A REVIEW OF THE ENERGY RETROFITTING GOAL AND METHODS OF THE BUILDING STOCK ACROSS THE EU

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This study aims to compare and evaluate various energy retrofitting strategies and methods employed in the building sector, with a focus on analysing their effectiveness and feasibility in enhancing energy efficiency. Current renovations in the EU are mostly response to policies in force; however, there is an increasing demand for renovation projects to align with the goals set for 2050. Subsidies or barriers may differ across a whole spectrum, depending on various factors, but leaving the building with the same expected outcomes. It is also important to apply measures in design phases which end in feasible and flexible execution.

The paper elaborates an assessment background for the selection of studies. It identifies four main key objectives: improving energy efficiency, phasing-out of fossil fuels, increase the share of renewable energy and applying circularity. These objectives were gathered from various studies and reports, in response to which quantifiable and non-quantifiable values of three energy renovations were compared. The results highlight not only energy, financial and carbon-saving aspects but also address current retrofitting trends and climate change. Performing a comparison along these points helps to understand what drives a renovation and what can be achieved with certain inputs in the beginning.

This review explores the extent to which renovation case studies vary in terms of their goal, approach, and the way results are published. It aims to help deciding whether an intervention is adequate or not, through a set of criteria presented.

Key words*: energy retrofit, renovation process, literature review, energy savings, carbon savings.*

1. Introduction

The unsustainable trend evident in recent history urges action to prevent further climate change. The greenhouse effect is strongly promoted by embodied and operational carbon (EC and OC) emission of the building sector. In quantities, approximately 20% [1] of the greenhouse gas (GHG) emissions in the European Union (EU; 27 countries) were originated from household activities. That means, from 2012 until 2021, 800 million tons of CO_2 equivalent GHG [2] was emitted each year respectively. It is also worth to mention that this value ranged from 26 kg per capita (Sweden) up to 1636 kg per capita (Luxembourg) in 2021, in terms of heating and cooling.

Main activities responsible for energy consumption are summarized in a chart, Figure 1 [3]. It can be concluded, that in the European Union (EU), space heating constitutes the largest portion, followed by water heating. Therefore, the decarbonization of heating is a key initiative. An examination of households' composition in terms of energy efficiency and the size of the building stock collectively suggests the potential for significant improvement in energy consumption reduction. The total number of households from 2020 was 198 million [4] and those were responsible for 27% of the total final energy consumption (FEC), which amounted to 2 893 in [TWh] [5], with an average of 14 611 [kWh] per household ins 2020.

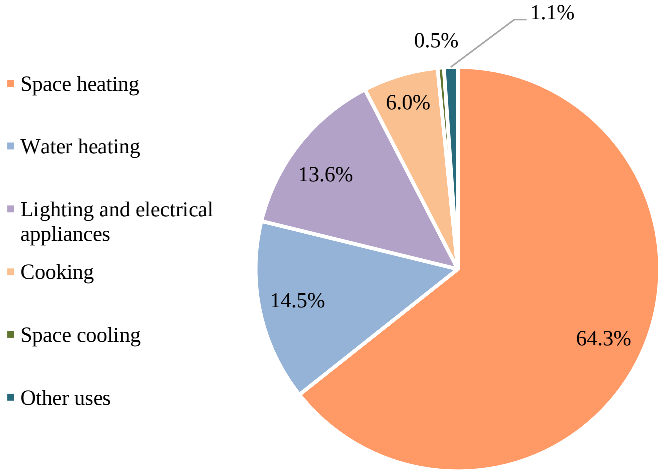


Figure 1 - Energy consumption in a household by type of activity.

The importance, goal and strategy of an energy refurbishment is well summarized in a publishment, titled "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives" [6]. Its clear object is to contribute achieving climate neutrality by 2050, setting a closer target as more than halving emissions by 2030 compared to 1990 state. It prescribes a total 14% of energy use reduction in building sector (125 million buildings in 27 EU countries in 2020 [7]) of which 116.4 million are residential, representing a huge portion of the entire sector. Bringing this sector into focus is justified by its sheer size and taking its mostly similar intended use, lot of buildings share incentives, barriers, and the attributes of a future architectural intervention.

Currently there is an ongoing trend in renovations, characterized by such small numbers it is nearly impossible to comply with the aforementioned goals [6]. Boza-Kiss et al. [8] mention that, to achieve climate goals set by 2050, a climate-neutral building stock, 90% of the existing buildings should undergo deep renovation or even be demolished. This translates to at least 3% annual deep renovation reached no later than 2030 [9] and maintained annually thereafter until 2050.

To address the problem and boost the renovation wave, as presented in numerous papers, a proper assessment of strategies and comprehensive depiction of the building sector are necessary. According to a market report [10] published in 2021, alongside a complete modernization and digitalization of the construction sector, an annual €275 million expenditure would be necessary from the financial side to achieve projected targets until 2030. One of many, following the coronavirus crisis, The Recovery and Resilience Facility [11], approved by the European Council raised €723 billion, earmarked to fund investments and projects to foster energy use reduction and substituting fossil fuels (FF) by clean energy [12]. In other words, roughly 1/3 of the amount to be used for climate related expenditures [6]. Cohesion fund, European Regional Development Fund, Just Transition Fund, European Agricultural Fund for Rural Development or European Maritime and Fisheries Fund all have programs likely to support and accelerate the green transition.

In the first half, this paper analyses current trends, explores and lists resources connected to this topic and derive key points. Based on these findings, a renovation strategy can be interpreted and in the second half, three case studies will be examined.

2. Materials and methodology

2.1. Mitigating building stock related GHG emissions in the EU

2.1.1 Legislative steps to reduce fossil fuels and greenhouse gas emissions

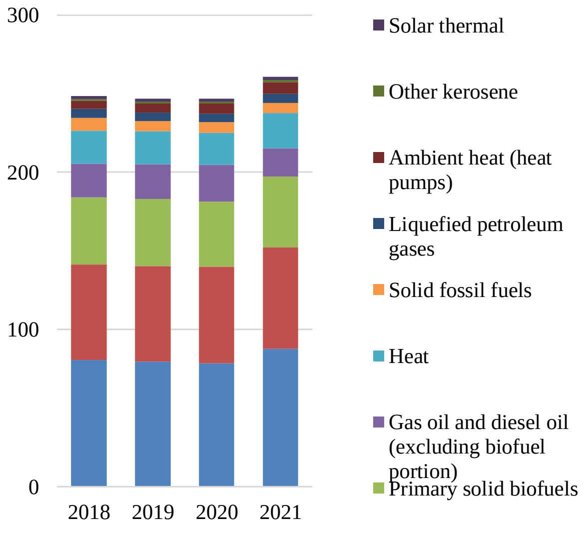


Figure 2 - Final energy consumption in households by type of fuel [Mtoe]

As shown in Figure 2, the final energy consumption in households by type of fuel in the EU [13], a strong direct dependence on FFs can be observed. The European Green Deal (EGD) [14] aims to place the EU's economy on a sustainable path and suggests reducing GHG emissions to tackle climate change. As a key component of the EGD, the European Climate Law [15] sets a clear goal of reducing the net GHG emissions by 55% by 2030 compared to 1990 level. The presented goal is outlined in the 8th Environment Action Programme [16] which repeatedly calls for reducing the use of environmentally harmful agents, especially those related to FFs. However, a quick turnaround could be observed in 2022 due to rapid changes in energy prices and exceptionally high subsidies, amid the onset of the war in Ukraine. Summed financial aid in 27 Member States in this year almost doubled compared to the average amount in the previous 5 year period (in 2022 prices) [17].

In 2018 it was decided that Member States must submit a National Energy and Climate Plan (NECP) by the end of year 2019, addressing 5 main points [18] (decarbonization, energy efficiency, energy security, internal energy market, research, innovation, and competitiveness) of the climate change. It was then followed by the Commission's assessment of the reports. Based on the latest NECP, the assessment [19] (published in 2023) reported that the current trend and also the planned value (45% and 50% respectively) falls short of the legislative target (55%).

On building level, a statement made by the European Council [20] proposes a complete ban on boilers using FFs in buildings by 2040, replacing the need with renewable alternatives. Share of renewable sources was set to be at least 32% of the gross final consumption by the Renewable Energy Directive [21], which was further raised in an amending directive to 40%, then eventually determined as 45% in the REPowerEU Plan [22]. As this plan above suggests, boosting renewables should manifest in the scaling up of PV panel installation in line with the EU's Solar Energy Strategy [23], individual heat pump (HP) installations, extending and modernizing district heat (DH), communal heat and exploiting industrial waste heat where possible.

2.1.2 Building related targets in the EU

Regarding new buildings falling into the defined category and ones subject to major renovation, the Energy Performance of Buildings Directive (EPBD) [24] and Energy Efficiency Directive [25] marked out the way. Latter sets a yearly target of 3% renovation rate for public buildings (to be renovated to NZEB level) and former highlights a minimum energy performance level, introduced them as a binding criterion to be worked out on national level. It also required the Member States the elaboration of long-term renovation strategies, the results of which must be reported biennially in the NECP. An assessment of these are to be published as the “Report on renovation of the national stock of residential and non-residential buildings and on nearly zero-energy buildings” [26]. Based on the submitted NECPs, relevant facts and trends were highlighted regarding building stock and its renovation.

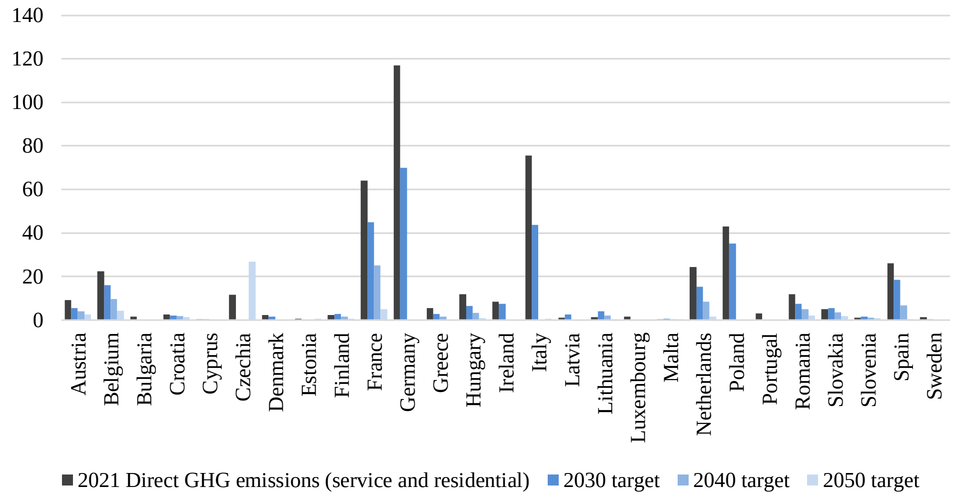
In the aforementioned report [26], in conjunction with many recommendations, the assumptions of the following relevant points of the NECPs are listed and explained:

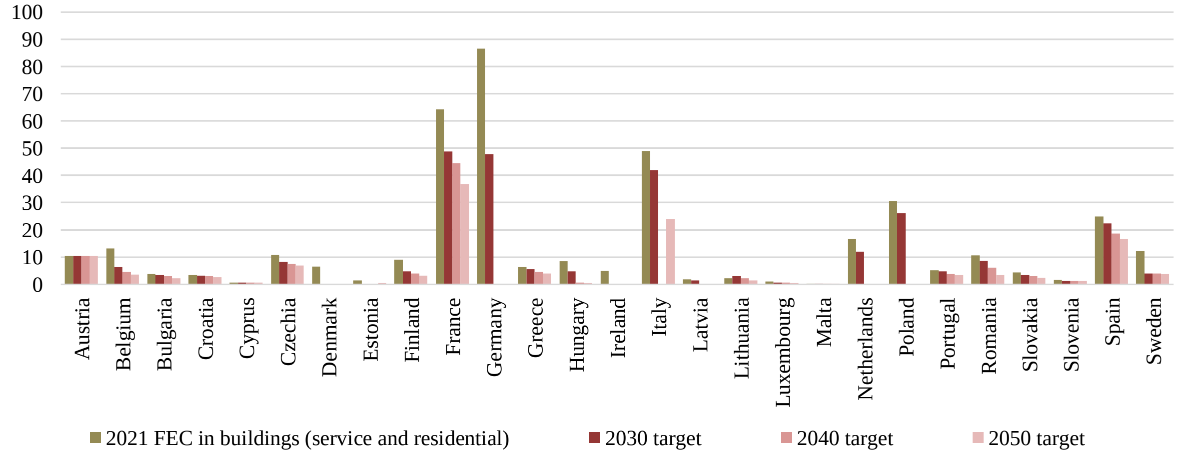
1 GHG emissions, Figure 3 (elaboration based on [7] and [26])
2 energy consumption of the buildings of the 27 States, Figure 4 (elaboration based on [7] and [26])

3 renovations and renovation rates, Figure 5 (elaboration based on [7], [26])

Note to Figure 3 [26]: **BG** – the prognosis for Bulgaria was not in line with data in BSO direct emissions and no reference value was given in NECP; **DK, FI, EL, IE, LT, MT** – total emission targets; **LU** – values were given as comparative values but no reference was determined; **CZ, LV** – emission targets may refer to direct and undirect emissions together, as it depicts a higher value than the

Figure 3 - Direct GHG emissions from buildings in EU and emission targets [MtCO2eq/year]





Note to Figure 4 [26]: **BE** – consists of data from 3 regions: Belgium-Flanders (prognosis only for residential buildings), Belgium-Wallonia, in case of Brussels-Capital Region, no reduction was assumed; **DK** – no prognosis is given, indicative milestones will be determined in connection with the climate action plan; **EE** – data only available for 2050; **FI** - values representing the gross heating demand; **FR** – a comparative value was given to 2015 consumption data (62.54 Mtoe according to [7]); **DE** – prognosis is given in PEC and only for 2030; **EL** - average reduction values for 2040 and 2050; **HU** - 2030 milestone for residential buildings (3917 ktoe) and public buildings (764 ktoe); 2040 and 2050 milestones only for public buildings; **IE** - NECP targets: PEC savings in residential sector: 2020: 8.44 [TWh]; 2030: 23.7 [TWh]; **LT** – prognosis is given in PEC; **LV** - 2030 milestone from NECP; **MT** - a comparative value was given to 2018 residential consumption data (0,093 Mtoe according to [7] for residential buildings); **PT** - a comparative value was given in PEC to 2018 consumption data (5,26 Mtoe according to [7]); **SE** – milestones for purchased heat and electricity for apartment buildings, schools, offices.

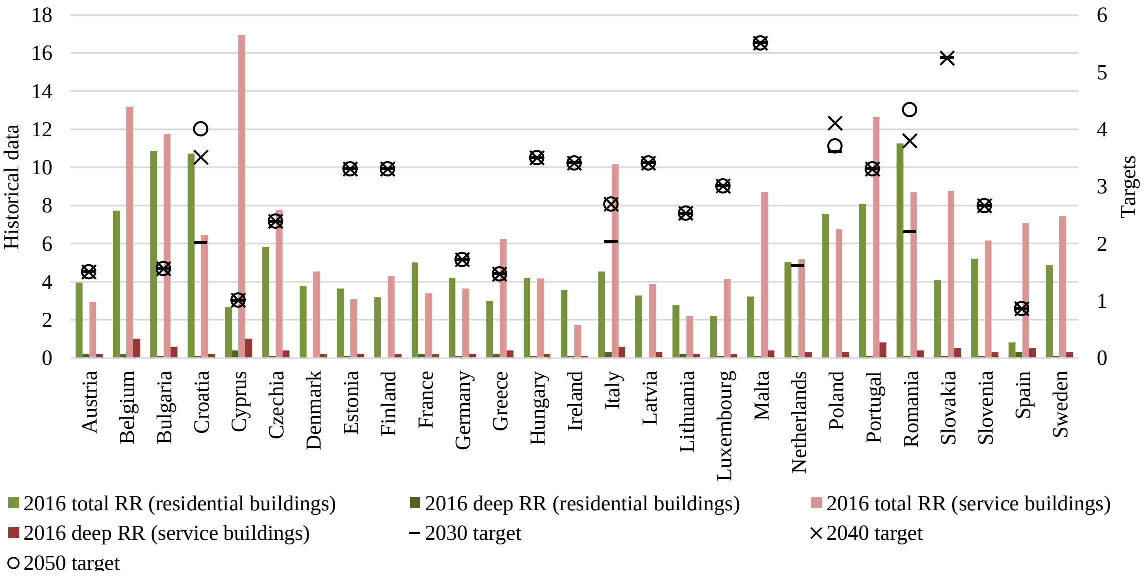


Figure 5 - Annual renovation rates of buildings in Member States and targets [%]

Note to Figure 5 [26]: **AT** – 1.5% annual renovation rate used to estimate the energy and emissions savings targets; **BE** – BE - Br 80% cumulative for residential buildings, BE – Fl 96.5% cumulative for dwellings, BE - Wa 99% for residential buildings by 2050; **BG** – end target (46% cumulative) by 2050 was calculated with, elaboration based on [26]; **CY** - 1% annual renovation rate considered in the realistic scenarios used to estimated energy and GHG emissions savings; **CZ** – end target (70% cumulative) by 2050 was calculated with, RR for public buildings was 2% until 2050 and for different housing types it was given as single-family house (SFH) and multi-family house (MFH) renovation rate (RR), elaboration based on [52] and [26]; **EE, FI, PT** – end target (100% cumulative) by 2050 was calculated with, elaboration based on [26]; **FR** – value between 1.5-3% was declared for the whole 2020-2050 period; **DE** – end target by 2050 was calculated with, RR was given as SFH and MFH RR, elaboration based on [52]; **EL** – end target by 2050 was calculated with, elaboration based on [52] and [26]; **HU, IT** - elaboration based on [7] and [26]; **IE** – all public buildings will be renovated by 2030 and end target (1,5 m dwellings cumulative) by 2050 was calculated with, elaboration based on [26]; **LT** - end target (46% cumulative) by 2050 was calculated with, elaboration based on [26]; **LU, MT** – only for residential buildings; **NL** - end target (1,5 m dwellings cumulative) by 2030 was calculated with, elaboration based on [26]; **SK** - end target 100% cumulative MFH by 2030 and 100% cumulative SFH by 2040 was calculated with, elaboration based on [26]; **SI** - end target 91% cumulative MFH and 74% cumulative SFH by 2050 was calculated with, elaboration based on [26]; **ES** - end target (7,156 m dwellings cumulative) by 2050 was calculated with, elaboration based on [7] and [26];

2.2. Energy renovation attributes: assessment background

2.2.1 Goals of renovation of residential buildings and saving potentials

A possible future renovation, aimed at reducing carbon emissions, may have different scope, goals or even phases which may vary. Nijs et al. [27], Boza-Kiss et al. [8], and Kruit et al. [28], list aspects of a renovation that adequately cover possibilities for achieving climate goals, summarized in Table 1.

Table 1 - Aspects of renovation

1. improving energy efficiency achieved by	2. phasing-out fossil fuels on different levels	3. increase the share of renewable energy on different levels	4. applying principles of circularity
• building envelope • engineering systems • smart control systems	• individual usage • district heating • electricity production	• individual production • district heating • renewables in electricity production	

2.2.2 Improving energy efficiency; quality of improvement

Many studies analyse renovation processes with the aim of reducing energy use or improving thermal comfort. According to Nijs et al. [27], improvements in energy performance of buildings can lead to an overall 50% reduction in heating demand by 2050. However, due to the unique attributes of many buildings, interventions must necessarily be tailored to individual cases. Schnap et al. [29], based on research and questionnaires listed the type interventions and assigned definitions to them, which may occur throughout a building's lifespan. To positively influence processes through legislation, regulation or sponsorship, identifiers must be established to clearly determine the goals and provide direction.

Many studies emphasize the importance of deep renovation. For instance, the term 'renovation' is often associated with a broad range of improvement works, wherein greater depth typically leads to better performance. Expectations regarding buildings may vary depending on their age, condition, architectural style, urban fabric, ownership, and many other factors. Lynn et al. [30] mention a perpendicular view to the depth of renovations, namely broad and narrow renovations, extending the definition in another dimension. Broad are defined as improvements in which the whole life cycle of the building is considered, while narrow renovations focus solely on the building's enhanced energy performance. However, the most common aspect of a renovation, its depth, usually divided into categories based on criteria.

In the EU, a legislative framework was developed to boost energy performance of the buildings: the EPBD [24] distinguishes between major and minor renovations. Additionally, it mentions deep renovation without providing a specific definition. Some papers commonly mention three types of renovation: deep, medium, and light. Sibileau et al. [9] and Schnap et al. [29], provided a foundational definition for deep renovation, from which different degrees are typically derived. Table 2 summarizes the most common – mainly quantitative – definitions used to determine the extent of renovation in one direction.

Table 2 - Definitions of renovation depth

Minor	EPBD [24]	opposite of the major (below) energy savings up to 30%
	BPIE [31]	
Light	Sibileau et al. [9]	3-30% energy savings
	Kruit et al. [28]	
Medium	Sibileau et al. [9]	30-60% savings
	Kruit et al. [28]	
Moderate	BPIE [31]	energy savings between 30-60%
Deep	BPIE [31]	energy savings between 60-90%

	Schnap et al. [29]	energy use (heating, cooling, ventilation, hot water) reduction at least 75% or below 60 [kWh–1m^{2}–1a]
	D'Oca et al. [32]	"minimum primary energy saving objective of 60%"
	Sibileau et al. [9]	more than 60% savings, remaining fully covered by renewables
	Kruit et al. [28]	more than 60% savings
Major	EPBD [24]	"the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or more than 25 % of the surface of the building envelope undergoes renovation;"
NZEB renovation	EPBD [24]	"'nearly zero-energy building' means a building that has a very high energy performance [...]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;"
	BPIE [31]	energy savings more than 90%

2.2.3 Phase-out of fossil fuel

As dwellings typically feature different conditions, heating and cooling systems, these aspects may affect them in different order of importance. However, it is stated that under the current energy efficiency policies, measures will only reduce energy-related CO_2 emissions by 53% by 2030 and 65% by 2050, compared to 1990 level [33].

FFs taking a large share of household energy consumption, as indicated by a study presented by Nijs et al. [27] and Tsiropoulos et al. [34], Table 3 shows historical and projected data regarding the consumption of fossil fuel by boilers (BO), stoves (ST), heaters (HEA) and district heating (DH) across eight scenarios in buildings.

As shown, a total phase-out of the FFs in case of district heating is expected to occur by 2030 at latest. Individual usage will remain in place, although a significant decline will be closely accompanied by renovations. In 2021, 37% of net electricity production and 60% of derived heat production was covered by FFs [35]. Additionally, 60% of the FEC of households was covered by FFs, with direct usage being responsible for more than 54% of a household's total heating energy consumption [36].

Table 3 - Historical and projected fossil fuel use in EU [Mtoe]

	year	**Coal BO and ST**	**DH from coal**	**Oil BO and HEA**	**DH from oil**	**Natural gas BO and HEA**	**DH from natural gas**
Historical data	1990	43	19	82	6	77	7
	2000	10	12	76	3	108	10
	2009	12	11	59	2	123	13
	2019	8	9	39	1	116	11
Projected average value of scenarios	2030	2.8	0	15.6	0	80.6	0
	2050	0.1	0	1.3	0	7	0

Depending on the environment of a renovation project, investing in FF systems must be reconsidered as novel technologies will certainly be more common, cheaper, and potentially subsidized. Conversely, the use of FFs may be restricted through bans on the sale of products using them or legislative changes preventing the design of such systems. A transition to renewable sources, such as ambient heat is inevitable, with the EU planning to ban the sale of all FF boilers from 2040 [37].

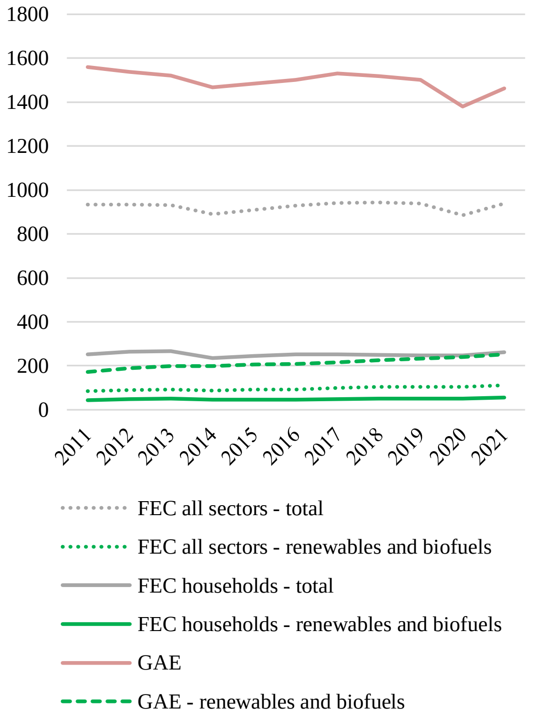


Figure 6 - FEC and gross available (GAE) energy in the EU [Mtoe]

2.2.4 Presence of renewable energy

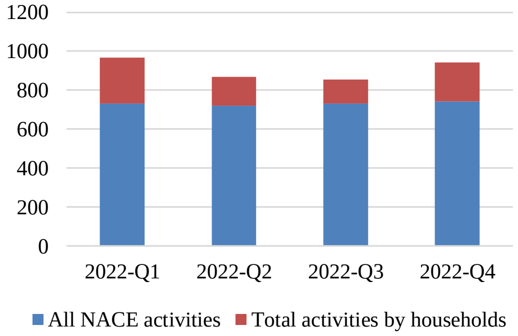
Even buildings improved to the level of NZEB have some sort of energy demand which must be covered with the energy sector playing an important role in meeting that demand. Figure 7 [1] shows that the total GHG emissions caused solely by household activities were 701 mto in 2022.

To tackle building related emissions effectively, a set of actions must be considered. Mainly Directive (EU) 2018/2001 [21] outlines the role of governments responsibility through incentives, subsidies, and policymaking, defining the sources from which renewable energy can be extracted. It is promoted that the use of renewables locally should be strongly encouraged in new buildings and those undergoing major renovation or heating system changes. Moreover, in short, it requires member states to undertake a total obligation of increasing the share of gross use of renewable sources to 42,5%, and at least 49% share in buildings' FEC by 2030. This affects households depending on FFs directly and indirectly as well, playing an exemplary role regarding public buildings, and making a strong recommendation to embrace renewables self-consumers. Indirect dependency can be reduced by transitioning to renewable sources for direct heating and electricity production.

Based on an analysis provided by Nijs et al. [27], scenarios indicate a stable growth in the of use of electricity for heating and ambient heat. As the renewables gradually take up a larger share of the overall FEC, beside a relatively constant total consumption, it comes hand in hand with an increase in household's FEC as well. Figure 6, based on [38] and [39], illustrates the subtle growth of renewables and renewable consumption in households.

In 2021, 21.4% of the household's FEC was covered by renewables, but prognosed by Nijs et al. [27], out of 275 million dwellings, 267 million would use non-fossil-based heating systems by 2050, Figure 8.

Figure 7 - Air emissions accounts for GHGs by NACE [Mtoe]



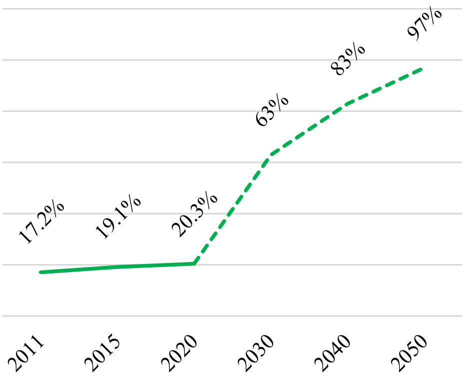


Figure 8 - Renewable energy share in households (historical data and projection) [%]

2.2.5 Circularity

Efforts to decarbonize buildings mainly focused on operational carbon emissions, as the efficacy is at the centre. However, embodied, or embedded carbon emissions also play an important role and suppressing them requires intervention on larger scale as well. The share of EC emissions from new constructions between 2020 and 2050 is prognosed to be 49%, based on a UN report [40]. Following current trends, this is just slightly less than operational carbon emissions. The revaluation of circularity in building sector is due to a rising importance of embodied energy or EC, the main two reasons for which were identified and described by Seo et al. [41]. This can be traced back to an intensive improvement. As a result, operational carbon and energy use gradually lessens against EC and EE, thus the growing importance of LCA methods. This aspect may counter the narrative, where the aim is to replace and use the most novel technologies in as many places as possible to mitigate operational carbon.

Resource extraction on Earth has been increased more than threefold over the last 50 years, and global resource extraction with processing accounts for half of total GHG emissions, according to a report by Oberle et al. [42]. Evaluating the effect of EE and EC, a study published by Roh et al. [43] conducted a life LCA on 6 typical residential buildings in South Korea, showing that five major works - reinforced concrete work, masonry work, glass work, plaster work, and carpentry work - and six major materials - (ready-mixed concrete, rebar, insulating materials, concrete bricks, glass, and gypsum boards - account for more than 95% of six different environmental impact categories. In the case of materials, production is responsible for 90% of the embodied environmental impact. It is also stated that among the analysed buildings, reinforced concrete works clearly account for 90% of the global warming potential.

Energy retrofit measures mainly consist of two main components, heating system change and insulation. Reusing the existing structure of the building, it is reported by Bienert et al. [44] that the older renovated buildings tend to outperform newly built ones considering the whole life cycle, applying a system boundary where initial embodied carbon of the renovated building is not counted. It is also said that beside the significant impact of a renovation, a carbon payback is about to be reached, even in case of a deep renovation, within less than 5 years from the improvement.

Reflecting on the above, some aspirations of the EU are summarized in form of action plans and initiatives [45], moreover, other studies also accentuates strategies to boost circularity, namely: use of low carbon materials, reward products and materials coming from sustainable sources and low EC, EE; improve durability, recyclability, reparability; ban on single-use items; reduce use of materials and resources, including transportation.

3. Analysis and evaluation of the case studies: Case study I - Energy saving retrofit in a heritage district: The case of the Budapest, Sugár et al. [46], Case study II - Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach, Jradi et al. [47], Case study III - Holistic renovation of a multi-family building in Greece based on dynamic simulation analysis, Bellos et al. [48]

Amidst much attention towards energy improvements performed on buildings, it is important to look back and assess achieved goals relative to the preliminary thoughts. Case studies were selected to present diversity and even though, to find common ground. The scale of the projects, suggested end uses, details, research methods and improvement levels all played a role in the selection phase. With the help of the beforehand presented background, three case studies will be assessed, and consequences will be drawn. Climate goals set for the next decades can only be achieved by enforcing large-scale improvements on the existing building stock. These can be performed in 5 different phases mentioned by Ma et al. [49] and listed in chronological order on Figure 9. Studies presented usually occupy the first 3 phases of the mentioned ones with additions and specific sub elements.

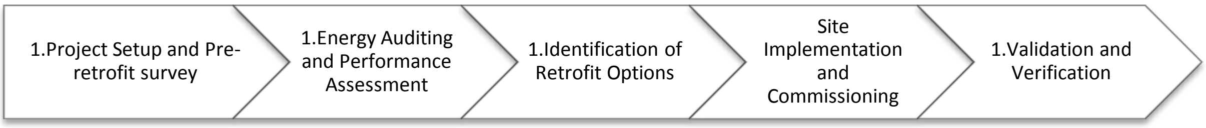


Figure 9 - Phases of energy refurbishment

3.1. Case study I

3.1.1 Main topic

Main topic of this paper is to provide a holistic approach to energy improvement strategies, including structural and engineering implications. Through a set of studies and examples, different aspects of a renovation were synthesized, giving a complex scenario applicable to similar situations in the future. Adhering to the strict protection guidelines aimed at preserving the cultural heritage value of the city presents a strong barrier achieving nearly zero-energy level. However, paying attention to the older building stock is exceptionally important, particularly in cases where aesthetic value is at stake. Besides the potential for significant energy savings, preserving buildings representing a particular era is crucial.

3.1.2 Review of the methodology of study

3.1.2.1 Simple input parameters; style and footprint

The study focuses on the VII. district in the capital of Hungary, which features various blocks of houses from eras spanning from the start of the 19th century to the contemporary architecture. The relevance of the paper can be justified, as barriers on different levels and in different forms, often associated with attributes, tend to obstruct energy renovation projects. Based on own perception and studies presented by Pérez-Navarro et al. [50], Persson et al. [51], via simplification, the followings serve as the main barriers in similar projects:

- financial constraints,
- ownership (multi-flat buildings),
- lack of awareness or unbelief in the benefit (unclear objectives or achievable benefits resulting in false perceptions),
- lack of knowledge or preparation from the side of professionals,
- lack of incentives (cheap alternatives of NZEB initiatives, cheap energy from fossil fuels),
- lack of subsidies (financial or administrative or even legal barriers),
- heritage guidelines.

Sugár et al. aims to give answers to the most critical questions by unveiling attributes specific to a certain architectural era, connecting to them a general estimated energy demand as Table 4 shows.

The energetic characteristics - compliance of the envelope, geometry, and engineering systems - were established according to the relevant legislation in force at the time. A pairing of these characteristics with architectural style was then performed, and conclusions were drawn; architectural style and footprint (ground floor area) of the building serve as a simple but relevant decision support parameter. Due to this approach, some of the well-known barriers can be reduced for different reasons:

- Since the approximation of the energetic characteristics was derived from simple input parameters (style and footprint), an estimated value after renovation can alleviate unwillingness and support investment planning even on large scale.
- Architectural style often the determines heritage guidelines or geometry ([A–1V] ratio). Therefore, through ornaments, geometry, and structural attributes, it also defines the possible and necessary depth of renovation.

Table 4 - The summed average and specific value of the total PEC of the buildings per style and of net heated area

	Neo-Classicism	**Romanticism**	**Historicism**	**Freestyle**	**Premodernism**	**Modernism**	**Socialist Modernism**	**Contemporary**
Total PEC [GWh–1a]	17.28	5.69	123.28	87.17	27.14	0.3	4.24	9.56
Net heated area $[m^2]$	67 558	22 220	442 477	346 731	122 757	1 926	26 027	101 163
Average total PEC [kWh–1m2–1a]	267	276	289	259	226	153	167	102

3.1.2.2 Renovation scenarios

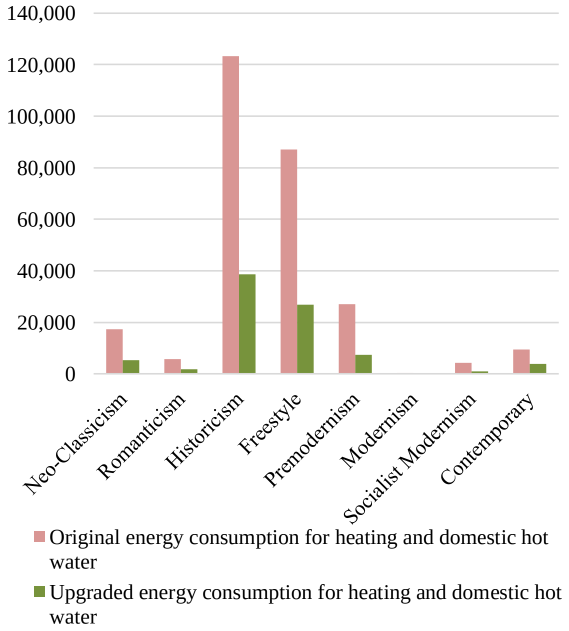


Figure 10 - The summed total primary energy consumption (PEC) before and after renovation [MWh–1a]

It is important to investigate envelope renovation scenarios because of its major impact on the operational carbon. Buildings in different architectural styles can be renovated to a different depth also, see Figure 10; however, bearer of heritage value poses limitations. In the study, two different scenarios or packages were created, namely least invasive and nearly zero package. Each consists of a total of three intervention points, with a fourth point mentioned as a possible option, without further elaboration:

1 Envelope structure upgraded to different level – internal or external insulation,
2 Window replacement,
3 Heating system change
4 Geometry improvement ([A–1V] ratio or increased fenestration ratio).

On a large scale, two renovation scenarios work well. However, it must be noted that developing an assessment database on smaller scale is indispensable, suggesting an interesting and promising research area. Intervention points were then combined and experimented with, resulting in different renovation depths. The reduction of possible energy demand could then be calculated.

The total PEC was calculated for each renovation scenario by coupling structural renovation with engineering systems replacement. The investigation advises the use of DH or HPs, which follows trends and provides an effective way to combat GHG related emissions. Condensation boilers as heaters were also investigated but resulted in worse efficacy in each comparison, thus phasing out of FFs emerged as a viable solution.

3.1.3 Conclusion

Significant findings were noted for both individual buildings and entire districts with mixed architectural styles. Renovating to nearly zero energy levels and switching to HP or DH showed the highest energy reduction potential. However, a less invasive method also achieved similar results. Modernist and social modernist buildings had the highest energy-saving ratio, but the total reduction was greatest in historicist buildings due to their prevalence, see Figure 10. All scenarios comply with heritage guidelines.

Three of the four main points were addressed, but circularity was not. This is due to the nature of renovation projects focusing on OE reduction, comfort improvement, and adherence to heritage guidelines. Providing clear parameters can help decision-makers govern future investments and persuade residents, reducing ignorance and serving a beneficial purpose.

3.2. Case study II

3.2.1 Main topic

Unlike the previous study, this one focuses on deep renovation packages for the office sector in Denmark, along with an evaluation process. The main source of pollution in this sector is heating, with losses primarily from exterior walls, ventilation systems, and windows in buildings constructed between 1960 and 2004. Denmark is noted for its significant role in reducing building-related carbon emissions without compromising stakeholders, supported by a cooperative regulatory approach. Annual savings of 6 PJ from envelope improvements in the commercial sector are highlighted, representing one-fifth of the residential sector's potential savings.

The building studied was first used in 1995, with a total heated area of 2563 m² across two floors and a basement, primarily for office functions with additional laboratories and amenities. A detailed simulation model using EnergyPlus was developed to assess energy performance and renovation scenarios.

This study, like the previous one, aims to serve as a decision support document for existing buildings amid the trend towards low-emission strategies, citing numerous energy renovation projects and potential outcomes.

3.2.2 Review of the method

The study can be comprehended by exploring phases [49] up to the Phase III, since the concept was not eventually implemented. The authors translated the task into the steps to be seen on Figure 11.

Figure 11 - Energy refurbishment phases of Case study II

It should be noted that the steps between 3 and 5, steps were particularly detailed. 485.25 [MWh] of energy was the calculated result for yearly energy consumption and a specific goal was then determined. To comply with the local standards at the time, the overall consumption must be decreased by roughly 60%, from 176 [kWh–1m2] to 72 [kWh–1m2]. In total, 7 intervention points were suggested, investigated, and used to form the renovation packages, Table 5.

Table 5 - Intervention points of Case study II and packages depending on intervention points

	1	2	3	4a and 4b	5	6
Intervention point	Modifying heating setpoints schedules	Installing efficient lights	Installing triple pane windows	Adding external insulation; ext. walls (a) or the roof (b)	Improving the equipment efficiency	Installing PV panels
Maximum extractable improvements	32.1% reduction in heating demand	32.24% in electricity	8.45% in heating	23.7% or 26.4% in heating (a) and 15.8% or 18.3% in heating (b)	11.5% in electricity	17.6% in electricity
Included in packages:						
I.		✓			✓	✓
II.	✓		✓	✓		
III.	✓	✓	✓		✓	✓
IV.	✓	✓		✓	✓	
V.	✓			✓	✓	✓
VI.	n/a	n/a	n/a	n/a	n/a	n/a
VII.	n/a	n/a	n/a	n/a	n/a	n/a
VIII.	✓	✓	✓	✓	✓	

Throughout the whole list, three interventions belong to the building envelope and four are closely linked to heating. By selecting these setpoints, attention was paid to the cornerstones of an effective renovation and later justified by the outcome.

3.2.3 Renovation packages and their effect

Dealing with the 7 intervention points mentioned above, the maximum extractable improvements were significant, see Table 5.

The packages were designed for optimization, as the best energy-performing option isn't always the most profitable. Table 5 shows 8 packages with different interventions, though their rationale was partly justified, leading to assumptions. Interesting findings include that updating electrical appliances can increase heating demand if the building envelope isn't improved, and replacing double-pane windows with triple-pane ones improves PEC by 2.3 [kWh –1m2].

Packages 4 and 8 differed only in window replacement, but due to minor PEC changes, package 4 was chosen for financial reasons. PV panels added extra savings, achieving a 51.3% reduction in heat demand and 36.6% in electricity demand, with a total electricity reduction of 49.9% compared to the initial state.

3.3. Case study III

3.3.1 Main topic

The following study presents the holistic renovation of a multi-family building in Greece, focusing on energy improvements. It consists of a total 8 apartments on 4 floors, with an approximate net heated area of 600 m^2. The declared aim is to drastically reduce its energy needs, while considering the EC and EE. Therefore, the retrofitting scenario was later subjected to an LCA, including LCC, resulting in specific numbers regarding emitted GHG or financials.

On one hand, the methods beyond manual calculations were well described and justified, with multiple examples provided using different software and tools. The authors differentiate between two types of interventions: passive and active. The former includes envelope renovation, fenestration replacement and parts not covering engineering systems in the building, while the latter covers heating systems, installation of renewable energy systems, lighting etc. On the other hand, later the in the modelling phase, explicit accuracy was added, and corresponding standards were used at the validation process. For the simulation, a new software as building performance simulator, called INTEMA was used. It was developed in the framework of EU HORIZON 2020.

3.3.2 Renovation scenarios

It is declared that the main objective of renovation scenarios is not only to reduce the energy consumption, but also to extract energy from the building. Considering the building envelope, a total 6 intervention points were suggested:

1. Installation of external insulation,
2. Windows replacement,
3. Decentralized mechanical ventilation with heat recovery,
4. Installation of decentralized reversible air-to-air HPs,
5. Installation of PV panels installed with net-metering connection,
6. Solar thermal collectors coupled to storage tanks.

Table 6 - Thermal loads and primary energy demand (PED) at base scenario and after renovation (bold) [kWh–1a]

Apartments	**Heating load**		**Cooling load**		**PED**	
	before	**after**	**before**	**after**	**before**	**after**
A0	11618		12123		34423	
B0	10771		13571		35293	
A1	8770		5195		20251	
B1	8625		6537		19543	
A2	10633		5161		22901	
B2	9391		6471		23000	
A3	16071		8608		35786	
B3	15011		9907		35125	
Total	90890	**6441**	67573	**14624**	226322	**14709**

This study places more emphasis on the engineering systems with four points and attributed only two to the building envelope. Strong presence of renewables and system changes was urged. Beside the base scenario, only one package was simulated, aiming for the maximum potential savings.

Heating and cooling demands of the apartments were presented, and the wide range of values were explained by differences in fenestration quality, the significant effect of the orientation and the unit’s location within the building. Exceptionally low PED values can be attributed to the low primary energy conversion factor in Greece (natural gas: 1.05, electricity: 2.9) as well.

With the renovation scenario, it was possible to reduce the heating load by 93% and cooling load by 78%, resulting in a significant net energy demand reduction. The phase-out of the fossil fuel in the form of gas or oil proved to be effective with all measures taken, as PED values could be kept low, even without considering the exploitation of solar energy. In the renovation scenario, heating (domestic hot water (DHW) and space heating) replaced the two least consuming activities, aligning with the highlighted trends.

The contribution of the PV panels was represented, and data extracted from the simulation software showed that mean average of the electricity demand is covered after 10th of March. Cumulative energy produced turns to positive on the 5th of May. Additionally, it is explained that the demands are not satisfied at every moment, thus investing in some form of electricity storage system would be beneficial.

3.3.3 LCA and LCC

In accordance with the EU EPBD, it is expected that existing buildings should undergo major renovations, only with a clause of feasibility, functionality, and financial viability. Balancing OC and EC could serve as evidence of the effectiveness of the renovation efforts. A carbon payback period of just under 1 year was calculated, while the financial payback period was determined to be 3.8 years. Economic viability was demonstrated alongside a considerably short carbon payback period.

4. Results and discussion

Comparative analysis of the case studies in this field necessitates special attention due to potential differences in the way data is presented. Authors often highlight various values and may focus on different aspects of the renovation study. It is common for the impact of individual intervention points to remain unpublished, which could be valuable for stakeholders seeking to make informed decisions about potential cost reductions. Occasionally, U-value improvements are stated, or their effects on the overall setup are described. Table 7 compares the different renovation strategies of the case studies, to assess motives and draw conclusions.

All three studies follow a similar renovation structure, starting with intervention points based on specific building possibilities. Case study I faced constraints from heritage conservation laws, limiting major changes like heating system upgrades or insulation. Renovation scenarios assess financial and technical feasibility, presenting various choices. In the second study, window replacement in the renovation package made minimal difference, suggesting it was unnecessary. The creation of renovation packages depends on the overarching goal, whether mitigating OE, addressing EC, or balancing both, often leading to financial burdens. Most papers do not explore all three aspects simultaneously, highlighting a research gap and the need to optimize variables at intervention points.

Table 7 - Summary of the evaluation of the case studies

	Energy saving retrofit in a heritage district: The case of the Budapest	**Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach**	**Holistic renovation of a multi-family building in Greece based on dynamic simulation analysis**
base data			
goals	residential buildings in a district: mainly to reduce heat losses and improve heating system (DHW and space heating)	individual office building: reduce heat losses and improve electronic appliances	residential building; operational and embodied energy
	decision support scheme and pre-assessment		
building age	Package 1, built between 1800-1840	1995	1970
total energy savings	net 63%[1]	primary 60%	net 85.5%
method comparison			
calculation	manual calculation	dynamic simulation	dynamic simulation
intervention points	4	7	6
envelope improvement	+	+	+
geometry improvement	mentioned	-	-
heating system impr.	+	-	+
cooling system impr.	-	-	+

Table 7 - Summary of the evaluation of the case studies

	Energy saving retrofit in a heritage district: The case of the Budapest		**Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach**		**Holistic renovation of a multi-family building in Greece based on dynamic simulation analysis**	
window replacement	+		+		+	
(smart) control system	-		++		-	
lighting and electrical appl. improvement	-		+		+	
solar energy exploitation	mentioned		+		+	
solar thermal energy expl.	mentioned		-		+	
renovation packages	2		8		1	
compliance with the criteria (2.1 chapter)						
criteria 1: improving energy efficiency						
building envelope efficiency growth and insulation (if applicable)	in U-value	thickness	effect on total net energy savings	thickness	in U-value	thickness
external wall	75.5%	20 cm	20.7%	15 cm	92.8%	12 cm
empty firewall	84%	20 cm	-	-	-	-
cellar wall	65.1%	10 cm	-	-	-	-
window	49.6%	-	5.8%	-	78.3-88.1%	-
cellar upper slab	48.8%	5 cm	-	-	79.5%	3 cm
floor on soil	90.8%	15 cm	-	-	-	-
arcade	79%	20 cm	-	-	-	-
closing upper slab	80.7%	20 cm	13.5%	15 cm	95.8%	20 cm
attic	81.5%	30 cm	-	-	-	-
improving geometry	[A–1V] ratio improvement, new windows to improve solar gains were mentioned		n/a		n/a	
engineering systems	type	total primary energy savings	type	total net energy savings	type	net energy savings
heating	original state with only envelope renovation	0%	n/a		decentralized reversible air-to-air HP	93%[3]
	centralized CH	25.9%				
	DH	60.4%				
	centralized HP	60.4%				
cooling	n/a		n/a		decentralized reversible air-to-air HP	78%[4]
ventilation	n/a		n/a		decentralized mechanical ventilation with heat recovery	direct effect not disclosed
lighting	n/a		efficient lights installed (LED)	10.5%	retrofitted/replaced	60%
electrical appliances	n/a		replacing water circulation pumps, printers, televisions, and kitchen devices	6.6%		
(smart) control system	type	net energy savings	type	net energy savings	type	net energy savings
heating control	n/a		modified heating setpoint schedules	26.3%	necessary for the operation of renewables cooperation	direct effect not disclosed
lighting control	n/a		added daylight sensors	4.2%	n/a	

Table 7 - Summary of the evaluation of the case studies

<table>
<tr><th></th><th>Energy saving retrofit in a heritage district: The case of the Budapest</th><th colspan="2">Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach</th><th colspan="2">Holistic renovation of a multi-family building in Greece based on dynamic simulation analysis</th></tr>
<tr><td colspan="6">criteria 2: phasing-out fossil fuels</td></tr>
<tr><td>intervention point</td><td>type</td><td colspan="2">type</td><td colspan="2">type</td></tr>
<tr><td>heating/cooling</td><td>HP or DH fulfils it</td><td colspan="2">n/a</td><td colspan="2" rowspan="2">installation of PV panels with net-metering connection</td></tr>
<tr><td>electricity production</td><td>installation of PV panels was mentioned</td><td colspan="2">installation of PV panels was calculated with</td></tr>
<tr><td>DHW</td><td>solar thermal collectors were mentioned</td><td colspan="2">n/a</td><td colspan="2">installation of solar thermal collectors with storage tanks</td></tr>
<tr><td colspan="6">criteria 3: increase the share of renewables</td></tr>
<tr><td rowspan="4">local production</td><td>type</td><td>type</td><td>CO_2e savings compared to fossils</td><td>type</td><td>total CO_2e savings over 25 years</td></tr>
<tr><td>ambient heat was used in HP calculation</td><td rowspan="3">PV panels coupled with envelope renovation</td><td rowspan="3">40 t CO_2eq/a[2]</td><td>ambient heat was used in HP calculation</td><td rowspan="3">1586 t[5]</td></tr>
<tr><td rowspan="2">solar energy exploitation was mentioned</td><td>solar energy exploitation</td></tr>
<tr><td>solar thermal energy exploitation</td></tr>
<tr><td rowspan="3">distant production</td><td>type</td><td colspan="2">type</td><td colspan="2">type</td></tr>
<tr><td>valid if increased in DH production</td><td colspan="2">valid if increased in DH production</td><td colspan="2" rowspan="2">valid if increased in electricity production</td></tr>
<tr><td>valid if increased in electricity production</td><td colspan="2">valid if increased in electricity production</td></tr>
<tr><td colspan="6">criteria 4: circularity</td></tr>
<tr><td rowspan="2">LCA</td><td rowspan="2">n/a</td><td colspan="2" rowspan="2">n/a</td><td colspan="2">carbon payback period</td></tr>
<tr><td colspan="2">0.9 years</td></tr>
<tr><td colspan="6">financial viability</td></tr>
<tr><td rowspan="2">LCC</td><td rowspan="2">n/a</td><td colspan="2" rowspan="2">n/a</td><td colspan="2">payback period</td></tr>
<tr><td colspan="2">3.8 years</td></tr>
</table>

Notes:
1 Average value; 2 Calculated values (285 g [gCO2eq–1kWh] emissions of electricity production) based on 2023 data (*CO2 Emissions per KWh in Denmark - Nowtricity*, n.d.), embodied carbon of the installed system was not considered, and 100% utilization was presumed; 3 In heating load (combined effect of system replacement and envelope improvement); 4 In cooling load (combined effect of system replacement and envelope improvement); 5 Results of the complete renovation scenario, not just the renewables

5. Conclusion

Most studies available prioritize envelope renovation and place other aspects behind. It is justified by the vast number of studies' suggestions; however, attention must also be paid to measures deemed incidental. In Case study II, resetting the heating setpoint schedule saved 1/4th of the total heating energy demand of the building. The engineering system received the most attention in Case study III, and significant reduction was achieved. Presenting an LCA and LCC analysis was unique to this study also.

Based on the comparative analysis, it is evident that the three studies employed different approaches to renovation strategies. While each started with intervention points determined by building-specific opportunities, the varying circumstances led to different priorities and constraints in each study. The results indicate that comparing renovation strategies can help uncover benefits and limitations, as well as inform future decision-making. Even though a method might differ from conventions, each renovation scenario is investigated to serve current and preliminary information about options or limitations of an existing building renovation.

The future continuation of this study may focus on establishing a system, in which the collected four main points serve as a base for a framework. This framework then supports renovation projects with the help of a scoring scheme, extending to various buildings, informing future decision-making. It may also bring sociological aspects into focus, considering human-related factors such as aesthetics and comfort.

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Nomenclature

Abbreviations

BSO	Building Stock Observatory	GHG	Greenhouse Gas
CH	Condensation Heater	HP	Heat Pump
DH	District Heating	HVAC	Heating, Ventilating, Airconditioning
DHW	Domestic Hot Water	LCA	Life Cycle Assessment
EC	Embodied Carbon	MFH	Multi-Family House
EE	Embodied Energy	NACE	Nomenclature of Economic Activities
EGD	European Green Deal	NECP	National Energy and Climate Plan
EPBD	Energy Performance of Buildings Directive	OC	Operational Carbon
EU	European Union	OE	Operational Energy
FEC	Final Energy Consumption	PEC	Primary Energy Consumption
FF	Fossil Fuel	PED	Primary Energy Demand
EEA	European Environment Agency	RR	Renovation Rate
GAE	Gross Available Energy	SFH	Single-Family House

Dimensions

[A–1V]	net surface to heated volume ratio
[gCO2eq–1kWh]	grams of carbon dioxide-equivalent to generated electricity
[GWh–1a]	annual energy consumption
[kWh–1m2]	specific energy consumption
[kWh–1m2–1a]	annual specific energy consumption
[MtCO2eq–1a]	annual metric tons of carbon dioxide-equivalent
[Mtoe]	millions of tons of oil equivalent
[MWh–1a]	annual energy consumption

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