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The relationship between renewable energy use, energy efficient building renovation and the role of windows in achieving EU climate targets: A comprehensive scientific review

Conducted for European Trade Association of PVC Window System Suppliers, European Aluminium Association and EuroWindoor

This Report contains
36 pages of text
20 figures
1 table

Sumee Park
Cosima Wörle

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Harald Will — Digital unterschrieben von Harald Will Datum: 2023.12.22 11:15:38 +01'00'

Sumee Park — Digital unterschrieben von Sumee Park Datum: 2023.12.21 15:26:54 +01'00'

Head of Department
Dr. Harald Will

Researcher
Dr.-Ing. Sumee Park

Fraunhofer Institute for Building Physics IBP
Nobelstrasse 12 | 70569 Stuttgart
Phone +49 711 970-00
www.ibp.fraunhofer.de

Holzkirchen Branch
Fraunhoferstrasse 10 | 83626 Valley
Phone +49 8024 643-0
Fax +49 8024 643-366

Content

1 Objectives

The European Green Deal aims to achieve carbon neutrality by 2050. As buildings account for 43 % of final energy consumption in the EU, mostly for heating, reducing GHG for heating buildings is an important aim of the energy policy in the EU [1].

With the new version of the EPBD (Energy Performance of Buildings Directive) [2], the EU Commission intends to phase out fossil fuel in heating and cooling in new buildings and in buildings undergoing major renovation or heating system replacement. The initial proposal for a recast regulation (Building Energy Act [3]) in Germany, according to which each newly installed heating system must be powered by at least 65 % renewable energy from January 2024, has raised a strong public debate in 2023. The role of energy efficiency measures in the building sector has rarely been explored in this public discussion, even though the Building Energy Act (BEA) not only regulates heating systems, but also the energy efficiency of the building envelope.

This highly politicized debate in Germany has, on the one hand, created the impression that relying solely on new renewable heating systems can drive the decarbonization in buildings. On the other hand, the limited number of heating technologies that meet the requirements of the BEA and different consumer experiences contribute to uncertainty among building owners. This often leads to delays in implementing energy efficiency measures and replacing heating systems, both of which are crucial to achieving the goals of the European Green Deal.

Recognizing that the focus of this discussion should be on scientific facts rather than on any public political awareness, EPPA (European Trade Association of PVC Window System Suppliers), European Aluminium Association and EuroWindoor engaged Fraunhofer IBP to conduct a comprehensive literature review of key research studies addressing the economic, societal and other multiple aspects of energy efficient renovation and the renewable energy use. Additionally, the role of windows in the context of the entire building envelope in energy efficient building renovation is to be identified from the existing research studies.

The first objective of this project is to provide an overview of the state of knowledge on the multiple impacts of energy efficient measures (demand side) and the use of renewable energy (supply side) in the building sector to achieve the zero-emission for heating in buildings. The second objective of this project is to present a comprehensive literature analysis of the contribution of windows to energy efficient renovations of building envelopes in the EU.

2 Background

2.1 Literature searching

A comprehensive review of scientific literature was conducted as part of this study. This report extensively reviewed scientific literature, including reports from EU research projects available in the European Commission's CORDIS (Community Research and Development Information Service) database, as well as the official reports published by the European Commission. In addition to EU research projects, this study also considered projects conducted under the International Energy Agency's (IEA) EBC (Energy in Buildings and Communities) research program.

2.2 EU Policy

The European Green Deal aims to achieve carbon neutrality by 2050, meaning that the economy as a whole should have no net greenhouse gas (GHG) emissions. The EU Commission aims to reduce the EU's net GHG emissions by 57 % (at least 55 %) by 2030. The Energy Efficiency Directive (EED), the Renewable Energy Directive (RED) were revised in 2023 and the recast Energy Performance of Buildings Directive (EPBD) is currently awaiting Parliament's position at first reading [1].

Energy Efficiency Directive

The 2023 revised directive [4] increases the EU energy efficiency target, requiring EU countries to collectively achieve an additional 11.7 % reduction in energy consumption by 2030 compared to the 2020 projections.

The revised directive includes the “Energy Efficiency First” principle (see the next paragraph) und addresses energy poverty by requiring Member States to prioritize vulnerable customers and social housing in their energy savings measures. It sets an annual energy consumption reduction target of 1.9 % for the public sector, extends annual building renovation obligations by 3.0 % to all levels of public administration.

Energy Efficiency First principle

The “Energy Efficiency First principle” [4] guides EU energy policy and investment decisions to prioritize cost efficient energy efficiency measures. The goal is to produce only the amount of energy needed, avoid investment in stranded assets, and effectively manage energy demand. Reducing the energy demand helps to control the investments needed for the transition to renewable energy sources, promotes the sustainable use of resources and enhances the resilience of the EU's energy system. The principle encourages both the public and private sectors to prioritize investments in energy efficient production over, other more complicated or expensive solutions for the energy transition [5].

Renewable Energy Directive (RED)

The revised Renewable Energy Directive sets the EU's binding renewable energy target for 2030 at a minimum of 42.5 %, with the aim of reaching 45.0 %. The current share of renewables in EU energy consumption in 2021 is 21.8 %, which has increased from 12.5 % in 2010.

Energy Performance of Buildings Directive (EPBD)

In order to reach the overall 55 % emission reduction target by 2030, the Climate Target Plan requires GHG emissions in buildings to be reduced by around 60 %. The EU Commission proposed a revision of the directive in December 2021, and it is currently awaiting Parliament's position at first reading.

The proposal for the recast of the EPBD aims to accelerate building renovation rates and to reduce GHG emissions, and promote the use of renewable energy in buildings.

The proposal introduces the following aspects:

- All new buildings from 2028 should achieve the status of a "zero-emission building". A zero-emission building is defined as a building with high energy performance, which complies with the "energy efficiency first principle" and is exclusively powered by renewable energy sources.

- Minimum energy performance standards that would accelerate energy efficient renovations in the 15 % of buildings with the worst energy performance in the EU. Non-residential buildings with an Energy Performance Certificate (EPC) class G (the lowest) will have to be renovated and improved to at least EPC class F by 2027 and class E by 2030. The worst performing residential buildings will need to achieve at least Class F by 2030 and Class E by 2033.

- Long-term renovation strategy to be replaced by national building renovation plans that are more operational and have a stronger monitoring framework.

- Energy performance certificates must be based on a harmonized energy performance scale by 2025 to ensure comparable national standards and increase reliability, quality and digitization.

- Life cycle Global Warming Potential (GWP), which quantifies a building's contribution to global warming potential over its entire life cycle, must be calculated and disclosed in the building's energy performance certificate by 2027, for all new buildings.

- Voluntary renovation passports will be introduced by 2024, and a smart readiness indicator will be introduced by 2026 to help building owners plan renovations.
- There is an aim to phase out the use of fossil fuel heating systems in all buildings by 2035, with a deadline of 2040 at the latest, if feasibility is demonstrated to the Commission.

2.3 Assessment criteria

2.3.1 Energy efficiency

The energy efficiency of buildings is assessed using "final energy" and "primary energy". Final energy is what end users consume e.g. for heating, cooling, ventilation, hot water, lighting and auxiliary energy, while primary energy is energy from resources without any conversion or transformation process [4]. GHG emissions from energy use in buildings can be calculated using primary energy consumption and determined primary energy factors for given energy sources.

2.3.2 Greenhouse gas emission (GHG)

The European Green Deal target is set on the basis of GHG emissions. In the building sector, these emissions can occur based on the energy consumption during the operational phase of the buildings or during the pre- and post-operational phases, e.g. the product phase, the construction process and the end-of-life phase. The last emissions are estimated using Life Cycle Assessment (LCA), which will be described in 2.3.3.

Until now, building assessments have primarily focused on the energy use of buildings during their operational phase. In EU households, heating and hot water consumption make up approximately 78 % of the total energy use [6]. Therefore, it is reasonable to prioritize efforts to decrease energy consumption for heating. However, with the increased energy efficiency of new buildings, the meaning of emissions from other phases e.g. production or end-of-life phases is increasing for new buildings [7].

2.3.3 Overall impact on the environment

Life Cycle Assessment (LCA) is a comprehensive analysis of the environmental impacts of a product, process, or service throughout its entire life cycle. This includes all environmental impacts during production, use, and disposal, as well as upstream and downstream processes such as raw material extraction and fuel production [8].

In the LCA, the global warming potential (GWP) is estimated using various greenhouse gases estimated from the LCA analysis and GWP factors for these gases.

In addition to GWP, LCA also includes other environmental criteria such ODP (Ozone Depletion), POCP (Photochemical Ozone Creation Potential), AP (Acidification Potential), EP (Eutrophication Potential) and further criteria [9].

The EU Commission will establish a common EU framework for the calculation of the life-cycle GWP by December 2025 [2]. This framework will be developed in collaboration with stakeholders and will be based on the Level(s) framework and standard EN 15978 [2], which means that the framework will consider not only ecological aspects based on the LCA calculation, but also overall impact on the environment. Level(s) is a voluntary reporting framework that measures the sustainability performance of buildings across their entire life cycle [10].

The six most important aspects of sustainability determined in Level(s) are:

1) Greenhouse gas emissions along a building's life cycle

2) Resource efficient and circular material life cycle

3) Efficient use of water resources

4) Healthy and comfortable space

5) Adaptation and resilience to climate change

6) Optimized life cycle cost and values

The framework provides step-by-step guidance and checklists for each indicator, covering also the renovation [11]. Additionally, it already contains the multiple aspects discussed in the following chapter.

2.3.4 Multiple aspects

In recent years, numerous research projects have explored multiple aspects beyond the non-energy benefits of energy efficient measures, ranging from macro-level considerations for policy decisions to micro-level considerations for individual building owners or tenants.

For example, Figure 1 shows the criteria of multiple aspects of energy efficiency improvement as identified by International Energy Agency [12].

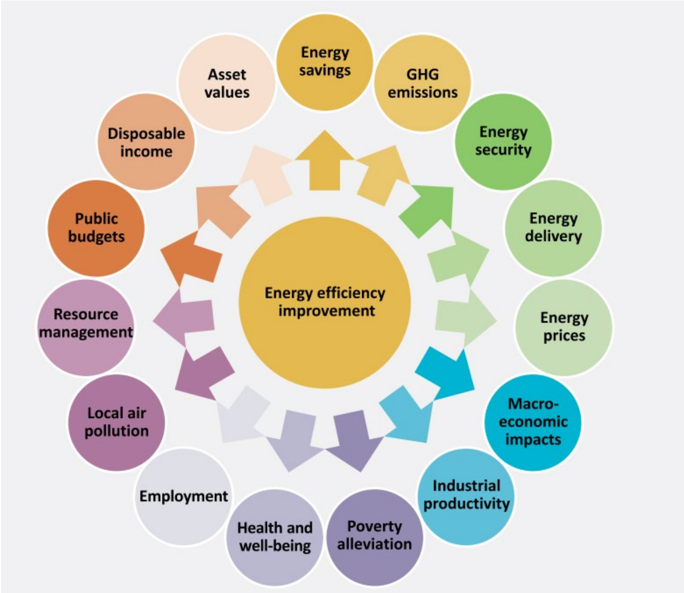

Figure 1:
Criteria for multiple benefits of energy efficiency [12].

At the macro level, criteria such as "macro economy" (labor productivity, industrial competitiveness, gross domestic product, employment and public budgets), "health and well-being" (air pollution), social welfare (poverty), "energy system and security (electricity reliability)" have been considered extensively, going beyond the typical focus on "environment and climate". At the micro or building level, "economics aspect", such as energy costs and property values of buildings, as well as "health and comfort" considerations, were often taken into account [13,12,14].

EU policies, e.g. EPBD considering Level(s), not only address the carbon neutrality target, but also these multiple aspects.

3 Results

3.1 Energy efficient measures (demand side) and the use of renewable energy (supply side) in the building sector

During the literature review of the first topic, the following research questions were formulated:

1. What is the current situation of energy supply and energy consumption for heating in the building sector in the EU?

2. What are the available options for reducing energy demands and using renewable energies for heating buildings?

3. Is there a relationship or link between these two strategies?

4. Between improving energy efficiency on the demand side and increasing the supply of renewable energy, which is the most beneficial strategy from an economic perspective?

5. Between improving energy efficiency on the demand side and increasing the supply of renewable energy, which is the most beneficial strategy from a social or other perspective?

3.1.1 Current situation of energy supply and consumption in the building sector in the EU

Buildings account for 43 % of final energy consumption in the EU, with two-thirds of that being consumed in residential buildings, mostly for heating [6].

Since 2000, heating consumption per square meter has decreased due to stricter building codes, financial incentives for retrofitting, and adoption of more efficient heating systems. However, since 2008, the annual reduction rates of heating consumption have slowed down in some EU countries [6]. Especially, in recent years the annual reduction rates for heating have decreased significantly, as shown in Figure 2. About 20 % of heating energy is saved over 10 years from 2000 to 2010, but only 9 % in the last decade (see Figure 4).

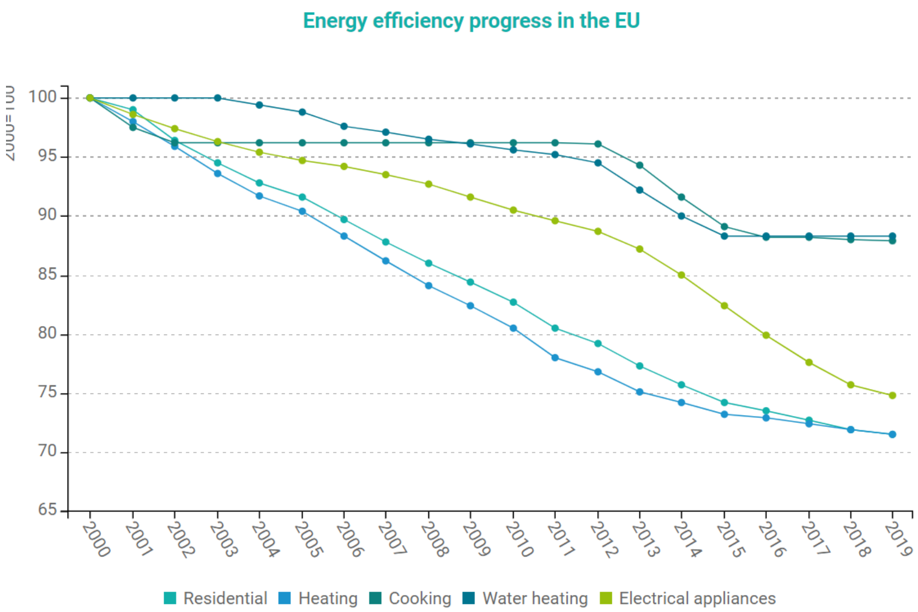

Figure 2:
Energy reduction rates per year in the household in EU countries, source: [6].

Figure 3 shows the reduction rates of final and primary energy consumption in the EU for whole sectors, including transport, industry, household and service [15]. Energy efficient measures contribute to achieving a reduction in final energy consumption, whereas a decrease in primary energy consumption can be accomplished through both energy efficiency and the integration of renewable energy sources.

The recent rate of final energy reduction between 2014 and 2019 per year has not changed compared to the period between 2000 and 2007. However, the rate of primary energy reduction has increased from 1.25 % to 2.0 % over the same time period. This suggests that the intensity of energy efficiency measures to reduce final energy consumption has remained constant over the past 20 years, while the intensity of renewable energy supply has increased significantly. Nevertheless, the share of renewable sources for heating and cooling in EU is still only 23 %. Sweden shows the highest share with just under 70 % (see Figure 4) [16].

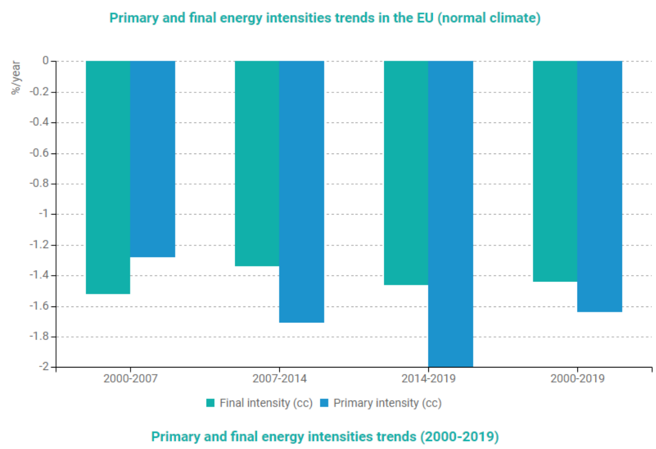

Figure 3:
Trends in the intensity of primary and final energy reduction rates in the EU, source: [17].

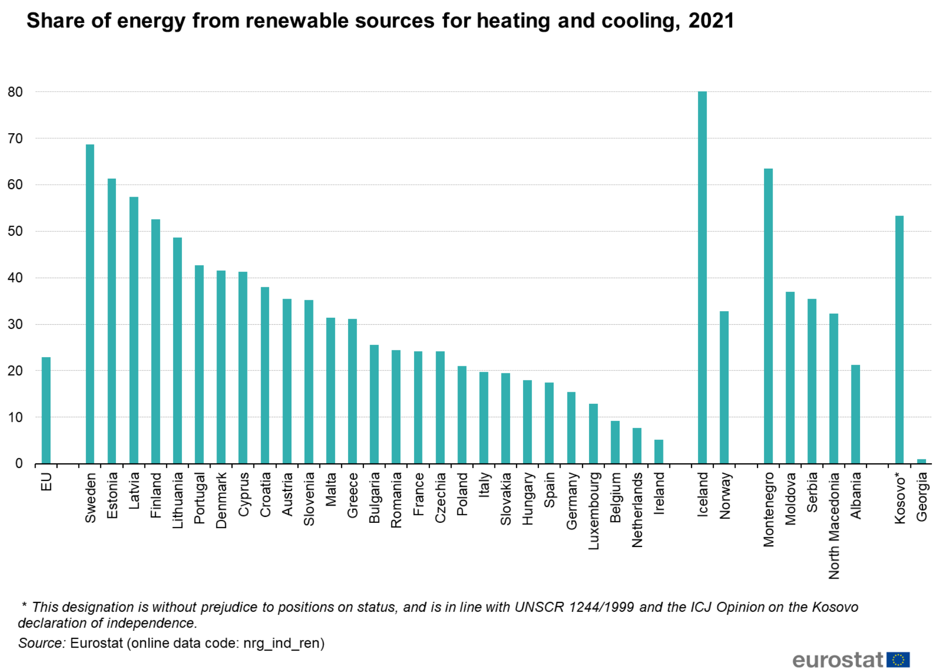

Figure 4:
Share of energy from renewable sources for heating and cooling in EU countries, 2021 source: Eurostat, data source: nrg_ind_ren [16].

3.1.2 Available options for increasing the supply of renewable energy and reducing heating energy demand

The heating energy demand in buildings can be reduced by insulating the building envelope, using more energy efficient windows, reducing thermal bridges, increasing air-tightness, and insulating pipes. Additionally, implementing heat recovery of ventilated air with a ventilation system, using efficient heating systems, and optimizing their control further contribute to energy savings.

To meet the heating energy needs of buildings, renewable energy sources such as solar, geothermal, biomass, ambient energy and waste heat are utilized to generate heat (see [18] for more information about current renewable heating technologies). The discussion around biomass heating systems has been controversial due to concerns about high GHG emissions, air pollution resulting from burning forest biomass, and potential impacts on biodiversity [19]. In addition to direct use of renewable heat sources such as biomass, heat pumps and district heating systems can be used for renewable heating if the electricity and the district heating system are produced from renewable energy sources.

Heat pumps constituted a 21.5 % market share of all heating systems sold in the EU by 2021 [20], however, existing buildings predominantly still rely mainly on gas, oil and wood for heating. The share of electricity-based heating systems in residential buildings is only 5.8 % in 2019 [17]. The share of renewables in electricity generation in the EU is in 2020 approximately 38 % [21].

District heating and cooling systems follow a similar pattern to heat pumps, where they have a relatively low share of heating systems and a moderate reliance on renewable sources. About 12 % of the final energy consumption for space heating and hot water is provided in 2018 by district heating systems. Of this, around 27 % of the district heating supply comes from low-carbon fuels (biomass, biofuels, and renewable waste) and renewable energy sources (geothermal, solar thermal, heat pumps, and industrial waste heat [22], see Figure 5).

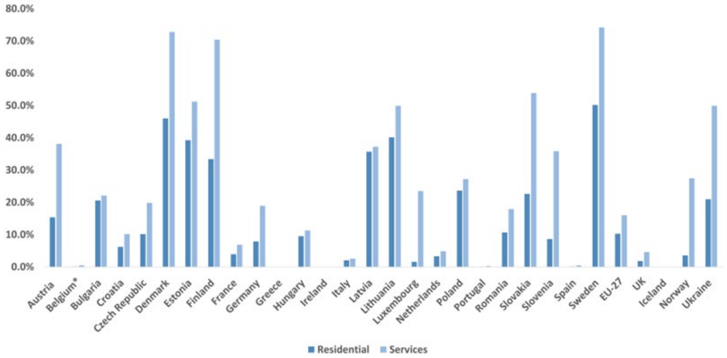

Figure 5:
District heating share of final energy consumption for the space and hot water heating in the residential sector and services in 2018, source: [22].

3.1.3 Relationship between renewable energy supply and energy demand reduction

Efficiency of a heat pump and a modern district heating system

The efficiency of a heat pump depends on the temperature of the heat source and the flow temperature. This refers to the temperature of fluid, usually water in the EU, that circulates through pipes and emitters like radiators.

The buildings with low energy efficiency in their envelope will demand more energy, therefore high flow temperature to maintain the desired indoor temperature, resulting in a decrease in the efficiency of the heat pump.

In residential buildings with oil and gas boilers, the hydronic distribution systems typically have flow temperature levels ranging from 55 °C to 90 °C. However, for a heat pump to operate efficiently, the flow temperatures should be reduced to a certain low-temperature threshold approximately 55 °C [23]. To reduce the flow temperature when heating with radiators, buildings may need to be better insulated, the surface area of the radiators increased, or floor heating systems installed.

The analysis of the large scale deployment of heat pumps [20] indicates that around 40 % of all EU dwellings currently heated by gas boilers are properly insulated and that heat pumps can function at high efficiency in these buildings. For almost 60 % of dwellings, energy efficiency improvements or adjustment to the heating distribution system (radiators and pipes) should be pursued to ensure that heat pumps operate efficiently. Otherwise a hybrid system combining a heat pump and another condensing boiler is required [20].

COP of heat pump depending on average temperature of heating systems

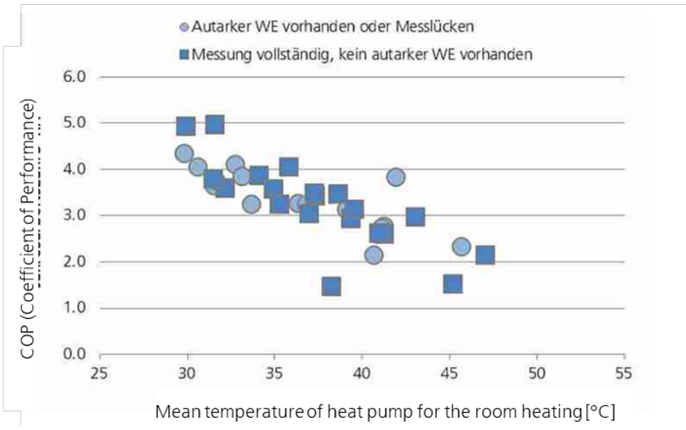

Figure 6:
Measured efficiency of the heat pump as a function of the average flow temperature of the heating system, source: [24].

This coefficient of performance (COP) range from 1,5 to 5 of the heat pump (see Figure 6), depending on the energy efficiency of buildings creates uncertainty for building owners regarding its environmental and economic aspects.

To address this, researchers in [25] propose integrating heat pump readiness (HPR) into building energy performance certification. HPR assesses the ability of a heat pump to meet a building's heating demand using outside air, taking into account the characteristics of building envelope, the climate, and the reference heat pump. If the building is not ready for the heat pump, the energy efficiency measures should be implemented before a heat pump is installed.

Not only the heat pump, but also the modern district heating systems require low operating temperature levels for high efficiency. DH systems have evolved from first generation systems (steam systems powered by coal-fired boilers or waste incineration units) with an operating temperature of 200 °C to fourth generation systems (4GDH) characterized by a higher share of local renewable and waste heating technologies, lower operating temperatures (50 ~ 60 °C), and increased interaction between consumers and producers in a smart local energy system (see Figure 7). Improving the energy efficiency of buildings can support the deployment of fourth generation DH systems, especially the economic use [22].

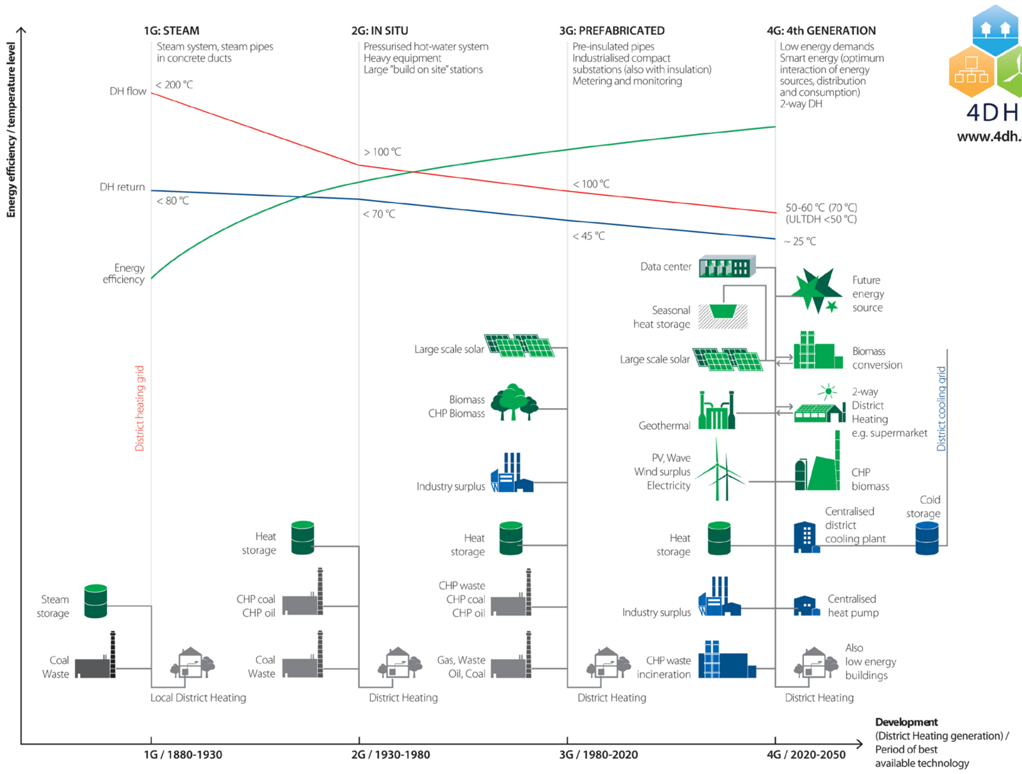

Figure 7:
Overview of district heating and cooling markets and regulatory frameworks under the revised renewable energy directive, source: [26].

3.1.4 Cost optimal strategy

Macro-Level: The EU research project ENEFIRST investigated the cost-optimal combination of demand and supply-side resources to achieve net-zero GHG emissions in the building sector by 2050 at the macro-level. This study considered the investigation as well as operating costs for energy generation, network and storage infrastructures to meet the energy requirement for space and water heating, space cooling, electrical appliances, lighting and cooking in both residential and non-residential buildings.

Different scenarios were considered based on the contribution of energy efficiency in buildings, which influence the deployment of energy generators and networks for electricity, district heating and hydrogen.

1. The LOWEFF scenario assumed a 21.1 % reduction in final energy demand for buildings by 2050 and decarbonization mainly through the use of renewable resources.

2. The MEDIUMEFF scenario had a 30.2 % reduction in energy demand, with a balanced approach between demand- and supply-side resources.

3. The HIGHEFF scenario assumed at a 35.5 % reduction in energy demand by prioritizing energy efficiency measures in buildings.

The comparison of the scenarios reveals a small cost difference between them (see Figure 8). The high allocation of resources to building retrofitting in the HIGHEFF scenario leads at the same time to a significant cost reduction for district heating and electricity generation. As a result, HIGHEFF shows higher costs, but the cost difference between the HIGHEFF and LOWEFF scenarios is less than 1 %. These additional annual costs correspond to less than 0.03 % of the EU's gross domestic product [27].

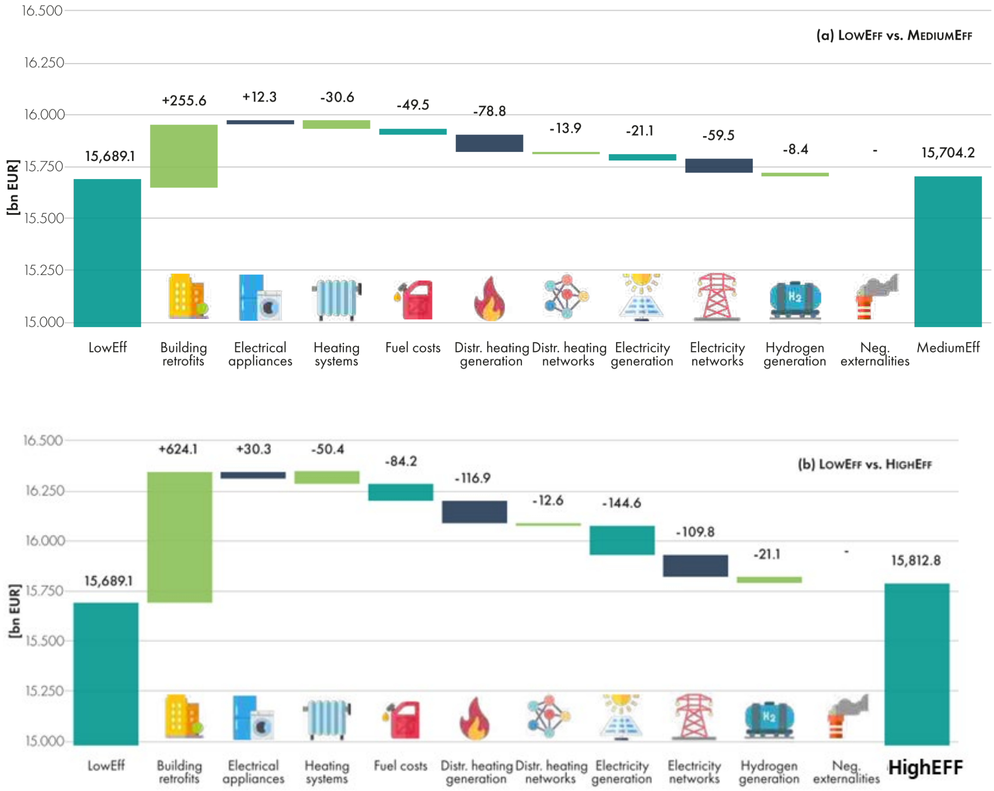

Figure 8:
Decomposition of the cumulative differential over 2020 – 2050 for MEDIUMEFF (top) and HIGHEFF (bottom) compared to LOWEFF for EU-27, source: [27].

Building-Level: An international research team of IEA-EBC Annex 56 [28] investigated the „Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation". The study, published in 2017, focused on generic single-family and multi-family residential buildings from seven EU countries and Switzerland, representing the typical building stock in these countries and were constructed between 1975 and 1980 without major energy-related renovations. Additionally, case studies were conducted in five countries. The research assessed the costs of the renovation packages and energy savings for 40 years by comparing them with a hypothetical "anyway renovation" case, including measures necessary to maintain basic functionality without improving energy performance.

This study found that renewable energy systems, such as heat pumps and wood-based systems, were more effective in reducing GHG emissions than energy efficiency measures in the buildings studied. In Portugal, due to the relatively high emission factor of the Portuguese electricity mix in the reference years of 2010 and 2013 in the study, replacing gas heating with a heat pump is not as effective as insulation. However, the wood pellet system proves to be more cost-effective than insulation.

In addition, the study concludes that energy efficiency measures remain more cost-effective when combined with a renewable heating system than when focusing on energy efficiency measures alone. However, the higher cost-effectiveness of renewable heating systems compared to energy efficiency measures was not clearly demonstrated in the study.

Another research team from Switzerland and Sweden conducted a parameter study to evaluate renewable heating systems and energy efficiency measures of three buildings from different construction periods. The goal was to determine a suitable and robust renovation strategy based on LCA and LCC (Life Cycle Cost) analysis. The energy consumption for heating of investigated buildings ranges between 91 and 110 kWh/m²a [29]. The results show that replacing the heating system during renovation is more environmentally and economically advantageous compared to insulation measures, even at building level.

However, the cost-effectiveness of energy efficiency measures at building level is highly dependent on the insulation level of the individual building, in addition to the climate. Buildings with lower insulation in the envelope will have higher cost-effectiveness when implementing energy efficiency measures.

This literature review could not identify any comprehensive study on the cost-effectiveness associated with varying insulation levels and climates in the context of building renovation.

3.1.5 Considering the multiple aspects and discussion

Macro-Level: Creating jobs

According to the International Energy Agency [12], energy efficiency measures can account for the macroeconomic development, with annual economic growth ranging from 0.25 % to 1.1 % and create job opportunities, with 8 to 27 job years generated per 1 million Euro invested. When such energy efficiency policies lead to job creation, one of the greatest impacts is the reduced budget for unemployment payments. Industrial energy efficiency measures enhance competitiveness, profitability and product quality while reducing operational costs. A recent literature review about the multiple benefits of energy efficiency can be found in [30].

In 2016, the EU-28 had 660,000 jobs directly related to the production of energy from renewable sources. When considering total employment, the renewables sector contributed to over 1.5 million jobs in the EU in 2018 [31]. In comparison, the construction of buildings accounted for 13 million direct jobs in the EU. Building renovation jobs in the construction sector involved in the renovation of residential buildings are estimated to be around 4.6 million on average for the period 2012–2016 (see Figure 9) [32]. More than 75 % of jobs in the construction sector are found in small or micro enterprises. The value added in the construction sector is generally significantly lower than in the energy sector [33].

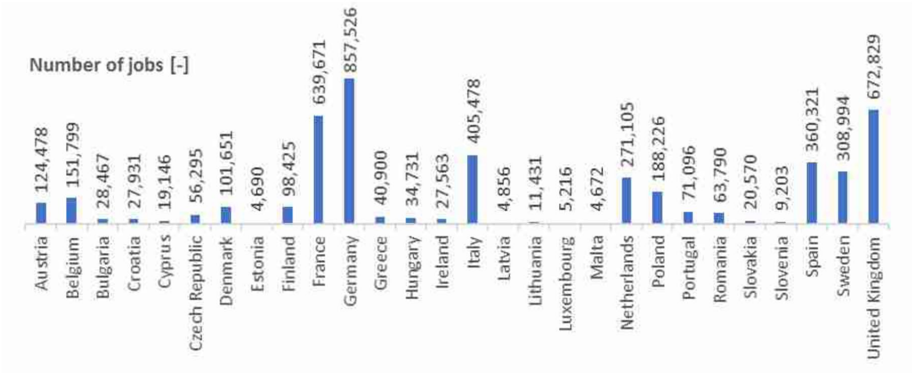

Figure 9:
Jobs maintained by building renovations for residential buildings (average 2012–2016), Source: [32].

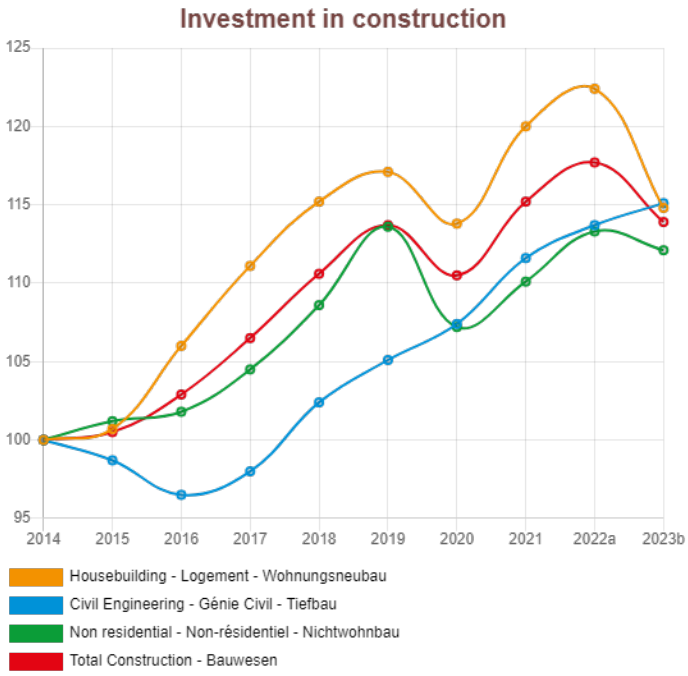

Figure 10:
Investment trends in the construction sector in the EU, source: [34].

According to the European Construction Industry Federation [34], rising energy and construction material prices in Europe have adversely affected contractors, risking their ability to meet contractual obligations or participate in public tenders. Outlook for 2023 predicts a 2.5 % decrease in construction investment and a 4.0 % decline in employment compared to 2021 (see Figure 10).

According to some studies listed in [31], the strengthening of the Energy Performance of Buildings Directive (EPBD) could lead to an increase of up to 568,000 jobs by 2030, compared to a reference case of no changes in EU initiatives related to buildings. The impact of a highly ambitious energy efficiency program running until 2030 could result in an increased labor demand of 2.3 million job-years in 2030.

The statistics from both sectors indicate that there is a greater potential for job creation and construction sector stabilization through investments in energy efficiency measures, especially in the current situation.

Macro-Level: Health and Well-Being

According to the IEA, energy efficiency retrofitting in buildings improve occupant health, especially for vulnerable groups, and can save the European Union's economy up to 190 billion Euro annually [12]. Another study assumed in 2020 the annual health benefits of 64–140 billion Euro, resulting from improved life quality, reduced public health spending and fewer working days lost for the scenario with the high energy efficiency, cited in [35].

There is evidence linking mold to respiratory tract symptoms, and a significant portion of the population is affected by respiratory diseases [36]. However, the average share of the total population in EU-27 countries living in dwellings with problems such as a leaking roof, damp walls, floors or foundations, or rot in window frames or floors is still around 15 % (see Figure 11). The implementing of energy efficiency measures in buildings can play a crucial role in preventing mold growth and protecting the health and well-being of the population [36]. This has the potential to reduce health costs associated with respiratory diseases and other health conditions related to poor housing conditions in the EU.

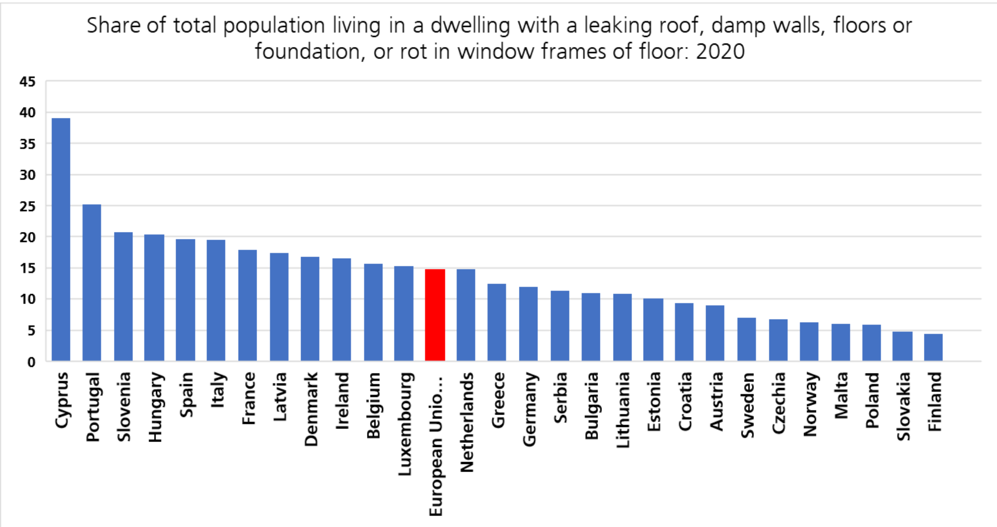

Figure 11:
Share of total population in European countries living in a dwelling with a leaking roof, damp walls, floors or foundations or rot in window frames in 2020, data source: [37].

Macro-Level: Energy poverty

Energy poverty refers to a situation where a household is forced to reduce its energy consumption to a level that negatively impacts the health and well-being of its residents. This problem is primarily driven by three causes: a high proportion of household expenditure spent on energy, low income, and the low energy performance of buildings and appliances [38].

The percentage of Europeans unable to keep their homes adequately warm increases from 8.0 % in 2020 to 9.3 % in 2022 due to the high energy prices following the Russian invasion [38].

Energy efficient buildings are less sensitive to energy prices, which can help offset the impact of rising energy costs. This, in turn, contributes to the reduction of energy poverty by lowering the overall energy expenses for households.

Renewable energy supply can only reduce energy poverty if energy prices for electricity and district heating remain consistently low over the long term, since energy consumption is not significantly affected by the replacement of heating systems.

Macro-Level: Electricity systems and demand flexibility

The widespread deployment of electric heat pumps is expected to moderately increase electricity demand in buildings, especially in advanced economies, where it could rise from 22 % to 27 % between 2021 and 2030 [23]. However, adding an electric heating to a household can increase significantly their peak demand during the winter. Peak demand refers in electricity to the period of highest electricity consumption. The increase in peak demand requires additional investment in the electricity sector to meet the demand, which in turn increases the overall costs of grid maintenance.

In France, electric resistance heating is common, so the customer connections and the distribution grid have been developed accordingly. However, in regions where electric heating is not yet as widespread as in Germany, the deployment of heat pumps could substantially increase peak demand, requiring upgrades to the distribution grids [23].

To address this issue, the Dutch government has proposed introducing hybrid heat pumps, which combine heat pumps with other heating systems, as the default option in new buildings to manage grid congestion. Another alternative is demand response programs offered by some electricity supplier, which encourage users to reduce consumption during peak periods. In a pilot project in Germany, a company aggregated the flexibility potential of heat pumps from participating customers and offered the resulting energy volume to grid operators. The electricity use of the aggregated heat pump units is reduced by turning them off or lowering their operation to reduce load during peak periods [23]. To maintain indoor temperatures, heat is stored in a hot water buffer tank. This concept works effectively in well-insulated buildings, as demonstrated in Figure 12. In the case of a heating supply cut-off, the indoor temperature in existing buildings in the Alpin region would decrease by about 2.6 to 5.2 °C after one hour, and by around 4.1 to 8.1 °C after five hours. However, deep renovation can reduce these temperature decreases, with the one-hour decrease being less than 2.4 °C and the five-hour decrease less than 3.6 °C [25].

According to [23], the poorly insulated buildings limit the potential for heat pumps to play a role in demand-side flexibility.

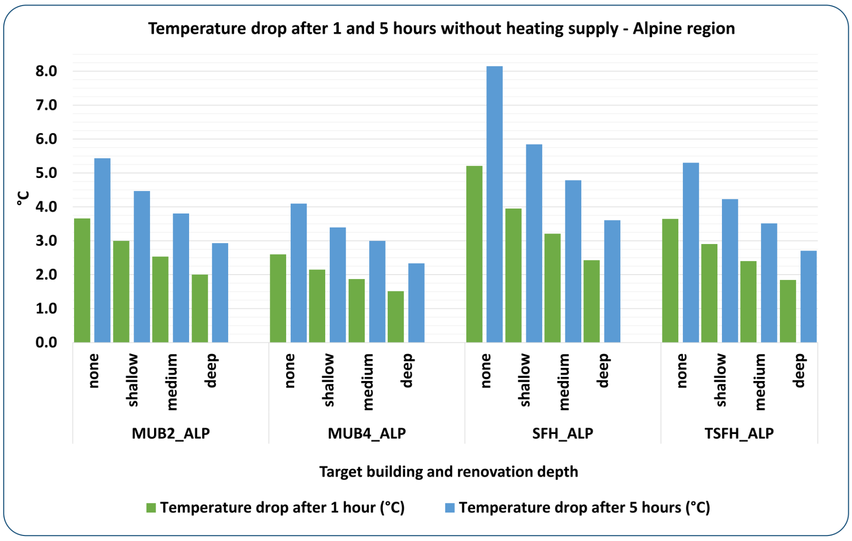

Figure 12:
Average temperature drop after 1 and 5 hours without heating supply in Alpine region, source: [25].

Building-Level: Comfort, health and aesthetics

The lack of insulation in buildings, especially in winter, can have a significant impact on thermal comfort, which is influenced by factors such as air temperature, radiant temperature and air velocity.

For the same thermal comfort, the air temperature in a room with cold surface e.g. wall or window should be significantly higher than that of a well-insulated room, as shown in Figure 13 using two differently insulated windows. The thermal insulation property of the building element is described by the so-called U-value (heat transfer coefficient). The lower the U-value, the lower the heat loss of the building element.

In this scenario, while maintaining the same operative temperature (considering both air and radiation temperature) of 24 °C, the room on the left with a less well insulated window requires an air temperature of 27 °C in the zone closer to the external envelope. In contrast, the other room requires only 25 °C in the same areas. However, despite the same operative temperature, the two rooms do not provide the same level of thermal comfort due to local discomfort. The window with worse insulation causes higher radiation asymmetries between the front and back thermal perception compared to the other window. These higher radiation asymmetries can result in increased discomfort. Therefore, well-insulated buildings reduce energy consumption also by reducing air temperature while maintaining the same thermal comfort. In addition, they help minimize the local thermal discomfort in winter [39].

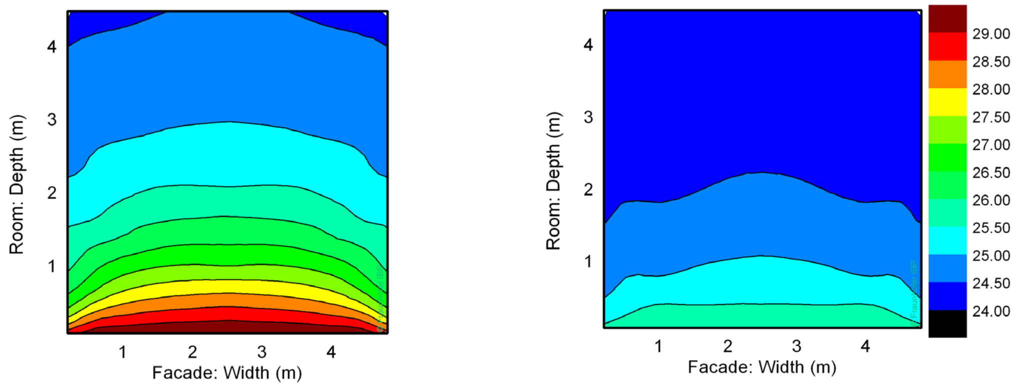

Figure 13:
Required air temperature depending on the U-value of window for the same operative temperature of 24 °C (left: window with U-value of 3,3 W/m²K on the facade, right: window with U-value of 1,1 W/m²K on the facade), source: [39].

Occupants of poorly insulated buildings often have to choose between high indoor temperatures and reduced thermal comfort in order to save on energy costs.

Building-Level: Property of Buildings

Most of the European studies, which are reviewed in [40], found a positive impact of energy efficiency on real estate prices of around 2 % to 10 % and about 6.5 % for rental markets. In comparison, some studies found only small or negligible effects of energy labels on the prices of dwellings. Further investigations show that it is not the energy label itself, but the dwellings' energy performance that has the positive effects on transaction prices [40].

The EU research project REVALUE [41] aimed to develop an international guide for real estate valuers, emphasizing the value of energy efficiency in the valuations of housing stock and analysed 120,000 data points across four countries. The research team found a less obvious correlation between a home's energy efficiency and its value, which is linked rather to visual and individual features such as new windows and the occupant's well-being and satisfaction. However, the team pointed to the risk of "brown discounting," of real estate with low energy efficiency, where properties with low energy efficiency experience a decrease in value relative to the average [41].

After the literature review and based on the research project REVALUE, RICS concludes that energy efficiency is beginning to have a gradual impact on value, though this is at a very small scale compared to traditional value drivers such as location or size of buildings [42]. Investment in energy efficiency improvements may not yield an immediate economic return due to the uncertain payback periods. Therefore, relying on cost-saving or value-added incentives in the residential sector may not be appropriate. The evolving business case emphasizes priorities like comfort, well-being, a reduced risk of 'brown discounting' and preparedness for future regulatory changes, reducing the reliance on immediate finance.

3.2 The role of the windows in the context of the entire building envelope in the energy efficient building renovation

During the literature review for the second topic, the following research questions were formulated:

1. How important are windows in the energy efficient building renovation?

2. What are the advantages and disadvantages of window replacement compared to other energy efficiency measures, from an environmental, economic, social and other perspectives?

3.2.1 Potential of window replacement for energy efficiency improvement

The role of windows for energy efficiency in terms of overall efficiency will depend strongly on the proportion of window area to the building envelope, as well as the difference between the energetic properties of windows in the existing building stock and the actually affordable windows on the market.

Although there are some comprehensive studies on the building stock, e.g. on the year of construction, the heat transfer coefficients of the building envelopes as well as the average final heating energy consumption for all EU countries [43], no reliable study on the window area of the building stock in the EU could be identified during this literature review. A study on the potential impact of high performance glazing on energy savings assumed a window share in residential buildings of 25 to 75 % of the facade area and for non-residential buildings approximately 80 % [44]. In another study, a window area of about 20 % of the floor area for residential buildings was assumed [45], which calculated the energy saving potential of window replacement in the EU using a generic building model.

The average heat transfer coefficient of windows in the existing EU building stock is about 3.4 W/m²K, while that of commonly available windows is between 1.4 and 0.9 W/m²K [46]. The huge potential for window replacement is based on this difference and the fact that today's buildings in Europe are still equipped with inefficient windows.

Figure 14 shows the average heat transfer characteristics of building elements in the EU building stock as a function of the year of construction.

Compared to walls, roofs and floors with for example less than 1 W/m²K for the year of construction between 1980 and 1989, windows have a very high heat transfer coefficient of 3.7 W/m²K for the same year of construction. This means that 3.7 times more thermal energy can be lost through the window than through other areas of the envelope. If these windows are replaced by new windows with an U-value of 1 W/m²K, the heat energy of 27 Wh/m² can be saved for 1 hour by the temperature difference of 10 K between indoor and outdoor, while the renovation of the wall from 1 W/m²K to 0.2 W/m²K can save 8 Wh/m². Despite the smaller proportion of windows compared to walls in residential buildings, the replacement of old windows in enhancing energy efficiency is crucial.

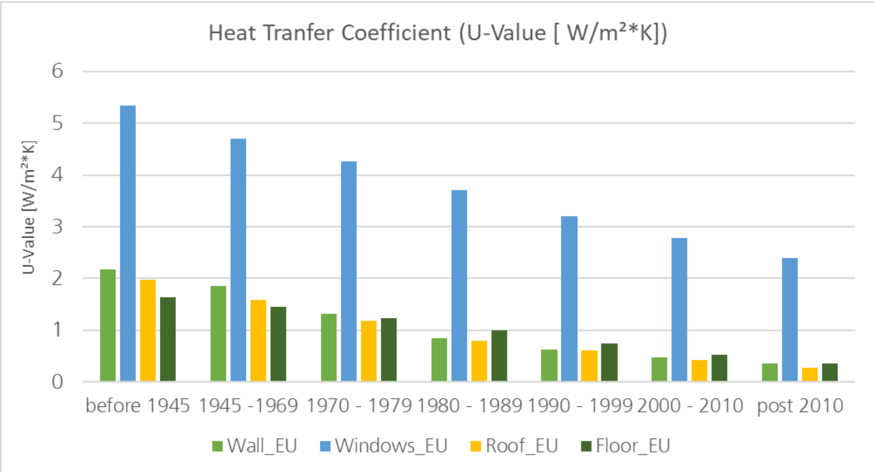

Figure 14:
Average heat transfer coefficient (U-value) of building elements in the EU building stock, source: own presentation based on [39].

Figure 15 shows the U-values of windows (U_w) in different countries according to the year of construction. Spain has the highest values in buildings built between 1970 and 1979. It indicates that the windows of the buildings before 1970 are partially replaced, whereas the windows between 1970 and 1979 are hardly replaced. Poland shows a very low performance of windows before 1980 in comparison to Sweden and Germany, while the performance in recent years is very similar to Sweden or Germany. This indicates the low level of window replacement in this period in Poland.

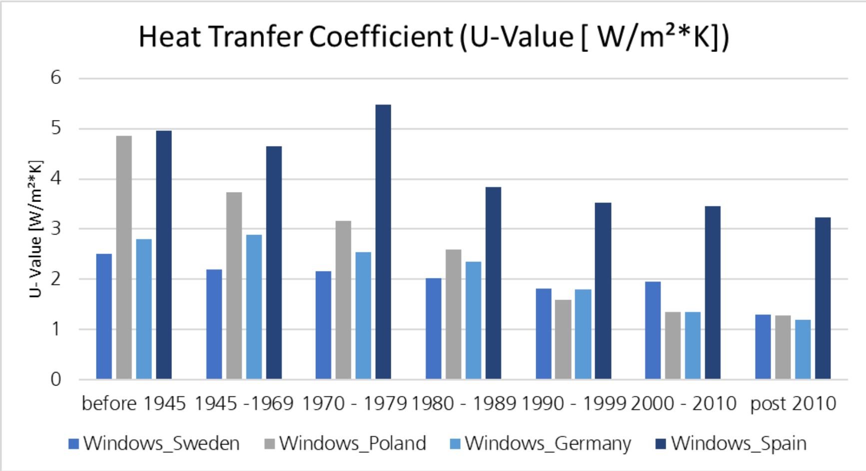

Figure 15:
Average heat transfer coefficient (U-value) of windows in four countries, source: own presentation based on [39].

According to [44], a 1 % window replacement rate over 10 years with high performance windows can save 3.5 % energy compared to the baseline situation without window replacement. The savings potential depends on the climate region and typical U-values in the existing buildings in countries. The highest savings potential is in the Baltic countries with 4.5 % and the lowest in the Southern countries with 2.1 %. If all buildings in the EU were equipped with high-performance windows, 31 % of annual energy could be saved.

The characteristics of a window go beyond just thermal insulation. They also include solar heat gain, which is measured by the g-value. A g-value of 1 represents 100 % of the solar radiation passing through the window. A higher g-value indicates increased solar gain for the building, which is desirable in winter and less desirable in summer. Another comprehensive study on the potential of window replacement shows the high influence of the g-value on the heating energy and requires the consideration of the solar gain factors of windows for the energy calculations. According to this study, most European countries use technical requirements for the replacement of windows based only on the U_W-value. However, this simulation study shows that replacing window in the EU building stock with a window with U_W-value of 1.3 W/m²K and g-value of 0.60 results in the same savings as replacing it with a window with U_W-value of 1.1 W/m²K and g-value of 0,54. Therefore, this study suggests that the g-value of the window should be considered in addition to the U-value when selecting windows, and that window replacement policies based on U_w-value requirements should be replaced with energy performance requirements to ensure the optimal contribution of window replacement. This study shows that more than 15 % of the heating energy of the existing building stock can be reduced by replacing windows [45].

The most important shares of the energy demand within the European building stock are, in decreasing order, space heating, domestic hot water and space cooling with about 3,200,890 and 107 TWh per year [43]. The cooling energy consumption is still marginal with only 3 % of the heating energy, but due to climate change the number of warm days is expected to increase. According to IEA, cited in [46], currently 15 % of residential buildings are equipped with air conditioning, which is expected to increase to 50 % by 2050. Due to climate change, managing solar gain during the summer is crucial, particularly in the southern and increasingly in the central EU regions. Solar shading systems are commonly implemented to reduce the solar gain in the summer and allow high solar gain in the winter. Where solar shading systems cannot be installed for aesthetic or wind speed reasons, high-performance glazing can be used instead, such as switchable glasses that can change their g-values or solar protection glasses with a low solar gain factor. This, combined with effective daylighting and good thermal performance, helps achieve the desired balance between solar control, energy efficiency and high levels of visible light.

3.2.2 Assessment of window replacement

Environmental impact

Based on an embodied GHG analysis of a multi-family house with plus-energy standard in Germany, the following shares of GHG emissions were found [47]:

- Concrete: 34 %
- PV-system: 17 %
- Reinforcing steel: 12 %
- Windows: 10 %
- Heating system (including heat pump, buffer storage, water pipes, floor heating, and central ventilation system with heat recovery): 6 %
- Insulating the building envelope with EPS insulation and mineral wool: 6 %

In this case, windows have a lower share compared to the PV-system but a higher share compared to insulation materials and the heating system with a heat pump.

The case studies collected in the IEA Annex project "Assessing life cycle related environmental impacts caused by buildings [48]" indicate that there are only a few cases that investigate the renovation strategy in terms of embodied and operational GHG emissions from retrofitting measures.

In the benchmark study conducted in Switzerland, it was found that windows have the third highest average GWP per square meter, ranking below the roof and exterior wall underground in terms of their environmental impact.

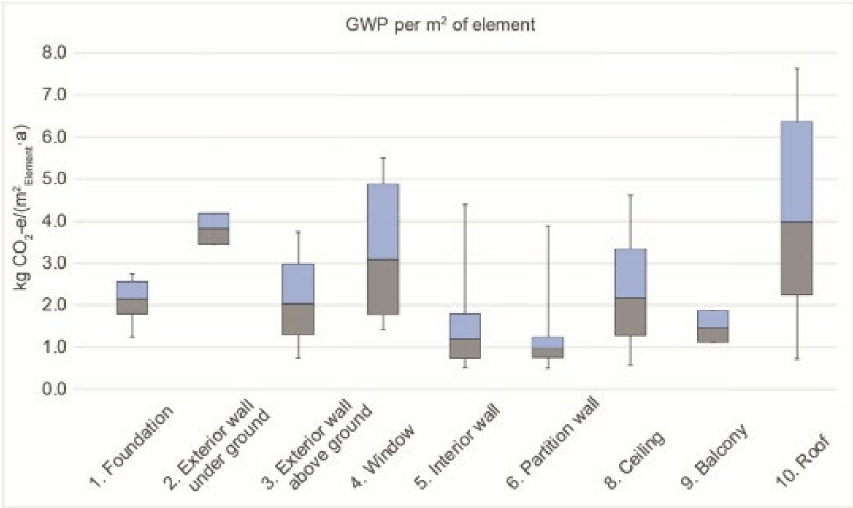

Figure 16:
Variation in the GWP of construction elements per square meter in the Swiss benchmark study. The middle line describes the weighted mean value [49].

Another study [29], also conducted in Switzerland, investigated three retrofitting case studies of residential buildings from different construction periods. Through sensitivity and uncertainty analysis, the research team concluded that the priority in renovation, based on life cycle environmental and cost analysis, should be given to the replacement of the heating system, followed by exterior wall insulation and windows. All the measures investigated in the study compensate for the embodied emissions of additional materials throughout the entire life cycle by utilizing the saved energy.

Evaluating the environmental impact of window replacement compared to other energy efficiency measures in the EU is challenging due to limited case studies and variations in geometry, construction components, and available materials across countries. Nevertheless, available studies indicate that the production of windows makes a substantial contribution to GHG emissions compared to typical insulation measures. In this study, no comprehensive research project could be identified that evaluates the impact of building elements and materials utilizing the EU building stock and the LCA database while considering energy efficient retrofitting.

Cost optimal strategy

As described in section 3.1.4, an international research project aimed to discover cost-effective retrofitting strategies, exploring various renovation measures on the building envelope across Austria, Denmark, Italy, Norway, Portugal, Spain, Sweden and Switzerland. These measures included insulation of walls, roofs, and basement ceilings, as well as the installation of new energy efficient windows [28].

The study took into account the typical constructions of the building stock, national framework conditions, and GHG emission factors of energy sources specific to each country. Consequently, variations in typology, actual energy efficiency levels of reference buildings, the depth of insulation measures, and energy prices were observed between countries.

In nearly all investigated cases, window replacement was not considered cost-effective compared to other insulation measures, except in Norway, where the installation of the most energy efficient windows proved to be the most cost-effective measure. This may be attributed to the cold climate and the relatively high U-value (2.7 W/m²K) of the reference case in Norway. For example, the U-value of windows in the reference building in Sweden is assumed to be 2.3 W/m²K in the study.

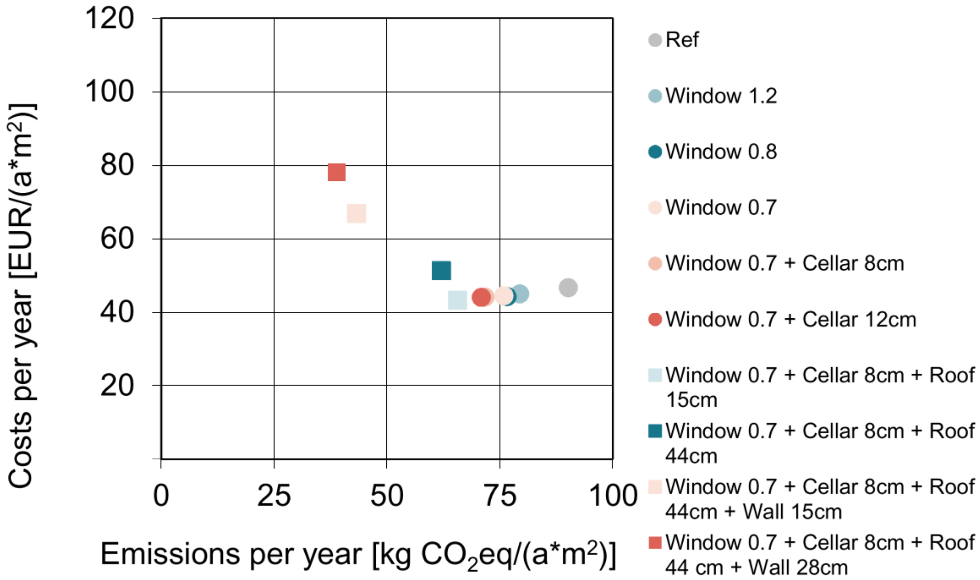

Figure 17:
Comparison of cost-effectiveness of energy efficiency renovation measures for a single family house in Norway, U-value of reference window: 2.7 W/m²K.

In countries with cold or alpine climates such as Sweden, Denmark, Austria and Switzerland, new windows with a wooden frame can reduce GHG emissions, but not cost-effectively. Figure 18 illustrates, using the case of Austria, a typical trend in the results of the cost-effective analysis in these countries. Insulation measures on walls and roofs prove to be more cost-effective in reducing emissions compared to window replacement. While window replacement can also reduce emissions, it does not belong to the cost-optimal solution.

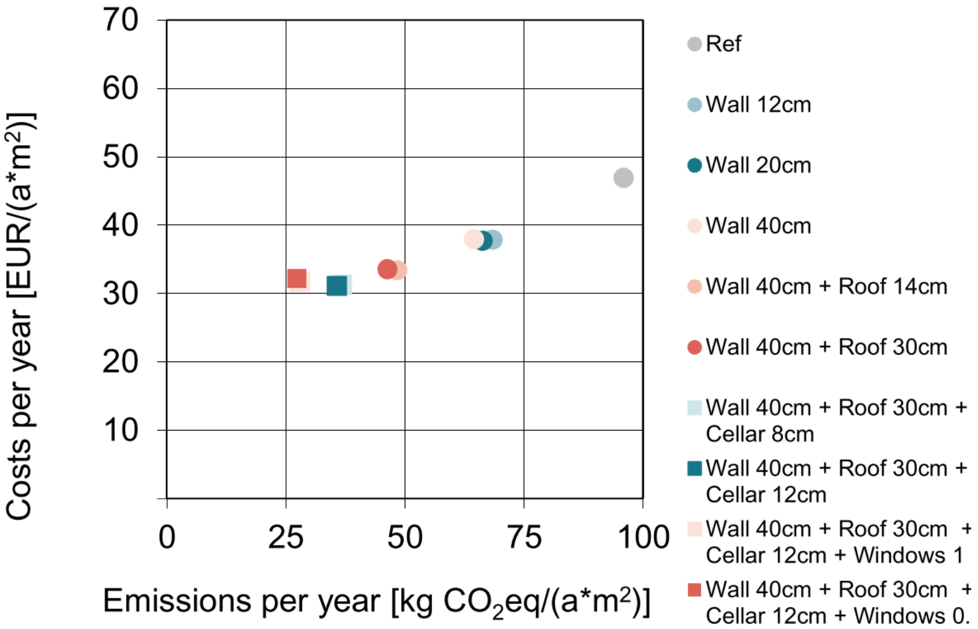

Figure 18:
Comparison of the cost-effectiveness of energy efficiency renovation measures for an single family house in Austria (U-Value of windows: Reference: 2.9 W/m²K, 1st measure: 1.0 W/m²K, 2nd Measure: 0.7 W/m²K).

In Portugal, the replacement with U_W-values of 2.7 and 2.5 W/m²K leads to a reduction in GHG emissions. However, replacing windows with a better U_W-value of 2.3 W/m²K actually increases GHG emissions. It could be based on the reduced heat loss in summer during cold night. This suggests that when replacing windows, the selection of the U_W-value should be done carefully, taking into consideration the specific climate region.

An analysis of the window stock in Germany [50] reveals that 3 % of windows still have single-pane windows with a U_W-value of 4.7 W/m²K or worse, and 41 % have double glazing without low-E coating with the U_W-values between 2.4 and 2.7 W/m²K. According to the VFF and BF, replacing single-pane windows with triple-pane windows with a U_W-value of 0.95 W/m²K and g-value of 0.62 can save about 491 kWh per window unit (1.3 m * 1.3 m) per year. This replacement can cover the cost solely through energy savings.

Multiple aspect

Drivers for energy efficient renovation from a consumer perspective: A representative survey study was conducted across 28 EU countries, involving over 30,000 individuals who had conducted building renovations within the past five years. The aim of the study was to investigate the triggers and drivers that motivated consumers to undertake renovations [32].

Triggers for energy renovations are the necessary maintenance, the replacement of a defective component, the available budget and the desire to counteract health issues. The last trigger reflects consumers' belief that deficiencies in their living environment can negatively impact their health. Energy labels on components or the Energy Performance Certificate (EPC) are less commonly considered as triggers. This has already been reported in another study [41].

The drivers for energy efficient retrofitting are property and health improvement, energy cost saving and environmental considerations (see Table 1). A further detailed study conducted in five EU countries yielded similar results to the previous study (see Figure 19). Thermal comfort, saving money and a healthy environment are the main motivations for the energy efficient renovation [51].

Table 1:
Drivers of consumers for the energy renovation in the 28 EU countries based on the quantitative research, data source: [32].

	Questions	Ratio [%]
Skills	I believe I am skilled in craftsmanship and can do installations on my own	43
	I believe I found installers who I trust to handle it	82
	I believe I personally or my family have sufficient knowledge to handle it	63
Environment	I believe I should contribute to protect the local environment	85
	I should contribute to protect us from global warming	83
Personal benefits	I believe it makes living in the residence healthier	88
	I believe I need to secure my living when I'm old	82
Financial	I believe you should always strive to improve your home/property	92
	I believe my family and friends appreciate it	79
	I believe it increases the market value of the residence	85
	I believe it enables me to increase the rent (landlords only)	58
	I believe it reduces energy cost	89

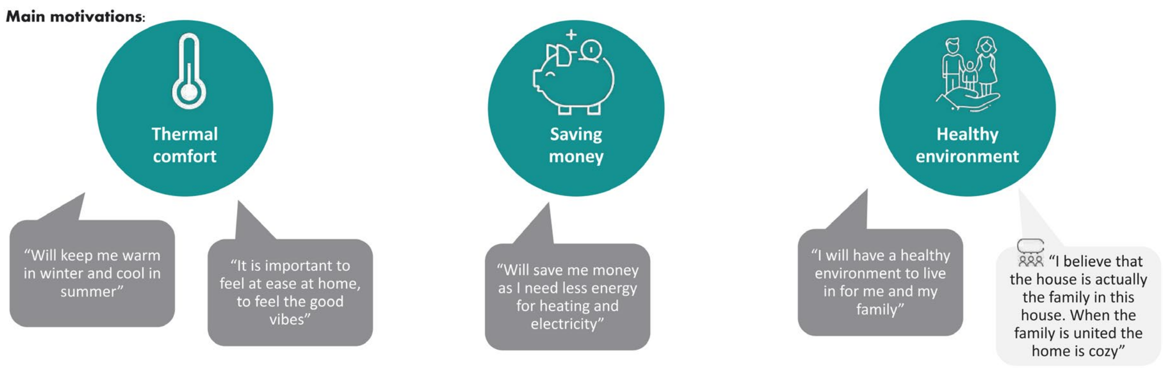

Figure 19:
Main motivation of consumers for energy renovation in five EU countries based on qualitative and quantitative surverys, source: [51].

Thermal Comfort and Health: As reported already in section 2.3.4, the lower heat insulation values of windows compared to walls often lead to colder surface temperatures on windows. This can result in thermal discomfort caused by radiation asymmetry, which means a contrast between the warm air temperature and the cold temperature of the window surface. Additionally, this temperature difference can lead to high air velocities near the window, particularly in cold outdoor temperatures. The sensation of cold air dropping from windows is a commonly reported issue that can have a significant impact on local comfort levels. Due to better insulation values, this type of discomfort rarely occurs with wall surfaces, even in old buildings.

Window replacement plays therefore a crucial role in improving thermal comfort and enhancing the occupants' health in several ways. By replacing old or inefficient windows, drafts and air leakages can be eliminated, resulting in a more airtight and well-insulated building envelope. This helps to reduce local thermal asymmetry, ensuring more consistent temperatures throughout the space. Moreover, new windows provide improved sound insulation, more daylight.

However, replacing old windows with airtight windows without renovating the building envelope can lead to mould growth in the absence of adequate ventilation. Therefore, the decision to replace windows should be made considering the entire scope of building energy efficiency measures on the building, such as insulation of the building envelope and installation of ventilation systems.

Climate Resilience: There is a growing demand for climate resilient buildings, prompting renovations to enhance resilience against climate-related hazards. These hazards include extreme temperatures, high winds, water-related issues (such as flooding or heavy rainfall), and solid mass hazards.

Figure 20 emphasizes the importance of windows in addressing these aspects of the building envelope, influencing basic performance requirements, safety requirements, and aesthetic considerations [52].

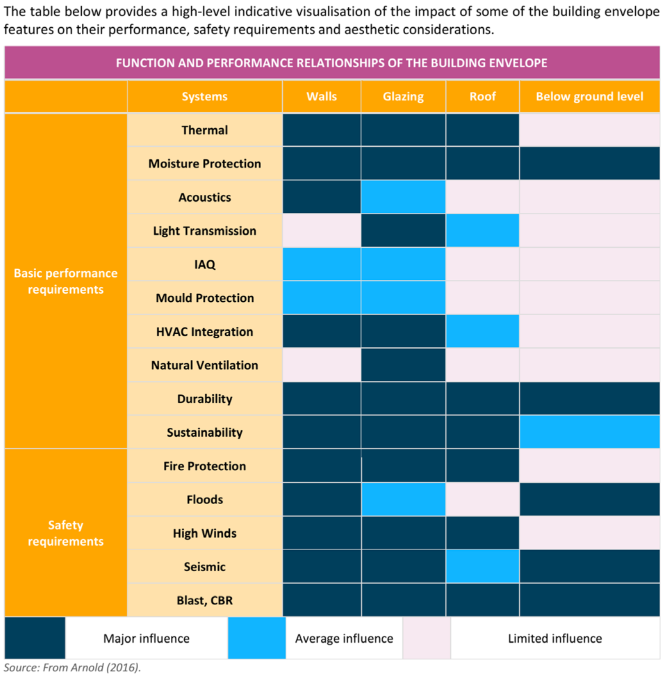

Figure 20:
Building envelope component and their impacts, source: [51].

4 Conclusion

Recently, the intensity of renewable energy supply in the EU has increased significantly. This trend creates optimism about the capacity of renewable energy resources to meet future consumption, without any need for additional energy savings.

However, comprehensive studies [22,23,20] on deploying heat pumps and district heating systems emphasize the importance of energy efficient buildings for achieving high efficiency, reliable functionality, and economical use of heating systems based on renewable energy. In addition, this literature study shows that energy efficient measures have a high potential considering multiple aspects such as job creation, health and well-being, reduction of energy poverty and stabilization of the electricity system through demand flexibility. Therefore, key researches suggest that the policy and stakeholders at the building level should acknowledge the correlation between energy efficient measures (demand side) and the use of renewable energy (supply side) in energy planning. Moreover, it is important to consider the additional benefits of energy efficiency measures in the long term and to avoid short-term and short-sighted economic considerations [27,53].

Windows play a crucial role in energy efficient building renovation, considering the low insulation properties of windows in the existing building stock and the advancements in window technologies over the past 15 years (such as low-e coating and triple glazing).

Assessing the environmental impact of window replacement compared to other energy efficiency measures in the EU is challenging due to differences in geometry, construction components and available materials between countries, as well as the insulation status of the building envelope of the buildings studied. The main advantage of window replacement lies in its ability to substantially enhance thermal, visual and acoustic comfort. Specifically, it significantly improves thermal comfort in buildings, preventing local thermal discomfort near the windows. Additionally, it contributes to resilience against climate-related hazards such as strong winds or heavy rainfall. The main advantage of window replacement lies in its ability to substantially enhance thermal, visual and acoustic comfort. Specifically, it significantly improves thermal comfort in buildings, preventing local thermal discomfort near the windows. Additionally, it contributes to resilience against climate-related hazards such as strong winds or heavy rainfall.

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