subsidy).

	Investment Costs (€)	Subsidy level	Lifetime (years)	Discount Rate (%)	NPV (€)	PP (years)	LCSE (€/kWh)
EEM$_1$	4,209	75%	30	4.00%	2,061.3	6.8	0.015
EEM$_2$	3,357		30	4.00%	1,075.6	6.9	0.019
EEM$_3$	822		30	4.00%	17,466.7	0.2	0.001
EEM$_4$	900		20	4.00%	-15,692.7	-	0.004
EEM$_5$	2,500		20	4.00%	6,067.1	1.3	0.008
EEM$_6$	3,000		20	4.00%	15,834.7	0.6	0.003
EEM$_7$	50		23	4.00%	416.1	0.4	0.003

The energy-saving potential and the LCSE indicator differ between the different EEMs countries under study. As indicated by **Figure 92**, the replacement of the existing heating system with an energy-efficient heat pump (EEM$_6$) is the most cost-effective measure (energy savings: 40,521.4 kWh/year, LCSE: 0.007€/kWh), followed by EEM$_3$ and EEM$_4$. On the contrary, EEM$_2$ and EEM$_1$ are shown to be the least cost-effective EEMs due to their higher LCSE values.

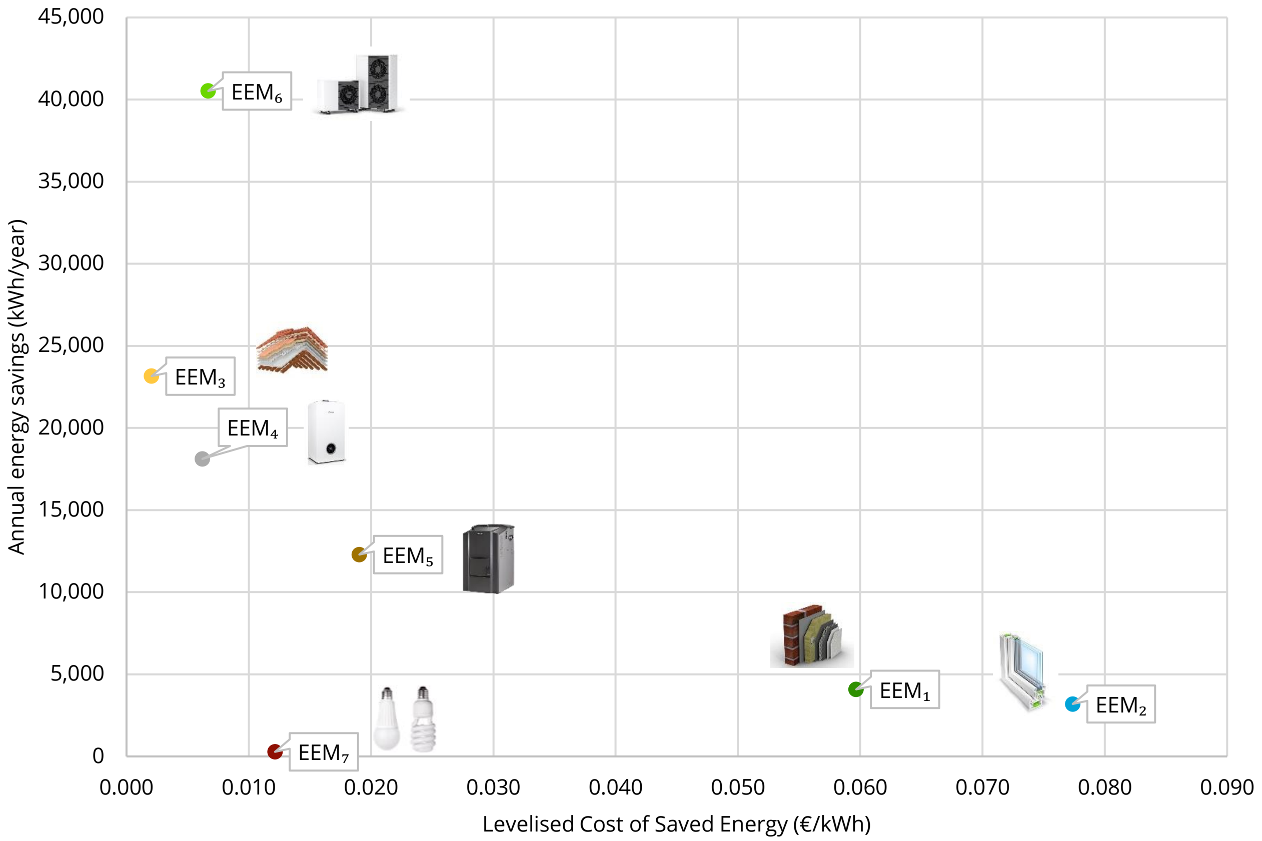

Figure 92. Energy-saving potential and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Coimbra in Portugal.

Additionally, we seek to analyse the correlation between NPV and cost effectiveness of the different EEMs under study. **Figure 93** indicates that EEM_3, EEM_6, EEM_5 and EEM_7 rank highest, as they include the best combinations of NPV and LCSE. In contrast, EEM_2, EEM_1, and EEM_4 rank lowest, with negative NPVs and higher LCSEs, indicating less attractive investments.

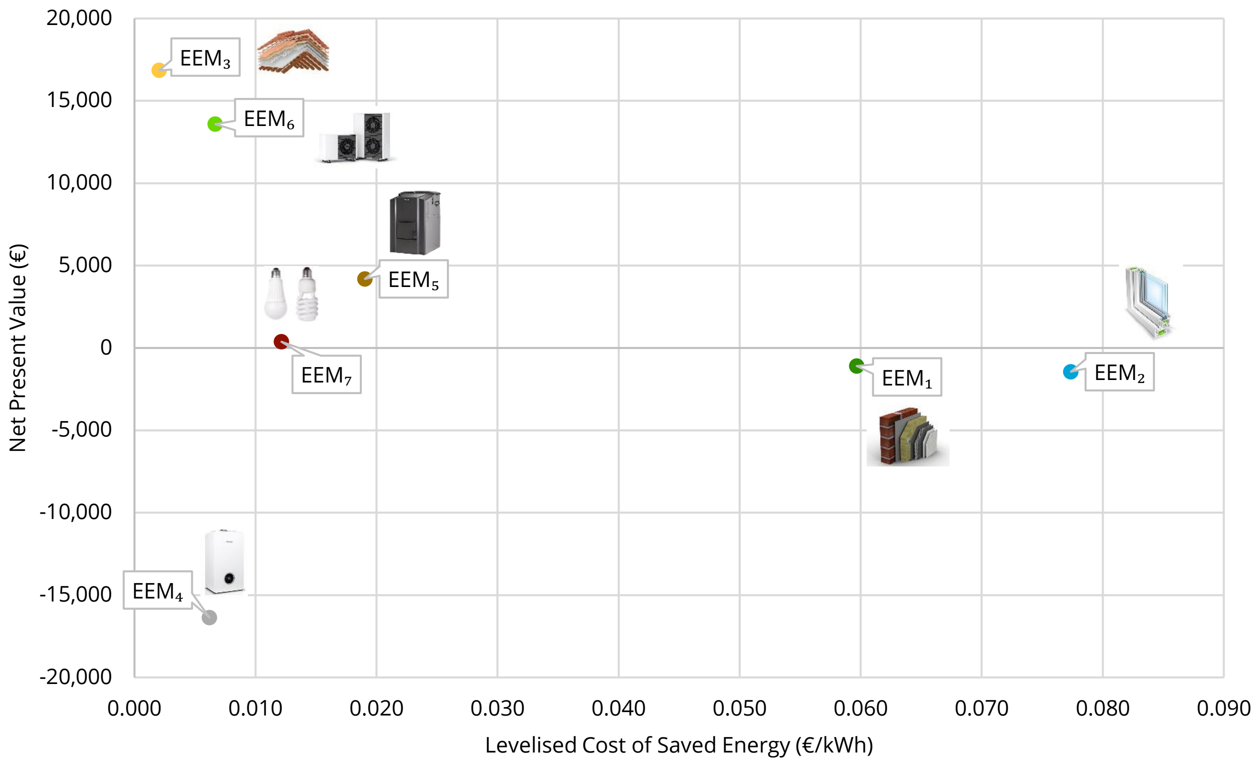

Figure 93. Profitability and cost-effectiveness of the EEMs under study in the case of the SFH typology in the rural region of Coimbra in Portugal.

The same ranking among the different EEMs is observed in the case of the different of subsidisation levels leading to increased cost-effectiveness and profitability, due to the lower LCSEs and the higher NPVs, for the same amount of energy savings achieved. EEM_1 and EEM_2 lead to positive NPVs for a subsidy level of at least 50%, while the NPV of EEM_4 remains negative at all subsidy levels.

7. Comparative analysis and discussion

7.1 Cross-country insights

Modelling results reveal a diverse landscape in the effectiveness of the different EEMs under study, which is affected by several factors such as building characteristics, geographical variations, and local economic conditions.

Overall, cross-country findings underscore the critical importance of tailored approaches to enhance the uptake of energy efficiency measures to address energy poverty in rural contexts.

Despite facing common challenges, each area exhibits distinct characteristics shaped by the regional building characteristics, and diverse geographical and socioeconomic conditions. These differences highlight the necessity for customised interventions and policies that can effectively enhance energy efficiency and combat energy poverty.

By recognising and addressing these nuances, policymakers can better align strategies with regional needs, maximising the impact of EEMs and fostering sustainable development across diverse EU contexts. This approach not only ensures efficient use of resources but also promotes economic resilience and environmental sustainability in each participating region.

7.1.1 Single-family house typologies

Table 114 presents relevant information for the SFH typologies under study. Comparisons among pilot countries highlight distinct EEM groupings based on their effectiveness in achieving energy-saving goals, while maintaining adequate thermal comfort levels. For instance, transitioning to heat pumps (EEM_6) consistently leads to adequate thermal comfort levels with the higher energy reduction percentages ranging from 63.6% in Parma (Italy) to 79.4% in Coimbra (Portugal) at an annual basis, indicating that the more inefficient the existing heating system (e.g., the case study in Coimbra uses wood stove) the more the benefits derived from substituting it.

Regarding the rest of the measures involving a transition to more efficient heating systems (EEM_4 and EEM_5), we observe various trends depending on the specificities of each case study. For EEM_4, the lowest impact on the improvement of the energy performance is indicated in the typologies already using gas boilers for covering their heating needs, like Parma (Italy) with energy reduction of 13.4%, the SFH typologies in Sveta Nedelja and Žumberak (Croatia) (15.5%) and Bükk (Hungary) with 15.6%.

On the other hand, EEM_4 leads to increased energy savings in the cases of Coimbra (35.5%), Sveta Nedelja and Žumberak (wood stove) with 26.1% and SMB (25.6%). For EEM_5, the highest value is recorded in Coimbra (24.1%) and the lowest in Sveta Nedelja and Žumberak (gas boiler) with 2.9% indicating once again the impact of the existing state of heating in the impact of these measures.

Measures concerning the upgrade of the building envelope, i.e., EEM_1, EEM_2, and EEM_3 are also proven to have differentiated impacts across the case studies. EEM_3 has the most consistent performance in the most inefficient buildings, e.g., 45.4% and 23,155 kWh annually in Coimbra (Portugal), and 45.2% and 12,224.5 kWh annually in Zasavje (Slovenia), while the lowest percentage is met in Osona (Spain) with 14.7%.

The energy-saving potential of EEM_1 has wider variations ranging from 8.0% in Coimbra and around 10.0% in Sveta Nedelja and Žumberak in Croatia, to 21.3% in Osona (Spain), 28.1% in Bükk and 39.5% in SMB (Hungary), and is significantly influenced by the baseline state of the dwellings' building envelope. Finally, the performance of EEM_2 is in general the lowest ranging from around 1% to a maximum of 6.3%.

Except for the energy-saving potential, the analysis of the cost-effectiveness of the different EEMs under study across the different pilots also reveals significant variations influenced by the baseline conditions and the different socioeconomic contexts.

In regions like Osona (Spain) and Parma (Italy), where SFH typologies predominantly use oil and gas boilers respectively, EEMs like heat pumps (EEM_6) demonstrate favourable LCSE values. In Osona, EEM_6 shows an LCSE of 0.026€/kWh, significantly lower than EEM_2 (Double-glazed windows) at 0.094€/kWh or EEM_1 (Exterior wall insulation) at 0.081€/kWh, emphasising the economic advantage of transitioning to heat pumps despite the higher electricity prices (0.212€/kWh).

In Hungary's Bükk and SMB regions, where gas boilers are prevalent, and in Zasavje, Slovenia, where wood stoves are common, LCSE trends reflect varying dynamics. In Bükk, EEM_1 (Exterior wall insulation) and EEM_3 (Roof insulation) demonstrate LCSEs of 0.052€/kWh and 0.042€/kWh, respectively, while in Zasavje, Slovenia, the LCSE value of EEM_1 is higher (0.091€/kWh) and of EEM_3 lower (0.009€/kWh).

Croatia's case studies in Sveta Nedelja and Žumberak further illustrate the impact of the baseline heating sources on the LCSE values. In areas using wood stoves like Žumberak, EEM_5 (Boiler upgrade- biomass) and EEM_6 (Heat pump) have LCSE values of 0.033€/kWh and 0.018€/kWh, respectively. In contrast, Sveta Nedelja, where gas boilers are common, exhibits higher LCSE values for the same EEMs (EEM_5 at 0.277€/kWh and EEM_6 at 0.028€/kWh), which can be attributed to the higher efficiency of natural gas boilers compared to wood stoves.

Lastly, in Coimbra (Portugal), where wood stoves prevail, EEM_6 (Heat pump) emerges as a highly cost-effective option with an LCSE of 0.007€/kWh, leveraging Portugal's lower household electricity prices (0.090€/kWh). Complementary measures such as EEM_3 (Roof insulation) also exhibit strong LCSE performance at 0.002€/kWh, underscoring Portugal's favourable dynamics when it comes to building envelope upgrades such as the insulation of the roof.

Overall, the installation of heat pumps (EEM_6) consistently emerges as one of the most cost-effective options across different contexts, with LCSE values ranging from 0.011€/kWh in Bükk, Hungary (lowest) to 0.053€/kWh in Zasavje, Slovenia (highest).

Similar results appear in the case of roof insulation (EEM_3), which shows favourable LCSE values in most cases, ranging from 0.002€/kWh in Coimbra, Portugal (lowest), to 0.048€/kWh in Sveta Nedelja and Žumberak, Croatia (highest). On the contrary, double-glazed windows (EEM_2) exhibit varied LCSE values, ranging from 0.094€/kWh in Osona, Spain (lowest), to 0.679€/kWh in Parma, Italy (highest). This variability can be attributed to factors such as climate conditions, energy prices, and characteristics of the housing stock in the regions under study. For the cases that it may appear less cost-effective, it is crucial to recognise the broader benefits beyond just energy cost savings. Double-glazed windows enhance comfort by reducing drafts and noise, improve indoor air quality, and increase property value. These benefits can be substantial and should be factored into the decision-making process.

Furthermore, the cost-effectiveness of the rest energy efficient heating systems (EEM_4 and EEM_5) varies widely in their LCSE values across regions, reflecting regional dynamics and the effectiveness of each technology in achieving energy efficiency goals.

EEM_4 (Boiler upgrade- gas) ranges from 0.003€/kWh in SMB, Hungary (lowest), to 0.065€/kWh in Sveta Nedelja and Žumberak, Croatia (highest), influenced by the varying investment costs and natural gas prices.

EEM_5 (Boiler upgrade- biomass) varies from 0.078€/kWh in Bükk, Hungary (lowest), to 0.277€/kWh in Sveta Nedelja and Žumberak, Croatia (highest), reflecting regional pricing dynamics.

Finally, the LCSE of EEM_7 (energy-efficient lighting) consistently ranges in lower values, from 0.003€/kWh in SMB, Hungary (lowest), to 0.012€/kWh in Coimbra, Portugal (highest), highlighting the cost-effectiveness of modern lighting upgrades.

Table 114. Summary of the energy-saving potential, CO_2 emissions reduction and cost-effectiveness (LCSE) of the different EEMs in the SFH typologies under study.

SFH typologies		Annual energy savings (kWh)	Energy reduction (%)	LCSE (€/kWh)
Osona (Spain)	EEM_1	6,806.0	21.3	0.081
	EEM_2	340.8	1.1	0.094
	EEM_3	4,694.6	14.7	0.036

	EEM$_4$	7,111.6	22.3	0.019
	EEM$_5$	3,318.6	10.4	0.058
	EEM$_6$	23,072.2	72.2	0.026
	EEM$_7$	658.2	2.1	0.007
Parma (Italy)	EEM$_1$	4,711.1	16.9	0.270
	EEM$_2$	367.5	1.3	0.679
	EEM$_3$	10,816.4	38.7	0.015
	EEM$_4$	3,751.0	13.4	0.044
	EEM$_5$	1,912.1	6.8	0.233
	EEM$_6$	17,758.0	63.6	0.036
	EEM$_7$	490.5	1.8	0.009
Bükk (Hungary)	EEM$_1$	8,547.1	28.1	0.052
	EEM$_2$	731.8	2.4	0.514
	EEM$_3$	3,032.6	10.0	0.042
	EEM$_4$	4,752.2	15.6	0.008
	EEM$_5$	923.5	3.0	0.078
	EEM$_6$	20,911.3	68.9	0.011
	EEM$_7$	390.7	1.3	0.003
SMB (Hungary)	EEM$_1$	16,196.4	39.5	0.033
	EEM$_2$	2,503.0	6.1	0.150
	EEM$_3$	13,275.5	32.4	0.013
	EEM$_4$	10,477.1	25.6	0.004
	EEM$_5$	8,149.7	19.9	0.009
	EEM$_6$	29,415.3	71.8	0.008
	EEM$_7$	390.4	1.0	0.003
Sveta Nedelja and Žumberak	EEM$_1$	5,814.1	10.1	0.048
	EEM$_2$	1,100.1	1.9	0.240

(wood stove) (Croatia)	EEM$_3$	14,311.2	24.9	0.019
	EEM$_4$	15,017.0	26.1	0.019
	EEM$_5$	9,724.8	16.9	0.033
	EEM$_6$	43,280.4	75.3	0.018
	EEM$_7$	579.7	1.0	0.005
Sveta Nedelja and Žumberak (gas boiler) (Croatia)	EEM$_1$	4,322.0	11.0	0.065
	EEM$_2$	857.5	2.2	0.308
	EEM$_3$	10,618.0	27.0	0.026
	EEM$_4$	4,520.4	15.5	0.064
	EEM$_5$	1,154.0	2.9	0.277
	EEM$_6$	27,996.8	71.3	0.028
	EEM$_7$	597.7	1.5	0.006
Zasavje (Slovenia)	EEM$_1$	4,024.0	14.9	0.091
	EEM$_2$	464.3	1.7	0.270
	EEM$_3$	12,224.5	45.2	0.009
	EEM$_4$	5,619.8	20.8	0.043
	EEM$_5$	2,625.0	9.7	0.117
	EEM$_6$	18,269.8	67.5	0.053
	EEM$_7$	353.6	1.3	0.005
Coimbra (Portugal)	EEM$_1$	4,079.6	8.0	0.060
	EEM$_2$	3,192.2	6.3	0.077
	EEM$_3$	23,155.0	45.4	0.002
	EEM$_4$	18,114.1	35.5	0.006
	EEM$_5$	12,289.6	24.1	0.019
	EEM$_6$	40,521.4	79.4	0.007
	EEM$_7$	277.1	0.5	0.012

Modelling results also provide calculations on the NPV of investing in the different EEMs under study across the RENOVERTY pilot areas, providing insightful observations regarding households' profitability and the impact of financial subsidies (**Table 115**). Across the pilot countries, distinct groupings, and contrasts in NPV outcomes for EEMs reveal nuanced regional dynamics and context influences.

In Spain's Osona, Slovenia's Zasavje, and Italy's Parma, EEM_3 (Roof insulation) consistently shows robust household profitability across all subsidy levels, reflecting a strategic emphasis on thermal performance enhancements in these regions. For instance, in Osona, EEM_3 consistently shows positive NPV values as it yields NPVs of 8,318.8€ without subsidies, rising to 10,506.1€ with a 75% subsidy, indicating substantial household profitability enhancements through financial support.

Moreover, for households across Hungary's Bükk and SMB regions higher profitability is identified for EEM_4 (Boiler upgrade- gas) without subsidies, suggesting cost-effectiveness driven by lower natural gas prices and heating demands- however susceptible to future energy crises and geopolitical developments.

In Bükk, subsidies play a crucial role in transforming NPV outcomes for various EEMs. Subsidies can reduce investment costs, enhancing the economic viability of several EEMs, such as EEM_2 and EEM_6. For instance, without subsidies, EEM_6 starts with negative NPV in Bükk, but with increasing subsidy levels, the NPV is improved from -1,664.8€ to 772.7€ with a 75% subsidy.

In Croatia's Sveta Nedelja and Žumberak, the baseline heating source of the typology, i.e., wood stove and gas boiler, influences NPV outcomes significantly. For example, EEM_6 (Heat pump) emerges as more profitable for the gas boiler typology due to the specific context of energy pricing.

Moreover, in both cases, it is important to comment that given the existing energy pricing, EEM_5 showcases losses instead of gains, as the annual savings generated cannot overcome the difference between the current gas prices (0.027 €/kWh and 0.043 €/kWh respectively) and biomass prices (0.061 €/kWh and 0.060 €/kWh respectively).

In Zasavje, Slovenia, EEM_1 (Exterior wall insulation) and EEM_5 (Boiler upgrade- biomass) demonstrate negative NPV values without any subsidy, which become positive for subsidy levels of at least 50%, highlight the need for supportive subsidy frameworks to allow a positive effect on EEMs' investment returns.

Conversely, in regions like Sveta Nedelja and Žumberak in Croatia, where wood stoves are prevalent, EEM_5 (Boiler upgrade- biomass) and EEM_6 (Heat pump) show varying NPV responses to subsidies, underscoring the influence of biomass and electricity pricing on profitability.

Table 115. Summary of the profitability (NPV) of the different EEMs for different subsidy levels in the SFH typologies under study.

SFH typologies		NPV (no subsidy)	NPV (25% subsidy)	NPV (50% subsidy)	NPV (75% subsidy)
Osona (Spain)	EEM$_1$	6,705.8	9,101.4	11,497.1	13,892.69
	EEM$_2$	262.7	400.9	539.2	677.44
	EEM$_3$	8,318.8	9,047.9	9,777.0	10,506.14
	EEM$_4$	24,997.8	25,447.8	25,597.9	26,347.83
	EEM$_5$	42,646.2	43,114.2	43,764.2	44,414.17
	EEM$_6$	28,600.1	30,600.1	32,600.1	34,600.13
	EEM$_7$	2,008.1	2,024.4	2,040.6	2,056.896
Parma (Italy)	EEM$_1$	-13,072.3	-7,569.0	-2,065.8	3,437.5
	EEM$_2$	-3,615.0	-2,536.9	-1,458.8	-380.6
	EEM$_3$	17,765.9	18,456.3	19,146.6	19,837.0
	EEM$_4$	3,364.8	3,548.6	3,732.3	3,916.0
	EEM$_5$	7,568.6	8,443.6	9,318.6	10,193.6
	EEM$_6$	3,078.9	4,578.9	6,078.9	7,578.9
	EEM$_7$	1,871.6	1,886.6	1,901.6	1,916.6
Bükk (Hungary)	EEM$_1$	-3,716.2	-1,811.68	92.8	1,997.3
	EEM$_2$	-6,165.9	-4,540.9	-2,951.9	-1,290.9
	EEM$_3$	-804.6	-257.3	289.9	837.0
	EEM$_4$	1,165.0	1,300.0	1,435	1,570.0
	EEM$_5$	-13,251.5	-13,006.5	-12,761.5	-12,516.5
	EEM$_6$	-1,664.8	-852.3	-39.79	772.7
	EEM$_7$	462.9	467.1	471.2	475.3
SMB (Hungary)	EEM$_1$	-1,836.2	471.3	2,778.8	5,086.3
	EEM$_2$	-5,357.4	-3,732.4	-2,107.4	-482.4
	EEM$_3$	3,167,4	3,890.6	4,613.9	5,337.1

	EEM$_4$	3,219.0	3,354.0	3,489.0	3,624.0
	EEM$_5$	-11,464.4	-11,219.4	-10,974.4	-10,729.4
	EEM$_6$	1,008.5	1,821.0	2,633.5	3,446.0
	EEM$_7$	462.7	466.8	470.9	475.0
Sveta Nedelja and Žumberak (wood stove) (Croatia)	EEM$_1$	1,185.1	2,396.9	3,608.7	4,820.5
	EEM$_2$	-2,687.0	-1,791.0	-895.0	1.0
	EEM$_3$	10,060.6	11,257.5	12,454.4	13,651.3
	EEM$_4$	18,583.9	19,450.9	20,317.9	21,184.9
	EEM$_5$	3,593.3	4,507.5	5,421.8	6,336.0
	EEM$_6$	3,108.6	5,608.6	8,108.7	10,608.6
	EEM$_7$	962.7	973.9	985.2	996.4
Sveta Nedelja and Žumberak (gas boiler) (Croatia)	EEM$_1$	-1,633.5	-421.7	790.1	2,001.9
	EEM$_2$	-3,082.9	-2,186.9	-1,290.9	-394.9
	EEM$_3$	3,107,6	4,304.5	5,5501.4	6,698.2
	EEM$_4$	-1,381.6	-514.6	352.4	1,219.4
	EEM$_5$	-11,834.3	-10,920.1	-10,005.8	-9,091.6
	EEM$_6$	-2,896.4	-396.2	2,103.8	4,603.8
	EEM$_7$	957.7	970.2	982.7	995.2
Zasavje (Slovenia)	EEM$_1$	-459.0	1,117.0	2,693.0	4,269.0
	EEM$_2$	-1,173.9	-747.9	-321.93	104.1
	EEM$_3$	15,812.5	16,298.5	16,784.5	17,270.5
	EEM$_4$	3,089.4	3,776.9	4,464.4	5,151.9
	EEM$_5$	-1,182.8	-307.8	567.2	1,442.2
	EEM$_6$	2,416.4	5,541.4	8,666.4	11,791.4
	EEM$_7$	818.7	8250.5	832.2	839.0
Coimbra (Portugal)	EEM$_1$	-1,095.6	-43.3	1,009.0	2,061.3
	EEM$_2$	-1,441.7	-602.6	236.5	1,075.6

EEM$_3$	16,850.5	17,055.9	17,261.3	17,466.7
EEM$_4$	-16,367.7	-16,142.7	-15,917.7	-15,692.7
EEM$_5$	4,192.1	4,817.1	5,442.1	6,067.1
EEM$_6$	13,584.7	14,334.7	15,084.7	15,834.7
EEM$_7$	378.6	391.1	403.6	416.1

7.1.2 Multi-family house typologies

Table 116 presents relevant information for the MFH typologies under study. Across the board, most of the regions with older typologies, like Parma in Italy and Tartu in Estonia, showcase substantial benefits from building envelope upgrade measures such as the insulation of exterior wall (EEM$_1$).

For instance, Parma achieves annual energy savings of 8,423.2 kWh and a reduction of 1,701.5 kg CO$_2$ emissions per year with EEM$_1$, while Tartu in Estonia achieves energy savings of 5,522.1 kWh and emissions reduction of 1,330.8 kg CO$_2$ annually.

Comparisons among pilot countries highlight distinct EEM groupings based on their effectiveness in achieving energy efficiency goals while maintaining adequate levels of thermal comfort. For instance, transitioning to heat pumps (EEM$_6$) consistently leads to the higher energy reduction percentages ranging from 55.2% in Tartu, Estonia to 66.0% in Zasavje (Slovenia).

Regarding the rest of the measures involving transitioning to more efficient heating systems (EEM$_4$ and EEM$_5$) we observe various trends depending on the specificities of each case study. For EEM$_4$, for the same thermal comfort levels compared to the baseline scenario, the reduction of energy consumption is generally consistent ranging from 13.5% to 18.3%, while for EEM$_5$, the highest value is 8.5% (Osona, Spain) and the lowest is 2.8% (Parma, Italy).

Measures concerning upgrades of the building envelope, like EEM$_1$ and EEM$_2$ are also proved to have differentiated impacts across the case studies. The energy-saving potential of EEM$_1$ is in general better than the potential of EEM$_4$ and EEM$_5$ ranging from 10.7% in Zasavje (Slovenia) to 32.6% in Parma (Italy). Finally, the performance of EEM$_2$ is also varied, although in lower values compared to EEM$_1$, ranging from 0.9% in the case of Zasavje to 10.0% in the case of Tartu (Estonia).

Except for the energy-saving potential, the analysis of the cost-effectiveness of the different EEMs under study across the pilot areas also reveals significant variations influenced by the baseline conditions, and the different socioeconomic contexts. MFH typologies predominantly using gas boilers, EEMs like heat pumps (EEM$_6$) demonstrate favourable LCSE values.

For EEM$_6$ (Heat pump), LCSE values range from 0.039 €/kWh in Tartu in Estonia to 0.061€/kWh in Zasavje in Slovenia, making it a consistent and reliable option. The latter also highlights the economic advantages of transitioning to heat pumps even in cases with higher electricity prices, like in the case of Italy. In contrast, EEM$_1$ (Exterior wall insulation) and EEM$_2$ (Double-glazed windows), show varying dynamics in LCSE ranging from 0.027 €/kWh to 0.130 €/kWh and 0.063 €/kWh to 0.525 €/kWh, respectively.

Furthermore, considering that in the baseline situation, the majority of MFH typologies use gas boilers to cover their heating needs, an interesting observation concerns the fact that in all cases the LCSE is lower than the gas price in each country's context, apart from Slovenia, indicating the economic viability of upgrading the heating system. LCSE values for the implementation of EEM$_4$ range from 0.028€/kWh in Osona to 0.044€/kWh in Parma, while EEM$_5$ values are between 0.109€/kWh and 0.621€/kWh.

Table 116. Summary of the energy-saving potential, CO$_2$ emissions reduction and cost-effectiveness (LCSE) of the different EEMs in the MFH typologies under study.

MFH typologies		Annual energy savings (kWh)	Energy reduction (%)	Annual emissions avoided (kg CO$_2$)	LCSE (€/kWh)
Osona (Spain)	EEM$_1$	5,114.2	24.8	1,380.8	0.027
	EEM$_2$	360.6	1.8	97.4	0.098
	EEM$_4$	3,765.7	18.3	2,101.6	0.028
	EEM$_5$	1,757.9	8.5	4,0181.1	0.109
	EEM$_6$	12,244.6	59.5	3,339.7	0.048
	EEM$_7$	847.3	4.1	231.3	0.007
Parma (Italy)	EEM$_1$	8,423.2	32.6	1,701.5	0.130
	EEM$_2$	1,085.4	4.2	219.2	0.151
	EEM$_4$	3,675.8	14.2	745.5	0.044
	EEM$_5$	716.3	2.8	4,182.0	0.621
	EEM$_6$	15,696.7	60.7	2,965.5	0.041
	EEM$_7$	713.5	2.8	183.4	0.007

Tartu (Estonia)	EEM$_1$	5,522.1	28.1	1,330.8	0.055
	EEM$_2$	1,959.7	10.0	472.3	0.063
	EEM$_4$	3,602.1	18.4	1,390.9	0.033
	EEM$_5$	728.4	3.7	3,985.0	0.321
	EEM$_6$	10,837.2	55.2	2,770.1	0.039
	EEM$_7$	85.4	0.4	21.3	0.016
Zasavje (Slovenia)	EEM$_1$	2,096.8	10.7	423.6	0.056
	EEM$_2$	170.1	0.9	34.4	0.525
	EEM$_4$	2,634.0	13.5	532.1	0.091
	EEM$_5$	1,341.7	6.9	3,262.4	0.229
	EEM$_6$	12,912.7	66.0	2,604.6	0.061
	EEM$_7$	314.4	1.7	69.3	0.005

Modelling results also include calculations on the NPV of investing in the different EEMs under study across the RENOVERTY pilot areas, providing insightful observations regarding households' profitability from their implementation and the impact of financial subsidies (**Table 117**). Across the pilot countries, distinct groupings, and contrasts in NPV outcomes for EEMs reveal nuanced regional dynamics and context influences.

In Spain's Osona, Slovenia's Zasavje, and Estonia's Tartu, EEM$_1$ (Exterior wall insulation) consistently shows robust profitability across all subsidy levels, reflecting a strategic emphasis on thermal performance enhancements in these regions. For instance, EEM$_1$ (Exterior wall insulation) consistently shows positive NPV values across these regions, such as Osona where it yields NPVs of 9,852.4€ without subsidies, rising to 11,624.7€ with a 75% subsidy, indicating substantial profitability enhancements through financial support.

Moreover, Parma, Osona, and Tartu regions demonstrate higher profitability for EEM$_4$ (Boiler upgrade- gas) without subsidies, suggesting economic benefits driven by natural gas prices- however susceptible to future energy crises and geopolitical developments. The situation is similar for EEM$_5$ (Boiler upgrade- biomass), which also shows high profitability without subsidies and is regarded as a profitable investment, in all cases except Zasavje.

In general, subsidies play a crucial role in transforming NPV outcomes for various EEMs, as they can reduce investment costs, enhancing the economic viability of the EEMs' investments. For instance, in Parma EEM$_1$ (Exterior wall insulation) and EEM$_2$ (Double-glazed windows), start with negative NPVs without subsidies, but with increasing subsidy levels, the NPV improves significantly: from -2,177.8€ without subsidies to 2,557.9€ with a 25% subsidy for EEM_1 and from -552.2€ to 32.8€ with a 25% subsidy for EEM_2.

This specific example illustrates how financial incentives can substantially boost the attractiveness of energy efficiency investments, particularly in regions facing increased energy poverty challenges.

Table 117. Summary of the profitability (NPV) of the different EEMs for different subsidy levels in the MFH typologies under study.

MFH typologies		NPV (no subsidy)	NPV (25% subsidy)	NPV (50% subsidy)	NPV (75% subsidy)
Osona (Spain)	EEM_1	9,852.4	10,449.2	11,045.9	11,642.7
	EEM_2	251.0	404.0	557.0	710.0
	EEM_4	16,258.2	16,708.2	17,158.2	17,608.2
	EEM_5	21,269.0	21,918.9	22,269.0	23,219.0
	EEM_6	11,455.2	13,455.2	15,455.2	17,455.2
	EEM_7	2,361.1	2,381.1	2,401.1	2,421.1
Parma (Italy)	EEM_1	-2,177.8	2,557.9	7,293.5	12,023.1
	EEM_2	-552.2	32.8	587.8	1,142.8
	EEM_4	3,789.5	3,973.2	4,157.0	4,340.7
	EEM_5	6,777.5	7,652.5	8,527.5	9,402.5
	EEM_6	4,836.3	6,336.3	7,836.3	9.336.3
	EEM_7	2,643.9	2,662.7	2,681.4	2,700.2
Tartu (Estonia)	EEM_1	3,573.9	4,876.6	6,179.4	7,482.2
	EEM_2	776.2	1,194.7	1,613.2	2,031.7
	EEM_4	6,359.9	6,609.9	6,859.9	7,109.9
	EEM_5	9,236.1	9,861.1	10,486.1	11,111.1
	EEM_6	943.0	2,193.0	3,443.0	4,693.0
	EEM_7	201.4	206.4	211.4	216.4
Zasavje (Slovenia)	EEM_1	1058.3	1,528.0	2,033.9	2,539.8
	EEM_2	-1,018.5	-717.0	-413.3	-109.5

EEM$_4$	-237.1	209.4	896.9	1,584.4
EEM$_5$	-2,421.1	-1,772.9	-897.9	-22.9
EEM$_6$	343.5	2,843.5	5,343.5	7,843.5
EEM$_7$	789.6	796.4	803.1	809.9

7.2 Comparing energy efficiency measures based on geographical context

7.2.1 Exterior wall insulation (EEM$_1$)

Figure 94 and **Figure 95** indicate the performance of EEM$_1$ (Exterior wall Insulation) in terms of the combinations of energy-saving potential with cost effectiveness (LCSE) and profitability (NPV) with cost effectiveness (LCSE).

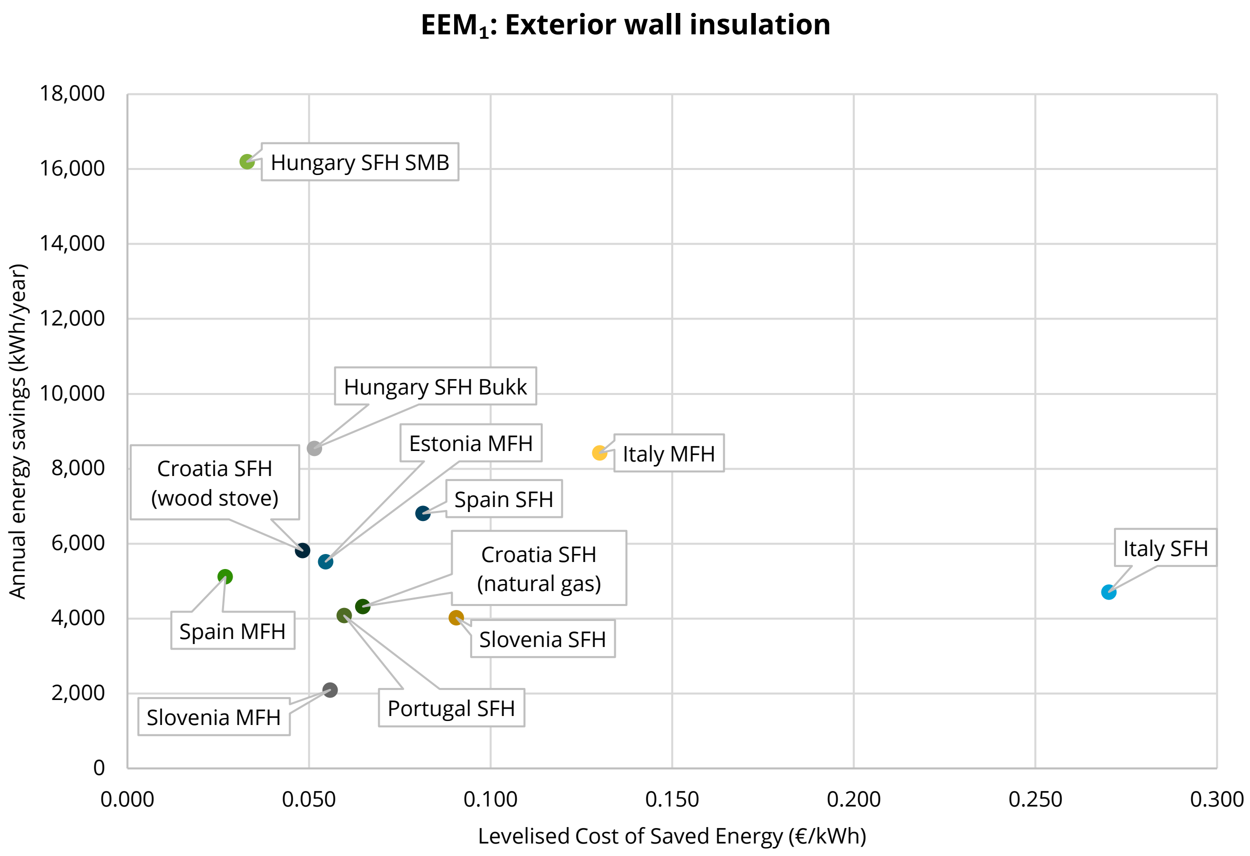

Figure 94. Cross-country comparison of the performance of EEM$_1$ in energy-saving potential and cost-effectiveness.

We observe that EEM$_1$ results in favourable combinations of energy-saving potential and cost effectiveness for most pilot cases, with notable exceptions. The Italian SFH typology shows the highest LCSE, indicating lower cost effectiveness compared to other cases. In contrast, the Hungarian pilot areas (Bükk and SMB) demonstrate the most beneficial combinations, showcasing both higher energy savings and lower LCSE values. Other notable performers include the Italian MFH, the Croatian SFH (wood stove), the Spanish SFH and MFH, the Estonian MFH, and the Slovenian and Portuguese SFH typologies.

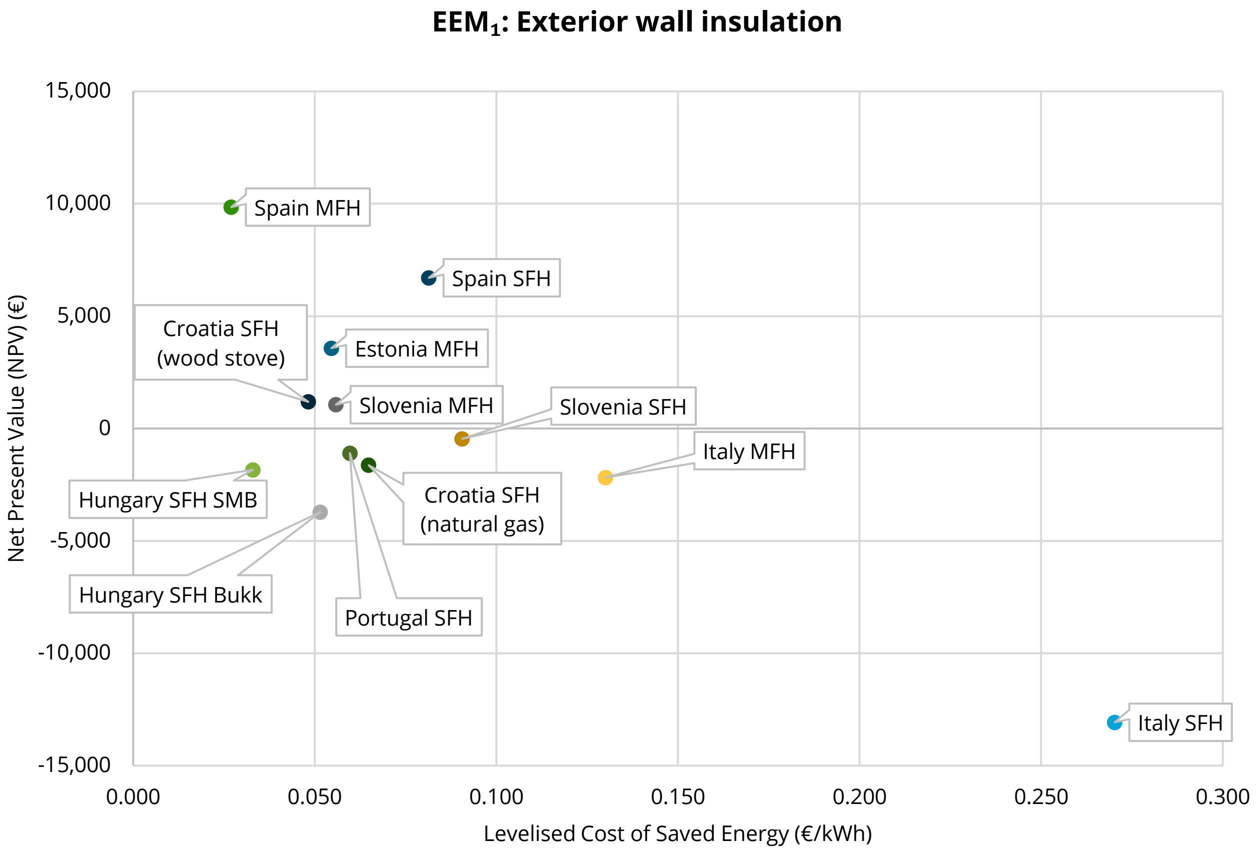

Figure 95. Cross-country comparison of the performance of EEM_1 in household profitability and cost-effectiveness.

Regarding the performance of EEM_1 in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the highest performance is observed in the MFH and SFH typologies in Spain, followed by the MFH typology in Estonia and the SFH (wood stove) and MFH typologies in Croatia and Slovenia, respectively. The worst ranking is observed in the SFH typology in Italy, where the lowest NPV and highest LCSE are identified. Negative NPVs with lower LCSE are also observed in the SFH pilots of Hungary, Portugal, and Croatia.

7.2.2 Double-glazed windows (EEM_2)

Figure 96 and **Figure 97** indicate the performance of EEM_2 (Double-glazed windows) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

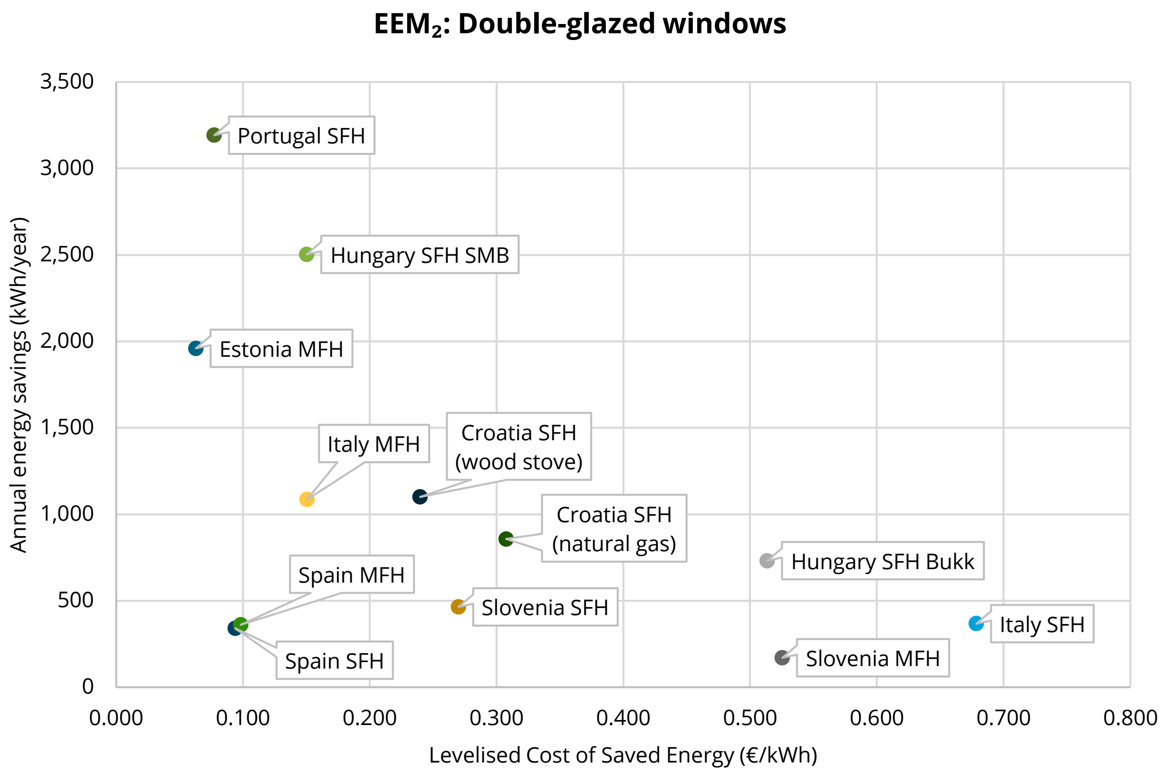

Figure 96. Cross-country comparison of the performance of EEM_2 in energy-saving potential and cost-effectiveness.

Notably, the SFH typologies in Portugal and SMB (Hungary) exhibit the most favourable combinations of high energy savings and low LCSEs, indicating cost-effective interventions. The MFH typologies in Estonia and Italy, and the SFH typology (wood stove) in Croatia also demonstrate beneficial outcomes with moderate savings and relatively low LCSE. In contrast, the Italian SFH and the Slovenian MFH typologies show the least cost-effective results, with higher LCSEs and lower annual energy savings.

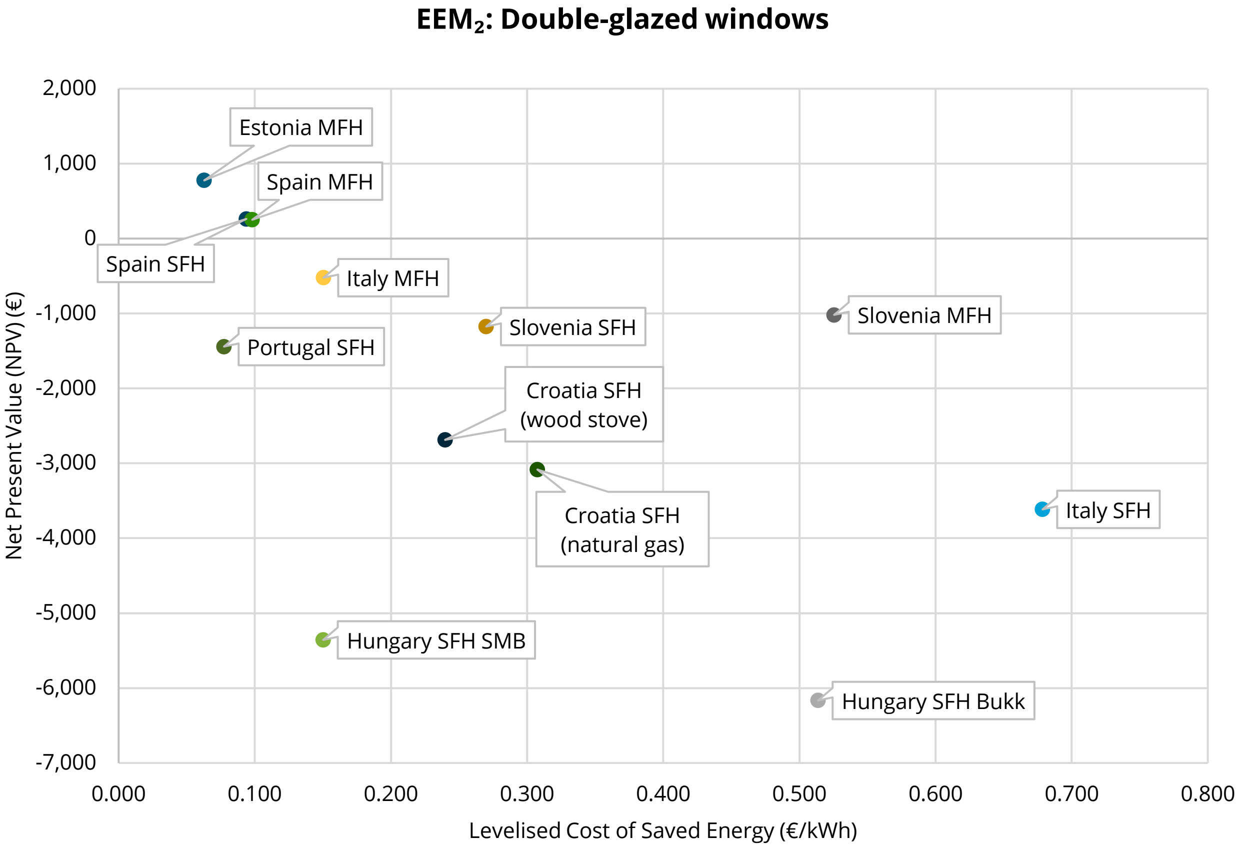

Figure 97. Cross-country comparison of the performance of EEM_2 in household profitability and cost-effectiveness.

Regarding the performance of EEM_2 in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the highest performance is observed in the MFH typology in Estonia and the MFH and SFH typologies in Spain. For the rest of the pilot areas, the NPV of EEM_2 is negative, with the worst performance observed in the SFH typologies in Hungary and Italy.

7.2.3 Roof insulation (EEM_3)

Figure 98 and **Figure 99** indicate the performance of EEM_3 (Roof insulation) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

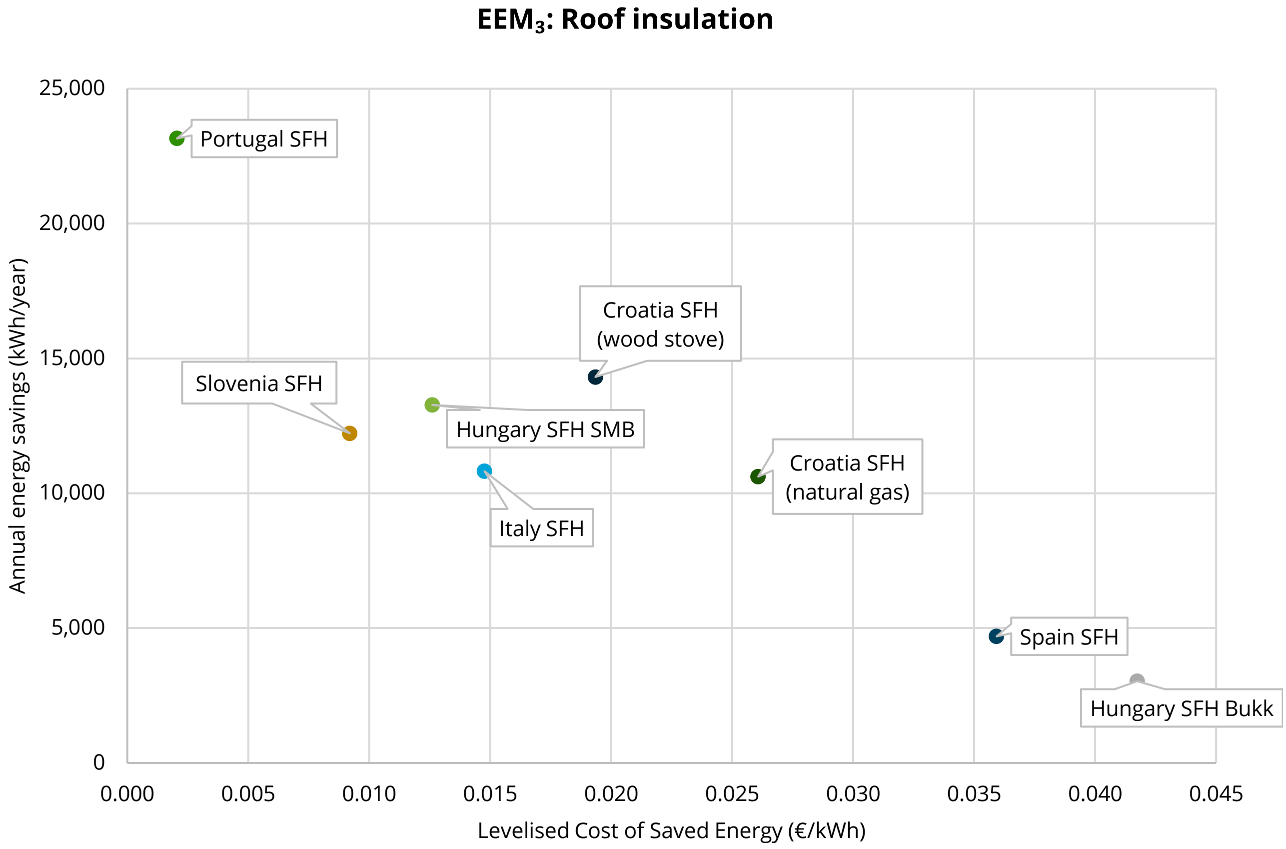

Figure 98. Cross-country comparison of the performance of EEM₃ in energy-saving potential and cost-effectiveness.

We observe that EEM_3 leads to beneficial combinations of energy-saving potential and cost-effectiveness in most pilot cases, with the slight exception of the SFH typology in Bükk (Hungary) and Spain, where the highest LCSEs are indicated. The most beneficial combinations are indicated in the SFH typology in Portugal, followed by the SFH typologies in Slovenia, SMB (Hungary), Croatia, and Italy.

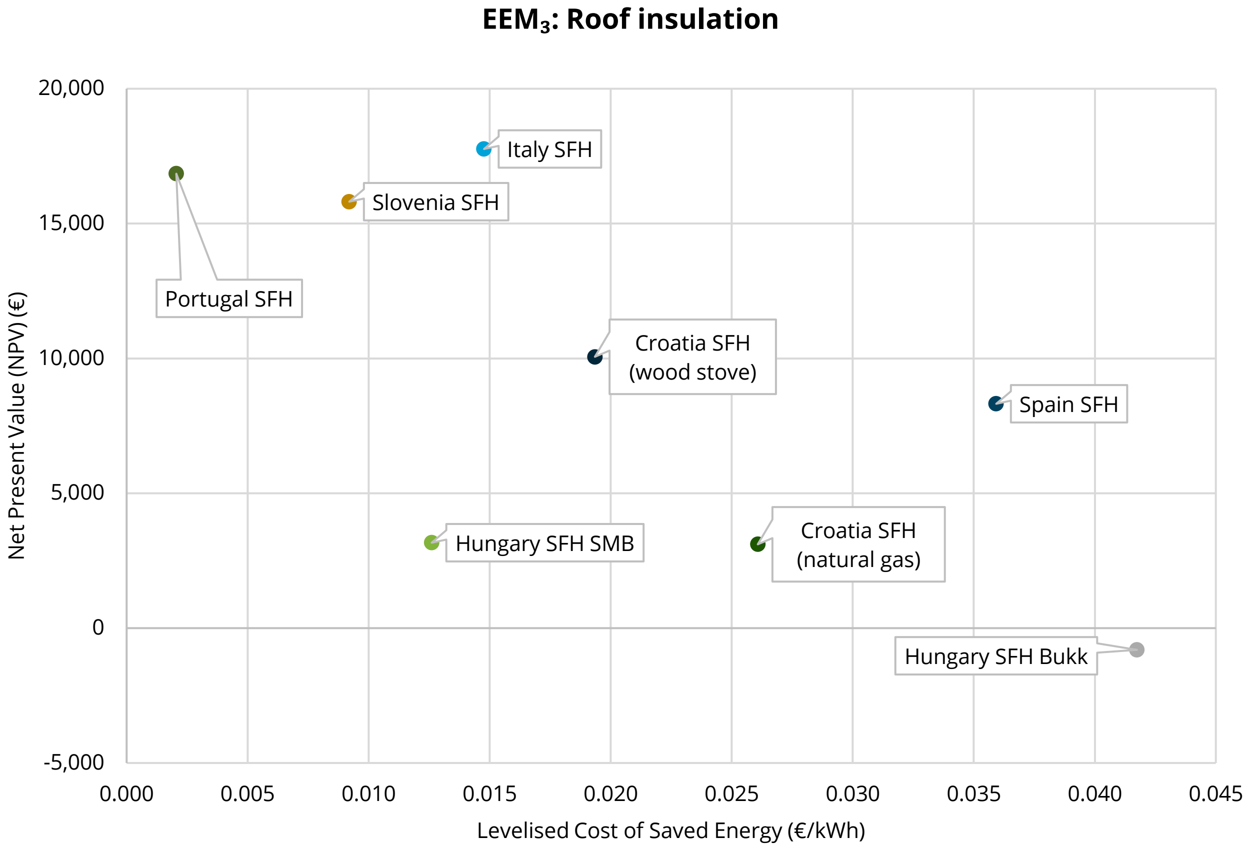

Figure 99. Cross-country comparison of the performance of EEM_3 in household profitability and cost-effectiveness.

Regarding the performance of EEM_3 in terms of household profitability (NPV) and cost-effectiveness (LCSE) combinations, the most preferable performance is observed in the SFH typology in Portugal, followed by the SFH typologies in Italy and Slovenia. On the other hand, the worst performance is observed in the SFH typology in Bükk (Hungary), where a negative NPV and the highest LCSE values are indicated, followed by the SFH typologies in Spain and Croatia, where combinations of lower NPV and higher LCSE values are identified.

7.2.4 Boiler upgrade - gas (EEM_4)

Figure 100 and **Figure 101** indicate the performance of EEM_4 (Boiler upgrade- gas) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

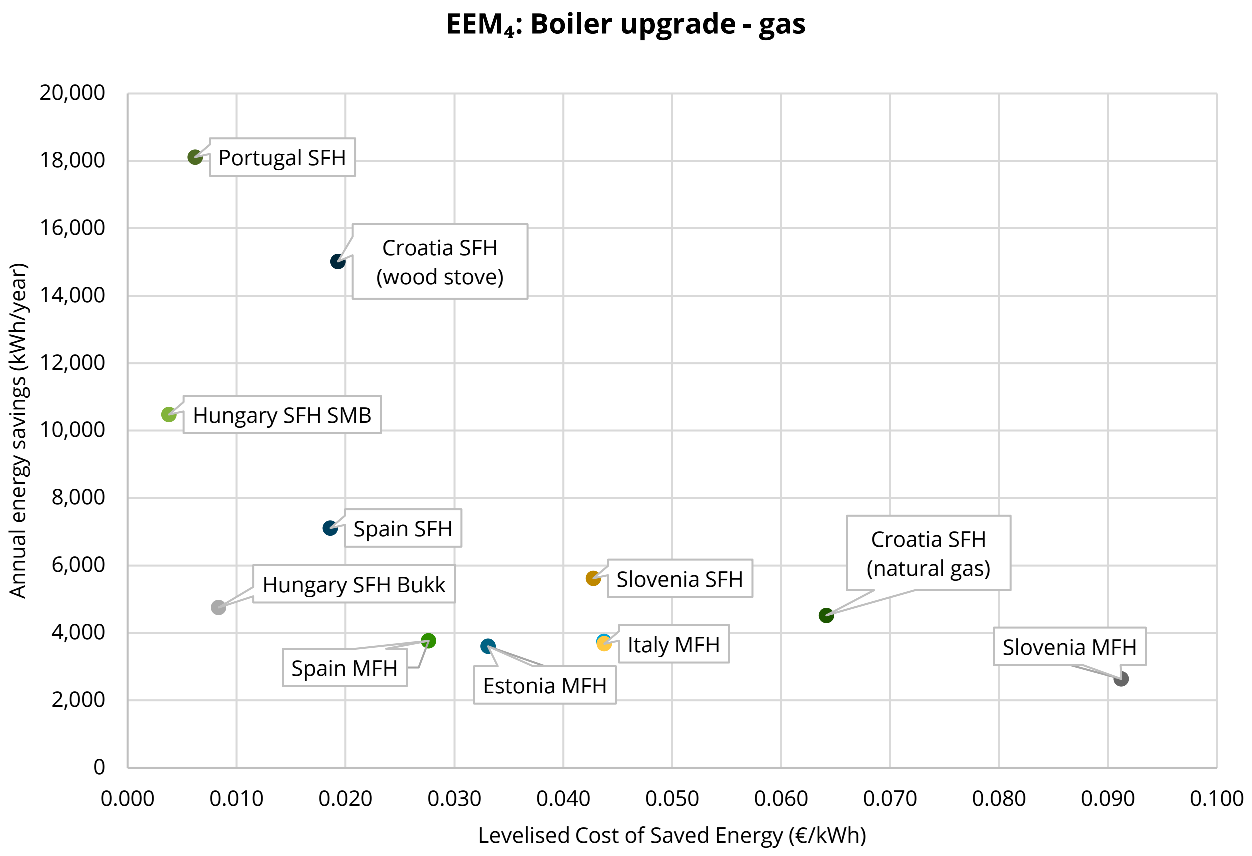

Figure 100. Cross-country comparison of the performance of EEM$_4$ in energy-saving potential and cost-effectiveness.

We observe that EEM$_4$ leads to beneficial combinations of energy-saving potential and cost-effectiveness in several pilot cases, with the slight exceptions of the MFH typology in Slovenia, the SFH typology (natural gas) in Croatia, and the MFH and SFH typologies in Italy and Slovenia, respectively. The most beneficial performance is indicated in the SFH typology in Portugal, followed by the SFH typologies in Croatia (wood stove), SMB (Hungary), Spain, and Bükk (Hungary).

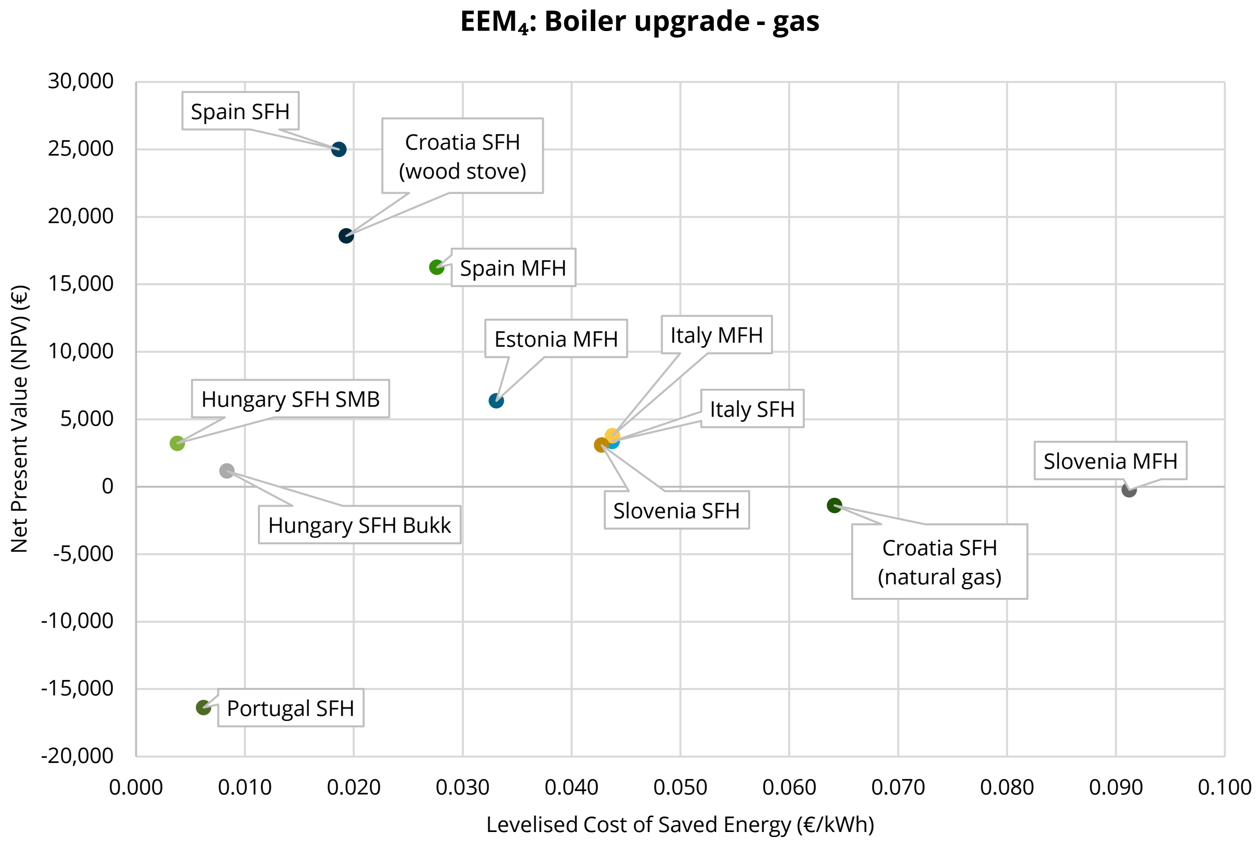

Figure 101. Cross-country comparison of the performance of EEM$_4$ in household profitability and cost-effectiveness.

Regarding the performance of EEM$_4$ in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the best performance is observed in the SFH typology in Spain and Croatia, followed by the MFH typologies in Spain and Estonia. Among the worst-performing cases is the SFH typology in Portugal, where the lowest NPV (negative) is identified. Negative NPV values with higher LCSE values are also identified in the MFH typology in Slovenia and the SFH typology (natural gas) in Croatia.

7.2.5 Boiler upgrade - biomass (EEM$_5$)

Figure 102 and **Figure 103** indicate the performance of EEM$_5$ (Boiler upgrade- biomass) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

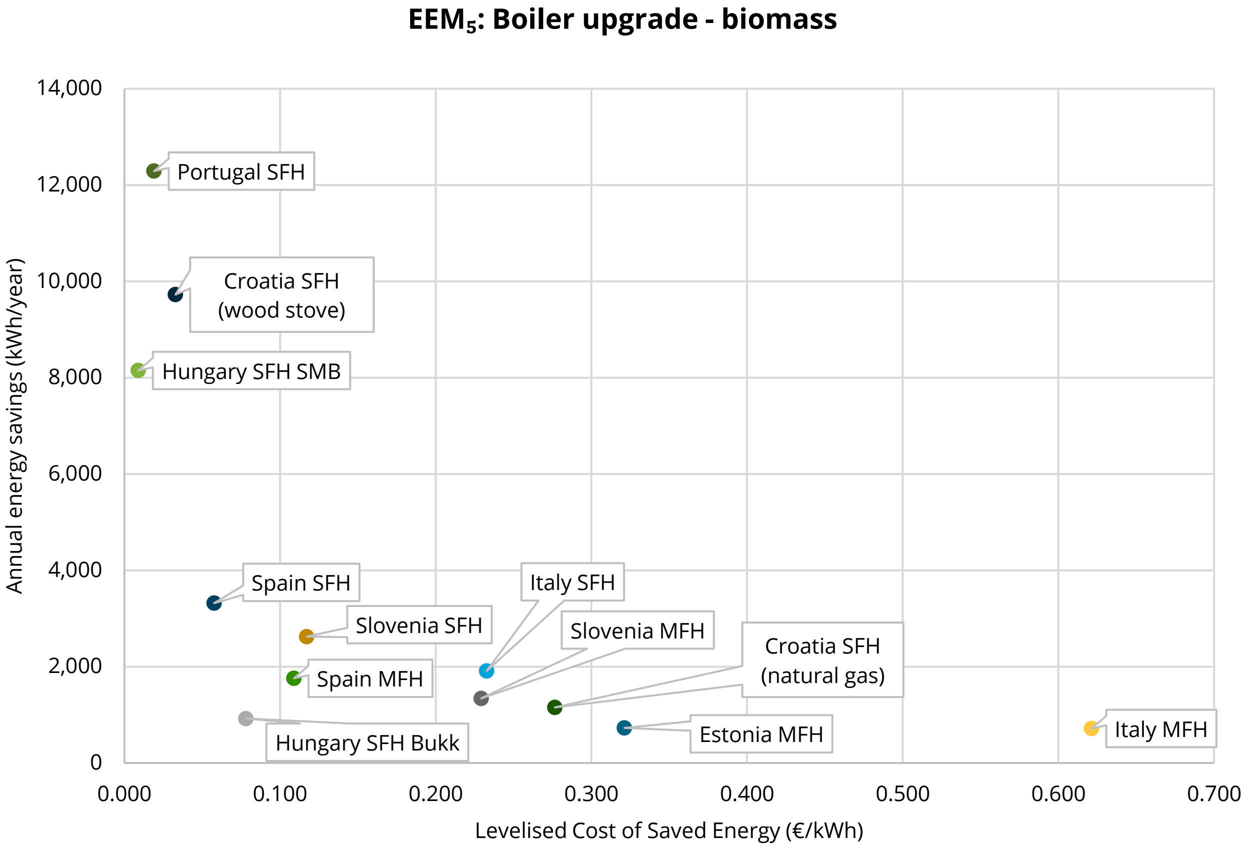

Figure 102. Cross-country comparison of the performance of EEM$_5$ in energy-saving potential and cost-effectiveness.

We observe that EEM$_5$ leads to beneficial combinations of energy-saving potential and cost-effectiveness in several pilot cases, with the major exception of the MFH typology in Italy, and the slight exception of the MFH typology in Estonia and the SFH typology in Croatia (natural gas) mostly due to its low performance in terms of energy savings. The most beneficial combinations are indicated in the SFH typology in Portugal, followed by the SFH typologies in Croatia (wood stove), SMB (Hungary), while good performance in terms of cost-effectiveness and lower in terms of energy savings is identified in the SFH typology in Slovenia, the MFH typology in Spain and the SFH typology in Bükk (Hungary).

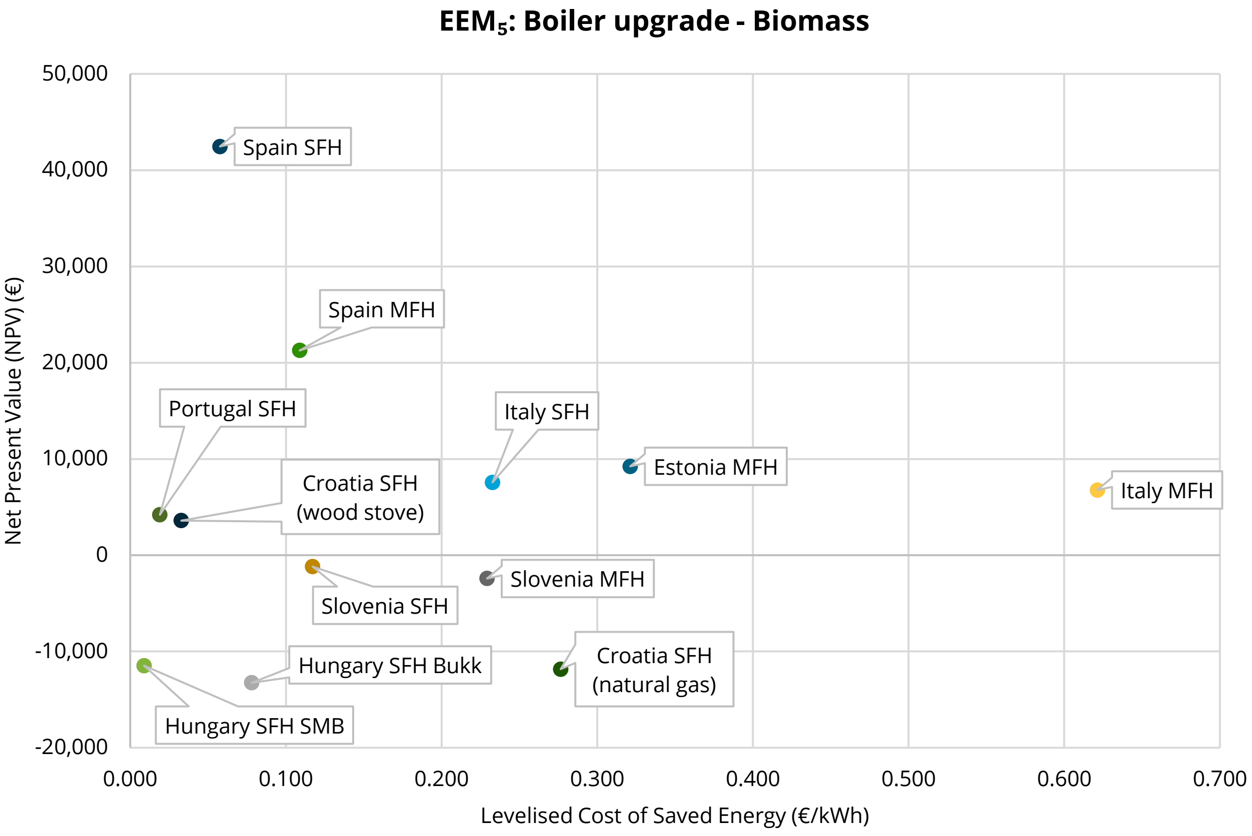

Figure 103. Cross-country comparison of the performance of EEM$_5$ in household profitability and cost-effectiveness.

In regard to the performance of EEM$_5$ in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the best performance is observed in the SFH and MFH typologies in Spain, followed by the SFH typologies in Portugal and Croatia (wood stove). The worst performance is observed in the MFH typology in Italy with lower NPV and higher LCSE values, while negative NPV values are also identified in both Hungarian and Slovenian typologies, and the SFH typology (natural gas) in Croatia.

7.2.6 Heat pump (EEM$_6$)

Figure 104 and **Figure 105** indicate the performance of EEM$_6$ (Heat pump) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

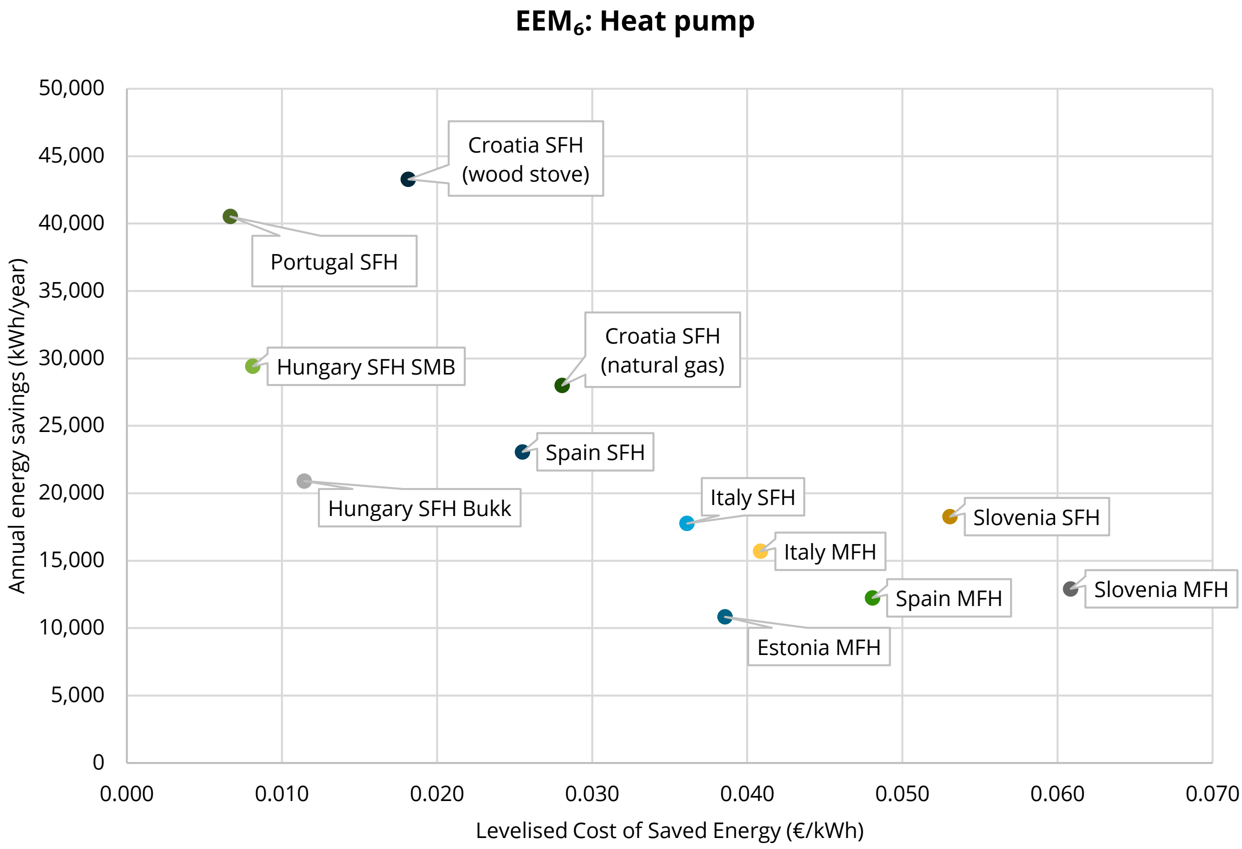

Figure 104. Cross-country comparison of the performance of EEM$_6$ in energy-saving potential and cost-effectiveness.

We observe that EEM$_6$ leads to beneficial combinations of energy-saving potential and cost-effectiveness in several pilot cases, with the slight exceptions of the MFH and SFH typologies in Slovenia and the MFH typologies in Spain and Italy. The most beneficial combinations are indicated in the SFH typologies in Portugal and Croatia (wood stove), followed by the SFH typologies in Hungary, Croatia, and Spain.

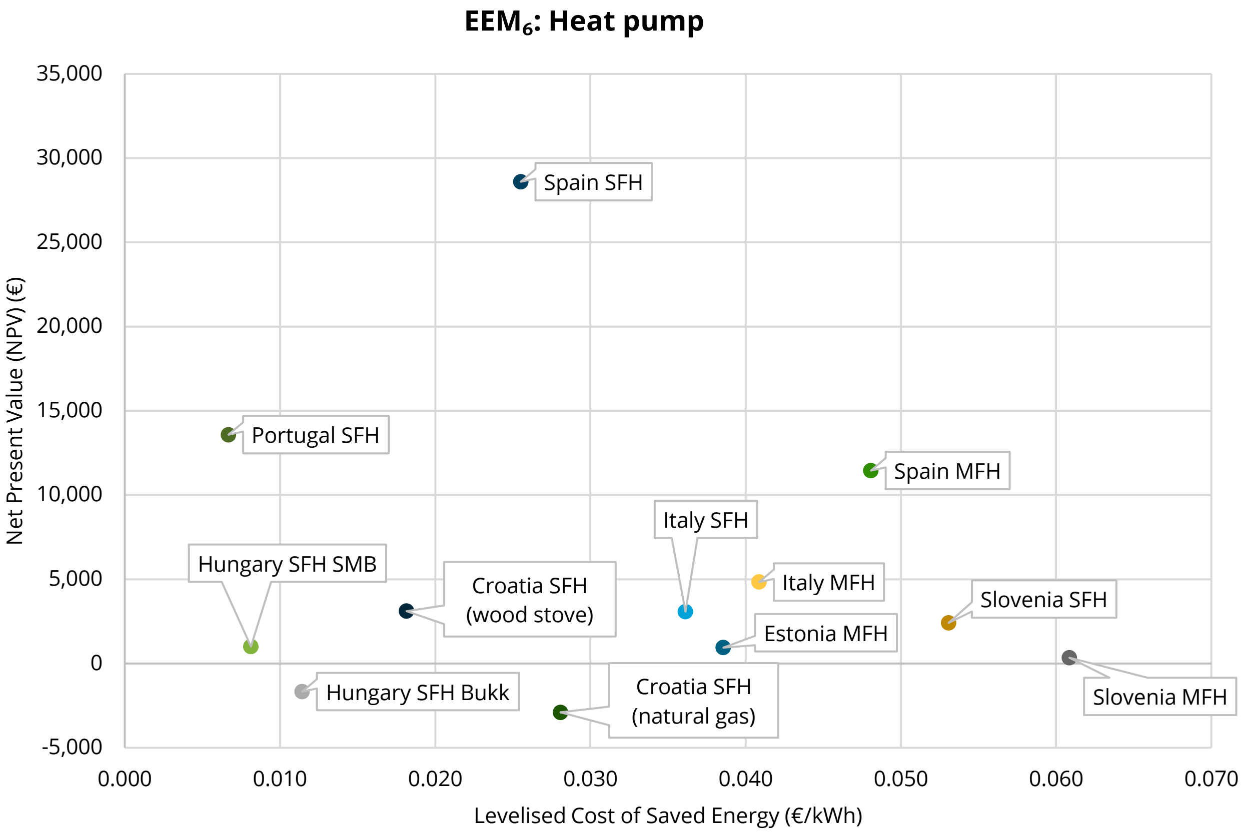

Figure 105. Cross-country comparison of the performance of EEM$_6$ in household profitability and cost-effectiveness.

Concerning the performance of EEM$_6$ in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the highest performance is observed in the SFH typologies in Spain and Portugal, followed by the SFH typologies in Croatia (wood stove) and SMB (Hungary). Worse ranking is observed in the MFH and SFH typologies in Slovenia with low NPV and high LCSE values, while negative NPV values are identified in the SFH typologies in Bükk (Hungary) and Croatia (natural gas).

7.2.7 Energy-efficient light bulbs (EEM$_7$)

Figure 106 and **Figure 107** indicate the performance of EEM$_7$ (Energy-efficient light bulbs) in terms of the combinations of energy-saving potential with cost-effectiveness (LCSE) and profitability (NPV) with cost-effectiveness (LCSE).

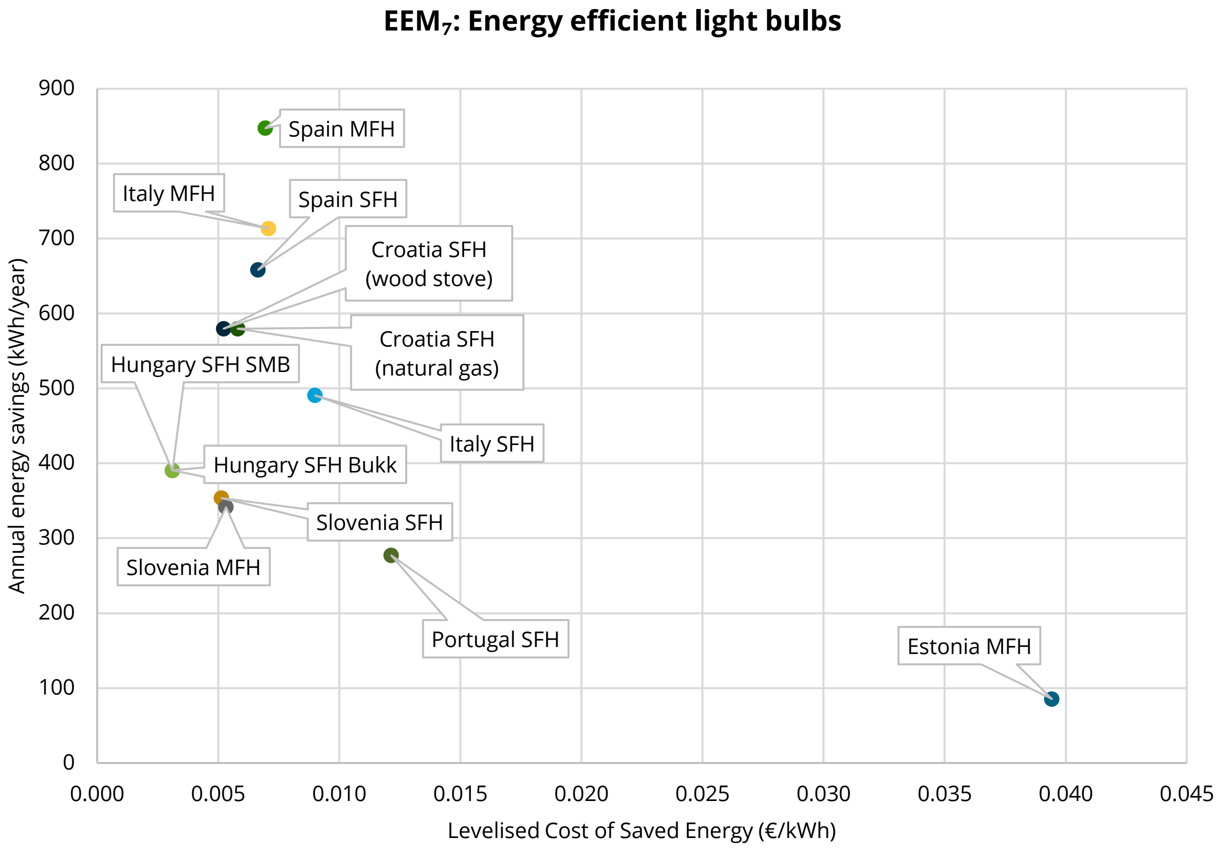

Figure 106. Cross-country comparison of the performance of EEM_7 in energy-saving potential and cost-effectiveness.

We observe that EEM_7 leads to beneficial combinations of energy-saving potential and cost-effectiveness in most cases, with the slight exception of the MFH typology in Estonia, where the lowest energy-saving potential and the highest LCSE are identified. The most beneficial combinations are indicated in the MFH typologies in Spain and Italy, followed by the SFH typologies in Spain, Croatia, Italy, and Hungary.

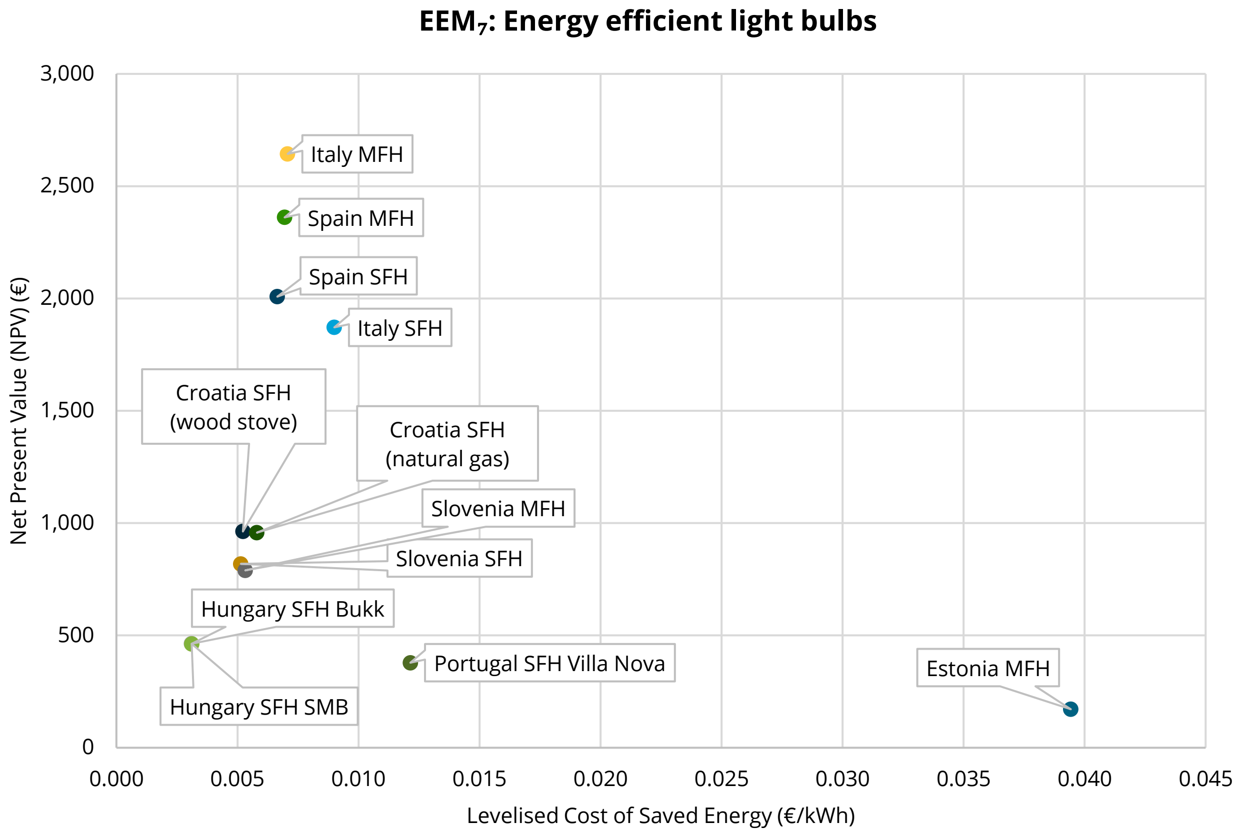

Figure 107. Cross-country comparison of the performance of EEM$_7$ in household profitability and cost-effectiveness.

Regarding the performance of EEM$_7$ in household profitability (NPV) and cost-effectiveness (LCSE) combinations, the highest performance is observed in the MFH typologies in Italy and Spain, followed by the SFH typologies in Spain, Italy, and Croatia. The worst ranking is observed in the MFH typology in Estonia where the lowest NPV and highest LCSE values are identified.

8. Conclusions, implications, and further research

While current efforts at both scientific and policy levels have focused on mapping and comprehending the driving forces, aspects and consequences of energy poverty, there are many gaps in knowledge and practice regarding energy poverty and energy efficiency in rural areas.

This situation is not merely coincidental, rather, it is influenced by various distinct characteristics inherent to rural areas that escalate the vulnerability of households to energy poverty. According to existing knowledge, rural households are more likely to be energy poor due to several unique factors that characterise them, such as the characteristics of the building stock, the more limited choice of energy sources, increased energy expenses, limited educational and labour capabilities, geographical remoteness, difficulties in renovation, etc. (Augère-Granier, 2017; Deng, 2012; M. Evans et al., 2014; McGookin et al., 2022; Shoemaker et al., 2018)

In this context, implementing energy efficiency policies to address energy poverty is not just a question of technical capacity, it is related to wider financial, social, geographical, and regulatory challenges, urging the need for tailor-made solutions specifically addressing the needs of rural households.

A useful approach to address the multidimensional challenges of energy poverty in rural areas and further support the implementation of energy efficiency policies to address energy poverty in these regions is the development of REERs. Their value in addressing specificities, like in the case of rural households, lies mainly in the fact that they can provide step-by-step guidance for the uptake of energy efficiency interventions, tailored to the unique characteristics and the needs of the households and regions of interest, while being able to be replicated in more cases.

The latter urges the need for rigorous scientific research that combines both qualitative and quantitative outcomes towards the development of REERs. This would facilitate better-informed decision-making and evidence-based policymaking that will ensure the effective design and implementation of energy efficiency policies for the alleviation of energy poverty in rural areas across the EU.

In that case, demand-side management modelling, which focuses on studying energy profiles, energy efficiency aspects, and the behavioural analysis of end-users, can provide critical insights into the effectiveness of various EEMs. This is particularly important for identifying measures that are most effective in alleviating energy poverty and can be included in the REERs as recommendations for those making use of them.

Detailed simulations and scenario-based analyses can enable the development of an assessment framework that supports the creation of REERs, and which will not only suggest technical improvements but also consider socioeconomic factors to ensure that measures are practical and sustainable for energy-poor households in the regions under study.

In this context, in this report, we contribute toward this direction by presenting simulation results from the DREEM model, which is applied to specific real-life EU pilots to determine the most suitable EEMs in each case, based on the energy-saving potential and the technoeconomic viability of each EEM under study.

Our working approach, coupling the strengths of energy system modelling with qualitative and semi-quantitative techniques, consisted of four (4) methodological steps guiding us right from the (**i**). updated framework of energy efficiency and energy poverty in rural areas, the (**ii**). stakeholders need assessment, and the (**iii**). RENOVERTY fieldwork (i.e., energy audits), as derived from the RENOVERTY report: "*Updating the energy poverty and energy efficiency framework in rural areas across the EU*"), to the application of the modelling assessment framework in real-life pilots, which allowed for the classification of potential EEMs based on their energy performance and technoeconomic viability.

Building upon the groundwork laid out in previous RENOVERTY activities and adhering to the overarching framework established by them, household typologies with the characteristics presented in **Section 4** were developed for all the RENOVERTY regions (**Table 118**). For these typologies, we evaluated a series of EEMs in terms of their energy-saving potential, environmental impact, cost-effectiveness, and profitability.

Table 118. The typologies developed across the different RENOVERTY pilot regions.

Pilot region	Typologies
Osona, Spain	SFH, MFH
Parma, Italy	SFH, MFH
Bükk, Hungary	SFH
SMB, Hungary	SFH
Sveta Nedelja and Žumberak, Croatia	SFH (wood stove), SFH (natural gas)
Tartu, Estonia	MFH
Zasavje, Slovenia	SFH, MFH
Coimbra, Portugal	SFH

The EEMs selected for each pilot are:

- **EEM_1 - Exterior wall insulation**: Insulating the main walls of the building under study from the outside, which commonly have solid walls with no cavities.
- **EEM_2 - Double-glazed windows**: Replacing single-glazing windows with energy-efficient glazing (double-glazed windows) to reduce heat loss.
- **EEM_3 - Roof insulation**: Insulated between and under the rafters of the roof itself, reducing the overall heat transfer coefficient by adding materials with low thermal conductivity (this measure applies only in the case of SFHs)
- **EEM_4 - Energy-efficient heating system** (*Boiler upgrade- gas*): In this case, the dwelling's outdated heating system is replaced by an efficient gas boiler with a higher efficiency ratio.
- **EEM_5 - Energy-efficient heating system** (*Boiler upgrade- biomass*): In this case, the dwelling's outdated heating system is replaced by an efficient biomass boiler with a higher efficiency ratio.
- **EEM_6 - Energy-efficient heating system** (*Heat pump*): In this case, the dwelling's outdated heating system is replaced by a heat pump with a higher efficiency ratio.
- **EEM_7 - Energy-efficient lighting**: In this case, the conventional tube lights and bulbs (fluorescent lamps) are replaced by high energy-efficiency ones (LED lamps).

Simulation results indicated that the energy-saving potential, the environmental impacts, the cost-effectiveness, and the profitability of the different EEMs differ across case studies. The energy-saving potential of the EEMs is highly affected by the baseline situation of the building stock and its existing heating systems, underscoring the critical role of baseline conditions in determining the effectiveness of interventions aimed at reducing energy consumption and environmental footprint. By targeting areas and cases with greater inefficiencies, policymakers and stakeholders can prioritise interventions that yield significant improvements in both energy efficiency and environmental sustainability.

The replacement of an existing heating system with a more efficient one, and specifically with heat pumps (EEM_6), is identified as the most cost-effective measure in most cases due to its high energy-saving potential and low LCSE values. The greatest value of annual energy savings achieved through EEM_6 is shown in the SFH typology in Sveta Nedelja and Žumberak in Croatia, which uses wood stove as a heating source in the baseline situation (43,280.4 kWh/year with an LCSE of 0.018€/kWh), followed by the SFH typology in Coimbra (40,521.4 kWh/year costing with an LCSE of 0.007€/kWh).

In terms of upgrades in the building envelope, EEM_3 (Roof insulation) is identified as the measure with the higher cost-effectiveness for the SFH typologies. The higher values are pointed out in the SFH typology in Coimbra, 23,155.0 kWh per year with an LCSE of 0.002€/kWh. For the MFH typologies, again EEM_6 proves to have a very good performance in terms of cost-effectiveness, like in the case of Parma with annual energy savings of 15,696.7kWh and LCSE of 0.041€/kWh.

On the contrary, window upgrades (EEM_2) are often identified as the least cost-effective measure due to their high costs and the relatively lower annual savings they typically yield. Nevertheless, they should not be discounted, especially if subsidies or incentives are/can be available for their implementation. Any reduction in energy demand contributes positively, particularly benefiting vulnerable groups who may struggle with high energy costs. Therefore, policies and decisions regarding energy efficiency improvements should consider not only economic factors but also social and environmental impacts, ensuring a balanced approach to sustainability and inclusivity.

Additionally, the cost effectiveness of EEM_4 (Boiler upgrade- gas) and EEM_5 (Boiler upgrade-biomass) varies significantly across different cases, primarily due to variations in investment costs and energy pricing across countries, making them vulnerable to future crises and changes in the energy landscape. For instance, in the SFH typology in Parma, EEM_4 and EEM_5 are less cost-effective with an LCSE of 0.044 €/kWh and 0.233 €/kWh, respectively, while in SMB (Hungary) they are more cost-effective, with LCSEs of 0.004 €/kWh and 0.009 €/kWh, respectively.

Beyond cost-effectiveness, our results underscore the necessity of subsidisation in most cases to achieve higher household profitability. This necessity is less pronounced in Osona, Spain, where all EEMs are profitable without any subsidy. Similarly, in Parma (Italy), and Sveta Nedelja and Žumberak (wood stove) in Croatia, all measures except EEM_2 are profitable without subsidies. This can be attributed to the regions' specific weather conditions, which moderate extreme temperature fluctuations, and the initial inefficient heating systems in the typologies under study (e.g., oil boiler, wood stove), which increases the household profitability from the implementation of EEMs.

On the other hand, the need for subsidies is particularly evident in Hungary for both typologies, mainly for EEM_1, EEM_2, EEM_5, and EEM_6, and mainly due to the lower price of natural gas in this context. Similar is the case in Zasavje (Slovenia), where the same need is indicated mainly for EEM_1 (at least 25%), EEM_2 (at least 75%), and EEM_5 (at least 50%) for the SFH typology, and mainly for EEM_2 (negative profitability at all subsidy levels), EEM_4 (at least 25%), and EEM_5 (negative profitability at all subsidy levels) for the MFH typology. In Sveta Nedelja and Žumberak SFH typology (gas boiler) in Croatia financial incentives are identified as crucial for all measures, except EEM_3 and EEM_7 (EEM_1, EEM_4, and EEM_6 require subsidisation of at least 50%, and EEM_2 and EEM_5 have negative profitability at all subsidy levels). Finally, in Coimbra financial incentives are necessary for EEM_1 and EEM_2 (at least 50%), and for EEM_4 (negative profitability at all subsidy levels).

Considering the above, our analysis indicates the rigorous need for policy transformations and improvements to address energy efficiency and energy poverty issues in rural areas.

Variations in the applicability and the decarbonisation impact of the different EEMs highlight the benefits and the consequent necessity for EU and national authorities to grant more funding for the needs of rural areas and offer strategies and plans that encourage regional and local development in a customised way, also to ensure targeted allocation and address the specific needs of vulnerable households.

To this direction, local and regional authorities can **benefit from the knowledge derived from this report on the very local specificities of the most vulnerable areas** under their responsibility. Additionally, they should be **encouraged to conduct more similar actions to enhance research activities within their contexts, aimed at alleviating rural energy poverty**. This involves collecting **accurate data to identify energy-poor households, facilitating data-driven interventions that effectively address the issue**. With this information at hand, **they can act as intermediaries, recording the unique challenges faced by rural areas**, including stakeholders and vulnerable communities in the energy efficiency policy discussion. They can also **communicate specific inquiries and support national and EU authorities in developing and disseminating targeted policy measures and financial grants to rural areas**.

Another finding of our work concerns the impact of the high investment costs and energy prices, especially in the profitability of the EEMs with high energy-saving potential and lower LCSE values.

High investment costs, especially in the case of the most effective interventions, like heat pumps, and higher electricity prices lead to less attractive investments for vulnerable households, despite their higher energy-saving potential. In this regard, financial support, timing and prioritisation of actions and support emerge as a central theme.

To properly overcome this hindrance, policymakers could examine the opportunities of promoting and expanding existing funding mechanisms (where applicable), developing new funding mechanisms and financial support, and providing incentives like subsidies and tax reductions that reduce investment costs for the case of vulnerable households, while encouraging them to overcome their reluctance to implement such EEMs and make relevant projects feasible and sustainable in rural settings by offering technical and administrative support.

Regarding the impact of energy prices, EU and national authorities could support rural energy-poor households by providing incentives for the use of environmentally friendly energy sources, such as renewable electricity, rather than fossil fuels. This is particularly relevant in countries like Hungary, where the price of natural gas is significantly lower than electricity.

Lower fossil fuel prices may discourage energy-poor households from adopting EEMs, as the immediate costs are lower. However, this situation is even more important in view of the establishment of the parallel Emissions Trading System in the building sector and the high vulnerability to external events, as demonstrated by recent energy crises, which can lead to increased energy burdens, especially for the most vulnerable. Additionally, reliance on inefficient technologies perpetuates inadequate energy usage, hindering progress towards greater energy efficiency and sustainability.

Overall, our work seeks to serve as a basis to initiate discussions aimed at facilitating policy improvements that effectively address the needs of energy-poor households in rural contexts. Our analysis includes findings and recommendations, which if considered could support stakeholders and end-users to recognise the particularities of rural areas when it comes to the implementation of EEMs and support policymakers in the effective design and implementation of energy efficiency policies to address energy poverty in rural contexts.

The primary limitation of this work concerns the representativeness of the households studied. While our current level of representativeness is good compared to the existing understudied situation (more than 85 audits conducted in the pilot areas), there remains a need for additional fieldwork and data acquisition to increase the sample size, develop more representative typologies, and, thus, enhance the accuracy and generalisability of our findings.

Therefore, future research should focus on conducting more detailed analyses of energy efficiency interventions in rural areas with increased resources and data acquisition. The varying results identified across the different EU countries highlight the need for targeted attention and research to more regions with specific characteristics, such as mountainous areas, islands, touristic regions, and just transition areas, to ensure a green and fair energy transition for all.

Additionally, this approach should be expanded beyond the residential sector to include micro-enterprises and other sectors with unique characteristics that are currently understudied. This comprehensive strategy will help ensure that EEMs are effectively implemented across all relevant sectors, addressing the specific needs of the most vulnerable members of diverse communities.

Acknowledgements

This work has received funding from the LIFE programme funds (Grant agreement 101077272, RENOVERTY project). We would also like to thank the stakeholders for taking the time to participate in the project's field work activities and the project's partners for the conduction of the energy audits. Specifically, we would like to acknowledge ECOSERVEIS for the audits organised in the rural region of Osona in Spain, AISFOR for the rural region of Parma in Italy, REFLEX for the rural regions of Somló-Marcalmente-Bakonyalja and Bükk-Mak in Hungary, REGEA for the rural regions of Sveta Nedelja and Žumberak in Croatia, TREA for the rural region of Tartu in Estonia, FOCUS for the rural region of Zasavje in Slovenia and the University of Coimbra- ISR for the rural region of Coimbra in Portugal. The authors would also like to acknowledge the support from the European Commission (EC). The content of the report is the sole responsibility of its authors and does not necessarily reflect the views of the EC.

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Co-funded by the European Union under project ID 101077272. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.`