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	EASI ZERo **GA n°101091531**
Deliverable	**ENVELOPE MATERIAL SYSTEM WITH LOW IMPACT FOR ZERO ENERGY RENOVATION AND CONSTRUCTION**

Deliverable ID	**D2.3**
Deliverable name	**Product design baseline report**
Deliverable description	Based on the product requirement inputs database and national regulations this product requirements baseline will be obtained. Certain product characteristics will also have to fulfil requirements related to whole building performance. This deliverable will support the Product Requirements Tool to assess products' performance at building level (task 2.3). It will incorporate description of relevant reference buildings or building stock segments to analyse how specific insulation products will perform.

WP	2	Specification and validation of products requirements
Task	2.3	Product design baseline and Product Requirements Tool

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Glossary

CO_2	-	Carbon dioxide
EZ0	-	EasiZero
GA	-	Grant Agreement
WP	-	Work Package
KPI	-	Key Performance Indicator
RES	-	Renewable Energy Sources
GHG	-	Green House Gas

1. Objectives and development process

1.1 *Objective of the report*

Objectives of the product design baseline report are:

Objective 1. Explain the Product Requirement Baseline

The product requirement baseline supports the Product Requirement Tool (hereafter referred to as 'the tool') in assessing performance of building envelope interventions at building level and providing inputs for later definition of EZ0 product requirements.

The product requirement baseline describes the key targets that EZ0 products must achieve based on project objectives described in the grant agreement. The focus of the product requirement baseline is on product characteristics that must be fulfilled at the level of building stock. This baseline therefore concerns KPIs 1, 2, 12, 13, and 18, as well as energy and CO_2 performance targets. The product requirement baseline in this report describes how these performance targets are operationalized to enable scenario analysis on building level in the product requirement tool.

Objective 2. Explain the methodology behind the Product Requirements Tool

This baseline report describes how the tool examines if and to what extent, building envelope interventions, when applied at building level, reaches one or more relevant KPIs of performance targets. The product requirement tool (D2.4) is based on several inputs, including the ISO 52016 standard and the KPIs in the Description of Work of the project. Moreover, a description of relevant reference buildings and building stock segments obtained from the Hotmaps project is provided. This baseline report also clearly and transparently describes the assumptions underlying the methodology of the product requirement tool.

Objective 3. Provide and explain the results of the tool

Results obtained from the tool are explained in the closing chapter of the report. These results will be used as inputs for the task 2.4 defining final product requirements in D2.5.

1.2 *Impact of the results*

During several meetings facilitated by BPIE, the tool content and method has been validated with project partners and external experts. Internal feedback shows that the tool might prove useful insights for work done in WP4 (construction product development and assembly). The tool is also foreseen to help validating the product design. This work is foreseen to start late 2024 (M24).
Feedback of EZ0 partners has been integrated into the tool where realistic and feasible.

1.3 *Feedback and validation of tool methodology*

A validation workshop has been carried out on 24 November 2023, discussing the assumptions of the tool, and collecting feedback from partners and external stakeholders. This workshop was publicized on social media and shared with the EZ0 stakeholder database.

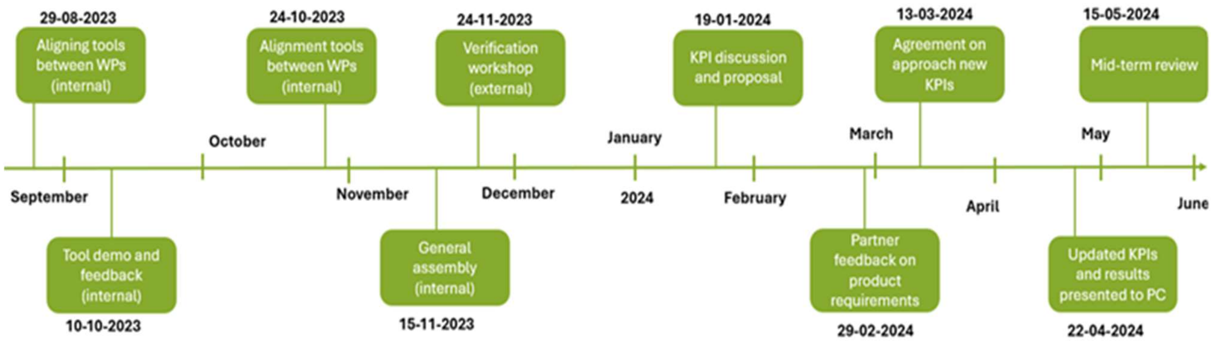


Figure 1: Internal and external feedback and validation meetings

During the workshop, consistent feedback has been retrieved from consortium partners to align the product requirement tool with other WPs and improve the method. Following the feedback, the assumptions of the product requirement tool were refined.

Secondly, the initial results of the tool confirmed that KPIs 1, 2, and 13 are too ambitious to be achieved by insulation materials only. These KPIs will be verified with use cases in WP6 where the combined impact of various renovation measures, including but not limited to insulation, will be assessed. These two statements indicated the need for an additional set of energy and CO_2 performance targets for defining product requirements in WP2. In conclusion these targets support achieving the project objectives, similar to the KPIs that are verified in other WPs (WP5, WP6, WP7), and not replacing the KPIs.

These additional targets include:

- Energy performance target 1: Marginal savings in final energy consumption <3%, achieved at building stock level,
- Energy performance target 2: Marginal reduction in net zero energy <3% for single family houses with PV, achieved at building stock level, and
- CO_2 performance target: Marginal reduction in CO_2 emissions <3%, achieved at building stock level.
- Payback time performance target: simple payback period of 12 years

Timeline of changes explained above is shown in Figure 1.

2. Product requirements and project objectives

The purpose of product requirements is to guide design and development of EZ0 products and make sure that, once produced, EZ0 products achieve project objectives. There are 8 project objectives defined with 19 key performance indicators.

Project objectives are:

1. Inclusive and versatile toolset towards efficient and easy renovation for buildings,
2. Durable performance gain for thermal insulation,
3. Low embodied energy and CO_2 of EASI ZERo bio-based components,
4. Easy, fast and reliable installation of panels, accessories and finishing materials,

5. Contribution to circular economy via recycling and material resources savings,
6. Sustainable material system demonstrated in zero energy buildings renovation,
7. Conformity to regulation and standards (fire, acoustics, pollutants, IAQ), and
8. Payback time through affordable material system and installation processes.

Key performance indicators that correspond to project objectives can be found in Table 1.

Table 1: Project objectives and their KPIs

Objective	KPI	KPI description and target values
Objective 1 - Inclusive and versatile toolset towards efficient and easy renovation for buildings	KPI 1	Final energy consumption < 50 kWh/m^2/year
	KPI 2	Carbon emission < 4 kgCO_2/m^2/year
Objective 2 - Durable performance gain for thermal insulation	KPI 3	Gain in thermal performance, +20%
Objective 3 - Low embodied energy and CO_2 of EASI ZERo bio-based components	KPI 4	Embodied energy relative reduction, -30%, compared to market available products with LCA analysis
	KPI 5	CO_2 emissions savings of opaque panels, -30% (panels), compared to a similar standard insulation product (mineral wool), CO_2 emissions savings of opaque panels, -60% (accessories), compared to actually available similar products in terms of performance
	KPI 6	CO_2 savings of window frames, -35%, compared to polymer frame with no bio-based products
Objective 4 - Easy, fast and reliable installation of panels, accessories and finishing materials	KPI 7	Cost reduction of installed material, -15%, cost analysis of components production, including logistics
	KPI 8	Installation worktime, -30%
	KPI 9	Drying time of plaster 20% faster, drying time for a usual thickness range
Objective 5 - Contribution to circular economy via recycling and material resources savings	KPI 10	Design for renovation allowing re-use >80%
Objective 6 – Sustainable material system demonstrated in zero energy buildings renovation	KPI 11	3 use case evaluation completed including initial performance evaluation, renovation development with EASI ZERo design methodology, performance simulation with full material system after renovation, financial evaluation
	KPI 12	Net energy use reduction of 5% (absolute minimum)
	KPI 13	Net zero energy for single family houses with PV < 35 kWh/m^2/year (45 kWh/m^2/year for Nordic climate zone
Objective 7 - Conformity to regulation and standards (fire, acoustics, pollutants, IAQ)	KPI 14	Pollutants and particles matter generation of indoor paint, plasters and panels < 25µg/m3 Particles up to 2.5µm, < 50µg/m3 Particles up to 10µm, < 2µg/m3 VOC measurements
	KPI 15	VOC neutralization efficiency 60%

	KPI 16	Fire resistance of materials A2, for bio PUR, coated mycelium, wood fibre panels, paint
	KPI 17	Acoustic performance Rw 40dB, measured according to standard on mycelium panels
Objective 8 - Low Short payback time through affordable material system and installation processes	KPI 18	Payback time, <7 years
	KPI 19	Cost to reach R=1 m²K/W = 0.5 EUR/m², for a 30 mm thickness

Product requirements are defined as product properties necessary for reaching one or more project objectives. The EZ0 products, along with their specific requirements and the steps required to meet these requirements, are comprehensively explained in the Final list of product requirements report (D2.5).

The Product Requirements Tool and this report assess post-renovation performance of residential buildings and residential building stocks in project countries. The report therefore analyses how KPIs 1, 2, 12, 13, and 18, that require specific building/building stock performance (energy, carbon and economic performance), can be used for defining product requirements. The report also presents results of such analysis and explains how they will be used for product requirement definition in the Final list of product requirements report (D2.5).

Examples of building or building stock performance include energy consumption or CO_2 emission of the building when a renovation measure is applied to it. On the other hand, performances that are not building dependent, such as embodied CO_2 emissions or drying time of certain construction product components (e.g., plasters) are therefore not addressed by the tool.

3. Scope of the tool

There are several results that will be obtained from the tool:

- Thermal resistance, i.e., R-value (m^2K/W) of additional insulation needed to reach specific energy and carbon performance targets when the insulation is added to existing:
  - Walls only,
  - Ground floors, walls, and roofs together,
- Thermal resistance, i.e., R-value (m^2K/W) of window frames[4] needed to reach specific energy and carbon performance targets when these window frames replace existing window frames,
- Product selling price (EUR/m^2) of additional insulation needed to reach specific payback period (economic performance), when the insulation is added to existing:
  - Walls only,
  - Ground floors, walls, and roofs together,

[4] When analysing window frames, change in glazing was not considered. It was assumed that new windows will have the same glazing as the old ones.

- Product selling price (EUR/m^2) of window frames needed to reach specific payback period (economic performance), when these window frames replace existing window frames.

The results and grouping of affected building envelope elements are selected to fully match relevant EZ0 products (analysed in EZ0 Final list of product requirements (D2.5)).

Product price is provided as one of the tool results because it simultaneously satisfies two criteria:

- Payback period defined in the KPI 18 is the payback perceived by a homeowner who invests in building renovation. The product price is an input for defining the homeowner's investment and the resulting payback period.
- A product requirement relevant for the manufacturer is the cost they face when making one unit of the product. Once available, product price can be relatively easily converted into production cost to be used by the manufacturers.

An important assumption behind the tool is that construction products are added to the existing building elements instead of replacing them. This is because the aim of the project is to develop solutions that mostly add to building parts instead of replacing them. For practical reasons, the only exception is replacement of the existing window frames with window frames developed within the project[5].

4. Methodology of the product requirement tool

The main components of the tool are visualised in Figure 2:

- External weather data for covered countries,
- Reference buildings obtained from the Hotmaps database and used to describe relevant building stock segments,
- Input from manufacturers on the application of products,
- Assessment of annual building energy needs for heating and cooling, based on ISO 52016 calculation procedure.

[5] Improvements in existing windows or window frames typically include minor interventions, such as weatherstripping, that are not considered in EZ0 project.

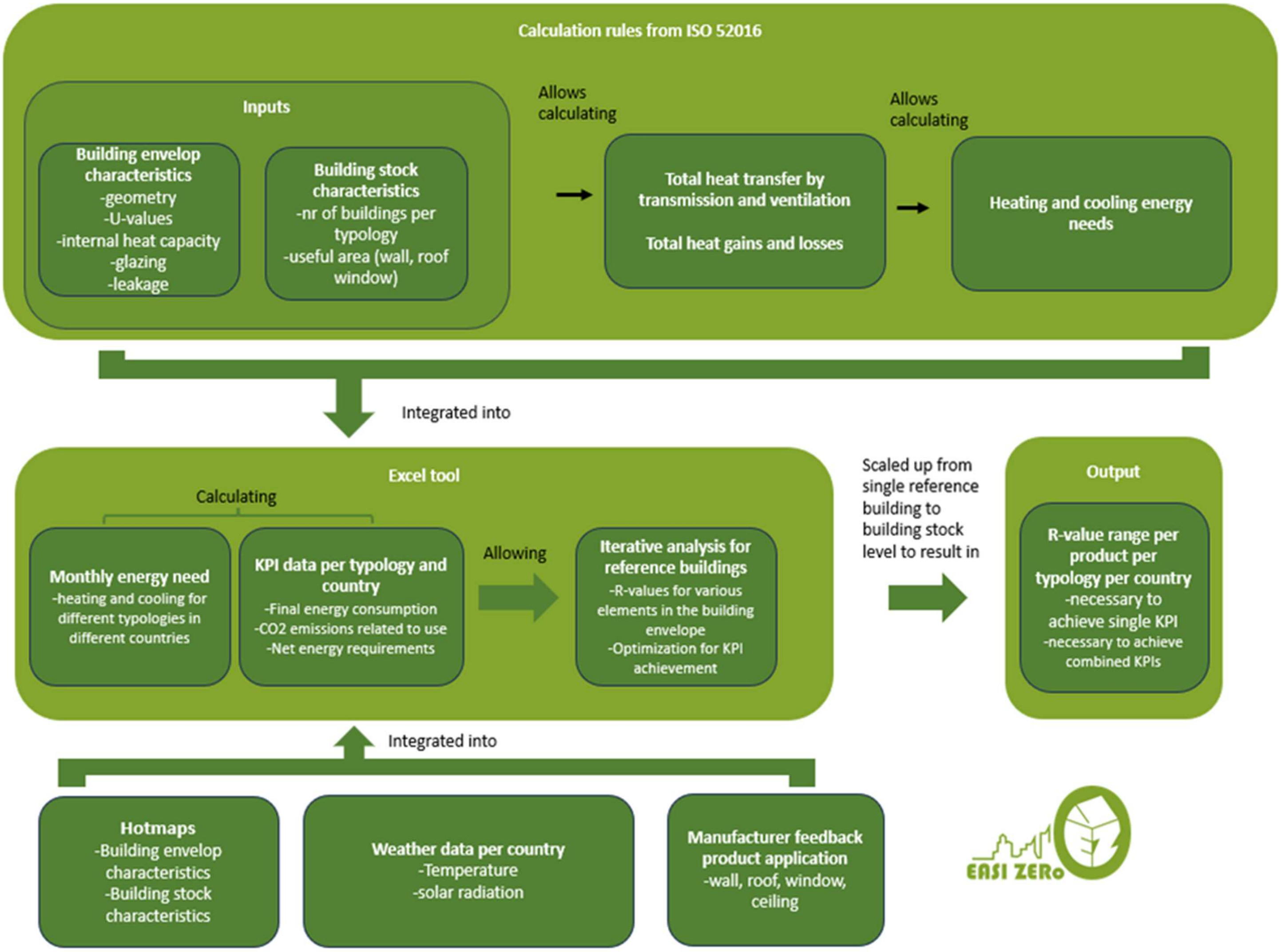


Figure 2: Methodological framework of the tool

Main components of the tool are described below.

4.1 *Weather data for selected geographies*

Weather data used in the tool related to solar irradiance (W/m^2), wind speed (m/s), and outdoor air temperature (°C). National averages for solar irradiance (south vertical, west vertical, east vertical, and north vertical and horizontal), wind speed, and temperature are obtained for each selected geography on a monthly basis [6].

[6] Solar irradiance values are obtained from the Solar Electricity Handbook 2019. See : http://www.solarelectricityhandbook.com/solar-irradiance.html. Values for wind are obtained from the Weather and Climate Information platform

4.2 *Reference building data from Hotmaps*

The tool will test the performance of different products at the building level. For this purpose, reference buildings and their respective building stock segments are defined.

Reference building data is obtained from the Hotmaps[7] open data repository for EU27 residential building stock.[8] Hotmaps database provides a broad range of data ranging from local, regional to national levels. The data is generated for different building uses, including the residential sector, which is the focus of the EasiZero project.

4.2.1.1 Countries covered by the tool

Reference buildings reflect building stocks and markets for insulation products in project target regions and 3 use case countries[9]. These countries are (also visualized in Figure 3):

- Germany
- Italy
- France
- Spain
- Poland
- Norway, and
- Denmark.

Figure 3: Countries covered in the tool

4.2.1.2 Building uses

The tool covers only residential buildings of the countries previously listed. This implies that product requirements are based on if and how project objectives are reached within residential segments of national building stocks. There are two main reasons for focusing on residential buildings only:

- Residential buildings make much larger share of national building stocks, and

[7] Hotmaps is a Horizon 2020 funded project providing the open-source mapping and planning tool for heating and cooling at EU level.
[8] https://wiki.hotmaps.eu/en/Hotmaps-open-data-repositories#building-stock_eu-building-stock
[9] These countries are included in the product requirements input database (covered in task 2.2).

- Reference buildings are rarely provided for non-residential buildings while residential ones are well covered with relevant reference building data.

In residential building stocks, single family houses[10] cover a dominant share of the markets in Denmark, France, Germany, Italy, Spain, and Sweden (Norway). At the same time, multi-family houses are dominant in Poland. This is explained in Figure 4 below.

Throughout the rest of the document, referring to building stock implies referring to residential building stock only.

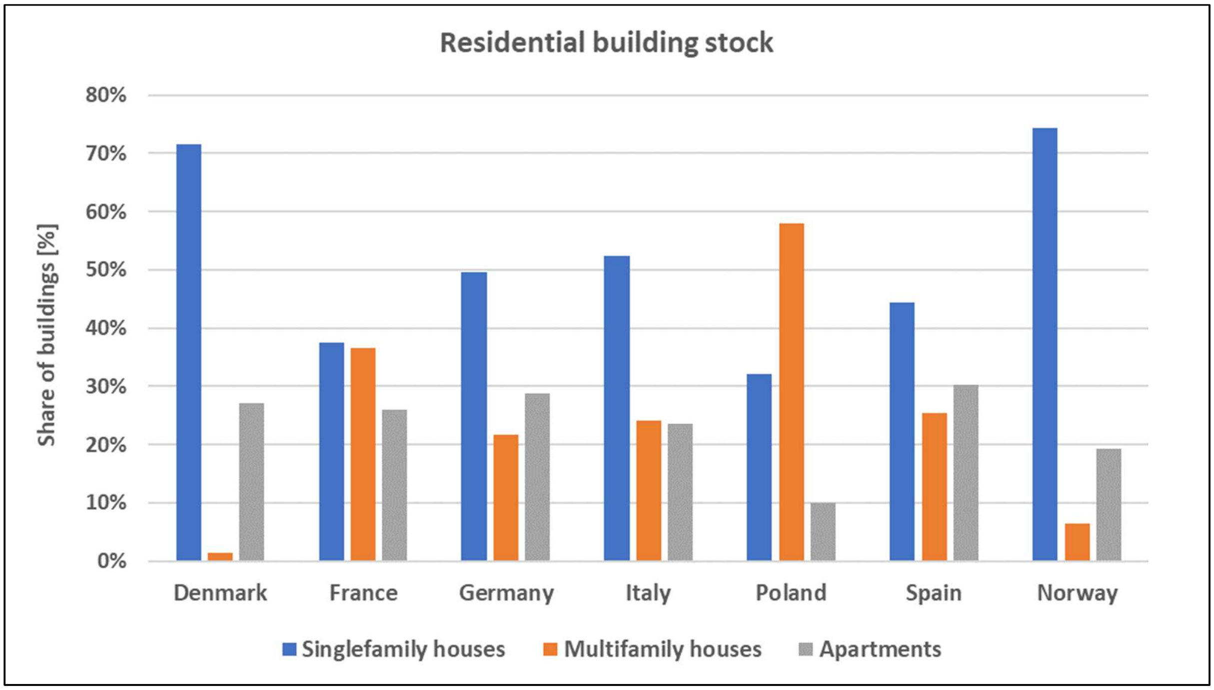


Figure 4: Share of the residential buildings used in the tool

4.2.1.3 Calibration of the tool

Prior to its use, the tool was calibrated against national statistics on final energy consumption.

The calibration started with calculating final energy consumption of each existing reference building (i.e., before renovation). After multiplying these results with total floor area covered by each reference building, total final energy consumption of the existing building stock was obtained. Results obtained in this way were compared with the same values provided by Eurostat, which provided corrections in number of, and total useful floor area covered by reference buildings.

Number and area of reference buildings in each country is shown in Figure 5 where each bar in a graph corresponds to one reference building. Final energy consumption of each reference building and the floor area it covers are shown on the horizontal and vertical axis, respectively.

[10] Including terraced houses.

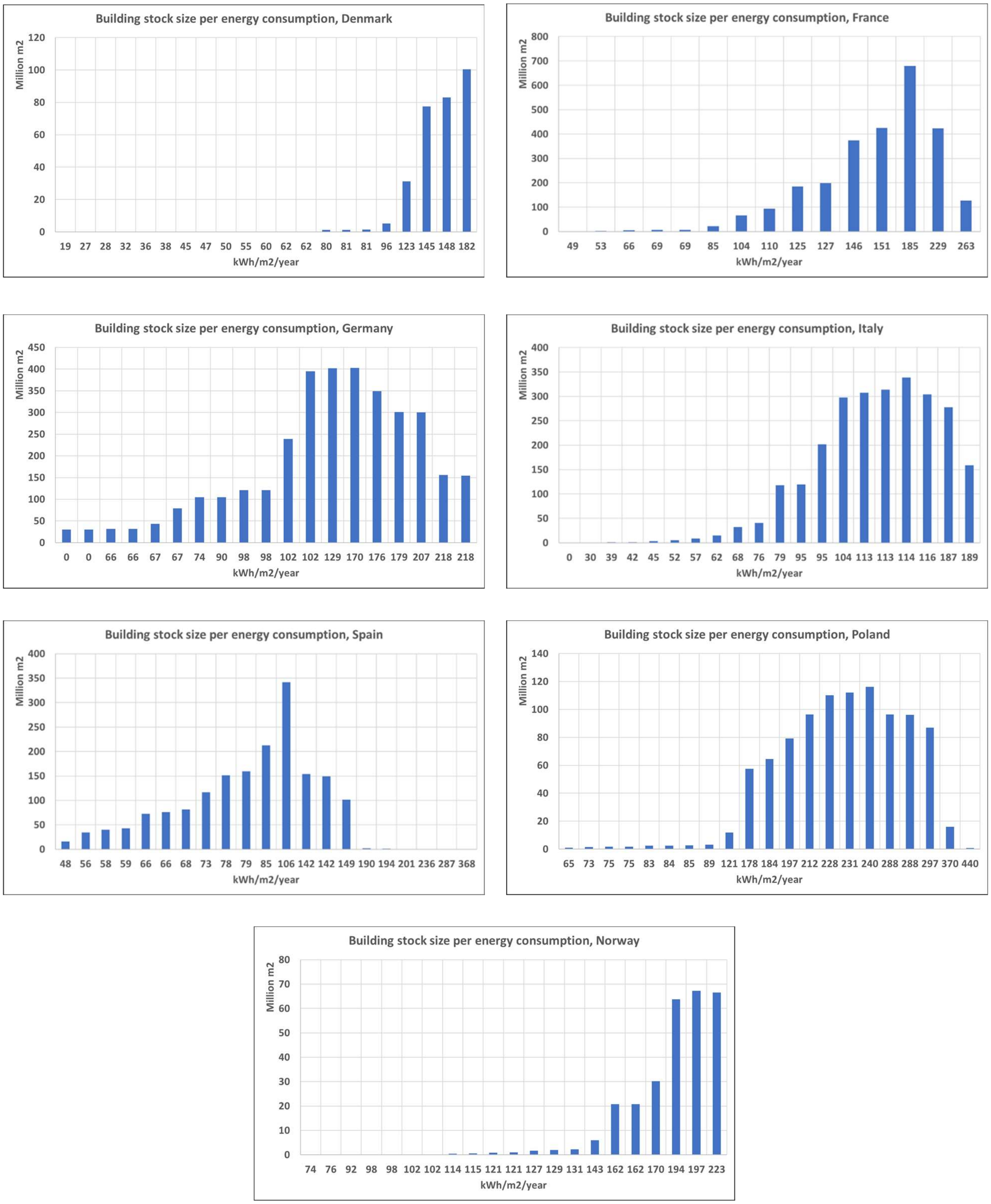


Figure 5: Distribution of reference buildings within each national building stock

4.2.1.4 Reference buildings characteristics

This section explains the characteristics of reference buildings used to cover the building segments listed above. Among other, the Hotmaps database provided data visualized in Figure 6 and Figure 7.

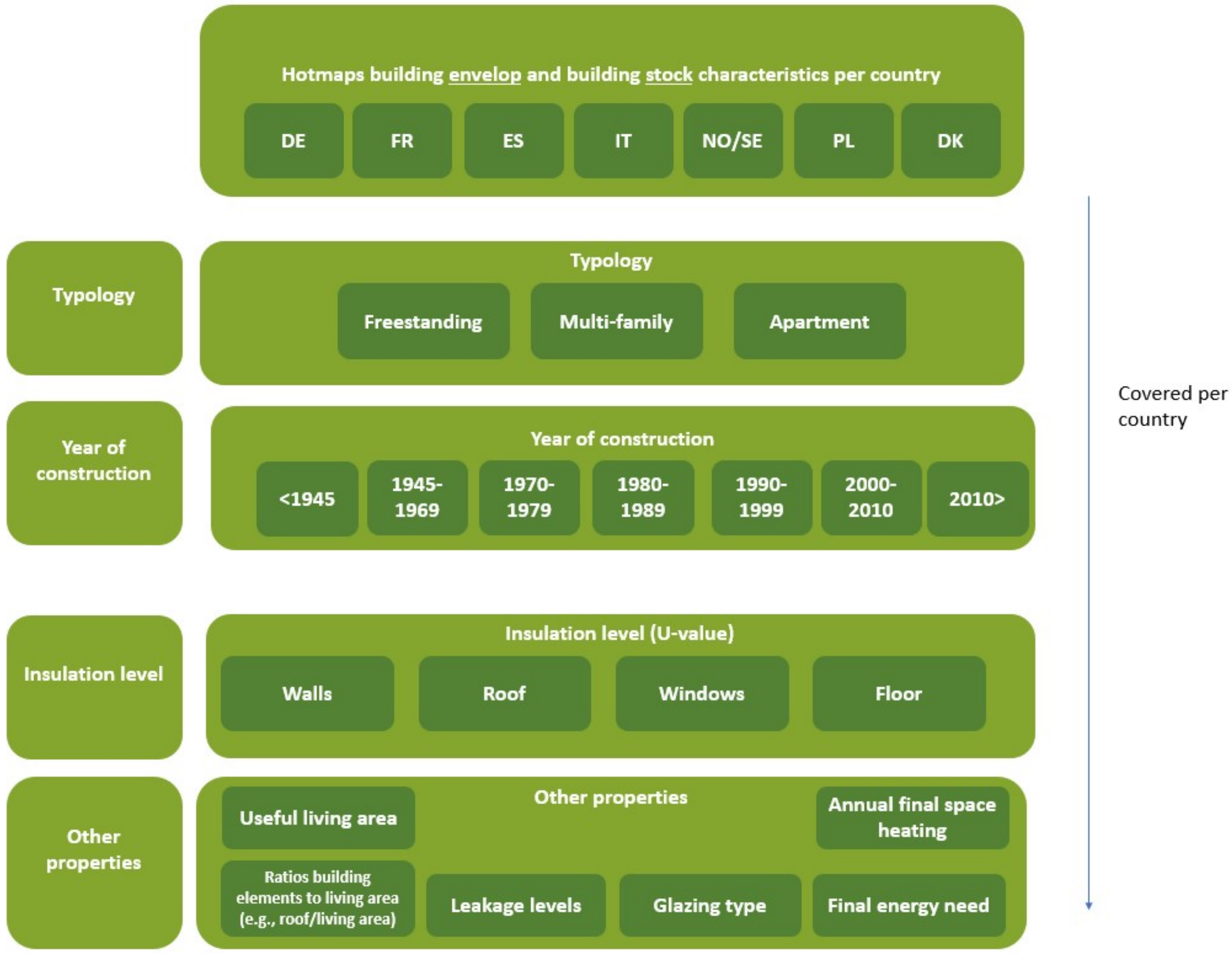
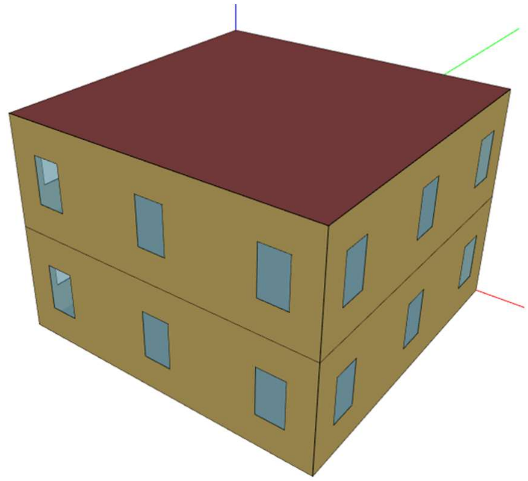


Figure 6: Scope reference building characteristics used in tool



roof area per building (m²)	wall area per building (m²)	windows area per building (m²)	basement area per building (m²)	base side (m)
167.31	209.64	44.35	137.07	11.71
roof u value	**wall u value**	**windows u value**	**floor u value**	**leakage level**
0.83	1.19	2.73	0.97	Average

Figure 7: Exemplary reference building from Hotmaps

4.3 *Energy calculations based on ISO 52016*

The energy calculations are fundamentally based on the quasi-steady-state approach as outlined in the ISO 52016-1:2017 standard. This standard represents an evolved and modified version of the previously established ISO 13790, which has since been withdrawn.

ISO 52016 provides a methodology for the calculation of the energy need for heating and cooling, internal temperatures, and sensible and latent heat loads. It's designed to assess the overall energy performance of buildings and is suitable for different climates, building types, and systems. The standard takes into account various factors such as building insulation, air tightness, windows, and shading, as well as building occupancy, equipment, and lighting.

The quasi-steady-state approach in ISO 52016 provides a simplified method for estimating the monthly heating and cooling energy needs of buildings. This approach involves monthly calculations. This means the energy needs for heating and cooling are estimated on a monthly basis, taking into account average or typical conditions for each month rather than hourly or daily variations. This method is particularly useful for general planning and compliance checks where detailed hourly simulations are not required.

The first key inputs of the model, focusing on building envelope characteristics and building stock characteristics are outlined as follows:

- **Building envelope characteristics:** this category encompasses the physical components and attributes of a building that influence its thermal performance.
  - U-values: these values for the roof, wall, window, and floor determine the rate of heat transfer, affecting insulation efficiency.
  - Other factors: different factors such as internal heat capacity, glazing type, and leakage level, each contributing to the building's thermal dynamics.
  - Geometry specifications: the physical dimensions and shape of the building, impacting its energy performance.
- **Building stock characteristics:** this category reflects the broader aspects of the building stock being analysed.
  - Number of buildings: the count of buildings for each reference type, essential for large-scale energy assessments.
  - Useful areas: quantifying the living, roof, wall, window, and floor areas to estimate the energy needs of diverse building types.

The building envelope characteristics are directly used to calculate the heating and cooling energy needs for each building. Here's how this calculation is approached:

- **Total heat transfer by transmission and ventilation**: the calculation of heating needs involves assessing the total heat transfer due to transmission through the building envelope (walls, windows, roof, and floor) and ventilation losses. Transmission losses are the heat lost or gained through the building's exterior surfaces, while ventilation losses arise from the air exchange between the interior and exterior environments.
- **Total heat gains and losses**: for heating, heat gains often reduce the energy required by naturally warming the building. Conversely, for cooling, these same gains increase the energy demand by raising indoor temperatures. Losses, primarily through transmission and ventilation, increase heating needs while reducing cooling requirements. This interplay of gains and losses dictates the overall energy demand for maintaining comfortable indoor conditions in different seasons.
- **External climate conditions**: Average monthly temperatures, solar radiation, and other relevant climate data are also used to calculate the heating and cooling energy needs.

This methodology is integrated into an Excel-based tool, which allows users to input specific data for various reference buildings drawn from a comprehensive database representing different building stocks across various countries through the following steps:

1. **Monthly energy needs calculation**: utilizing the quasi-steady-state approach, the tool calculates the monthly energy requirements for heating and cooling for each building. This calculation takes into account the provided building geometry and climate data. The

calculation considers thermal inertia by considering construction type (e.g., light, medium, or heavy) and corresponding time constant of the building[11]. Degradation of the materials is not taken into account in the calculations.

2. The tool goes beyond energy needs and calculates at building level:
    - Final energy consumption,
    - CO_2 emissions associated with the building's energy use,
    - Net energy requirements.
3. Iterative Analysis for Optimisation
    - **R-value iterations**: an essential feature of the tool is its ability to perform iterative calculations for different R-values (a measure of thermal resistance) for various elements of the building envelope, such as walls, roofs, windows, and floors.
    - **Optimisation for specific building stock performance targets**: by adjusting the R-values, the tool identifies the insulation levels required to achieve the predefined building stock performance. This iterative process is crucial for exploring and recommending the most energy-efficient insulation strategies.
4. Scaling to Building Stock
    - **From Building scale to building stock/country scale**: upon completion of the analysis for individual buildings, the tool scales the results to the building stock level. This approach provides a macroscopic view of the energy performance across a range of buildings within a specific country.

4.4 *Limitations of the tool*

The tool shows several limitations listed below.

The tool allows analysing performance of single product and assessing whether the product achieve KPIs or performance targets, without analysing renovation results obtained after combining two or more EZ0 products. The reason is that product requirements are defined for single products and its producer, rather than for a group of products.

Cost assumptions for our model are static, whereas in reality prices are subject to change and influenced by inflation. This applies mostly to the costs of energy and therefore monetary savings after renovation.

The inputs of the tool are based on national averages, such as average weather profiles or national (instead of regional) reference buildings. As a consequence, regional differences within countries are not taken into account.

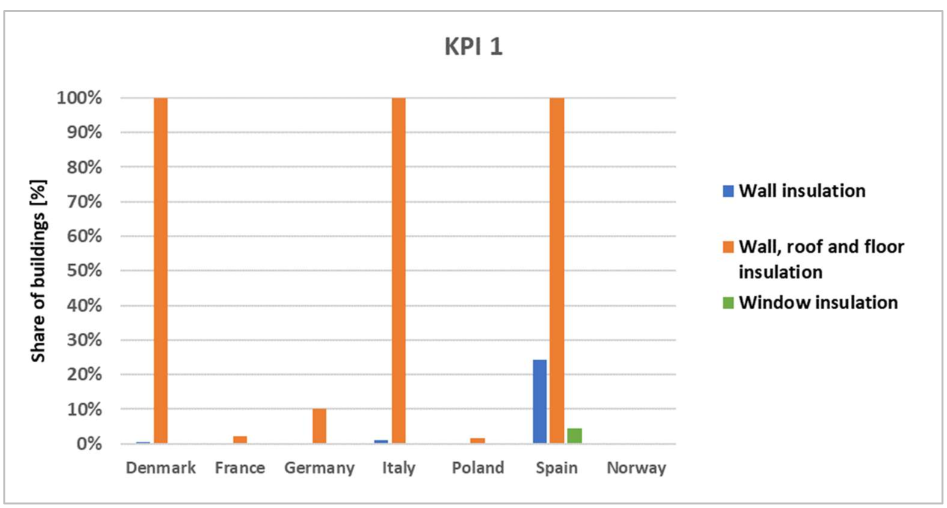
[11] As prescribed in the ISO 52016.

5. Initial conclusions on KPIs 1, 2, 13 and 18

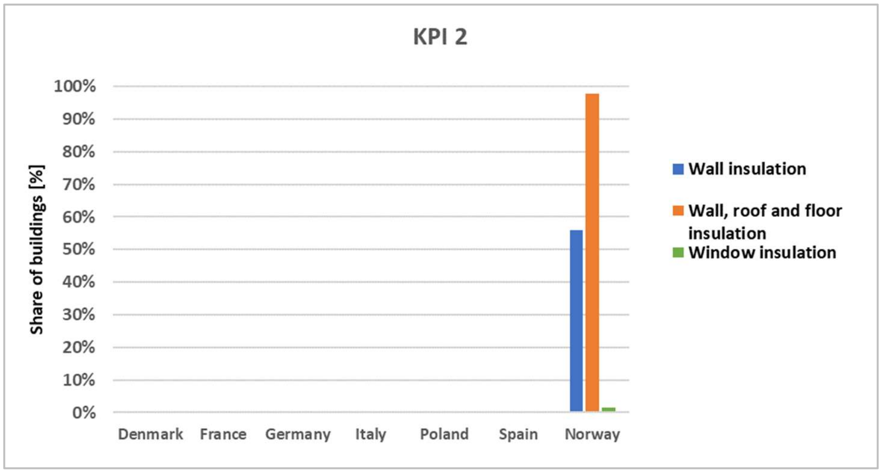
5.1 *Conclusion 1: energy consumption and CO_2 emissions*

While analysing KPIs 1, 2, and 13 (associated with final energy consumption and CO_2 emissions), it became apparent that the targets values — 50 kWh/m^2/year for final energy consumption and 4 kg CO_2/m^2/year for CO_2 emissions — proved to be overly ambitious to be reached with insulation materials only[12], as explained below.

When insulating a building there is a threshold value in insulation thickness[13] above which additional insulation cannot significantly reduce the building's energy consumption and CO_2 emission. Any additional energy and CO_2 improvement can be reached only with introducing other renovation measures, such as energy system upgrades. The results illustrated in Figure 8 indicate that achieving KPI 1 (final energy consumption < 50 kWh/m²/year) is challenging for wall insulation and window frame insulation/replacement. While it can be achieved for walls, roof, and floor insulation, it requires unrealistically high R-values for market products. KPI 2 (carbon emission < 4 kgCO_2/m²/year) is not met in most countries for all products, except for Norway, due to its low CO_2 conversion factor of 0.029 kg CO_2/kWh of final energy. KPI 13 (net zero energy for single family houses with PV < 35 kWh/m²/year and < 45 kWh/m²/year for Nordic countries) is achievable only in a few countries, with some success in Denmark, Italy, and Spain for a combination of walls, roof, and floor insulation. Overall, KPIs 1 and 2 seem too ambitious for insulation only, as these targets can be reached by only a very small portion of the building stock in most countries.



[12] Due to the fact that 50 kWh/m^2/year and 4 kg CO_2/m^2/year correspond to A label from French EPC scheme, a possible solution for reducing the ambition was to use B or C energy labels. However, in several countries, these may imply similar or even more ambitious performance.
[13] I.e., thermal resistance, or R-value, reached.



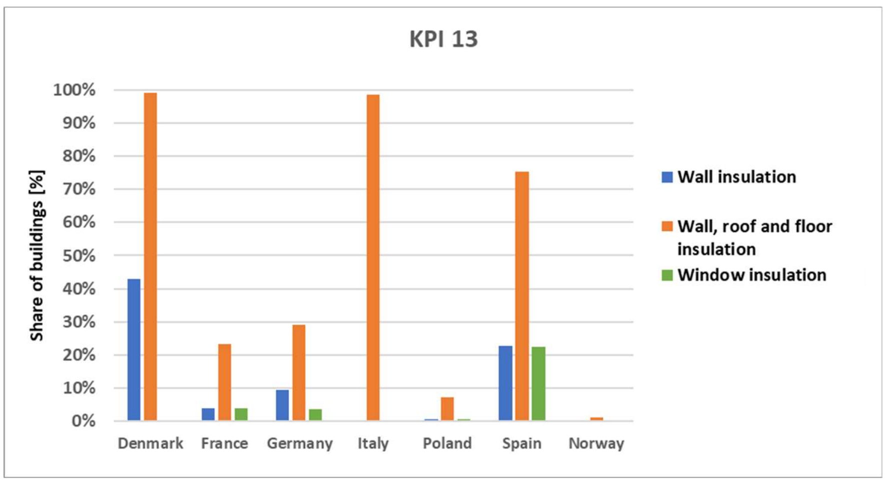


Figure 8: KPI 1, KPI 2, and KPI 13 assessment in the different countries.

5.2 *Conclusion 2: verification at the use case level*

As outlined in the project Description of Work, KPIs 1, 2, and 13 will be verified with use cases based on real buildings undergoing a deep renovation process (WP6). KPI 18 will be assessed with the global lifecycle analysis including cost analysis, where synergies between insulation materials, energy systems, and design methodologies will be analysed. EZ0 products will contribute to the achievements of low energy consumption and CO_2 emissions as far as the building envelope is concerned. But we emphasize that a deep renovation is mostly needed to reach the objectives (considering upgrades in energy systems and variability of green energy availability).

5.3 *Conclusion 3: payback time*

While analysing new energy and CO_2 related KPIs, it was noticed that KPI 18 is set at highly ambitious level as well. Some preliminary KPI 18 results showed that simple payback period of 7 years cannot be easily reached in analysed countries[14]. As shown in Figure 9, a 7-year payback would require product price below 15 EUR/m^2 in majority of the countries, which may be difficult to reach for most of the products with the tool in WP2. During verification in WP7, a different approach might complement the evaluation of products lifecycle as defined in the project objectives. The valuation of recycled raw material will be refined with new results arising from material optimisation and social-economical assessment.

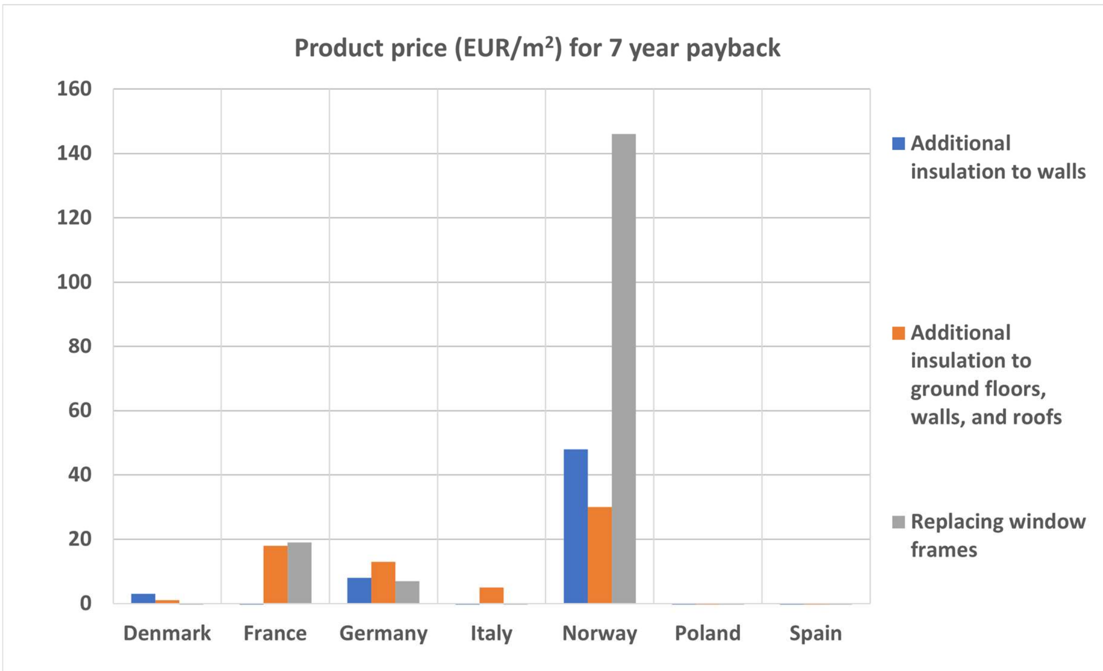


Figure 9: Product price (EUR/m^2) for 7-year payback

To enable proper product requirement definition in WP2, the payback time performance target has been redefined to include payback of 12 years, which will be further detailed in Section 6.5.

6. Performance targets and important KPIs

EZ0 focuses on insulation materials only, i.e., without considering other renovation measures. This implies that the potential of insulation materials for energy improvements plays an important role in defining building performance targets. Since KPIs 1, 2, and 13 can be achieved with and will be confirmed for combined renovation measures, it is clear that these KPIs should not be used for defining product requirements.

[14] In addition, feedback from the tool workshop (November 2023) suggested payback periods of minimum 10-15 years.

Instead with KPIs 1 and 2, project objective 1 (efficient and easy renovation for buildings) will be satisfied in the tool with additional energy and CO_2 performance targets achieved exclusively with insulation materials. The fact that insulation above certain R-value does not significantly improve the building's performance requires a switch from absolute targets (used in KPIs 1 and 2) to marginal reductions[15] in energy and CO_2 performance.

For this purpose, a critical R-value of additional insulation is introduced. A critical R-value is an R-value of an insulation product where additional energy or CO_2 improvements achieved with one additional unit of insulation are insignificant. For this report, insignificant additional improvements are improvements in energy savings lower than 3% (when comparing performance before and after an additional unit of insulation).

A critical R-value can be visualised on a curve that explains how energy consumption of a building depends on additional insulation in Figure 10. In such a curve, the critical R-value is the point where the curve becomes (close to) horizontal. An energy consumption vs. insulation curve and its critical R-value defined for a hypothetical building can be found in Figure 10.

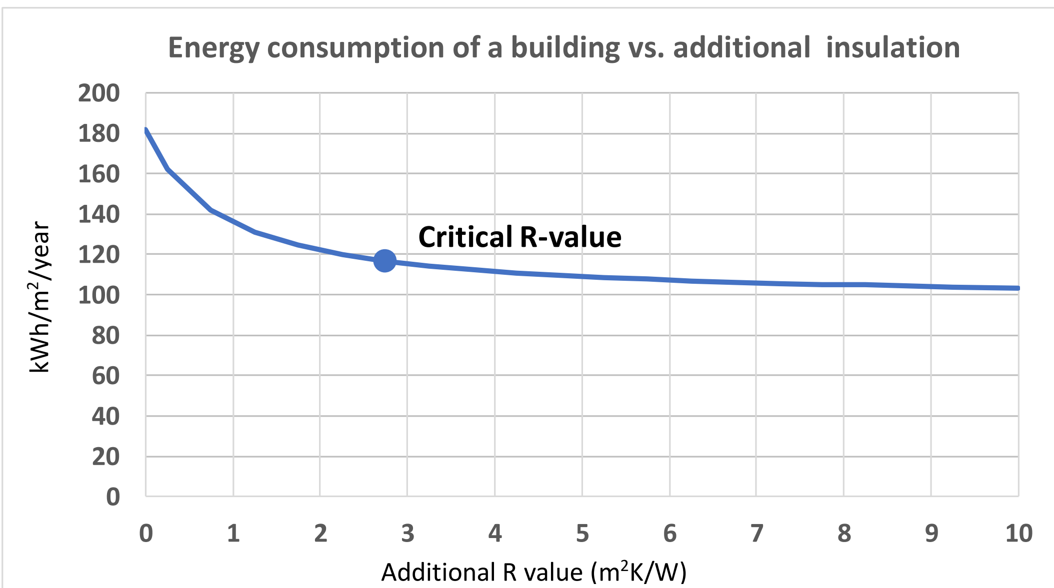


Figure 10: Energy performance vs additional insulation for a hypothetical building

As a conclusion, two energy and one CO_2 related performance targets are introduced:

- **Energy performance target 1**: Marginal savings in final energy consumption <3%, achieved at building stock level
- **Energy performance target 2**: Marginal reduction in net zero energy <3% for single family houses with PV, achieved at building stock level

[15] Achieved with an additional unit of insulation.

- **CO_2 performance target**: Marginal reduction in CO_2 emissions <3%, achieved at building stock level

Performance targets introduced here should provide the right balance between energy and CO_2 performance on one side, and economic performance of insulating materials on the other[16]. Also, by setting the target at ambitious 3% of marginal improvements, performance targets aim at achieving the highest possible, but still justified, energy and CO_2 reductions. This supports EZ0 efforts towards reaching near zero energy consumption and carbon emission of renovated buildings[17].

Together with introducing energy and CO_2 performance targets in the tool, initial conclusions described in section 0 on KPIs 1,2,13, and 18 suggested one additional payback performance target. This target is described in more detail below.

6.1 *Energy performance target 1*

The first building stock performance target addresses marginal savings in final energy demand of a building. As mentioned above, marginal savings are defined as increase in energy savings that result from increasing R-value by one additional unit. Energy performance target 1 is therefore used to identify critical R-value at which additional insulation (i.e., increase in R-value) no longer result in significant additional energy savings.

Although energy consumption is analysed at the reference building level, critical R-value for one country is obtained at the building stock level[18]. Obtaining this critical R-value requires extrapolating the energy savings obtained for different reference buildings to the building stock level. This enables estimating the average energy savings obtained per buildings when all buildings in a country would be renovated to the critical R-value. This eventually explains how energy savings obtained after insulating all buildings in one country depend on the insulation R-value. The critical R-value is eventually identified as the point where the addition of either an additional 0.5 m²K/W of insulation or the initial 0.25 m²K/W layer of insulation results in less than a 3% reduction in average relative final energy consumption.

To calculate the final energy consumption of buildings, a crucial step involves converting the calculated energy needs into final energy consumption. This conversion is necessary because the energy calculation model primarily calculates the energy needs of a building as explained in section 4.3. The conversion from energy need to final energy consumption is accomplished using specific conversion factors that vary from country to country. These conversion factors consider the national

[16] Low marginal energy savings beyond the threshold R-value result in low marginal monetary savings. This most likely implies that any additional insulation is economically unjustified as well.
[17] EZ0 objective 1.
[18] In this way it is possible to avoid using around several national critical R-values (around 15 to 20, i.e., one value per reference building) which may significantly decrease the accuracy of the results.

energy sources and efficiencies as shown in Table 2. The conversion factors for Germany, France, Italy, Poland and Denmark are obtained from Hotmaps[19] dataset by dividing the final energy consumption to the energy need for each country. For Norway, the conversion factor is obtained from national legislation in Norway[20]. Spain is assumed to use the same conversion factor of Norway[21].

Table 2: Final energy consumption conversion factors based on Hotmaps and Enova

Country	Final energy (unit) required by 1 unit of energy need
Germany	1.05
France	1.33
Italy	1.08
Spain	1.30
Poland	1.17
Norway	1.30
Denmark	1.21

6.2 *Energy performance target 2 with PV production*

This target uniquely emphasizes local PV production, which is expected to fulfil at least 50% of the final energy needs of the single family house. Consequently, the net energy for this target is calculated as the remaining 50% of the final energy consumption after considering the energy contributed by the PV system.

Following the approach used in other performance targets, energy performance target 2 is implemented at building stock level therefore providing single national R-value as a result. The critical R-value is at the level where additional 0.5 m²K/W of insulation (or the initial 0.25 m²K/W layer of insulation) results in less than 3% of reduction in average relative net zero energy for single family building stock with PV (kWh/m^2/year).

6.3 *CO_2 performance target*

The CO_2 performance target defines critical R-value beyond which any further increase in insulation does not result in more than 3% of reductions in average relative carbon emissions of the building

[19] https://wiki.hotmaps.eu/en/Hotmaps-open-data-repositories#building-stock_eu-building-stock
[20] Karakterskalaen | Enova
[21] For Spain Hotmaps suggested extremely high value of 1.70. Such high factor was decreased to the first lowest value found in other countries. The options were France (1.33) and Norway (1.30). Norway was selected because its value is provided from the national building code and therefore assumed to be more reliable than the French value obtained from Hotmaps.

stock (kg CO_2/m^2/year). Like energy performance target 1, critical R-value, i.e. the product requirement, for each country is obtained at the building stock level.
The tool exclusively accounted for operating emissions in its calculation of carbon emissions. This approach excludes embodied carbon, which pertains to the CO_2 emissions associated, for instance, with the production, transportation, installation, and disposal of building materials.
Calculating CO_2 emissions is based on the final energy mix in each country. Such national energy mix reflects the share of different energy sources[22] in and carbon emissions associated with each kWh of final energy.
By combining the national energy mix and the final energy use with CO_2 emission conversion factors for each energy carrier, accurate CO_2 emission conversion factors can be derived for each country. CO_2 emission conversion factors used in the tool are shown in Table 3. Most of the CO_2 emissions conversion factors were obtained from relevant national legislation, such as national building energy acts, and sources such as GHG emission Factors dataset[23] and NOWTRICITY[24].

Table 3: CO_2 emissions conversion factors based on JRC data and NOWTRICITY

kg CO_2 released from 1 kWh of final energy	Total
Germany	0.344
France	0.140
Italy	0.211
Spain	0.255
Poland	0.299
Norway	0.029
Denmark	0.123

6.4 *KPI 12: Net energy use reduction of -5% (absolute minimum)*

To be in line with energy and carbon building stock performance targets, KPI 12 is implemented at building stock level therefore providing single national R-value as product requirement. Since it already targets relative performance (5% reduction in net energy), KPI 12 does not include analysis of marginal effects.
KPI 12, which focuses on achieving a minimum of 5% reduction in net energy use in all building types, is an important metric covered by the tool. KPI 12 measures the effectiveness of renovation measures in reducing the overall energy consumption of a building or a group of buildings. Net energy use is calculated by taking the total final energy consumption and subtracting the portion of energy that comes from renewable sources within a specific country.

[22] Such as electricity, natural gas, primary solid biofuels, heat, solid fossil fuels, liquefied petroleum gases, and solar thermal energy.
[23] https://data.jrc.ec.europa.eu/dataset/919df040-0252-4e4e-ad82-c054896e1641
[24] https://www.nowtricity.com/

In this context, the renewable energy share for space heating and space cooling is used to calculate the net energy use for the different buildings in the different counties. Achieving a 5% reduction in this net figure indicates progress in enhancing energy efficiency and increased use of renewable energy sources (RES) in building operations. RES share in final energy consumption used for space heating and space cooling for households are shown at in Table 4, as provided by Eurostat[25].

Table 4: Renewable energy share in the final consumption for space heating and space cooling in households

Country	RES share in the final energy consumption for space heating and space cooling
Germany	0.15
France	0.24
Italy	0.20
Spain	0.17
Poland	0.21
Norway	0.33
Denmark	0.42

6.5 *Payback time performance target of 12 years*

Initially the tool was calibrated with a 7 years payback, aligned with KPI 18. This value will be verified in WP7 – not by the product requirement tool in WP2. Initial results obtained by the first version of the tool are shown in Figure 9.

The results suggested that very low product prices were required to achieve a 7 years payback period. When compared to the product price range obtained from partners, shown in Table 5, it seemed worthwhile to consider an approach different from using the 7 years payback time.

Table 5: Price range of products

Product	Price range
Mycelium-based inside-the-wall thermal insulating panels	Price is around 60€/m^2
Mycelium-based decorative insulating panels for inner walls	Price is around 80€/m^2
Sprayable Low density Bio-PUR foam	Price is around 15€/m^2
High density BioPUR molded frames for windows & doors	Price is around 18€/linear meter
"Low density BioPUR molded parts for blind box"	Price is around 35€/linear meter

The proposed payback time performance target used to define product requirements is therefore increased to 12 years.

[25] https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren__custom_9069057/default/table

In this study, both the initial results for KPI 18 and the payback time performance target relate to the simple payback period achieved after renovating a building with a specific product. Simple payback period of a renovation can be calculated after dividing the initial investment with achieved energy bill reductions.

Fixed costs, i.e., those that do not depend on the cost of material used, included in initial investments are:

- 82 EUR/m^2 for applying an insulation layer to external walls,
- 63 EUR/m^2 for applying an insulation layer to external walls, ground floors, and roofs
- 82 EUR/m^2 for replacing window frames, i.e., windows[26].

Finally, keeping the payback period equal to 12 years provides product price as an input for defining product requirements[27]. Product price obtained for the payback target corresponds to the maximum R-value obtained from building stock performance targets and KPI 12[28].

Simple payback period is based on the following assumptions:

- Total investment includes VAT and installation costs,
- Financing is provided by the homeowner only, i.e., neither financing costs (interest rates) nor home renovation subsidies are considered, and
- There is no effect of inflation on energy prices, i.e. future energy prices are kept constant and equal to the current ones (before renovation).

In reality, each renovation is performed at single building level. However, the tool shows the payback period achieved at the building stock level. In other words, initial investment and savings achieved in each building from the building stock are summed up to obtain the total initial investment and savings at the buildings stock level. When compared, these values provided payback period at the building stock level. The required product price obtained in this way is the price that would make average national payback period equal to 12 years. [29]

[26] ifeu, Fraunhofer IEE and Consentec (2018): Building sector Efficiency: A crucial Component of the Energy Transition. A study commissioned by Agora Energiewende, table 16.
[27] Included in the list of final product requirements (D2.5)
[28] Which corresponds to how final R-value product requirement is obtained in D2.5.
[29] In reality, whatever the product price, payback period will vary within a building stock with some buildings being below and some above the average payback period. The payback performance target analysis takes this effect into account and defines the product price by setting the **average** payback period (not payback period of all the buildings present in a building stock) at the level of 12 years.

7. Results

7.1 *Energy performance target 1*

Final energy consumption of national building stock after insulating different building elements or replacing window frames is shown in Figure 11, Figure 12, and Figure 13. The same figures also show critical R-values for each country, i.e., R-values at which additional insulation may not be justified with additional energy savings. Notably, when insulation is solely allocated to windows by replacing window frames, the critical R-value remains modest, ranging from 0.75 to 1.25 m²K/W. This indicates a limited capacity of window insulation alone to decrease the final energy consumption. Conversely, an exclusive focus on wall insulation yields a marginally higher critical R-value, spanning from 2.25 to 2.75 m²K/W. This suggests a more substantial reduction in final energy consumption compared to window insulation alone. However, the most pronounced reduction in final energy consumption is observed when insulation products are uniformly applied to walls, roof, and floor structures. Here, the critical R-value notably increases, ranging between 4.25 and 5.75 m²K/W, indicating superior efficiency in final energy consumption reduction.

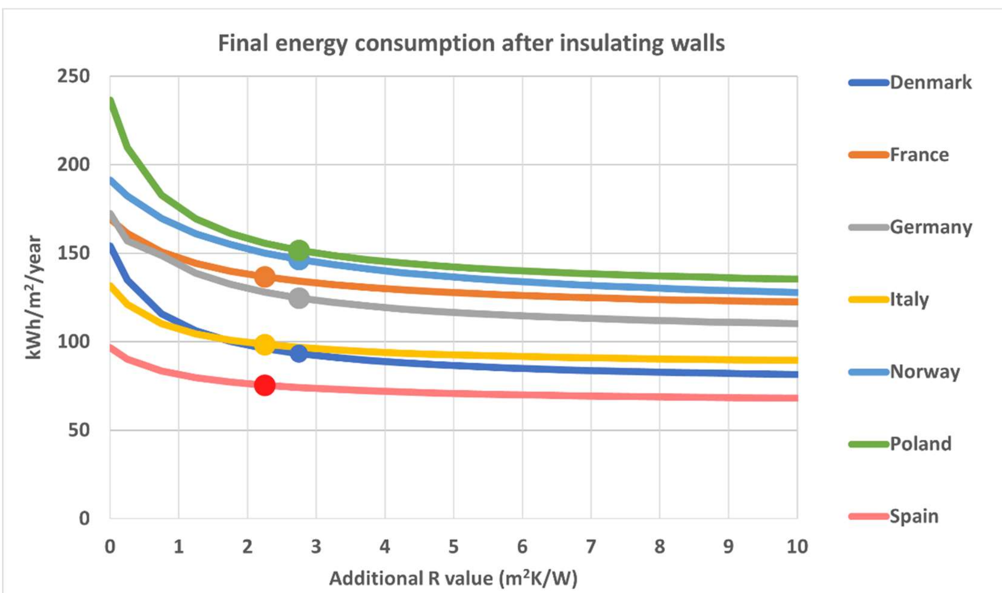


Figure 11: Final energy consumption after insulating walls

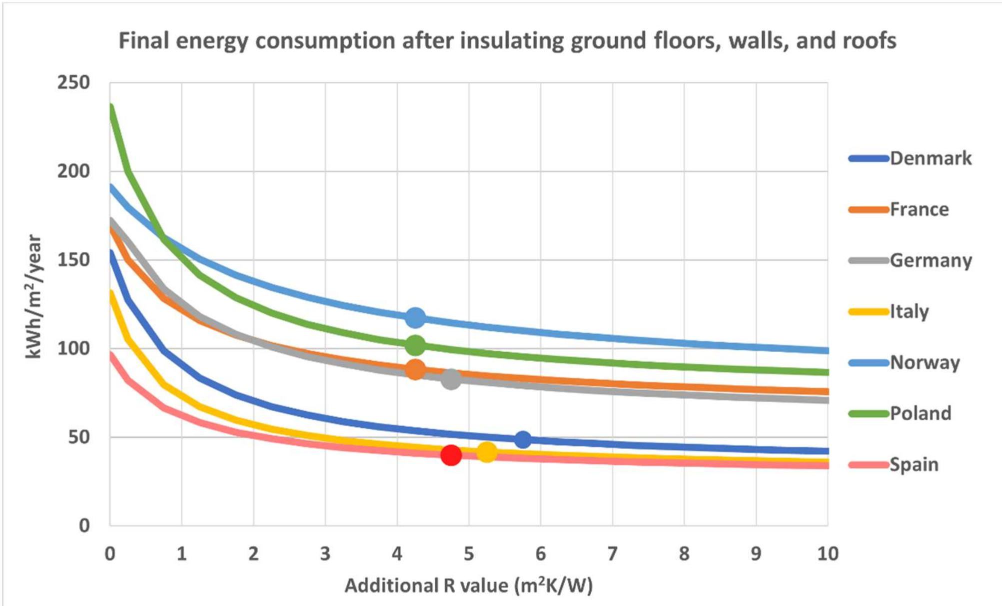


Figure 12: Final energy consumption after insulating ground floors, walls, and roofs

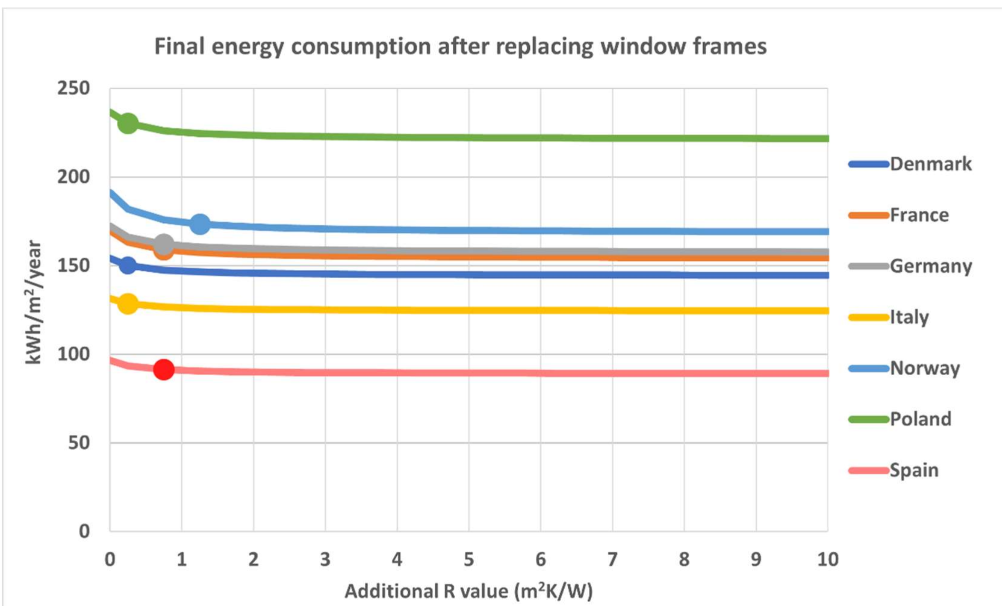


Figure 13: Final energy consumption after replacing window frames

7.2 *Energy performance target 2*

Net zero energy for single family houses with PV, how these values depend on R-values achieved with different renovation measures, as well as critical R-values can be found in Figure 14, Figure 15, and Figure 16. Similar to the findings in KPI 1 and KPI 2 concerning final energy consumption savings and CO_2 emissions reductions, the results for this KPI to achieve marginal reductions in net zero <3%

for single family houses with PV, follow a consistent pattern. When insulating only walls, the range of R-values falls between 0.25 and 2.75 m²K/W. Insulating walls, roof, and floor together widens this range to 3.75 to 6.25 m²K/W. Conversely, replacing only window frames results in R-values ranging from 0.75 to 3.75 m²K/W.

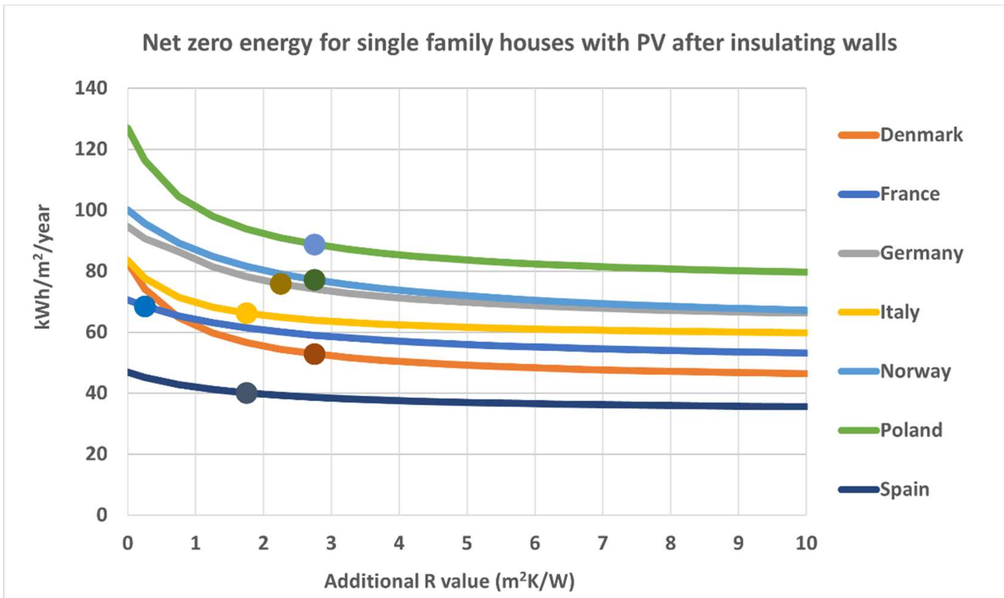


Figure 14: Net zero energy for single family houses with PV after insulating walls

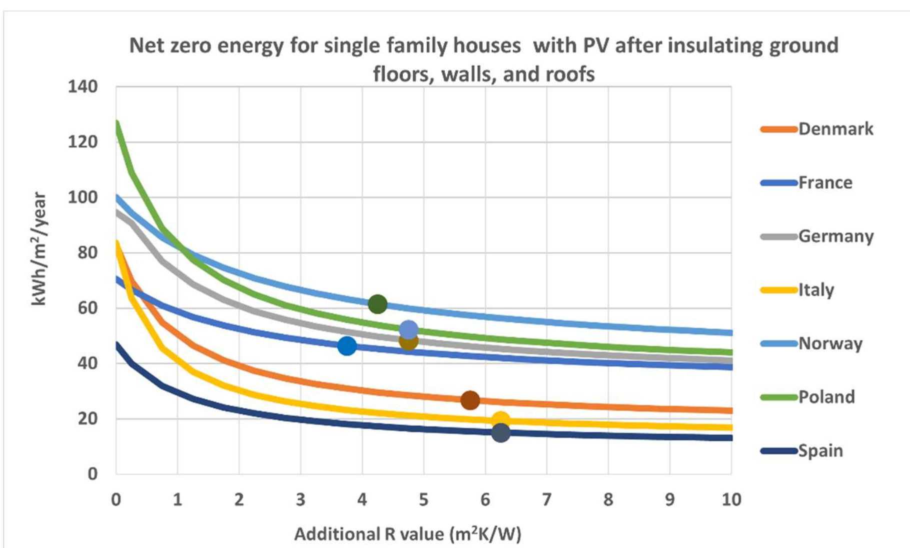


Figure 15: Net zero energy for single family houses with PV after insulating ground floors, walls, and roofs

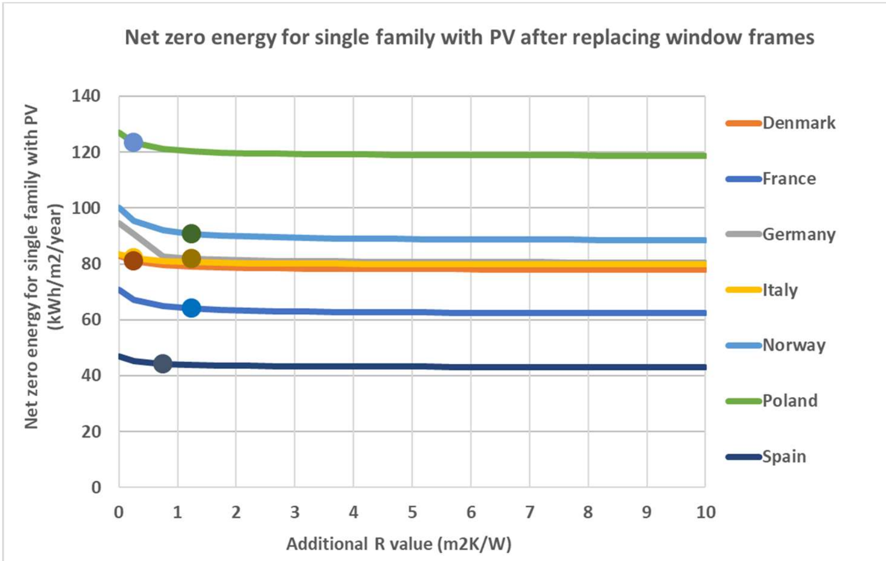


Figure 16: Net zero energy for single family houses with PV after replacing window frames

7.3 *CO_2 performance target*

CO_2 emissions of national building stocks and how these depend on insulating different building elements or replacing window frames is shown in Figure 17, Figure 18, and Figure 19. Critical R-values for each country, i.e., R-values at which additional insulation reduces total CO_2 emissions by less than 3% are shown as well.

Dependencies between CO_2 emissions and R-values follow the same pattern as final energy savings explained above. When insulation products are exclusively applied to walls, the critical R-value falls within the range of 1.75 to 2.25 m²K/W. Conversely, comprehensive insulation across walls, roof, and floor structures yields a notably higher critical R-value range, spanning from 3.75 to 5.25 m²K/W. This observation underscores the positive correlation between higher R-values and reduced CO_2 emissions reductions. The highest reductions in CO_2 emissions are achieved when insulating ground floors, walls, and roofs together.

Conversely, when insulation is solely targeted at windows by replacing window frames, the critical R-value shows a notably lower range, between 0.25 and 0.75 m²K/W, with the lowest reduction in CO_2 emissions.

However, one can notice that ranking of countries per CO_2 emissions intensity is significantly different from the ranking based on final energy consumption. The main reason is that analysed countries significantly differ in CO_2 released from when producing 1 kWh of final energy, as explained in Table 3in section 6.3.

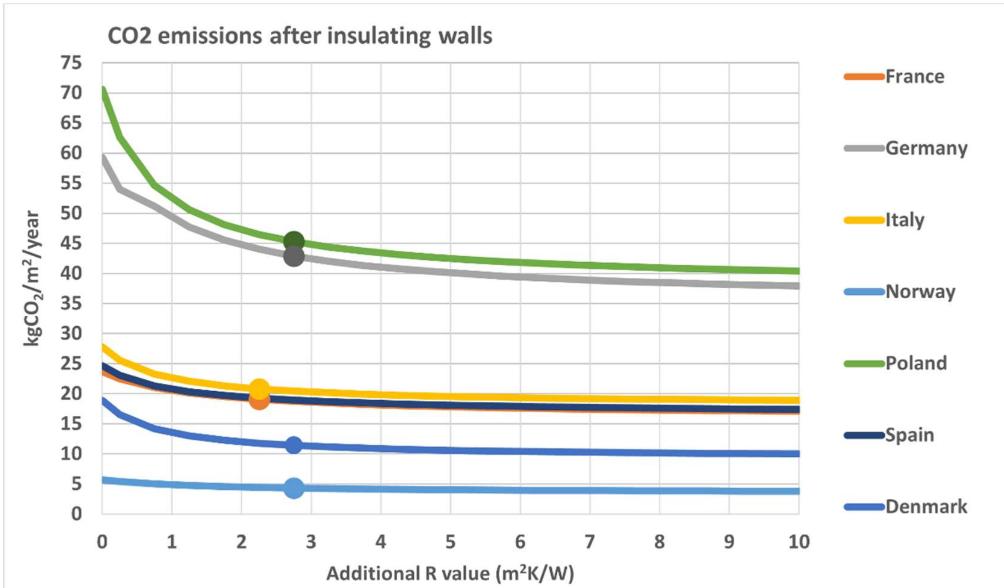


Figure 17: CO_2 emissions after insulating walls

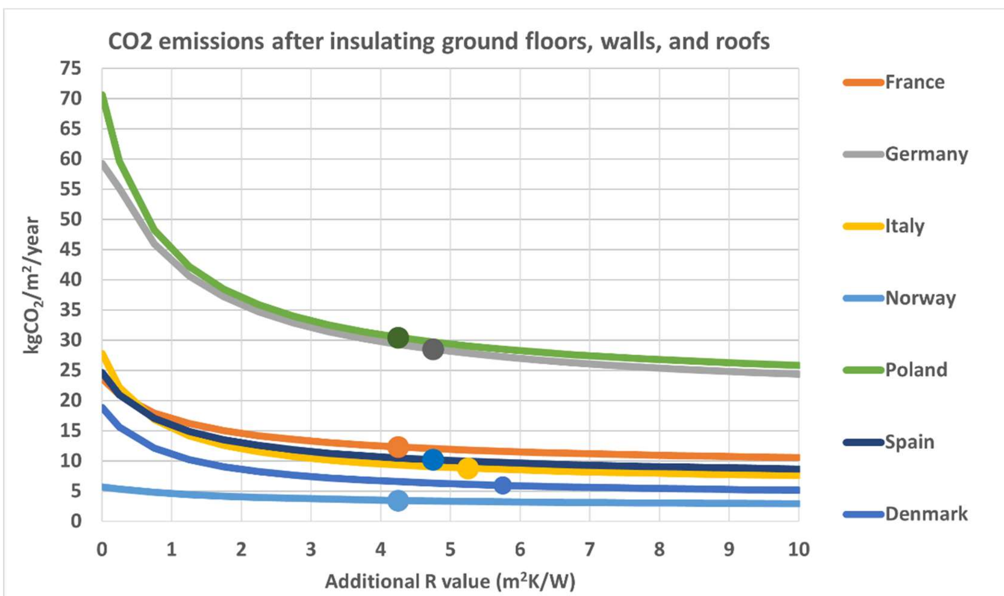


Figure 18: CO_2 emissions after insulating ground floors, walls, and roofs

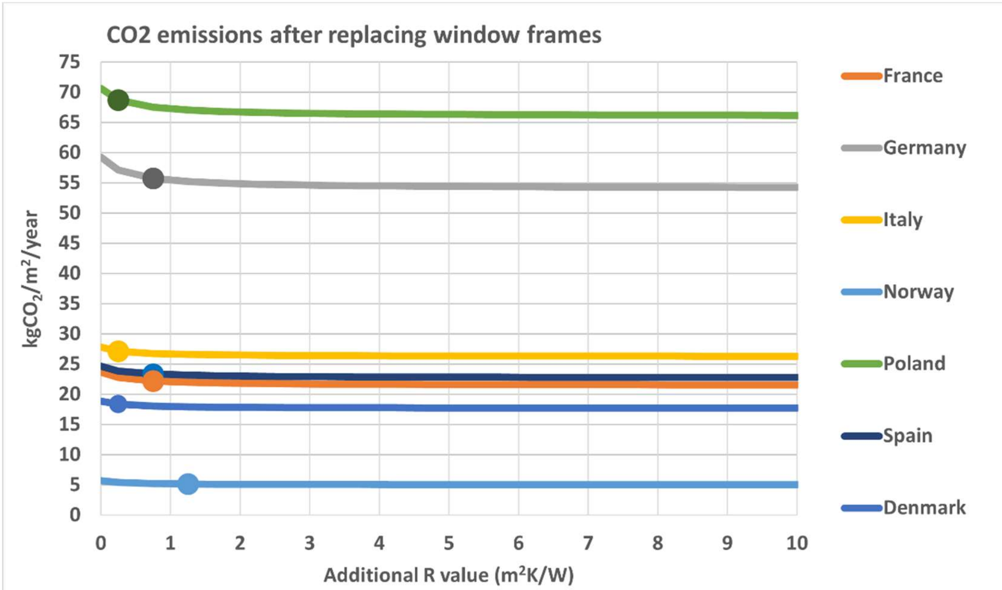


Figure 19: CO_2 emissions after replacing window frames

7.4 *KPI 12: Net energy use reduction of -5% (absolute minimum)*

The relationship between net energy use at national level and R-values achieved after insulating different building elements or replacing window frames is shown in Figure 20, Figure 21, and Figure 22. Insulating only walls yields a critical R-value range of 0.25 to 0.75 m²K/W to achieve a minimum 5% reduction in net energy use. However, when insulating walls, roof, and floor together, the critical R-value is 0.25 m²K/W. The lower R-value needed to achieve the same 5% reduction in net energy use in this case is due to the combined effect of insulating multiple areas, which collectively enhance the building's overall thermal performance and reduce the required R-value for energy savings. Conversely, replacing window frames requires a critical R-value ranging from 0.75 to 3.75 m²K/W to attain the same reduction in net energy use which shows the necessity for higher thermal resistance in new window frames to achieve substantial energy savings.

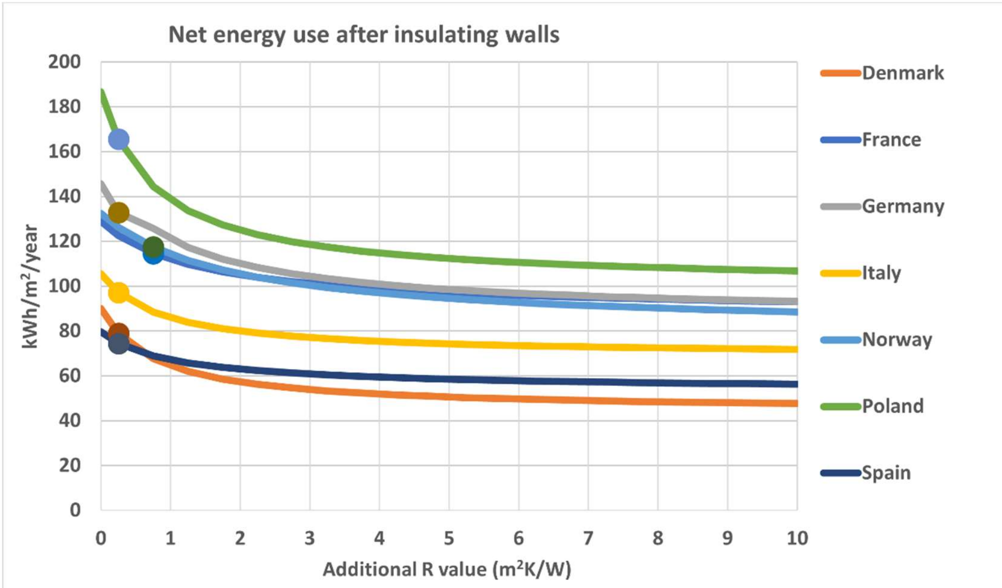


Figure 20: Net energy use after insulating walls

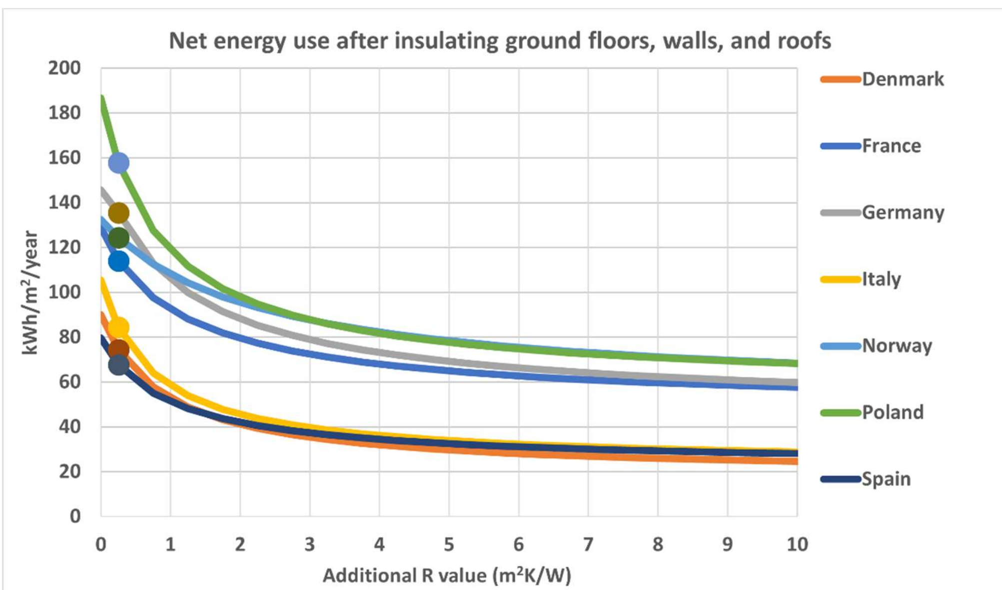


Figure 21: Net energy use after insulating ground floors, walls, and roofs

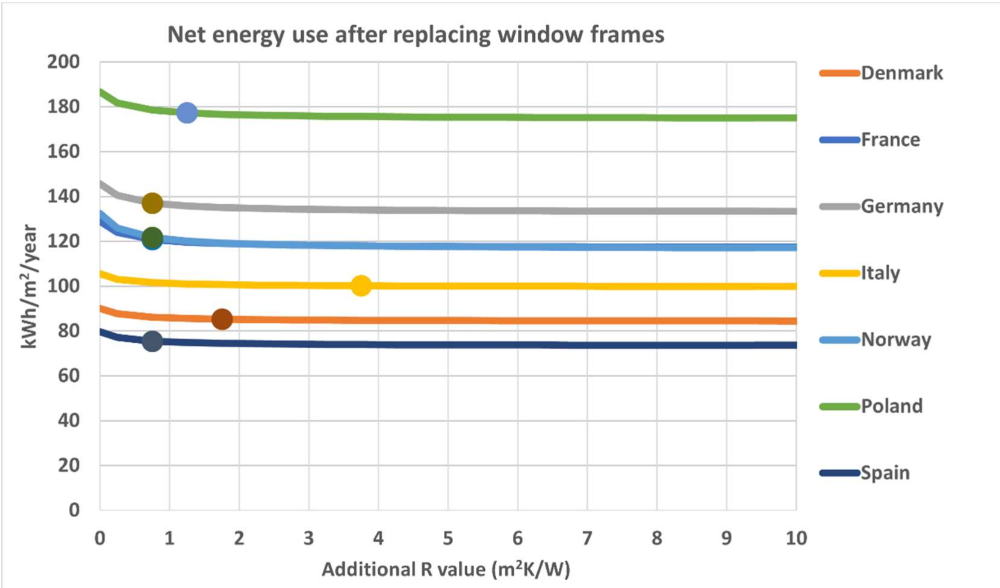


Figure 22: Net energy use after replacing window frames

7.5 *Payback time performance target of 12 years*

As mentioned before, Payback time performance target required the assessment of product price needed to achieve a simple payback period of 12 years after renovating a building. Figure 23 shows results obtained with the tool.

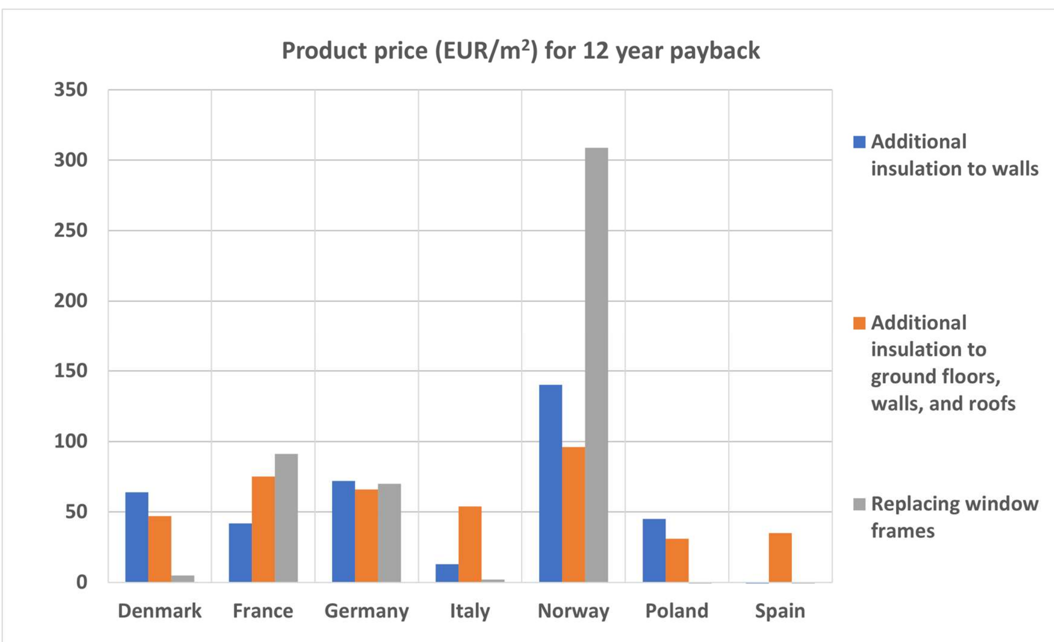


Figure 23: Product price (EUR/m^2) for 12-year payback

As shown in Figure 23, there are noticeable differences in how prices depend on renovation measures in specific countries[30]. The main reason can be found in different building geometries, and therefore in the savings per area ratio, present in analysed countries.

In brief, the prices are the highest in Norway where they lie between 100 and 300 EUR/m^2, which implies that payback period may be easily reached. On the other hand, the prices are low for Italy, Poland, and Spain[31], which suggests problems in achieving 12 years of payback period in these countries.

7.6 *Results per performance targets, country, and renovation measure*

Critical R-values and product prices for different performance targets, KPIs, countries, and renovation measures can be found in Table 6. Product price obtained in the payback time performance target corresponds to the maximum R-value obtained in three performance targets and KPI 12.

Table 6: Overview of R-values and product prices required for reaching performance targets and selected KPIs, per country and renovation measure

Renovation measure	Country	Energy performance target 1: R-value (m^{2}K/W)	Carbon performance target: R-value (m^{2}K/W)	KPI 12: R-value (m^{2}K/W)	Energy performance target 2: R-value (m^{2}K/W)	Payback time performance target: Product price (EUR/m^2)
Walls	Denmark	2.75	2.25	0.25	2.75	64
	France	2.25	1.75	0.75	0.25	42
	Germany	2.75	2.25	0.25	2.25	72
	Italy	2.25	1.75	0.25	1.75	13
	Norway	2.75	2.25	0.75	2.75	140
	Poland	2.75	2.25	0.25	2.75	45
	Spain	2.25	1.75	0.25	1.75	< 0
Ground floors, walls, and roof	Denmark	5.75	5.25	0.25	5.75	47
	France	4.25	3.75	0.25	3.75	75
	Germany	4.75	4.25	0.25	4.75	66
	Italy	5.25	4.75	0.25	6.25	54
	Norway	4.25	3.75	0.25	4.25	96
	Poland	4.25	3.75	0.25	4.75	31
	Spain	4.75	4.25	0.25	6.25	35

[30] E.g., when going from the first (walls) to the last renovation measure (window frames) prices drop in Denmark and increase in France.

[31] Some renovation measures applied in Poland and Spain result in negative prices, which implies that the payback period cannot be reached. In practice, negative product price means that the savings achieved over 12 years are low and not enough to cover the fixed costs of renovation.

Window frames	Denmark	0.25	0.25	1.75	0.25	5
	France	0.75	0.25	0.75	1.25	91
	Germany	0.75	0.25	0.75	1.25	70
	Italy	0.25	0.25	3.75	0.25	2
	Norway	1.25	0.75	0.75	1.25	309
	Poland	0.25	0.25	1.25	0.25	< 0
	Spain	0.75	0.25	0.75	0.75	< 0

8. Conclusion

In summary, this report explains the methodology behind the product requirement tool. Firstly, it shows the key targets for the performance of the products at the building stock level, focusing on final energy consumption, CO_2 emissions, net energy use reduction, net zero energy for single family houses with PV systems, and payback time. Secondly, the report clarifies how, by using the ISO 52016 standard, the product requirement tool evaluates performance of building envelope interventions (envelope insulation or window frame replacement) against project objectives and additional energy and CO_2 targets. Lastly, the report provides and explains the results obtained from the tool, setting the stage for defining final product requirements in subsequent deliverables.

The results shed light on the impact of various insulation measures on energy consumption, CO_2 emissions, net energy use, and net zero energy for buildings. Insulating different building elements or replacing window frames influences these factors. Notably, insulating walls, roofs, and floors together yields the most substantial reductions in final energy consumption and CO_2 emissions, requiring higher critical R-values. Conversely, focusing solely on window insulation offers limited benefits in energy savings and emissions reduction. Moreover, the relationship between insulation and net energy use reveals varying critical R-value ranges, with comprehensive insulation leading to lower requirements for achieving energy efficiency goals. These findings underscore the importance of strategic insulation measures in achieving energy efficiency and sustainability targets in building design and renovation efforts.