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Measuring the Influence of Industrialization in Deep Energy Renovations: A Three-Case Study Utilizing Key Performance Indicators (KPIs)

Juan G. Secondo-Maglia *, José Luis Alapont-Ramón, Marco De-Rossi-Estrada and Santiago Sánchez Gómez

Institute for Heritage Restoration, Universitat Politècnica de València, Camí de Vera s/n, 46022 Valencia, Spain; jalapont@upv.edu.es (J.L.A.-R.); marderos@upv.edu.es (M.D.-R.-E.); sansncgm@arq.upv.es (S.S.G.)
* Correspondence: jgsecmag@upv.edu.es

Abstract: Existing buildings in the European Union account for 40% of its energy consumption. To significantly reduce this impact, annual deep energy renovation rates should triple by the end of the 2020s. However, the lack of automation in the construction industry has hindered energy renovation efforts. Horizon Europe's INPERSO project (Industrialised and Personalised Renovation for Sustainable Societies) aims to create a user-centered energy rehabilitation method based on industrialized technologies and systems, enhancing efficiency and building performance. To bridge the gap between predictions and real-world outcomes, the 22 project partners—using a multi-criteria decision analysis (MCDA) process—devised a list of key performance indicators (KPIs) for evaluating rehabilitation based on economic, energy, environmental, social, and technological factors. Adopting a human-centric approach, these project partners aim to minimize the technologies' environmental impact while optimizing users' comfort and experience. The indicators are designed to evaluate performance at every stage of the renovation process, enabling continuous feedback and user engagement and ultimately ensuring that projected energy savings are met throughout the building's lifespan. The KPIs selected for INPERSO provide a solid framework for evaluating and monitoring sustainable renovation. However, challenges such as administrative reluctance and user disruption must be addressed to further boost the adoption of deep energy renovations.

Keywords: deep energy renovation; key performance indicators; industrialization; performance gap

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Citation: Secondo-Maglia, J.G.; Alapont-Ramón, J.L.; De-Rossi-Estrada, M.; Sánchez Gómez, S. Measuring the Influence of Industrialization in Deep Energy Renovations: A Three-Case Study Utilizing Key Performance Indicators (KPIs). *Buildings* **2024**, *14*, 3448. https://doi.org/10.3390/buildings14113448

Academic Editors: Haydee Blanco, Yosbel Boffill, Ignacio Lombillo and Alfonso Lozano

Received: 30 September 2024
Revised: 25 October 2024
Accepted: 28 October 2024
Published: 29 October 2024

1. Introduction

1.1. Use of Key Performance Indicators for Advancing Deep Energy Renovation and Productivity in the European Building Sector

As stated in the 2010/31/EU and 2012/27/EU [1,2] directives, the building stock in Europe produces 36% of the EU's total CO_2 emissions. With the last (2018/844) amendment [3], the Commission's main objective is to reduce at least 60% of the CO_2 emissions in the building sector, compared to the 2015 emissions, by 2030 [4]. Considering that 75% of the total building stock in Europe is considered energy inefficient, efforts should be made to boost the annual number of deep energy renovations from an average of 1% of all buildings to 3% to meet the CO_2 reduction target [3,5].

In line with points 18, 19, 29, and 30 of the 2010/31/EU directive, it is crucial to research and test new solutions that aim for high efficiency and optimal technical conditions. This will ensure economic and functional feasibility while helping maintain optimal indoor environmental quality standards by improving the digitalization and smart-readiness of buildings [1] (pp. 15–17). When tackling these challenges, involved actors such as architects, construction professionals, and management entities should embrace a "performance-oriented" mindset throughout their deep energy renovation design and implementation process to improve efficiency [6]. There is potential to improve productivity in the lagging construction industry by adopting technologies and methodologies that have allowed the manufacturing sector to improve its output. Still, it is a complex process that requires careful evaluation to determine the best approach [7].

Key performance indicators (KPIs) are a valuable tool for providing feedback on the progress toward specific goals and enhancing processes [8]. In this sense, their use in deep energy retrofitting is essential. They can represent the project's compliance with economic, social, and environmental considerations [9,10], referred to as the "pillars of sustainability" [6] (p. 8).

Renovation projects vary in scale, technical implications, socioeconomic context, and stakeholders, leading to sometimes divergent interests and concerns. Because of these differences, no definitive selection of KPIs applies universally [7,9,10]. However, applying KPIs adopted from literature or previous experiences can be a valuable starting point for any project.

In the eurozone, insufficient labor qualification and process industrialization [8], along with intricate regulations, designs, and supply chains, have contributed to static productivity rates in the construction industry that have remained largely unchanged for over three decades. Since 2014, productivity in construction has increased by only 10% [11]. The static productivity is notable compared to other areas such as the manufacturing industry, which has nearly doubled its productivity over the same period [5,12].

A growing focus has been placed on exploring innovative digital manufacturing technologies in construction research to bridge the productivity gap. However, this approach has emphasized manufacturing management, with comparatively less progress in industrialization and automation [11]. As a result, KPIs may play a pivotal role in achieving these transformative changes within the construction industry [13].

Besides productivity issues, there are significant restrictions on altering a building's existing constitution. These restrictions may be determined by local habits or standard solutions that affect the users' and public administration's willingness to incorporate new technologies and systems, particularly when they affect the building's envelope [14]. The project stakeholders' perceptions of the result considerably influence the adoption rate of new technologies and processes.

These challenges become greater when addressed on an urban scale. The urban renovation plans of the European Union aim for energy efficiency improvement while reducing the dependence on fossil fuels and increasing operating efficiency and comfort conditions. This implies the need for a collaborative energy and services exchange among stakeholders. The different social, cultural, and economic characteristics of existing European cities must be considered. Hence, a methodological proposal for speeding up annual energy renovations must consider the variations in existing urban conditions [15].

This paper describes the selection of key performance indicators (KPIs) for Horizon's European project INPERSO. The KPIs were chosen through an iterative process, combining a literature review and a multi-criteria decision analysis (MCDA) approach in collaboration with 22 expert partners [16]. The project focuses on evaluating emerging technologies and interfaces to improve building energy efficiency. These technologies, aimed at increasing their technological readiness level (TRL), will be integrated into three demonstration sites located in Valencia (Spain), Athens (Greece), and Velp (The Netherlands).

The process insights and methodology are poised for replication in other projects, encouraging collaboration between academia, industry, and public administration. By narrowing the gap between the projected and actual adoption of performance-based solutions, this approach will help the construction industry achieve more cost-effective, appealing solutions, ultimately increasing the annual rates of deep energy renovations.

1.2. INPERSO: Industrialised and Personalised Renovation for Sustainable Societies

The European Horizon project INPERSO, Industrialised and Personalised Renovation for Sustainable Societies, is a comprehensive deep renovation program. The project addresses the entire building life cycle, providing inclusive, affordable, and sustainable solutions that adapt to diverse climate zones and building configurations, with a focus on residential and heritage buildings. It tackles challenges related to digitalization, fragmentation, quality, efficiency, and speed while maintaining a human-centric approach throughout the process—from project design to end-of-life. The project proposes a "one-stop-shop" solution for industrialized renovation involving various technologies under development [17].

The INPERSO project is divided into three stages, namely, pre-, during, and post-retrofit. It must be completed in four years and has a clear set of objectives and expected implementation outcomes. Its development is based on renovating three "mock-ups" or demonstration cases (DCs) for residential use in three European cities: Valencia, Spain; Velp, The Netherlands; and Vouliagmeni, Greece. These three cities have various socioeconomic realities as well as diverse urban morphologies and climatic conditions, making them ideal for testing the adaptability of INPERSO to different contexts.

The particular selection of DCs considered the following contributions to the field of energy rehabilitation:

1. The variety of residential uses and users, as well as dwelling typologies;
2. The proper conditions for the scale-up of technologies and further method implementation;
3. The possibility of stakeholder engagement and communication;
4. The connection of small and medium enterprises (SMEs) with the local community;
5. Enhancing building managers' capability to address the EU's current renovation speed-up objectives;
6. The administration's willingness to adopt legislation and proper conditions for "sandbox" testing scenarios.

The experimental retrofits involve installing innovative technologies and interfaces to be tested throughout the project, focusing on the building envelope and increasing equipment efficiency without altering the heritage value. These areas of intervention—the envelope and active systems—are identified as the most impactful actions in the literature [18]. The technologies include an all-in-one pod that integrates heating, ventilation, and air conditioning (HVAC) and domestic hot water (DHW); photovoltaic integrated panels (PVIs); smart windows with photovoltaic energy production; and an intelligent and high-efficiency cladding system for wall insulation or "Smart Wall". These form the essential components of the "retrofit kit", a set of technologies to level up their technological readiness level—from 5–6 to 8–9, depending on the technology—by implementation and testing in actual scenarios provided by the demonstration cases. Additionally, digital interfaces are tested for real estate management, building energy management, and user behavior analytics and adaptation through demand response techniques to reduce the energy retrofit performance gap.

Although two DCs have heritage restrictions—the Spanish and Dutch DCs—traditional and experimental deep energy retrofits will be applied in each of the three demonstration cases. By doing so, results for each implementation situation may be easily compared. The demonstration cases' contextual differences make them ideal for testing the methods and technologies within the project's scope.

Owing to the project's main objectives, the three proposed demonstration cases present specific characteristics that make them ideal for the four-year study. They are expected to undergo a deep energy renovation—which affects over 25% of the envelope—and are managed by local municipal or non-governmental organizations, ensuring that replicability can be expected with the obtained experience.

Among these cases, certain participants play key roles in specialized areas. For instance, see the following:

- The Valencian Institute of Building (IVE) leads efforts in user engagement, economic analysis, and lifecycle analysis (LCA);
- Tampere University focuses on social-related studies, particularly stakeholder engagement and post-occupancy evaluations, to assess performance gaps;

- The Swiss Federal Institute of Technology of Lausanne contributes its expertise in Indoor Environmental Quality (IEQ), utilizing low-cost equipment to ensure affordability and conducting demand response studies to promote behavioral change;
- Core Innovation and Acciona provide valuable insights into energy evaluations and grid adaptability through self-generation.

The four technologies, fabricated by the four different providers related to the industry sector, will be implemented in the three demonstration sites. Each site is managed by a dedicated entity: Actuacions Urbanes Municipals S.A. (AUMSA) in Spain, Monumentenwacht (MWNB) in The Netherlands, and Vari-Voula-Vouliagmeni's municipality (VVV) in Greece.

Additionally, the partners' work also involves enhancing digital platforms focusing on energy monitoring and forecasting and real estate management through digitalization, led by R2M and Demo Consultants, experts in digital tools and real estate management respectively.

2. Literature Review

Building energy renovation is a complex, costly, disruptive, and time-consuming process. While past research has focused on various aspects of renovations, the failure to address the interdependency of these factors often results in fragmented assessments that do not capture the full scope of the problem [19]. KPIs have been proposed as a holistic tool for evaluating energy retrofits, providing a more comprehensive approach to decision-making [19]. These have been studied through various methods, including literature reviews, workshops, decision-making, and case studies [8,13,19–21].

One major concern expressed in the literature is the significant gap between projected and actual renovation performance, largely due to user behavior and perception. This discrepancy can account for nearly half of the efficiency gains in a renovation project, as real-world user behavior often diverges from theoretical models. As highlighted in the literature, this gap can be minimized by incorporating user-centric indicators [20].

Although EU projects offer an ideal environment for testing and refining KPIs, challenges remain in transferring these findings to the broader renovation industry. Standardization and proper methodological definitions for performance evaluations are still lacking [8].

Despite efforts to streamline indicators, researchers often end up with an unmanageable list of metrics that are unrealistic for most projects, especially on a large scale. Some studies have developed more manageable KPI lists that focus on essential aspects, but these tend to overemphasize economic factors and lack measures for evaluating new technologies and industrialization [19]. The absence of a concise, relevant set of indicators that addresses energy renovations with new technologies and user behavior in mind remains a significant gap in the literature.

This research aims to refine the existing KPIs by aligning them with the INPERSO project and the urgent energy transition, ultimately developing a more focused and relevant list of indicators for deep energy renovation.

3. Data and Method

This research took an iterative approach to selecting the final key performance indicators (KPIs), focusing on their relevance and applicability. The KPIs must address all critical aspects of the project without hindering implementation or renovation efforts. They must demonstrate progress to the stakeholders, including local and European authorities. The selection process, illustrated in Figure 1, includes three main steps: (i) conducting a review of the literature on KPIs and commonly used standards in deep energy renovations for residential buildings; (ii) using a multi-criteria decision analysis (MCDA) approach with the 22 partners involved in the INPERSO project; and (iii) finalizing the KPIs by defining their purpose, related standards, and timeframe for application.

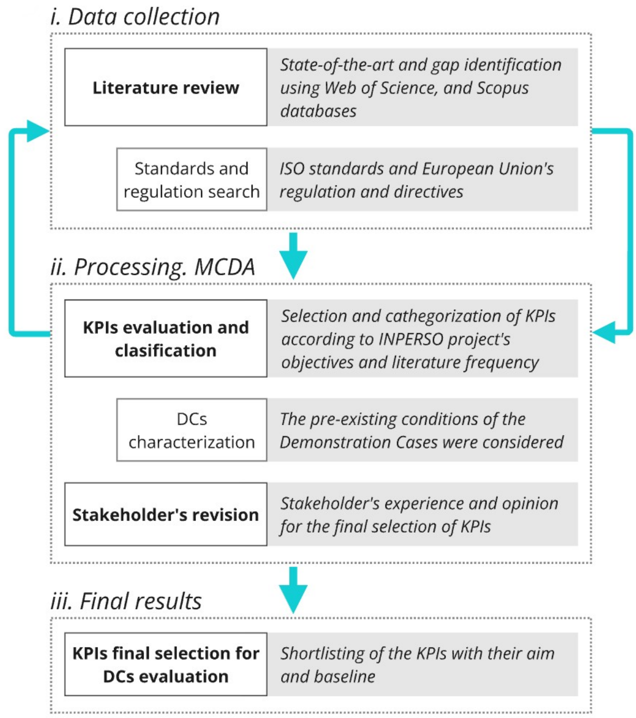

Figure 1. Selection process of the INPERSO project's KPIs.

3.1. *Characterization of the Demonstration Cases*

The DCs possess the characteristics described in Table 1.

Table 1. The main characteristics of the demonstration cases under study in the INPERSO project.

Parameter	DC#1	DC#2	DC#3
Location	València, ES	Velp, NL	Vouliagmeni, EL
Project type	Major renovation (>25% of the envelope)	Major renovation (>25% of the envelope)	Major renovation (>25% of the envelope)
Climatic Zone	Mediterranean Climate. Zone 1–2 ECOFYS	Temperate. Zone 4 ECOFYS	Mediterranean Climate. Zone 1–2 ECOFYS
Year of construction	1850	1860	1962–1964
Last intervention	2002 (major renovation)	1990 (major renovation)	2010 (minor intervention)
Building form	Two symmetrical multi-family apartment blocks	Two-story monastery with hipped roof	Detached four-story building
Floor area (sqm)	1024	256	885
Market Segment	Leasehold, market rental	Social shelter	Social shelter
Servicing	Without centralized heating, ventilation, and air conditioning	Natural gas boilers for domestic hot water, biomass water boiler heating, and no AC	Electric domestic hot water, oil boiler for heating, and individual splits for AC
Current Energy Demand (kWh/m^2 year)	52.83	417.11	326.40
Current annual CO_2 emissions (KgCO_2/m^2 year)	22.67	24.56	100.90
Standards used for the estimated data	HU CTE-HE and CEE (HULC)	IDA Indoor Climate and Energy 5.0. ASHRAE Weather Data Viewer 5.0	TEE-K.EN.A.K. 1.31 Software for national EPC

3.1.1. DC#1: Valencia, Spain

DC#1 consists of a symmetrical two-block multifamily building in Calle La Estrella in Valencia's Extramurs neighborhood (Figure 2a). The building houses 16 dwellings—eight on each block—for public rent purposes, currently inhabited by tenants. There are two typology configurations, one-room and double-room typologies, each including one bathroom, a kitchen, and a living room area.

(**a**) (**b**)

Figure 2. (**a**) Demonstration Case 1 in Valencia, Spain. (**b**) Demonstration Case 2 in Velp, The Netherlands.

The building has heritage protection for its main façade and roof. It underwent a major renovation in 2002, including replacing the wooden windows with aluminum ones, increasing the back façade's thermal performance by incorporating internal cladding, and improving the interior aesthetics and functionality (flooring, bathroom, kitchen finishing, and equipment). These interventions do not currently meet the current building performance standards; thus, the building owner, AUMSA, aims to improve its overall energy efficiency by undertaking a retrofitting project.

AUMSA manages a building stock of 598 dwellings, making it the ideal testing scenario for further replication. After application in one building belonging to this important public housing entity, further development of other assets managed by AUMSA and other local or regional housing entities is possible.

3.1.2. DC#2: Velp, The Netherlands

Demonstration Case 2 (Figure 2b) involves the Trinity Complex, located near Velp, in Noord-Brabant, The Netherlands. The three buildings—Saint Vincent's Church, Emmaus Monastery, and Brockhorst Monastery—dating back to the 12th, 17th, and 19th centuries, respectively, have complete heritage protection. Brockhorst Monastery will be subjected to interventions in this project.

In 1990, the monastery was redeveloped for residential purposes. Its current function is housing for temporary labor migrants. The building has several common rooms, around thirty apartments, and shared kitchen and sanitary facilities. The aim is to renovate the building into modern units. Both monasteries in the complex are privately owned by building contractors and developers, and the maintenance and renovation works are managed by the MWNB.

The strategic importance of this demonstrator lies in its cultural importance, considering the variety of user profiles consisting of managers, visitors, employees, and refugees. At the same time, the building presents the highest heritage restrictions among the three demonstrators, which makes it an ideal testing scenario for determining the compatibility between new deep energy retrofitting techniques and traditional heritage protection barriers.

3.1.3. DC#3: Vouliagmeni, Greece

Demonstration case 3 (DC#3), is the Litous Social Shelter in Vouliagmeni, Greece (Figure 3). Built between 1962 and 1964, it is a four-story building comprising a social shelter (the ground, 1st, and 2nd floors), owned by the public municipality of Vari-Voula-Vouliagmeni (VVV), and a privately owned floor (the 3rd floor) not included in the project.

Figure 3. Demonstration Case 3 in Voula, Greece.

The building comprises nine apartments that host up to 40 people, with 8 permanent staff members. The building has no official heritage protection, but the intervention aims to minimize negative appearance alterations. Advanced Management Solutions (AMS) is the technical representative for the retrofit project of the building.

The vulnerability of the residents of this demonstrator demands a special approach compared to the other demonstrators, making it ideal for testing how these new technologies and methods can minimize disturbing the lives of vulnerable users. Such an improvement will make the project appealing to a broader field of residential-related building typologies and programs.

3.2. Literature Review of KPIs and Standards

Starting with a comprehensive search for KPIs and standards, the literature review focused on previous experiences in performance evaluation related to the energy renovation of existing residential buildings [7,10,14,18]. This process was initiated by querying scientific databases—specifically, the Web of Science and Scopus—using targeted keywords such as “deep energy renovation” and “key performance indicator”. The initial results were screened based on their titles, filtering out articles that were irrelevant to the topic.

A more detailed selection was conducted by reviewing abstracts and full records, focusing on identifying the KPIs explicitly discussed in the literature. In addition to the KPIs identified in scientific articles, supplementary databases containing regulations, standards, and best practices—such as ISO, AENORmas, and Eurolex—were consulted. A similar filtering process was applied, focusing on the regulations and standards that emerged during the scientific literature review.

This approach led to a comprehensive list of indicators covering renovation, construction, and energy efficiency. This phase aimed to gather KPIs from various energy renovation projects and sources. Similar indicators were merged and irrelevant ones were discarded in collaboration with the partners taking part in the project. Key articles were used to categorize them. The final selection focused on indicators frequently used across multiple publications and highlighted by various authors [6,8,9,21–23].

3.3. Multi-Criteria Decision Analysis. KPI Evaluation and Expert Consultation Sessions Using the Weighted Sum Method

To assess whether the identified KPIs were sufficient for evaluating the project's future outcomes, the most relevant conditions and objectives were analyzed and the obligations were considered, as ensuring compliance with these is essential for determining success. At the end of the project, stakeholders must be informed of how well the results meet these obligations.

The strategic objectives of the INPERSO project regarding the retrofit technologies and interfaces are as follows:

1. Provide a unified, interoperable platform for information management across the building's life cycle, ensuring efficient stakeholder communication;
2. Develop affordable, adaptable, low-carbon renovation models that bridge the design–build gap, enhance resilience, and actively involve users in the process;
3. Speed up the adoption of advanced manufacturing and prefabrication technologies in renovation to reduce waste and lower energy demand during the process;
4. Inclusively address personalized comfort needs by enhancing building smartness;
5. Provide a complete system of near-commercial readiness products and processes.

Considering these objectives, the multi-criteria decision analysis (MCDA) method was applied after selecting KPIs from the literature. This process allowed adjustment of the indicators to better reflect the project's specific factors and the diverse perspectives within the consortium.

Using the weighted sum method (WSM) [16,24], the KPIs were refined to integrate both quantitative and qualitative aspects, aligning them with the project's objectives. This approach was essential for addressing the complexity of the project, where stakeholder interests may conflict and economic, social, and environmental factors must be considered for sustainability [25].

At this stage, the main goal was establishing a list of KPIs for the deep energy renovation of buildings. Criteria and alternatives were defined, as shown in Figure 4. The indicators were evaluated based on three criteria:

- Frequency of appearance in the literature (gathered during the literature review);
- Alignment with the five project objectives;
- The user-centric emphasis of each KPI.

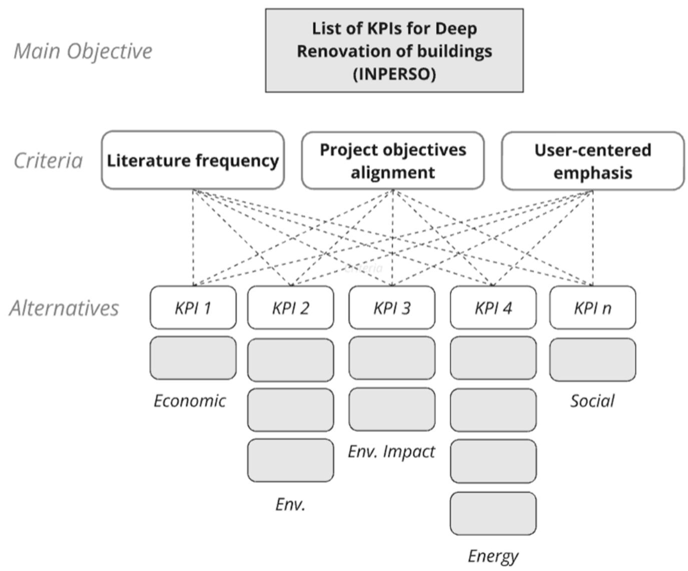

Figure 4. KPI selection process using the MCDA.

Each KPI was assigned a grade based on its alignment with these criteria—low, medium, or high—corresponding to values of 0.5, 0.7, and 1.0, respectively. Different weights were assigned to each criterion according to the project's priorities: the frequency of appearance in the literature was weighted at 20%, accounting for a half relative importance in comparison to the project objectives and user-centricity, which were each given an equal weight of 40% based on the partners' opinions and literature [20].

Each KPI was then assigned a score (S) considering the logic expressed in Table 2.

Table 2. Criteria for the MCDA using the WSM.

Criterion Weight	W1 (%)	W2 (%)	W3 (%)	Total Score per Alternative
Alternative	**Criterion 1**	**Criterion 2**	**Criterion 3**	
KPI 1	X11	X12	X13	S1
KPI 2	X21	X22	X23	S2
KPI n	Xn1	Xn2	Xn3 [1]	Sn

[1] Low (0.5), Medium (0.7), or High (1) evaluation according to the affinity.

The score for each KPI was obtained with the following equation:

$$Sn = [(Xn_1 \cdot W_1) + (Xn_2 \cdot W_2) + (Xn_3 \cdot W_3)] \quad (1)$$

in which the scores over 80% (Sn > 0.80) determined the selected KPIs.

After the MCDA process, the iterative process of refining and validating the KPIs was guided by partner input. To enhance efficiency, the specific KPI categories were assigned to the most relevant partners, minimizing duplication of effort. Stakeholders also contributed additional resources, such as articles, standards, and regulations, to complement the initial literature review. They provided final feedback on the academic and scientific relevance, as well as the feasibility of the KPIs.

Throughout this phase, any gaps or areas needing further refinement were identified. If a KPI lacked sufficient impact or a new one was needed, a follow-up literature review was conducted. This iterative process ensured a comprehensive evaluation of the KPIs.

3.4. Final Selection and Characterizacion of KPIs

After identifying and refining the most suitable indicators for the INPERSO project, the most impactful were selected as key performance indicators (KPIs) for the future deep renovation of the demonstration cases (DCs). For each KPI, a baseline was established based on literature reviews, expert interviews, and consensus among consortium partners. This baseline is a reference point for comparing KPI measurements, allowing for quantifying improvements throughout the project's development phases.

In addition to the baseline, a timeline for implementing each KPI was defined to clarify how the project's objectives will be achieved. The frequency of measurement or monitoring varies among the indicators. Given that the project is structured into three stages—pre-, during, and post-retrofit—the selected indicators are aligned accordingly.

4. Results

The KPI selection involved a refinement and consolidation process designed to optimize results by considering key factors such as sustainability, economic viability, social impact, and technological adaptability. The KPIs were categorized into major groups based on the literature reviews and expert input. A description, classification code, relevant units of measure, and a recommended baseline for comparison accompany each KPI.

From the initial search a total of 182 indicators were identified; these were screened and reduced by consolidating similar indicators and removing unrelated ones. During this initial process, consultation with partners took place to define which indicators had any relevance to the project and its objectives. Finally, a total of 26 indicators were pre-selected in five categories, namely, Economic, Environmental, Environmental Impact, Energy, and Social.

The final refined list of indicators resulting from the MCDA supported by the WSM (Figure 5) was decided among the experts and project coordinators, assigning major relevance to the indicators that, coming from the initial literature review, best represented the objectives of the project and the user-centric perspective. This final review reduced the list to 17 key performance indicators.

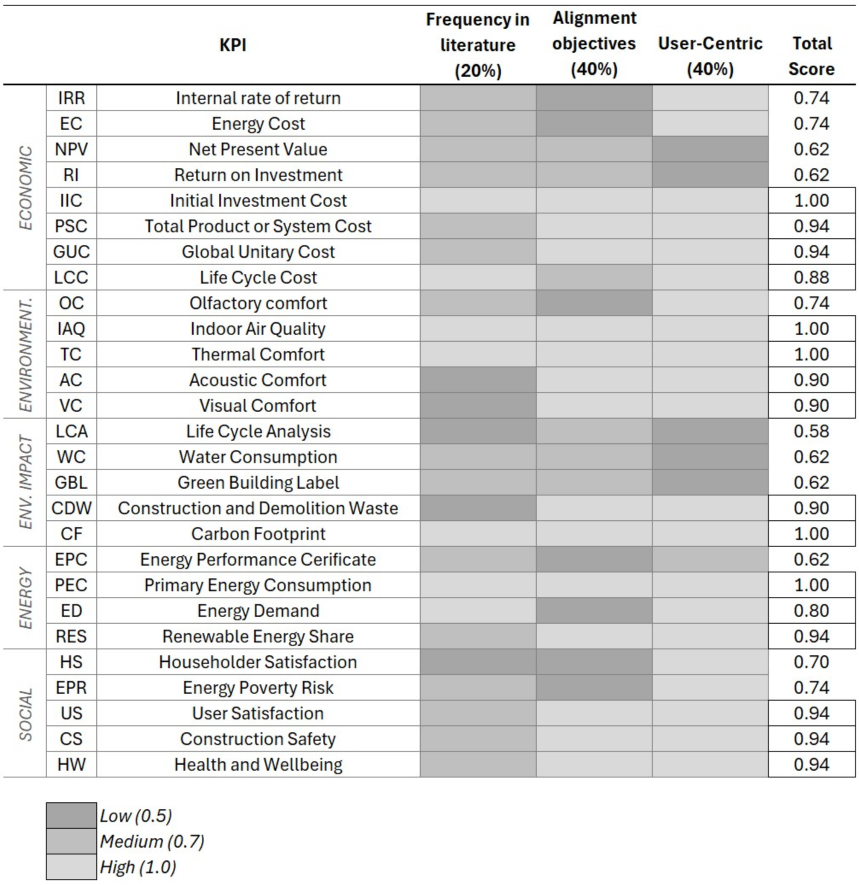

Figure 5. MCDA process using the WSM for KPI refinement.

After the MCDA process was performed, these five initial categories were complemented by a sixth one, Technological, whose two indicators were proposed to comply with multiple project objectives lacking any indicators proposed by the digital platform experts that monitor the DCs.

Table 3 presents the final selection, showing the KPI groups, specific indicators, and corresponding baselines. The baseline provides a framework for proper comparison and ensures alignment with the project's objectives. Each group and its corresponding KPIs are described in the following sections.

Table 3. Selected and refined sets of key performance indicators (KPIs) with their assigned group and baseline.

KPI Group	Included KPIs	Baseline
Economic	Initial Investment Cost (IIC) Total Product or System Cost (PSC) Global Unitary Cost (GUC)	The country's average costs Costs without interventions Traditional retrofit
Environmental	Indoor Air Quality (IAQ) Thermal Comfort (TC) Acoustic Comfort (AC) Visual Comfort (VC)	ASHRAE standards ASHRAE standards ASHRAE standards ASHRAE standards

Table 3. *Cont.*

KPI Group	Included KPIs	Baseline
Environmental Impact	Total Construction and Demolition Waste (CDW) Carbon Footprint (CF)	Average CDW per SQM in the city/country Pre-Retrofit LCA
Energy	Primary Energy Consumption (PEC) Energy Demand (ED) Renewable Energy Share (RES)	Pre-Retrofit values Pre-Retrofit values Pre-Retrofit values
Social	User Satisfaction (US) Construction Safety (CS) Health and Well-being (HW)	Pre-Retrofit values Local statistics for Spain, Greece, and The Netherlands Pre-Retrofit values
Technological	System Prediction Effectiveness (SPE) System Optimization Effectiveness (SOE)	Traditional systems Traditional systems

4.1. Economic KPIs

The economic sustainability KPIs mainly focus on design, construction, product purchase, installation, maintenance, and energy consumption costs. The life cycle cost (LCC) perspective is typically considered in the literature [6].

The chosen KPIs are based on the UNE-EN 15686-5 [26] standard, emphasizing the life cycle costs of buildings and constructed assets. The UNE-EN 15459-1 standard is also used to economically evaluate building energy efficiency [27]. These indicators enable analysis of the economic benefits of the new solution compared to traditional energy rehabilitation measures set as the baseline.

4.1.1. Initial Investment Costs (IICs)

The IICs are expressed in euros as all expenses incurred up to the point when the building or its elements are delivered and ready to use. The baseline selected considers each country's average cost for a rehabilitation project [27].

4.1.2. Total Product or System Cost (PSC)

The PSC represents the overall cost associated with a specific product or system. This global cost includes the present value of the IIC, running costs, replacement costs (from the starting year), and applicable disposal costs. The baseline is the dwelling's total operative cost (TOC) without intervention.

4.1.3. Global Unitary Cost (GUC)

The GUC is measured in euros per square meter per year and calculated by dividing the global cost of the building—across the calculation period—by its total area. Global cost includes the present value of the IIC; running and replacement costs (from the starting year); and, if applicable, disposal costs. The baseline is the GUC found in traditional interventions, which will occur simultaneously with innovative ones for all three demonstration cases [27].

4.2. Environmental KPIs (User-Centric)

With a user-centric approach, this category aims to ensure the optimal environmental conditions for the user. During deep energy renovations, it is vital to prioritize human health and well-being. According to the relevant literature, four key environmental variables significantly impacting health and productivity should be closely monitored as KPIs [22]. These KPIs reflect essential parameters throughout the renovation project, aiming for optimal user conditions. They are scored on a scale from 0% to 100%, with 100% being the optimal condition.

4.2.1. Indoor Air Quality (IAQ)

IAQ sets its baseline according to the toxic threshold of the most relevant and representative air pollutants, CO_2, volatile organic compounds (VOCs), and particulate matter of 2.5 µm ($PM_{2.5}$). The maximum score is represented by the external normal concentrations considered optimal.

Even though NO_2 (nitric dioxide) and formaldehyde are considered relevant and could be included, complex and expensive procedures are required and were not deemed justifiable due to their costs. Optimal ventilation conditions can ensure that these values are acceptable, making it unnecessary to consider the cost–benefit relation.

4.2.2. Thermal Comfort (TC)

Following the ASHRAE 55 2020 and ISO 7730 standards [28,29], this KPI combines six factors that define acceptable thermal conditions: metabolic rate and clothing insulation (occupant's characteristics), air temperature, radiant temperature, air speed, and humidity [27].

It is assessed using predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD), which reflect the users' subjective perceptions of indoor thermal conditions. For buildings with heating and cooling, thermal comfort (TCO) comprises six parameters: relative humidity, air temperature, airspeed, mean radiant temperature, clothing index, and activity index [22].

4.2.3. Acoustic Comfort (AC)

AC compares "actual sound pressure level" and "design sound pressure level" in decibels for the studied room to set the predicted percentage of dissatisfaction (PPD) [22]. A 100% score predicts total satisfaction if the measured noise level equals an appropriate noise level for the activity.

4.2.4. Visual Comfort (VC)

VC measures the end-user's satisfaction with the retrofit process, without compromising illumination standards and guaranteeing a comfortable living environment. It takes the statistical prediction of all dissatisfied users, considering the data of illumination in general, in addition to the conclusions extracted from user surveys [22].

For all four indicators, the baseline compares data before, during, and after retrofitting the three demonstration sites. This not only allows for the contrast between normal operating conditions before and after improving the energy efficiency of the buildings but also analyzes the impact that the construction process may have on the user's comfort.

4.3. Environmental Impact KPIs

It is important to measure how much the project affects the environment if a sustainable large-scale renovation process is to have a positive impact.

4.3.1. Carbon Footprint (CF)

The CF represents the amount of equivalent CO_2 produced throughout the entire life cycle of the retrofitted building. This value is derived from a life cycle analysis (LCA) study. It is expressed in carbon dioxide per square meter [30], quantified for various phases, including the building's renovation, use, maintenance, and disposal phases [31].

The baseline is set with the pre-retrofit conditions without any intervention. The objective of INPERSO is that, despite the initial CO_2 production when performing the retrofit, the long-lasting effect will result in a significant equivalent carbon reduction.

Even though the literature often includes the carbon footprint as an environmental KPI, within the framework of INPERSO, CO_2 has been deliberately disentangled from other environmental factors as the project's core priority is to emphasize the user's health and well-being. It is essential to clarify that the estimate of CO_2 discussed here should not be confused with the measurement of indoor environmental quality, expressed in parts per million; it is directly related to the detrimental effects of CO_2 on human health and well-being.

4.3.2. Total Construction and Demolition Waste (CDW)

CDW measures the kilograms of material sent to the landfill during the demolition and construction of the retrofit project. This KPI measures the magnitude of the renovation work's impact on the environment. The measurement results should be compared with local or national averages to help determine if the project has performed better than others, thanks to prefabricated elements or new installation systems. The LCA is performed using the Ecoinvent database.

4.4. Energy KPIs

The main energy performance evaluations are contained in the UNE-EN 15316-1 (Energy Performance of Buildings, or EPB) [32], EN-ISO 52000-1 [33] (overarching EPB assessment), and ISO 7345 [34] (Thermal insulation) standards, which were considered in the selection of standards for the project's evaluation.

4.4.1. Primary Energy Consumption (PEC)

The PEC is expressed in kWh per square meter per year and usually constitutes the main tool used to evaluate the amount of renewable and non-renewable energy consumed in a specific reference unit of space (sqm). It is commonly implemented as it does not discriminate among energy carriers, making it ideal for this kind of project in which we encounter several types of systems using different types of energy (fuel, gas, and electricity) that electrical ones will eventually replace.

To achieve "nZEB" (Nearly zero-energy buildings) standards, the efficiency of the energy pods comprising the HVAC and DHW systems will be evaluated, considering the primary energy comparison between the current and the renovated situation [33]. In this case, the baseline compares the standard energy consumption of existing systems with the post-renovation results using INPERSO technologies while ensuring there is no risk of energy poverty. In the initial scenario, comfort conditions are not fully met owing to the high energy cost, so energy consumption estimates are higher than currently used. Since many users cannot afford to maintain comfortable conditions, the simulations assume that comfort will be achieved after the renovation. As a result, even though efficiency will improve, overall energy consumption may increase because comfort is expected to be maintained throughout the day [35].

4.4.2. Renewable Energy Share (RES)

Expressed as a percentage of the total energy consumption, RES represents the share of renewable energies compared to the dwelling's total energy consumption. The baseline is set for the current situation, and the results range from 0% to 100% of the share [36]. This evaluation is crucial as we have more than one technology that generates renewable energy on-site, and each country has its specific renewable energy share available on the grid.

4.4.3. Energy Demand (ED)

ED is measured in kWh per square meter per year and represents the energy theoretically needed to maintain user comfort. Calculation standards vary across EU countries but should align with ISO 52016-1:2017 (Energy Performance of Buildings) [37]. The baseline is obtained by analyzing the data from energy performance certificates and/or simulations without any intervention. The interventions focusing mainly on the envelope and active systems will directly influence these results, enabling us to evaluate each proposed technology's impact on the overall performance.

4.5. Social KPIs

Social indicators are crucial for a "user-centered" renovation process in residential buildings. There is a direct relation between the expected performance shift of the building and the commitment to the users and their well-being [38]. Even though many standards remain under consideration, several aspects may be observed from the available literature.

4.5.1. User Satisfaction (US)

US is measured on a scale from 0% to 100%, using qualitative methods such as walkthroughs, user interviews, and surveys [38]. The reference value is based on a pre-intervention questionnaire or survey, and the main parameters assessed are thermal, acoustic, visual, usability/acceptance of technology, privacy, and satisfaction with the renovation work [39].

4.5.2. Construction Safety (CS)

CS is measured as the number of incidents for every 100,000 workers. There are four indicators used by contractors for safety performance: the Experience Modification Rate (EMR), Recordable Incident Rate (RIR), Lost Time Incident Rate, and Worker Compensation Claims Frequency Indicator (WCCFI) [40,41].

4.5.3. Health and Well-Being (HW)

HW is a difficult parameter to measure as it depends on many factors that impact everyone's health [41]. An adapted version of the EQ-5D-5L tool was considered, which can be used in population health surveys [42]. It evaluates users' well-being and health as impacted by indoor environmental factors. The baseline is established through a pre-intervention questionnaire that includes the EQ-5D-5L scale. The tool was adapted to the project's aim, and special care is needed when analyzing the results, considering all the contextual factors influencing people's perceptions.

4.6. Technological KPIs

Modern smart home systems offer a new dimension to energy efficiency and must be evaluated in renovation projects. While a technological KPI group is mostly absent in the existing literature, the need to assess the INPERSO smart systems led to the creation of technology performance indicators based on the literature found in other fields and expert consultation, such as in system engineering and industrial quality assurance.

4.6.1. System Prediction Effectiveness (SPE)

SPE measures how well the system detects environmental and energy device anomalies based on data and sensor inputs. It reflects the platforms and devices' predictions using available data to determine when active systems should take corrective or proactive measures or communicate to the user to improve their system effectiveness [43]. The system scores the SPE KPI from 0% to 100%, with 0% indicating "no correct predictions" [44]. This KPI is fundamental to identifying if a predictive system is working as intended, resulting in a more transparent way to determine the actual benefits of such systems.

4.6.2. System Optimization Effectiveness (SOE)

SOE refers to how effectively all active systems optimize energy and the environmental aspects of the dwelling. This KPI aims to convey the system's synergy and quantify improvements compared to a scenario without smart technologies. It is measured on a scale of 0% to 100%, with 0% indicating no improvement over the absence of smart systems. New active and responsive systems must be evaluated to determine their impact on the dwelling; active and reactive systems increase the cost and complexity of restoration and must be evaluated according to the benefit offered to the user or the project.

4.7. Timeline and Monitoring Framework for KPI Implementation

Figure 6 depicts the instances in which each KPI will be evaluated within the project's development, considering the pre-, during, and post-retrofit stages.

	Pre-Retrofit	Retrofit	Post-Retrofit
Economic	IIC GUC		
Environmental	IAQ TC AC VC	IAQ TC AC VC	IAQ TC AC VC
Env. Impact	CF	CDW CF	CDW CF
Energy	PEC ED RES	PEC ED RES	PEC ED RES
Social	HW	US CS HW	US HW
Technological	SPE SOE	SPE SOE	SPE SOE

Figure 6. Timeline for the application of each KPI for the INPERSO project's monitoring.

5. Discussion

The pressing need to increase annual deep energy renovations in the European building sector necessitates a performance-oriented approach among stakeholders to improve productivity and efficiency, particularly given the stagnant productivity rates in the construction industry compared to manufacturing [1,2,11]. The industrialization potential of deep energy renovations for dwellings highlights the importance of a KPI-based methodology for achieving more sustainable and cost-effective outcomes [8].

This investigation aims to develop and refine KPIs to evaluate industrialized solutions for deep energy renovations. The method draws from the experience of experts and field-related partners in defining the optimal way to evaluate the performance of innovative retrofitting technologies within three demonstration cases of Horizon's INPERSO project. The selected KPIs, obtained using a multi-criteria decision analysis process based on the weighted sum method, were then refined according to the standards and project references with the collaboration of all the stakeholders. By creating an industrialized solution integrating the design and fabrication aspects of retrofitting technologies, the project aims to significantly increase user comfort and reduce costs and environmental impacts by optimizing and standardizing these processes.

The KPIs established within this framework, with their corresponding categories—Economic, Environmental, Environmental Impact, Energy, Social, and Technological—serve multiple purposes: they facilitate comparisons across traditional retrofit stages (pre-, during, and post-) and enable contrasts between conventional retrofitting methods and those utilizing the INPERSO approach, retaining a strong user-centered perspective. This development is crucial for generating the structured information necessary for the rapid decarbonization of existing EU buildings with low disruption, thus allowing a greater pace of adoption [13]. While these KPIs were initially designed for the INPERSO project, they can provide the framework for other deep renovation initiatives incorporating innovative technologies.

The KPIs presented in this document represent one of many configurations adaptable to the specific goals and expected outcomes of various demonstration cases. The significance of each KPI and the decision to include or exclude others will depend on the project's objectives. Monitoring building conditions is vital to enhancing efficiency and minimizing harmful impacts. To illustrate the performance gap reduction from industrialized retrofitting, selecting KPIs must be complemented by robust and exhaustive monitoring practices.

The project implementation phase began in its second year of development. For this phase, the initial approach among partners and examples from the literature were crucial for organizing a clear analysis framework. The particular industrialization scenario of processes and technologies gave rise to a specific set of KPIs from previous experiences and the existing partners' know-how, which may be adapted at later stages of the project.

Distinguishing between the effects of traditional and innovative technologies on the KPIs is essential for analyzing results. It is crucial to differentiate between "business as usual" and innovative processes. Monitoring the impact of these technologies on environmental, social, and economic conditions is vital for the construction industry's transition toward greater sustainability and efficiency while maintaining a user-centric perspective. At future stages of the INPERSO project and for other studies, a cost-effectiveness approach will be essential for 75% of existing buildings to improve their efficiency.

Limitations

The MCDA applied in this investigation is based on the weighted sum method (WSM), which allows for translating complex qualitative data for decision-making into quantitative data, particularly when several interdisciplinary teams participate. In future studies, other methods could be applied to further systematize the decision-making.

The KPIs proposed in this project were derived from the literature review, systematic approach, and previous experiences of the partners in the field. Still, the finalization of the project will be the final validation, making it one of the major limitations in this investigation.

Additionally, further studies should investigate how to adapt these KPIs for various building types (apart from residential) and climates and explore their integration into digital building management systems to enhance their applicability and promote long-term energy savings.

The heritage restrictions on some buildings presented social and cultural barriers, which were present mainly in DC#1 and DC#2, complicating the approval from public administrations for new technologies. Thus, it is crucial to assess the willingness of public authorities to allow greater flexibility in adopting such innovations, as this is recognized as a major obstacle to the widespread adoption of deep renovations in the construction industry.

6. Conclusions

The KPIs developed within the INPERSO project present a significant advancement toward achieving the EU's energy reduction goals. By promoting a performance-oriented approach among stakeholders, these KPIs facilitate the evaluation of industrialized solutions for deep energy renovations, balancing technological advancements with human comfort.

Their Economic, Environmental, Social, and Technological categorizations allow for comprehensive comparisons across various retrofit stages and methods, which are essential for the rapid decarbonization of existing buildings. Continuous monitoring and real-time evaluation of these indicators will ensure that predicted energy savings are realized throughout a building's life cycle. While further adaptation is needed for diverse building types and climates, this research provides a robust framework for sustainable renovation practices. Integrating these KPIs into digital building management systems will enhance their applicability, creating a critical tool for driving innovation and achieving global sustainability goals in the construction industry.

Author Contributions: Conceptualization, J.G.S.-M., M.D.-R.-E., S.S.G. and J.L.A.-R.; methodology, J.G.S.-M., M.D.-R.-E. and S.S.G.; software, J.G.S.-M. and M.D.-R.-E.; validation, J.G.S.-M., M.D.-R.-E., S.S.G. and J.L.A.-R.; formal analysis, J.G.S.-M.; investigation, J.G.S.-M., M.D.-R.-E. and S.S.G.; resources, J.L.A.-R.; data curation, J.G.S.-M. and M.D.-R.-E.; writing—original draft preparation, J.G.S.-M. and M.D.-R.-E.; writing—review and editing, S.S.G. and J.L.A.-R.; visualization, J.G.S.-M. and M.D.-R.-E.; supervision, J.L.A.-R.; project administration, J.L.A.-R.; funding acquisition, J.L.A.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the HORIZON EUROPE project INPERSO, Industrialised and Personalised Renovation for Sustainable Societies, grant number 101069820.

Data Availability Statement: The data supporting the research carried out in this paper are available from the authors, and the INPERSO project results will be available on the Zenodo platform.

Acknowledgments: The Institute for Heritage Restoration (IRP) at Universitat Politècnica de València (UPV) supported the research. The authors express their gratitude to the INPERSO consortium for their contributions and support, in particular to Raúl Castaño-Rosa at the Tampere University. Also, to Ignacio Guillén-Guillamón, Vanesa Celina Saez, Alberto Quintana-Gallardo, and Fernando Aitor Mendiguchia-Fontes from the Physics Technologies Centre (CTF) at the Universitat Politècnica de València (UPV).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Official Journal of the European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings. *Off. J. Eur. Union* **2010**, *L153*, 13–35.
2. Official Journal of the European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. *Off. J. Eur. Union* **2012**, *L315*, 1–56.
3. Official Journal of the European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (text with EEA relevance). *Off. J. Eur. Union* **2018**, *L156*, 75–91.
4. Official Journal of the European Union. 'Fit for 55′: Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550 (accessed on 29 September 2024).
5. EU Building Stock Observatory. Available online: https://building-stock-observatory.energy.ec.europa.eu/database/ (accessed on 15 July 2023).
6. Mosca, F.; Perini, K. Reviewing the role of key performance indicators in architectural and urban design practices. *Sustainability* **2022**, *14*, 14464. [CrossRef]
7. Kibira, D.; Brundage, M.P.; Feng, S.; Morris, K.C. Procedure for selecting key performance indicators for sustainable manufacturing. *J. Manuf. Sci. Eng* **2018**, *140*, 011005. [CrossRef]
8. Kylili, A.; Fokaides, P.A.; Lopez Jimenez, P.A. Key performance indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review. *Renew. Sustain. Energy Rev.* **2016**, *56*, 906–915. [CrossRef]
9. ALwaer, H.; Clements-Croome, D.J. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Build. Environ.* **2010**, *45*, 799–807. [CrossRef]
10. Angelakoglou, K.; Chatzigeorgiou, E.; Lampropoulos, I.; Giourka, P.; Martinopoulos, G.; Nikolopoulos, N. Monitoring the sustainability of building renovation projects—A tailored key performance indicator repository. *Buildings* **2023**, *13*, 2046. [CrossRef]
11. Van Sante, M. Lagging Productivity in Construction is Driving up Building Costs. 2022. Available online: https://think.ing.com/downloads/pdf/article/lagging-productivity-drives-up-building-costs-in-many-eu-countries (accessed on 24 July 2023).
12. G3: Business Cycle; Short-Term Statistics Unit. Short-Term Business Statistics (STS). *Luxembourg: Eurostat, the Statistical Office of the European Union.* Available online: https://ec.europa.eu/eurostat/databrowser/product/view/STS_COPR_A?lang=en (accessed on 24 July 2023).
13. Abbà, I.; Crespi, G.; Vergerio, G.; Becchio, C.; Corgnati, S.P. Key performance indicators for decision support in building retrofit planning: An Italian case study. *Energies* **2024**, *17*, 559. [CrossRef]
14. Kamari, A.; Corrao, R.; Kirkegaard, P.H. Sustainability focused decision-making in building renovation. *Int. J. Sustain. Built Environ.* **2017**, *6*, 330–350. [CrossRef]
15. De Tommasi, L.; Ridouane, H.; Giannakis, G.; Katsigarakis, K.; Lilis, G.N.; Rovas, D. Model-based comparative evaluation of building and district control-oriented energy retrofit scenarios. *Buildings* **2018**, *8*, 91. [CrossRef]
16. San Cristóbal Mateo, J.R. *Multi Criteria Analysis in the Renewable Energy Industry*; Springer: London, UK, 2012. [CrossRef]
17. INPERSO. Industrialized and Personalized Renovation for Sustainable Societies. Available online: https://www.inperso-project.eu/ (accessed on 10 July 2023).
18. Mancini, F.; Nastasi, B. Energy retrofitting effects on the energy flexibility of dwellings. *Energies* **2019**, *12*, 2788. [CrossRef]
19. Ho, A.M.Y.; Lai, J.H.K.; Chiu, B.W.Y. Key Performance Indicators for Holistic Evaluation of Building Retrofits: Systematic Literature Review and Focus Group Study. *J. Build. Eng.* **2021**, *43*, 102926. [CrossRef]
20. Mohareb, E.; Hashemi, A.; Shahrestani, M.; Sunikka-Blank, M. Retrofit Planning for the Performance Gap: Results of a Workshop on Addressing Energy, Health and Comfort Needs in a Protected Building. *Energies* **2017**, *10*, 1177. [CrossRef]
21. McGinley, O.; Moran, P.; Goggins, J. An assessment of the key performance indicators (KPIs) of energy efficient retrofits to existing residential buildings. *Energies* **2022**, *15*, 334. [CrossRef]
22. Mujan, I.; Licina, D.; Kljajić, M.; Čulić, A.; Anđelković, A.S. Development of indoor environmental quality index using a low-cost monitoring platform. *J. Clean. Prod.* **2021**, *312*, 127846. [CrossRef]
23. Lavy, S.; Garcia, J.A.; Scinto, P.; Dixit, M.K. Key performance indicators for facility performance assessment: Simulation of core indicators. *Constr. Manag. Econ.* **2014**, *32*, 1183–1204. [CrossRef]

24. Schuschny, A.; Soto, H. Guía Metodológica Diseño de Indicadores Compuestos de Desarrollo Sostenible; Santiago de Chile. 2009. Available online: https://repositorio.cepal.org/entities/publication/968ca596-2b42-4bb3-8e46-a8c3dae15cd1 (accessed on 3 September 2023).
25. Jie, P.; Zhang, F.; Fang, Z.; Wang, H.; Zhao, Y. Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions. *Energy* **2018**, *159*, 1132–1147. [CrossRef]
26. *ISO 15686-5:2017*; Buildings and Constructed Assets—Service Life Planning—Part 5: Life-Cycle Costing. ISO: Geneva, Switzerland, 2017.
27. *EN 15459-1*; Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings—Part 1: Calculation procedures, Module M1-14. European Committee for Standardization: Brussels, Belgium, 2017.
28. *ASHRAE Standard 55-2020*; Thermal Environmental Conditions for Human Occupancy. ASHRAE: Peachtree Corners, GA, USA, 2021; pp. 1–80.
29. *EN ISO 7730*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. European Committee for Standardization: Brussels, Belgium, 2005; pp. 1–60.
30. *ISO 14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. ISO: Geneva, Switzerland, 2018.
31. *ISO 16745-1:2017*; Sustainability in Buildings and Civil Engineering Works—Carbon Metric of an Existing Building During Use Stage—Part 1: Calculation, Reporting, and Communication. ISO: Geneva, Switzerland, 2017.
32. *EN 15316-1:2018*; Energy Performance of Buildings—Method of Calculation of System Energy Requirements and System Efficiencies—Part 1: General and Energy Performance Expression, Module M3-1, M3-4, M3-9, M8-1, M8-4. European Committee for Standardization: Brussels, Belgium, 2017; pp. 1–86.
33. *ISO 52000-1:2017*; Energy Performance of Buildings—Overarching EPB Assessment—Part 1: General Framework and Procedures. ISO: Geneva, Switzerland, 2017.
34. *ISO 7345:2018*; Thermal Performance of Buildings and Building Components—Physical Quantities and Definitions. ISO: Geneva, Switzerland, 2018.
35. Jones, P.; Li, X.; Perisoglou, E.; Patterson, J. Five Energy Retrofit Houses in South Wales. *Energy Build.* **2017**, *154*, 335–342. [CrossRef]
36. *ISO/TR 52000-2:2017*; Energy Performance of Buildings—Overarching EPB Assessment—Part 2: Explanation and Justification of ISO 52000-1. ISO: Geneva, Switzerland, 2017.
37. *ISO 52016-1:2017*; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures. ISO: Geneva, Switzerland, 2017.
38. Elsayed, M.; Romagnoni, P.; Pelsmakers, S.; Castaño-Rosa, R.; Klammsteiner, U. The Actual Performance of Retrofitted Residential Apartments: Post-Occupancy Evaluation Study in Italy. *Build. Res. Inform.* **2023**, *51*, 411–429. [CrossRef]
39. Elsayed, M.; Pelsmakers, S.; Pistore, L.; Castaño-Rosa, R.; Romagnoni, P. Post-occupancy evaluation in residential buildings: A systematic literature review of current practices in the EU. *Build. Environ.* **2023**, *236*, 110307. [CrossRef]
40. Ogwueleka, A.C. A review of safety and quality issues in the construction industry. *J. Constr. Eng. Proj. Manag.* **2013**, *3*, 42–48. [CrossRef]
41. Mollo, L.G.; Emuze, F. The well-being of people in construction. In *Good Health and Well-Being*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 1–10. [CrossRef]
42. van Hout, B.A.; Shaw, J.W. Mapping EQ-5D-3L to EQ-5D-5L. *Value Health* **2021**, *24*, 1285–1293. [CrossRef]
43. Refaeilzadeh, P.; Tang, L.; Liu, H. Cross-validation. In *Encyclopedia of Database Systems*; Springer: Boston, MA, USA, 2009; pp. 532–538. [CrossRef]
44. Grimaldo, A.; Novak, J. Explainable needn't be (much) less accurate: Evaluating an explainable AI dashboard for energy forecasting. In *Artificial Intelligence Applications and Innovations*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 340–351. [CrossRef]