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ACHIEVING THE COST-EFFECTIVE ENERGY TRANSFORMATION OF EUROPE'S BUILDINGS

Combinations of insulation and heating & cooling technologies renovations

Methods and data

2019

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Foreword

The energy performance of buildings is so insufficient that the levels of energy consumption place the sector among the most significant CO_2 emission sources in Europe. Nearly 40% of the final energy consumption and 36% of Greenhouse Gas (GHG) emissions are attributed to the sector, becoming a priority to achieve the European Union (EU) long term energy and climate goals, as defined in the EU's Long Term Strategy (EU LTS). As a result, most of the EU energy policy initiatives address the building sector.

Within this context, renovation of existing buildings can lead to significant energy savings and plays a key role in the clean energy transition. However, the diversity of the EU building stock requires tailored strategies that take into account aspects such as climatic conditions, energy uses and, ultimately, the age of the building stock itself across Europe. To do so, Member States (MSs), within a general EU policy framework, have to define effective renovation strategies that address national conditions of the building stocks.

In order to ensure a common methodology for the calculation of energy performance and the establishment of minimum energy performance requirements for new and existing buildings, the Energy Performance of Buildings Directive asks MSs to follow a cost-optimal approach. But, the progress made differs among countries. This study facilitates the comparison between MSs that has been proven challenging due to diverse national and regional approaches and the use of different parameters and methodologies. Ultimately, it supports the benchmarking of the energy performance of building stocks of the MSs.

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Abstract

This report aims to answer the following question: *Which are the most cost-effective ways to decarbonise the existing EU building sector through energy renovations?* Replying this, we provide a method and a dataset to investigate the cost-optimal level of energy efficiency measures in combination with low carbon heating and cooling solutions. To showcase the application of the method, two EU Member States (Germany and Greece) are examined and targeted renovation solutions are discussed as examples.

This work begins with the characterisation of the current state of the very diverse EU building stock. Information is collected from European projects and the EU Building Stock Observatory (BSO). This information is analysed and restructured to provide a harmonised and ready-to-use dataset. This dataset is presented for the two exemplary cases, Germany and Greece.

Next, the method developed to assess the combination of insulation measures and efficient heating and cooling supply technologies for the existing residential EU building stock is presented. The method uses the basic principles of Cost Benefit Analysis (CBA) from an economic perspective. It allows the evaluation of the energy performance of different energy renovation options and their global costs. Through its application, we identify the cost effective and cost optimal solutions and how much primary energy and greenhouse gas emission reductions they achieve.

The study is performed on the existing EU building stock and explores the effect of both the current and future energy system fuel mixes. We consider the 2020 and 2030 fuel energy system mixes to better understand the impact of the power sector to the heating and cooling in the building sector.

By testing this method in Germany and Greece, we reach valuable results that contribute to a better understanding on how optimal energy building renovation strategies differ in southern and central Europe — when both heating and cooling are considered. The cost-optimal solution requires moderate thermal insulation in southern Europe, while efficient heating and cooling technologies should be prioritised. In other words, deep building envelope renovations are not always cost-optimal, nor do they necessarily maximise the environmental benefits. On the other hand, in central Europe deep energy efficiency improvements are cost-optimal and should be combined with efficient heating and cooling technologies.

Based on the outcomes from the two countries we tested, it is concluded that a holistic approach incorporating both energy efficiency and sustainable heating and cooling should be considered when planning the decarbonisation of the building sector. In other words, the transformation of both the energy system and the building stock in particular, has to be designed in coordination to avoid lock-in effects in terms of investments, or over investments in less than cost-optimal energy efficiency renovations, and the shortening of the renovation cycles of buildings. Ultimately, our work aims to set the fact-basis to reply to challenging policy questions on how to transform the existing building stock in the EU.

Disclaimer

This document was prepared by the Joint Research Centre. Results and conclusions drawn are based on assumptions and input data for the specific study. Views expressed in unofficial documents do not necessarily represent the views of the European Commission and the European Commission cannot be held responsible for any use of the information contained herein.

1 Introduction

The 2030 climate and energy framework agreed as part of the "Clean Energy for All Europeans" package entails a 40% reduction of greenhouse gas (GHG) emissions compared to 1990 levels; a 32% share of renewable energy consumption and 32.5% energy savings compared to 2005 levels (European Parliament & Council of the European Union, 2018). The building sector is a key actor to achieve the goals set (European Commission, 2018a). But what are the key facts and the contributions of the built environment?

The energy performance of buildings in the EU is so insufficient, based on the current building codes requirements, that the levels of energy consumption place the sector among the most significant CO_2 sources in Europe. Nearly 40% of the total final energy consumption (FEC) — of which 54% is for heating and cooling purposes — and 36% of greenhouse gas emissions are attributed to the sector, making it a priority to achieve the EU long term energy and climate goals, as defined in the EU's Long Term Strategy (EU LTS).

By 2050, the energy consumption of the residential sector should be reduced by 38% — compared to 2005 — following the baseline scenario of the EC (European Commission, 2018a). This baseline scenario is built upon the energy and climate policies, and targets set for 2030. It also includes the Regulation on Governance of the Energy Union and Climate Action ([1]).

In addition to the general roadmap to emission neutrality of the building stock by 2050, the EC has set policy targets and regulations to ensure the energy efficiency improvement of the European building stock. The Energy Performance of Buildings Directive (2010/31/EU - EPBD) is the main legislative and policy tool in the EU. It focuses on both new and existing buildings (European Commission, 2018b). The Directive was revised in 2018 with two complementary objectives: (i) to accelerate the renovation of existing buildings by 2050; and (ii) to support the modernisation of all buildings with smart technologies and make a clearer link to clean mobility. At the same time, the building sector plays a prominent role in the Energy Efficiency Directive ([EED] (European Commission, 2018c)). The EED (2012/27/EU) identified the existing building stock as the single biggest potential sector for energy savings and, as a result, crucial to achieving the EU objective of reducing GHG emissions (European Commission, 2016; Stadler, Kranzl, Huber, Haas, & Tsioliaridou, 2007a).

1.1 EU building stock — disparities and age across EU

The design and implementation of the above policy initiatives consider two main aspects of the EU building stock: the disparity in use and needs across the EU and its age.

Differences are also observed on aspects such as construction, size, energy performance requirements, regional climate and energy supply characteristics (Mata, Kalagasidis, & Johnsson, 2018). Looking into the residential sector — dwellings are responsible for 25% of the total energy consumption in the EU (Eurostat, 2018) —, the mean observed energy consumption in residential buildings in the EU was 159 kWh/m^2 in 2014 (specifically for space heating 124 kWh/m^2). However, this consumption differs significantly across countries. Examples of the energy consumption levels in a few selected EU Member States (MSs) are found in Table 1.

Table 1 Specific annual energy consumption in selected EU Member States ([2]) (EU Buildings Database, 2018)

Country	Annual energy consumption in 2014 [kWh/m^2]	
	all end-uses	space heating
Belgium	223	197
Cyprus	65	18
Germany	171	138
Italy	148	129
Sweden	188	122

1.1.1 The role of renovation

The energy consumption of the EU building stock, beyond the climatic conditions and uses, greatly depends on its age. One third (35%) of the EU building stock is over 50 years old, more than 40% of the building stock was built before 1960 and 90% before 1990 —and almost 75% of it is energy inefficient according to current

([1]) In the scenario the following are taken into account: a reformed EU emissions trading system, national greenhouse gas emission reduction targets, legislation to maintain the EU land and forests sink, the agreed 2030 targets on energy efficiency and renewable energy, as well as the proposed legislation to improve the CO2 efficiency of cars and trucks. These policies and targets are projected to reach reductions of greenhouse gas emissions of around -45% by 2030 and around -60% by 2050.

([2]) EU buildings database, http://ec.europa.eu/energy/en/eu-buildings-database building standards. At the same time, only 0.4-1.2% of the building stock is renovated each year — at different rates across the EU Member States (Artola, I., Rademaekers, K., Williams, R., & Yearwood, 2016; European Commission, 2019; Filippidou, Nieboer, & Visscher, 2017; Sandberg et al., 2016). Renovation of existing buildings can lead to significant energy savings and plays a key role in the clean energy transition.

Building codes with specific regulation on thermal insulation of the building envelope started appearing after the 1970s in Europe. This means that a large share of today's EU building stock was built without any energy performance requirement. What is more, due to the long lifespan of buildings, currently existing buildings will constitute a major part of the European housing stock for the coming decades (Sandberg et al., 2016). As a result, if the energy consumption of buildings must be reduced, the renovation of existing buildings will play a major role.

Energy renovation rates assumed or quoted as "needed renovation rates" usually range from 2.5-3% (Boermans et al., 2015; BPIE, 2011; Dixon, Eames, Hunt, & Lannon, 2014; Stadler, Kranzl, Huber, Haas, & Tsioliaridou, 2007b). However, at actual current rates, as indicated above, it is claimed that more than 100 years will be needed to renovate the EU building stock (European Commission, 2016).

The vast majority of these renovations do not use the full potential energy savings that can be achieved. An estimate by the Buildings Performance Institute Europe (BPIE) showed that minor renovations (e.g. new condensing boiler) were 85% of the market and moderate renovations (e.g. insulation of relevant parts and new condensing boiler) represented only 10% (BPIE, 2011). Research performed, so far, has revealed that the majority of building renovations consists of small scale projects and relatively low investments or occurs at the natural need of dwellings to be retrofitted (Filippidou, Nieboer, & Visscher, 2016; Filippidou et al., 2017; Sandberg et al., 2016). Large scale buildings renovation is still thought of as a difficult task to be accomplished. The most prevalent reasons for this are, among others, large investments, lack of awareness on the potential benefits and on skills required.

On top of that, the characteristics of the building stock are quite different across countries in Europe. This implies that there is no single solution identified for the EU building stock as a whole. Even more, building ownership and the construction sector are naturally fragmented in the EU countries. These facts hinder the transformation of the building stock in a cost-effective way.

1.2 Cost optimal energy renovation

The EC, despite these discrepancies, acknowledges the renovation of buildings as a 'win-win' option for the EU economy as a whole (Saheb, Bódis, Szabo, Ossenbrink, & Panev, 2015). Specifically, to achieve the full potential savings through renovation, the EC requires Member States (MSs) following a cost-optimal approach as described in the EPBD.

The cost-optimal method is provided in Regulation No. 244/2012 (European Parliament, 2012) in order to define minimum energy performance requirements for new and existing buildings. It also suggests that MS should strive for a cost-efficient equilibrium between the reduction of final energy consumption and the decarbonisation of energy supply (European Commission, 2012). According to article 5 of the EPBD, MSs have to report to the EC the results of the assessment of cost-optimal levels of minimum energy performance requirements, while this exercise has to be revised every 5 years in order to reflect technical progress in the building sector.

1.3 What do we propose?

We try to answer the following main question: *Which are the possible ways to decarbonise the EU building sector in a cost-effective manner through energy renovations?* This study provides a method and a dataset to investigate the optimal level of energy efficiency measures in combination with low carbon heating and cooling solutions. To showcase the application of the method, two illustrative EU Member States (Germany and Greece) are examined and targeted renovation solutions are discussed.

The homogeneous mapping of the potential for energy savings in EU buildings is a difficult task to be performed due to the differences of the MS building sectors. Nevertheless, studies, like the present one, are needed to generate a systematic overview of energy saving options and renovation solutions to reduce the energy consumption and CO_2 emissions in the EU.

The goal of this work is to provide tools and data to enhance energy policy advice on the optimal combination of cost-efficient energy renovations for the EU building stock. To do so, we provide a method and a dataset to assess the energy performance of the current and future renovated building stocks, including the combination of insulation measures and efficient heating and cooling supply technologies. On top of that, we assess the economics of the potential renovation solutions, following the global cost (GC) perspective, in order to identify the cost-optimal one for each reference case of the building stock.

Moreover, this study facilitates the comparison between MSs that has been proven challenging due to diverse national and regional approaches and the use of different parameters and methodologies. Ultimately, it supports the benchmarking mechanism of the energy performance of building stocks on the MS.

We apply the method and perform the analysis in two EU countries — Germany and Greece. This selection allows evaluating the effect of climate conditions in the design of cost-efficient energy renovations. What is more, we built our analysis based on national building typologies. Both elements, building types and climatic zones, should be considered by MS when identifying cost-effective approaches as described in the article 2a of the EPBD (European Commission, 2018c) on long-term renovation strategy. In other words, we provide the basis for MS to draft their strategies regarding buildings — an overview of the national building stock and the identification of cost-effective energy renovations (relevant to the building type and climatic zone).

Last, this work sets the fact-basis to reply to challenging policy questions providing a method that eventually can help to do so. In this work we concentrate on shedding light on the following:

- Is there a balance and a cost-optimum between the reduction of energy demand in buildings and the decarbonisation of the supply sector?

By further developing this work we could reply to questions like:

- Are the targets between decarbonisation and energy efficiency aligned?
- How can the EU building stock — under the current policies in place — contribute to the EU LTS?
- Are there or will be undesired lock-in effects vs no-regret investments regarding building renovation?

2 Energy efficiency state of the EU building stock

Improving the energy efficiency of buildings is widely acknowledged as one of the most promising, fast and cost-effective ways to mitigate climate change and achieve 2050 goals set for the building sector (European Commission, 2018a). Energy efficiency of the building stock is hard to achieve if we only focus on the design of new dwellings.

To design effective strategies to transform the existing building stock in Europe a complete and detailed assessment of the efficiency state of the existing building stock in Europe is necessary in order to examine the cost-efficient energy renovations at MS level. This chapter aims at evaluating the current energy performance state of the EU building stock.

We use data from TABULA and EPISCOPE, Intelligent Energy Europe (IEE) and Horizon 2020 projects, which contain the most updated information on building stock characteristics (EPISCOPE project consortium, 2016). The data include the age cohort, type, useful floor area, thermal transmittance (U-value) of the envelope (roof, façades and floor), thermal transmittance (U-value) of the windows, heating and domestic hot water (DHW) systems, ventilation system, the predicted heating energy consumption and energy production systems, if present.

2.1 Age of the EU building stock

One of the most effective ways to understand the energy performance of buildings is the age of the stock. In Figure 1, we show a breakdown of dwellings in the EU based on the building year cohort. We observe, as mentioned in the introduction of this report, that 90% of the EU building stock is built before 1990 and approximately 50% was constructed before 1970. Building code regulations regarding energy performance levels are scarce before 1970. This means that the majority of the EU building stock is performing inefficiently which can be explained to a large extent due to the low rates of renovation so far. A few countries are exceptions and their building stock is younger. As seen in Figure 1, in Cyprus, Portugal and Ireland the share of dwellings built after 1970 is larger compared to the rest of MSs.

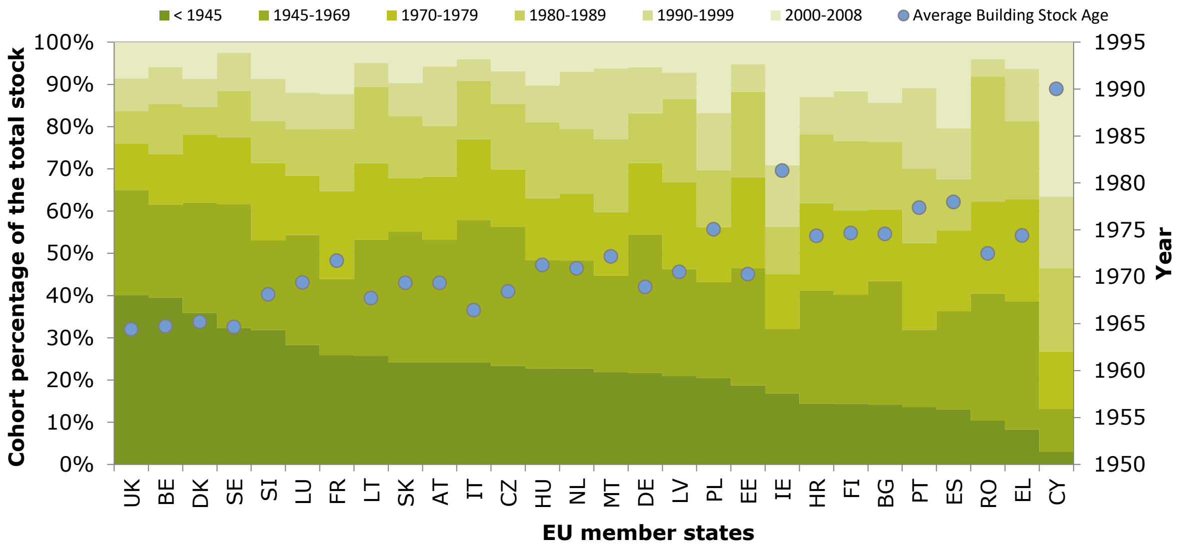

Figure 1 EU dwelling stock age cohorts (source: ENTRANZE, http://www.entranze.eu/)

The building year cohort is only one indication of the energy performance of buildings. To further understand and analyse the actual energy performance we need information on the thermal transmittance values of the envelope and the energy efficiency of the systems used for heating and cooling – along with the fuel mix of EU MSs.

2.2 Energy performance of the building envelope

To design effective strategies for the decarbonisation of the building sector it is essential to characterise the current status of the building stock. As said before, the construction year alone does not provide a clear picture of the state of the building stock in the EU.

The building shell, or otherwise called building envelope, consists of the construction elements that separate the indoor environment from the outside. These elements are the roof, floor, walls, windows and doors. Their thermal characteristics determine how much heat is lost to the outside and, thus, the energy required to keep thermal comfort conditions in a dwelling. The thermal behaviour of these elements is determined by their thermal transmittance that is described by the U-value. The U-values essentially describe the thermal insulation levels of the building envelope.

In Figure 2 we show the average U-values of the building shell per construction element (roof, floor, wall and windows). As these are largely dependent on the construction year of the buildings, we aggregate values before and after 1970s, when the introduction of thermal insulation standards took place in Europe.

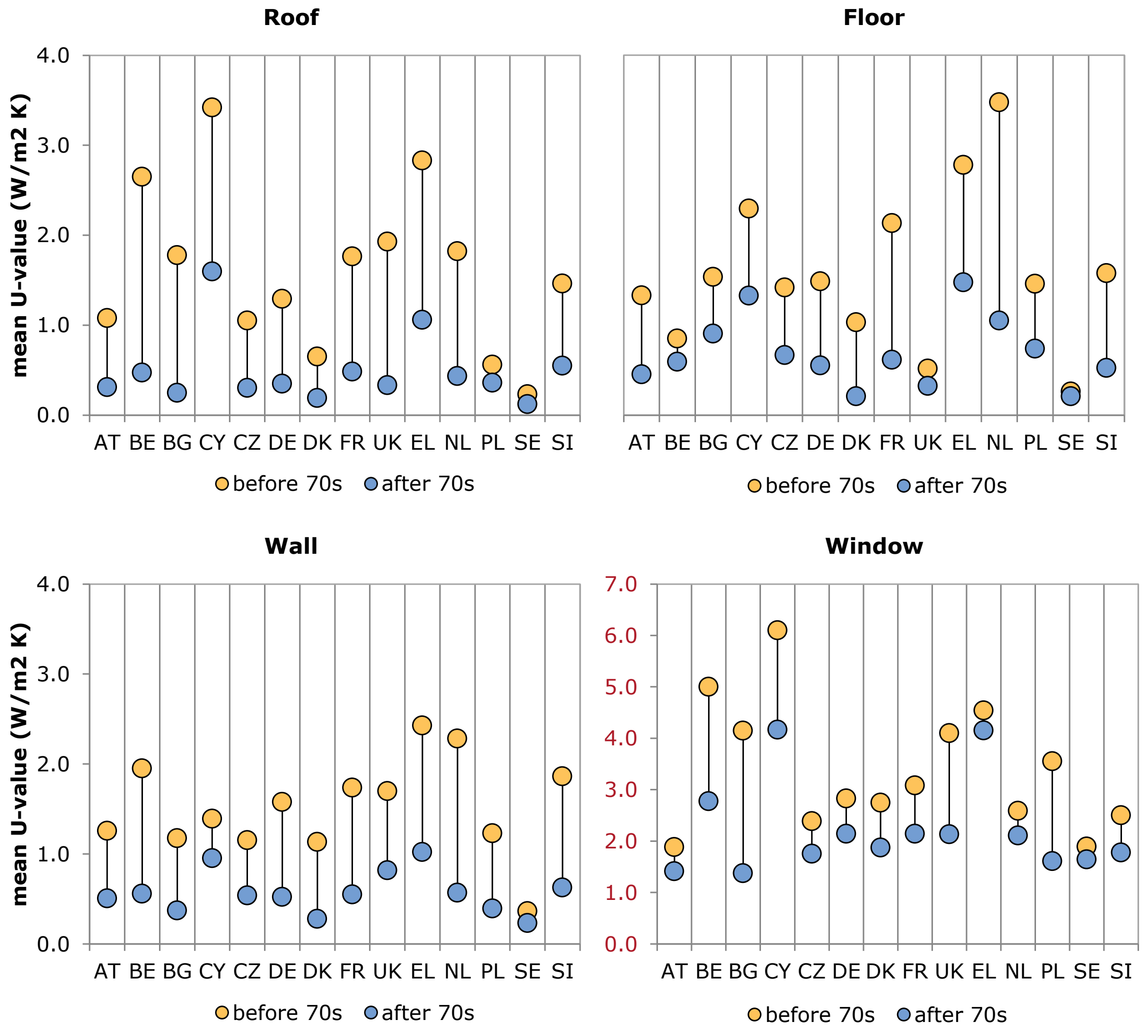

Figure 2 Mean U-value of the building's envelope elements (roof, floor, wall and window) calculated as a weighted average per surface area of each element for two subsets (built before and after the 1970s) of the national building stocks (source: EPISCOPE, http://episcope.eu/welcome/)

As it is observed, the introduction of thermal insulation standards, which took place in the 1970s, has lowered the U-values (thermal transmittance) of the average building stock in all MS. Exception to this is Sweden where the building stock was thermally insulated before the 70s. On the contrary, in cases like the Netherlands and Belgium, these standards increased the thermal efficiency of the stock twofold. Specifically, for the Dutch case, the U-value for roof decreases from 1.8 to 0.4 (320%), the wall from 2.3 to 0.6 (300%) and the floor from 3.5 to 1 (230%). The U-values for windows reduce only by 23% (Figure 2).

Still, to achieve policy goals and transform the building stock to a carbon neutral one, based on nearly zero-energy buildings (NZEB), a greater reduction of the U-values is required. As an example, Cyprus with an average wall U-value of 1 W/m^{2}K after the 70s has a goal of reaching wall U-values of 0.4 W/m^{2}K.

The mapping of the average U-values of the building stocks in Europe provides us with critical information about the state of energy efficiency of the stock. However, without information on the technical building systems [3]that supply heating and cooling needs, we are missing an important component of the energy performance of the building stocks. The efficiency of these systems determines the FEC of the building stock and, consequently, the associated GHGs. In the next section, we provide an overview of the overall national efficiencies for heating and cooling needs in the residential sector.

2.3 Heating and cooling efficiencies of the EU building stock

Heating and cooling (H&C) account for 54% of the total FEC in the EU building stock. The FEC, for H&C, is determined by the energy demand and the overall H&C efficiency of the building stock. This last parameter provides valuable information to identify room for improvement within the sector. In other words, a low overall heating & cooling efficiency suggests that a technology shift should be pursued to decarbonise the building stock.

In Figure 3, we present the overall efficiency — defined as the ratio of heating/cooling demand over consumption — of the residential sector in the EU MSs for the period 2000 – 2015 for both the heating and cooling supply (Mantzos, Wiesenthal, Matei, Tchung-Ming, & Rozsai, 2017). Similar to the age and the energy performance of the building stock, here too, we observe large differences across MS, especially for heating. In general, an increase in efficiency is evident for both heating and cooling along this period. Efficiencies for cooling are higher compared to heating. This is due to the fact that large shares of cooling needs are provided by electric-based technologies. These technologies perform at high efficiencies, ranging between 1.50 and 3.50 — expressed as coefficient of performance (COP).

Looking at MS level, countries like Sweden and Finland show overall heating efficiencies above 90% while others like Bulgaria and Romania barely reach an efficiency of 60%. These differences rely on the technology portfolio of the country in one hand and the fuel mix for heating of the MSs on the other, which ultimately determine the predominant technologies.

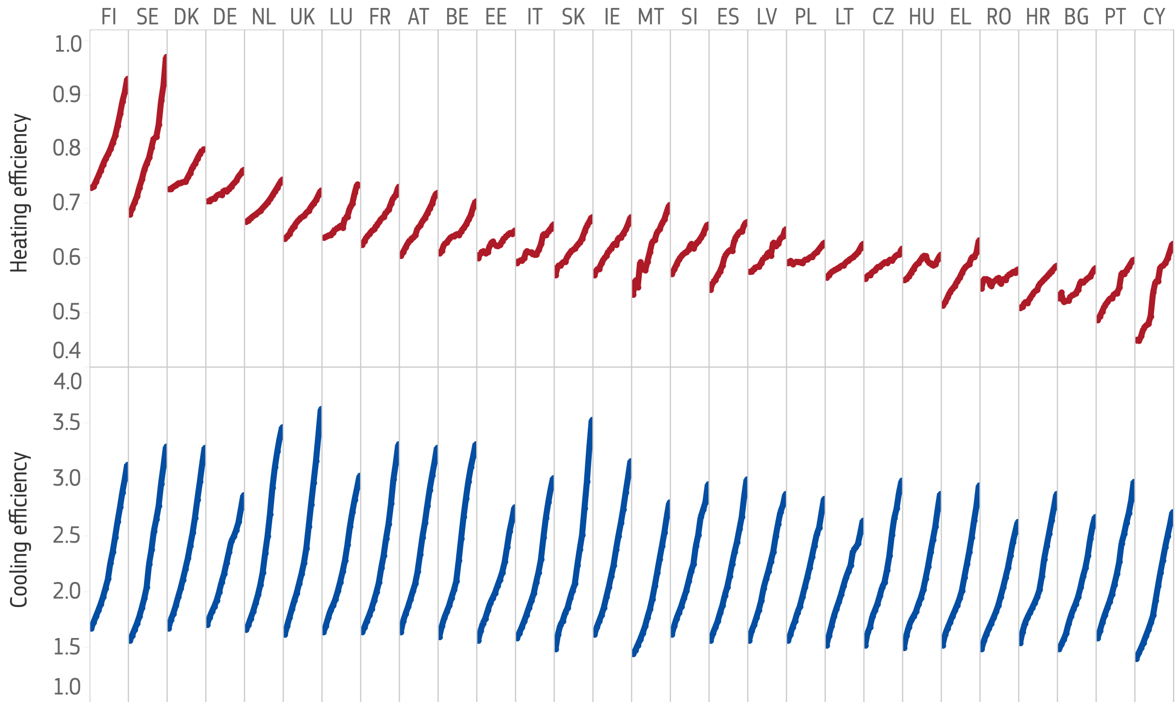

Figure 3 National heating and cooling efficiencies for the residential sector in the period 2000 - 2015 (Mantzos et al., 2017) — 2015 data.

[3] The term technical building system includes heating and cooling, domestic hot water, ventilation and self-production technologies. In many cases we refer to them as heating and cooling systems since those are the targeted energy services in this work.

2.4 National energy fuel mixes

When it comes to transforming the EU building stock, MSs should strive for a cost-efficient equilibrium between the reduction of final energy consumption and the decarbonisation of energy supply (European Commission, 2012). Otherwise, highly efficient technologies alone can lead to significant FEC reductions but moderate CO_2 emissions reductions if the input fuel is not clean. Heat pumps are a paradigm of this effect when the electricity mix mostly relies on fossil fuels. Therefore, we should evaluate the fuel mixes of MSs and incorporate the evaluation of CO_2 emissions in the selection of cost-optimal solutions.

In Figure 4, we show the shares of fuel that supply space heating demand in the residential sector per MS — sorted by the share of fossil fuels. It is observed that the Swedish and Finnish fuel mixes present the lowest share of supply from fossil fuels. In these two cases, the heating is largely supplied by district heating (DH), biomass and electricity — adding up to, roughly, 95% and 85% respectively. On the other hand, Ireland, Luxembourg, the Netherlands, Belgium and United Kingdom show fossil fuel shares above 80%. This suggests an extensive use of gas boilers and the potential benefit of replacing them by heat pumps — when the electricity fuel mix is clean enough.

In terms of shifting technologies, the share of buildings supplied by DH can have difficulties in replacing the supplying technology due to the commitment to the network infrastructure and the consequent business cases. Thus, countries like Sweden, Estonia, Latvia, Finland or Denmark have at least 40% of their heating supply in the building stock locked in thermal networks.

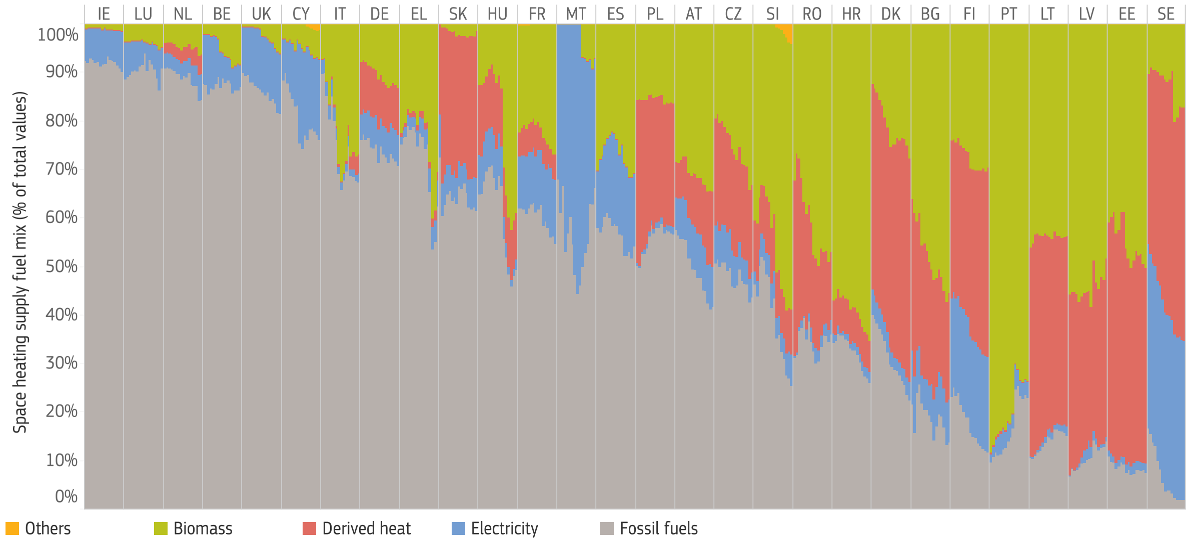

Figure 4 National shares of heating supply fuel mix (Mantzos et al., 2017) — 2015 data.

As shown, the fuel breakdown of MSs has an important effect in the selection of the renovation strategies of the building stock when it comes to identifying the appropriate heating and cooling technology and reducing the GHG emissions of the sector.

3 Methods

In order to identify possible ways to decarbonise the EU building sector in a cost-effective manner, through energy renovations, we create a tool and an EU dataset to facilitate it at national level. Through the method and using existing data, we assess the optimal combination of energy efficiency measures, regarding envelope upgrades, and the use of heating and cooling systems at building level. Not only that, but the method also offers the possibility of assessing local renewable energy sources.

Our approach follows the JRC Guidelines and fundamental principles of cost-benefit analysis[4] (CBA) as described both in the EPBD and EED (Jakubcionis, Santamaria, Kavvadias, Piers de Raveschoot, & Moles, 2015). At the same time, we follow the guidelines laid out in Regulation (EU) No 244/2012 supplementing the EPBD (European Commission, 2012). Those establish a comparative methodological framework for the calculation of cost-optimal levels of minimum energy performance requirements for buildings and building shell elements.

According to the revised EPBD and the following guidelines, specifically article 2a (European Commission, 2018c), EU MSs have to define "reference buildings" that represent the typical buildings of each country. Moreover, they also have to take into account the climatic conditions present in the country. This is needed to produce outcomes that can be generalised and applied to the whole national building stocks.

To apply the CBA analysis to the building stocks of MSs, we follow the process of:

- definition of the reference case buildings;
- definition of the packages of energy renovation measures and renewable energy measures;
- calculations to assess the building energy performance before and after the renovation measures take place – in terms of primary energy;
- calculation of the GC using the NPV (Net Present Value) method;
- identification of the cost optimal and cost-effective renovation solutions and the gap, if any, between the cost-optimal levels and minimum energy performance requirements.

The method, and ultimately the tool developed in this study, following the above mentioned guidelines, is depicted in Figure 5. It comprises of three main steps: the processing of the input data, the definition of the case study, and the calculations. The selection of the case study can vary from a neighbourhood to a whole country. The strength of this tool is that through reference cases, describing a building stock, we can calculate global cost-efficient and cost-optimal renovation options. Meaning the prioritisation of solutions.

To give an example, for a national evaluation, the tool requires the following elements as input data:

- national building stock, represented by reference buildings that are described by parameters such as their:
  - construction period,
  - the type of buildings,
  - the thermal transmittance values of envelope elements,
  - heating and cooling systems and
  - climatic data, and
- a catalogue of energy efficiency measures, including both building envelope upgrades and/or technical building systems (heating, cooling, ventilation and renewable sources). These catalogues can be customised based on the specific case study.

With this input we, first, create the reference buildings. Then, by the combination of the different renovation solutions included in the catalogue we create renovated versions of these reference buildings.

[4] CBA is not considered as a process that should be performed individually for a specific energy renovation case (Desideri & Asdrubali, 2019). On the contrary, it is meant to be applied to complete buildings stocks to identify appropriate cost-effective and cost optimal energy efficiency measures (EEMs) for their refurbishment.

Next, we calculate the demand and the consumption of both the reference and renovated buildings. By comparing the reference case to the renovated versions we are able to compute the energy savings achieved by each solution.

Going back to the goal of the study, identifying cost-efficient and cost-optimal solutions, we need to allocate costs to the different renovation solutions. These can be costs related to the upgrade of the building envelope or to the replacement of technical building systems or both. When it comes to building envelope upgrades, costs are calculated based on an empirical correlation between savings achieved and costs themselves (Annex 1). For the technical building systems we obtain the cost based on the required power capacity. This, we calculate based on the energy demand and the maximum heating and/or cooling degree days along the year.

With the previous results, we perform a cost-benefit analysis, assuming a building lifespan of 50 years following the EPBD guidelines. This means that our economic module considers additional investments needed along this period (i.e. replacement of technical equipment). We implement this process under the CBA module, shown in Figure 5. The cost-benefit analysis not only takes into account the primary energy consumption but also environmental parameters — CO_2 emissions.

We developed our tool to be open source, adaptable to different datasets and available to the building community for further developments. We used Python 3.6 as our programming language and all input data are open access (Van Rossum & Drake Jr, 1995).

Section 3.1 describes the input data while sections 3.2.1, 3.2.2 and 3.2.3 explain each calculation step in detail.

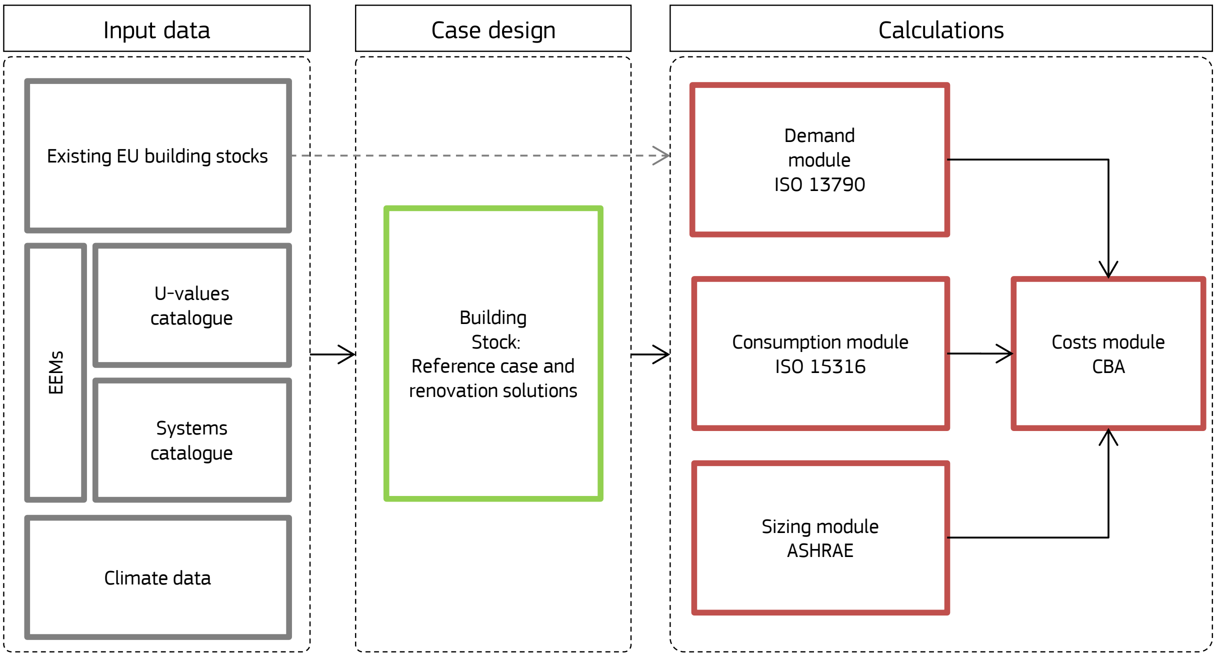

Figure 5 Model description (red: calculations, green: case design, grey: data input)

3.1 Input data

In this subsection we present the data, the assumptions and the cleaning and processing carried out before the design of the case studies. We describe the different boxes under the input data layer (upper-left box in Figure 5) including the characterisation of the existing building stocks, as well as the EEMs and climatic data considered.

3.1.1 Characterisation of the existing EU building stock and definition of reference cases

The first step focuses on the creation of the reference buildings. The upper-left "Existing EU building stock" box is the starting point to the definition of the reference case (middle part of the Building Stock module).

This process can be carried out in two different ways — based on real example or synthetic buildings. The reference cases based on real example buildings represent the most typical building of a specific category. These categories can be defined by the type of use and reference occupancy pattern, or the floor area, compactness of the building — expressed as the envelope area/volume ratio —, or building envelope constructions with corresponding U-values, technical systems and energy carriers, together with the share of energy use (Desideri & Asdrubali, 2019). When based on the synthetic building approach, the reference cases are defined through a “virtual building” which, for each relevant parameter, includes the most commonly used materials and systems (Desideri & Asdrubali, 2019).

In this work, we follow the real example of dwellings approach. We start by the characterisation of the existing EU building stock using the information presented in section 2. We use TABULA and national statistics as data input (EPISCOPE project consortium, 2016).

We process the data and classify it based on the country, typology, construction period, climatic data, and the respective thermo-physical characteristics (U-values of envelope elements) and technical building systems (space heating, domestic hot water, ventilation and space cooling). We use these parameters to cluster the building stock and thus define the reference cases that statistically describe it. Table 2 shows an example of the characterisation in terms of number of dwellings for the German building stock, after we have processed and categorised the data by the reference dwellings. We, then, go on describing each reference dwelling. The reference dwellings for each MS represent the current state of their residential stock.

Table 2 German building stock categorised by the reference dwellings (construction year cohort and type of dwelling classification). Number of dwellings (in thousands) (EPISCOPE project consortium, 2016).

	Type[5]		
Construction year cohort	**MFH**	**SFH**	**TH**
before 1860	54	330	0
1860 – 1918	442	966	640
1919 – 1948	388	1131	710
1949 – 1957	356	859	447
1958 – 1968	586	1509	633
1969 – 1978	412	1507	611
1979 – 1983	161	704	335
1984 – 1994	338	1160	652
1995 – 2001	265	1035	619
2002 – 2009	93	775	384

3.1.2 Energy efficiency measures (EEMs)

To create the renovated building stock we apply different sets and combinations of energy efficiency measures to the reference cases, as shown in the middle-left part of Figure 5. Energy efficiency measure (EEM) packages can be categorized as:

1. improvements in the building envelope (U-values catalogue in Figure 5),
2. upgrades in the technical building systems (e.g., space heating and cooling), and
3. the use of renewable sources for energy production (both thermal energy and electricity) — both included in the System catalogue in Figure 5.

The research community usually deals with packages of measures that include at least the first two categories and, when deep renovations are involved, the third category is also considered (Corrado, Ballarini, & Paduos, 2014; Mata et al., 2018; Mata, Sasic Kalagasidis, & Johnsson, 2015). The EEM packages can be based on current and future market trends following policy enforcement. They can also be defined according to scenarios that achieve EU and national goals.

In this study, we use the national cost-optimal reports of the MSs to define the different levels of U-values for envelope renovations (Table 3) and data from EPISCOPE and ENTRANZE projects as they were defined by national experts. These levels correspond to different energy policy goals. Level 0 represents a minimum intervention whereas level 3 represents an NZEB ambitious approach (ENTRANZE, 2019; EPISCOPE project

[5] Type of dwellings includes: multi-family house (MFH), single-family house (SFH) and terraced house (TH)

consortium, 2016). To make the idea of U-values and levels of envelope insulation more concrete we could think in the following terms for DE (SFH, 1949 – 1957). For example:

- A wall with a U-value of 1.4 W/m2K is equivalent to a two layer brickwork.
- A roof with a U-value of 1.4 W/m2K is equivalent to a tilted roof with masonry between rafters.
- A floor with a U-value of 0.9 W/m2K is equivalent to a concrete ceiling with wooden floor.
- A window with a U-value of 2.8 W/m2K is equivalent to a wooden window frame with dual-pane glazing.

Table 3 Envelope upgrade levels for Germany and Greece, expressed in U-values (W/m2 K)

Country	element	Current state/Reference case	level 0	level 1	level 2	level 3
DE	Wall	1.0	0.8	0.5	0.3	0.2
DE	Roof	0.7	0.8	0.5	0.3	0.2
DE	Floor	0.9	0.8	0.5	0.2	0.2
DE	Window	2.5	1.7	1.5	1.2	1.0
EL	Wall	2.3	1.9	1.3	0.7	0.6
EL	Roof	1.5	1.2	0.9	0.6	0.5
EL	Floor	1.8	3.0	1.9	0.5	0.4
EL	Window	4.5	4.3	3.6	2.7	2.6

Then, we create a catalogue of space heating, DHW, cooling, ventilation and production system upgrades (Table 4).

Table 4 Catalogue of energy systems

Category	Technology
Space heating system	Boiler, non-condensing Boiler, condensing Air heat pump Gas-fired instantaneous water heater, non-condensing Combined heat and power generation District heating
Space cooling system	Small Split (<5 kW) Big Split (>5 kW, incl. ducted) Chillers (A/W) < 400 kW Air heat pump reverse mode
DHW system	Solar thermal
Ventilation system	Heat recovery ventilation system
Production system	Combined heat and power generation Photovoltaics

As a result, we have two different catalogues of possible renovations – envelope and systems – that we use to create combinations for each reference dwelling. Continuing, using these combinations, we create the “renovated reference dwellings”.

In total, the U-values catalogue is composed of 16 possible building shell upgrades — 4 envelope elements and 4 upgrade levels. The Systems catalogue comprises of 18 space heating systems, 5 space cooling systems, two solar systems (thermal and photovoltaics) and a heat recovery ventilation system.

The combination of the two catalogues leads to a total number of 11 520 potential renovation options. However, for a better understanding of our results and based on the feasibility of these renovation packages we have selected 100 options — 25 from the systems catalogue and 4 from the U-values catalogue (we apply the same level of upgrade to all envelope elements). In Annex 2, we present the chosen combinations from the systems catalogue.

As a result, each reference dwelling has multiple “renovated reference dwelling” versions based on the combinations applied — 100 options. These constitute the "Renovated Building stock", as shown in Figure 5.

3.1.3 Climate data

The climatic data for each MS are used in several stages of this work. We use two variables: temperature and solar radiation. First, national hourly temperature profiles (Figure 6 left) are used as input in the "Sizing module" (right-bottom part of the calculations box in Figure 5). In addition, we use these temperature profiles to calculate the heating and cooling degree days of MSs following Eurostat guidelines (Eurostat, 2019b), consequently needed to calculate the energy demand of the dwellings. Solar radiation is required in the calculation of the production of the solar systems — thermal and photovoltaics (Figure 6 right).

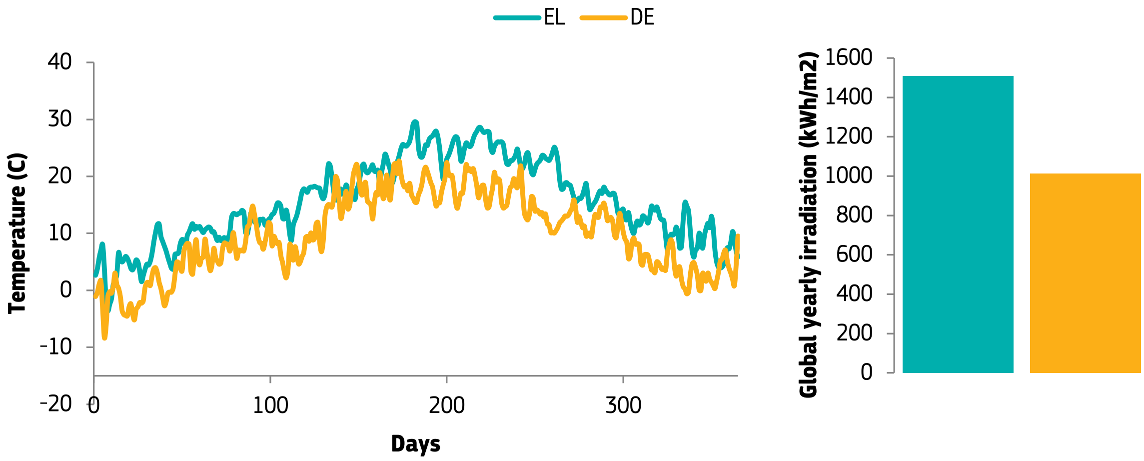

Figure 6 Average daily temperature (left) and global yearly radiation (right) for Greece and Germany

3.1.4 Data quality and availability

At European level, available data on energy-related residential building stocks is unsatisfactory. Today, available data sources are often not representative, nor complete, updated or consistent (EPISCOPE project consortium, 2016). This leads to wide information gaps that hinder a comprehensive overview at European level. To tackle this, efforts have been made by the development of the EU Building Stock Observatory by the European Commission.

Recently, there is a lot of interest and research initiatives, at both national and European levels, on the energy efficiency of buildings and their role in the energy transition. This fact creates the impression that data availability is not an issue when it comes to buildings. On the contrary, the data sources of many of these initiatives overlap and critical assumptions are needed in order to create a complete dataset that allows the completion of projects. Indeed, the Evaluation of the EPBD stated very clearly the lack of reliable and consistent data that would enable us to evaluate the actual effect of energy efficiency policies on the building.

In order to avoid uncertainty regarding input data, efforts should focus on filling in information gaps. Better data on the energy efficiency state of buildings, thermal insulation and technical building systems, will help enhance the understanding of the current state of the building stock and the definition of effective energy policies.

This work collects the up-to-date available data and creates a dataset that, after processing and cleaning, is easy and ready to be used. Of course, we faced the same problems as many other researchers before experienced. Here, we try to create a harmonised dataset that can be used together with our proposed method or independently.

3.2 Calculations

In this subsection, we present the modules under the calculations layer (right box Figure 5). Here, we do not go into detail on the mathematical formulation used but we provide an overview of the technical standards and assumptions followed in the development of the tool.

We start by describing the demand and consumption modules and we move on to the sizing and cost modules. All these are the final steps for the completion of the method and the identification of the cost-optimal solution for each building type.

3.2.1 Demand and consumption modules

According to EN ISO 13790 (Technical Committee CEN, 2005), there are three different energy calculation models that can be used to assess the building energy performance (EP): 1) a monthly quasi steady- state calculation; 2) a simple hourly dynamic calculation, and 3) a detailed (hourly) dynamic simulation method. Each member state has its own national method and tools to calculate the energy performance of buildings. The EP indicators, requirements, and ratings are provided in ISO 52003-1 (ISO, 2017).

In our in-house model, we use the quasi steady-state calculation which reflects the majority of MSs national methods. We calculate the energy demand and consumption twice – before and after the energy renovation measures are applied. We have considered the assumptions followed in (Institut Wohnen und Umwelt GmbH, 2013).

Consumption is derived from the energy demand and the seasonal energy expenditure factors (EEF)[6]. The EEF is defined as the ratio of delivered energy to useful heat (or cold). Thus, we obtain the energy consumption by multiplying the energy demand and the EEF.

3.2.2 Sizing module

To determine the size of the new equipment, for the renovated building stock, we have followed the method described in (ASHRAE, 2009). We calculate the ratio between the maximum value of the HDD and the sum of them over the year. The size of the equipment is determined by the annual demand (q_{h_del}), the fraction of the demand to be covered by the system ($\alpha_{i,h}$) and the aforementioned ratio (Eq. 1).

$$P_h = \alpha_{i,h} \cdot q_{h\_del} \cdot \frac{max_i\{HDD_i\}}{\sum_i^{8760} HDD_i} \qquad (1)$$

In Figure 7, we present the HDD for Germany, as an example. Qualitatively, the aforementioned ratio is calculated by the maximum HDD (numerator) — highlighted in green, while the sum of the HDD over the year (denominator) covers the grey area.

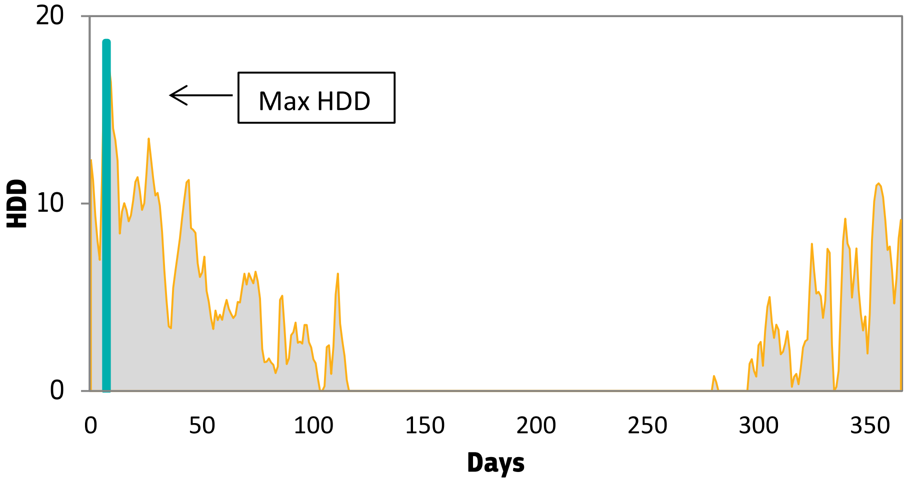

Figure 7 HDD over the course of a year in Germany

3.2.3 Costs module

To identify cost-effective solutions, and consequently the cost-optimal one, Regulation (EU) No 244/2012 requires a global cost approach, considering both a financial scenario and a macroeconomic scenario. The net

[6] The energy expenditure factor is defined as the inverse of the energy efficiency ratio

present value (NPV) method is the one that is widely used to find the optimal energy design for building renovation (European Commission, 2012).

On the financial level, the global cost (GC) includes the capital expenditure (CAPEX) and the operational expenditure (OPEX). Whereas the macroeconomic scenario also considers the costs that correspond to CO_2 emissions (i.e., monetary value of the environmental damage) (European Commission, 2012). In this study we work on the financial level following the GC approach. Therefore, for the CAPEX component we consider the cost of the envelope and technical building system upgrades whereas for the OPEX we assume an annual fix cost for each technology. In the calculation of the GC we take into account the lifetime of the envelope elements and building technical systems based on assumed market values. This means that, for the building lifetime — 50 years — we take into account the subsequent required replacements. On top of that, we also apply a 3% discount rate as indicated in the EPBD (European Commission, 2018c). Details on cost assumptions can be found in Annex 1. There we include all costs (CAPEX and OPEX) for the technical building systems along with the values of the lifetime and efficiency as applied in this work. Moreover, we provide the regression function developed for the envelope costs based on the information provided by the PRIMES model (Capros et al., 2018).

In order to identify the cost-optimal renovation solution, the cost-effective solutions need to be calculated first. A cost-effective solution leads to higher NPV, or lower GC, values compared to the current state of the dwelling, what we call in this work the reference case. The cost optimal energy renovation is the cost-effective solution with the highest NPV or the lowest GC over the estimated building life cycle (Corrado et al., 2014; Desideri & Asdrubali, 2019).

In Figure 8 (left) we present a GC curve for a set of energy renovation solutions. We can read the figure starting from the reference situation 'A' ("current state") towards renovation options yielding less primary energy consumption (PEC) than in the case of the anyway renovation. 'O' represents the cost optimal renovation option. 'N' represents the cost neutral renovation option with the highest reduction of primary energy.

On the right (Figure 8), we present the GC vs CO2 emissions curve. The concept of this representation, of cost optimal renovation options, is to understand the environmental impact (CO2 emissions) instead of the PEC. Comparing the two charts in Figure 8 we want to highlight how for some options the cost-optimal solution can be suboptimal from an environmental perspective. This is driven by the carbon intensity of input fuels, which highly depends on the national energy mixes in the present energy system. A future cleaner energy system would result in different cost-optimal solutions.

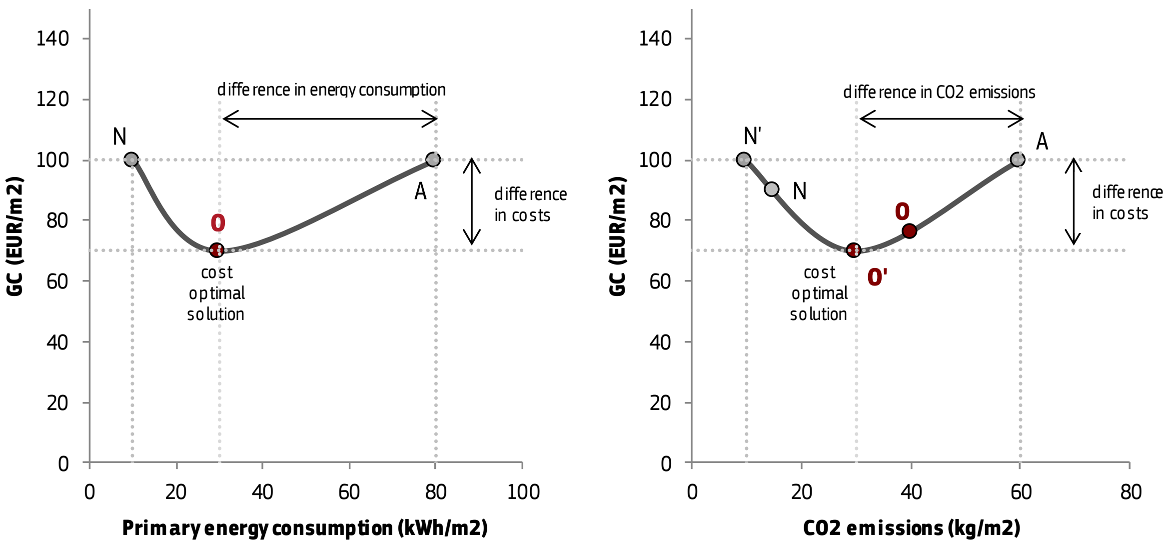

Figure 8 Global cost curve after renovation (yearly costs for interest, energy, operation and maintenance)

Cost optimal options

The last step of the CBA is the identification of the cost optimal solution among the different renovation options as introduced before. In Figure 9 we present the case for a MFH in Germany built in the period 1969-1978. We show different combinations of EEMs for two envelope renovations, one set to level 0 (left) and one to level 3 (right) together with the technical building systems solutions.

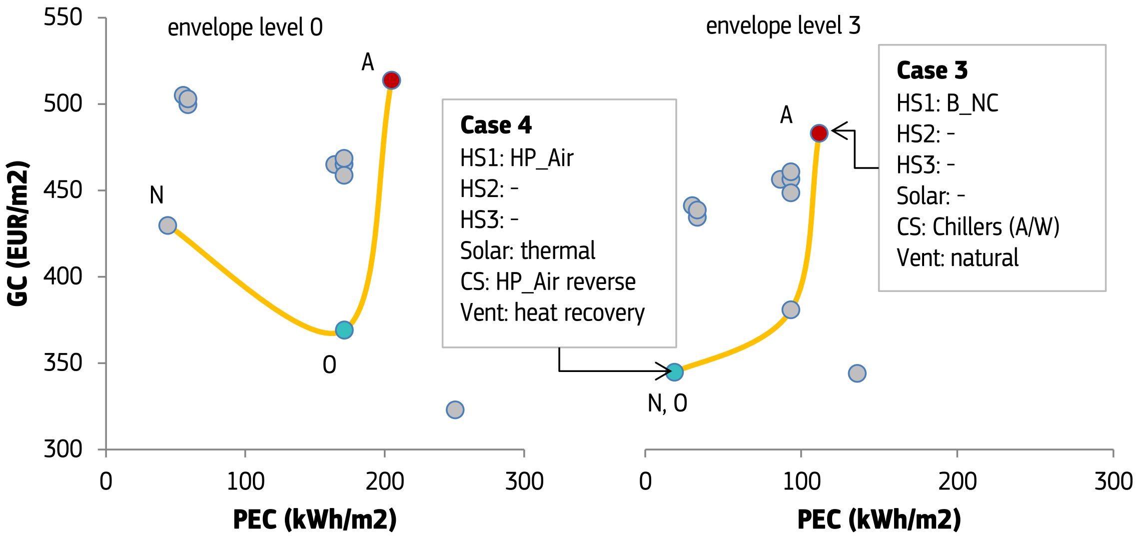

Figure 9 Two exemplary cases of the identification of the cost-optimal solution for Germany, MFH built in 1969-1978[7]

Every point in Figure 9 is an EEM. We highlight two cases to provide a better understanding of the process. Case 4 comprises of a heat pump as a primary heating system and as a cooling system (reverse mode), a solar thermal system and a heat recovery ventilation unit. In both cases, left and right, point 'A' describes an "anyway renovation", meaning an option where the GC is high and the reduction of PEC not satisfactory. Point 'N', on the left, shows the option with the highest reduction in terms of PEC but not with the lowest GC. On the right, however, point 'N' coincides with the cost optimal solution (point 'O'). This happens because the optimal solution (point 'O') achieves both the lowest GC and the highest PEC reduction. The yellow line is the Pareto front setting the boundaries of the cost-effective area of solutions.

In the next section we discuss the outcomes of the application of our method for the case of Greece and Germany for the whole national building stocks and including all possible combinations of EEMs considered.

[7] HS: Heating System, CS: Cooling system, HP_Air: Heat Pump Air Source, B_NC: non-condensing Gas Boiler, Vent: Ventilation system.

4 Results

This section presents the results of applying our method to national building stocks in order to identify the cost optimal renovation solutions. Two countries, Germany and Greece, were selected to showcase our method and the results that can be achieved. The selection of these two countries was based on the difference on the climatic conditions, energy uses and national energy mixes, and building stock characteristics. Especially, on the climatic conditions, we chose Greece and Germany in order to highlight the effect of an increased cooling demand versus no cooling demand (based on the quasi steady state modelling approach).

Along the section, first, we show the detailed characterization of the building stocks. We, then, present the energy performance of the stocks when different EEMs are applied. Following, the cost effective solutions are assessed and the cost optimal ones are determined. Last, we discuss implications of effects such as increased cooling demand, self-production, future energy mixes (2020 & 2030), and more.

4.1 Characterisation of the building stock

As the EU building stock is diverse, we need to understand its characteristics at national level to, then, apply effective energy renovation strategies. To begin with, in Table 5 we show the U-values per type and construction period for Germany and Greece. Based on the available data, even after the processing performed here, it is evident that there is no harmonisation across MSs. We are not only referring to the U-values but to the construction year cohorts and types. The German stock is classified based on eleven periods and four types of dwellings while the Greek one distinguishes only three periods and two types. This phenomenon is evident among all EU countries (EPISCOPE project consortium, 2016). The difference on the period breakdown is based on how the national building stocks evolve in time and availability of data. Historical events, which led to a rapid transformation of the building stock, or the introduction of building standards shaped the building year cohorts that define each building stock. The building types relate directly to cultural aspects while the U-values to climatic conditions and construction traditions.

Table 5 Building stock by construction period and type in Germany and Greece. U-values for the façade (W/m^2 K)

		U-values (W/m^2 K)			
Country	**Period**	**AB**[8]	**MFH**	**SFH**	**TH**
DE	before 1860		2.0	2.0	
	1860 - 1918	1.7	2.2	1.7	1.7
	1919 - 1948	1.4	1.7	1.7	1.7
	1949 - 1957	1.2	1.2	1.4	1.2
	1958 - 1968	1.2	1.2	1.2	1.2
	1969 - 1978	1.1	1.0	1.0	1.0
	1979 - 1983		0.8	0.8	0.8
	1984 - 1994		0.6	0.5	0.6
	1995 - 2001		0.4	0.3	0.6
	2002 - 2015		0.3	0.3	0.3
EL	before 1981		2.2	1.0	
	1981 - 2000		2.5	0.9	
	2001 - 2010		0.7	0.7	

Moreover, in some EU countries (e.g. Spain and Italy) the characterisation of the building stock remains at regional level. This happens due to different reasons such as specific differences in climatic conditions within countries, regional governance and different energy uses present in the countries. Even in those cases where national governments have an overview of their building stocks, this information is not available at an EU level.

Observing Table 5, U-values have been reduced over time. The energy performance increases when supported by the implementation of energy policies. As shown in Figure 2, the introduction of thermal insulation standards in the beginning of the 1970s had a big impact in lowering the U-value. The two countries studied (DE and EL)

[8] AB stands for Apartment Building | MFH for Multi-Family House | SFH for Single-Family House | TH for Terrace House

are not an exception to this. Even more, we observe this trend per building type and for each construction element — wall, roof, floor and windows.

4.2 Energy performance of the stock

As described in section 3, we apply different packages of EEMs to the existing building stock of MSs selected. The EEMs are determined by the combination of three renovation options: building envelope improvement, technical building system upgrade and the integration of renewable energy sources for self-production. Here, we present the energy performance of the stock before and after applying different EEMs.

4.2.1 Heating and cooling energy demand of the building stock

To better understand the impact of the renovation options we, first, present the single effect of the building envelope improvement. In Figure 10 and Figure 11, the energy savings per square meter, for different envelope improvement levels, are presented for Greece and Germany. In all figures we present the energy savings, for each envelope improvement level, compared to the reference case.

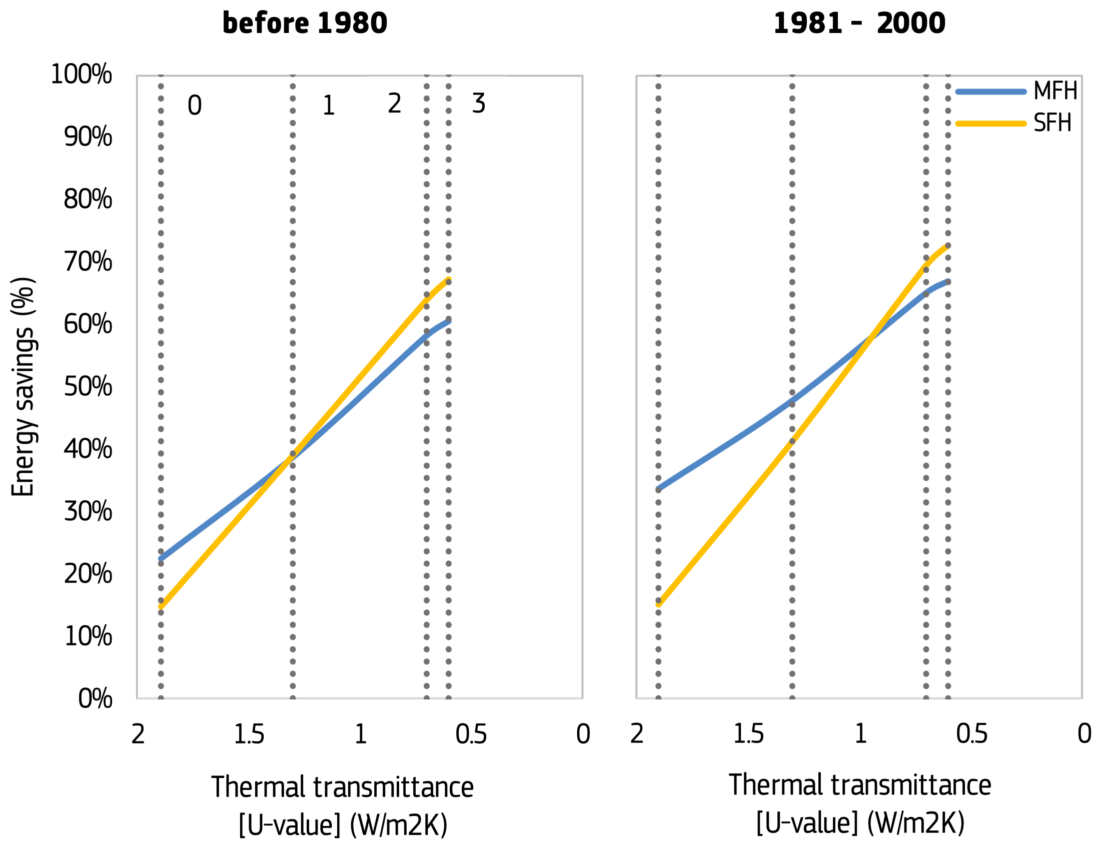

Figure 10 Heating saving for the Greek building stock for different building envelope improvement levels applied to MFH and SFH for the periods 'before 1980' and 1981 – 2000.

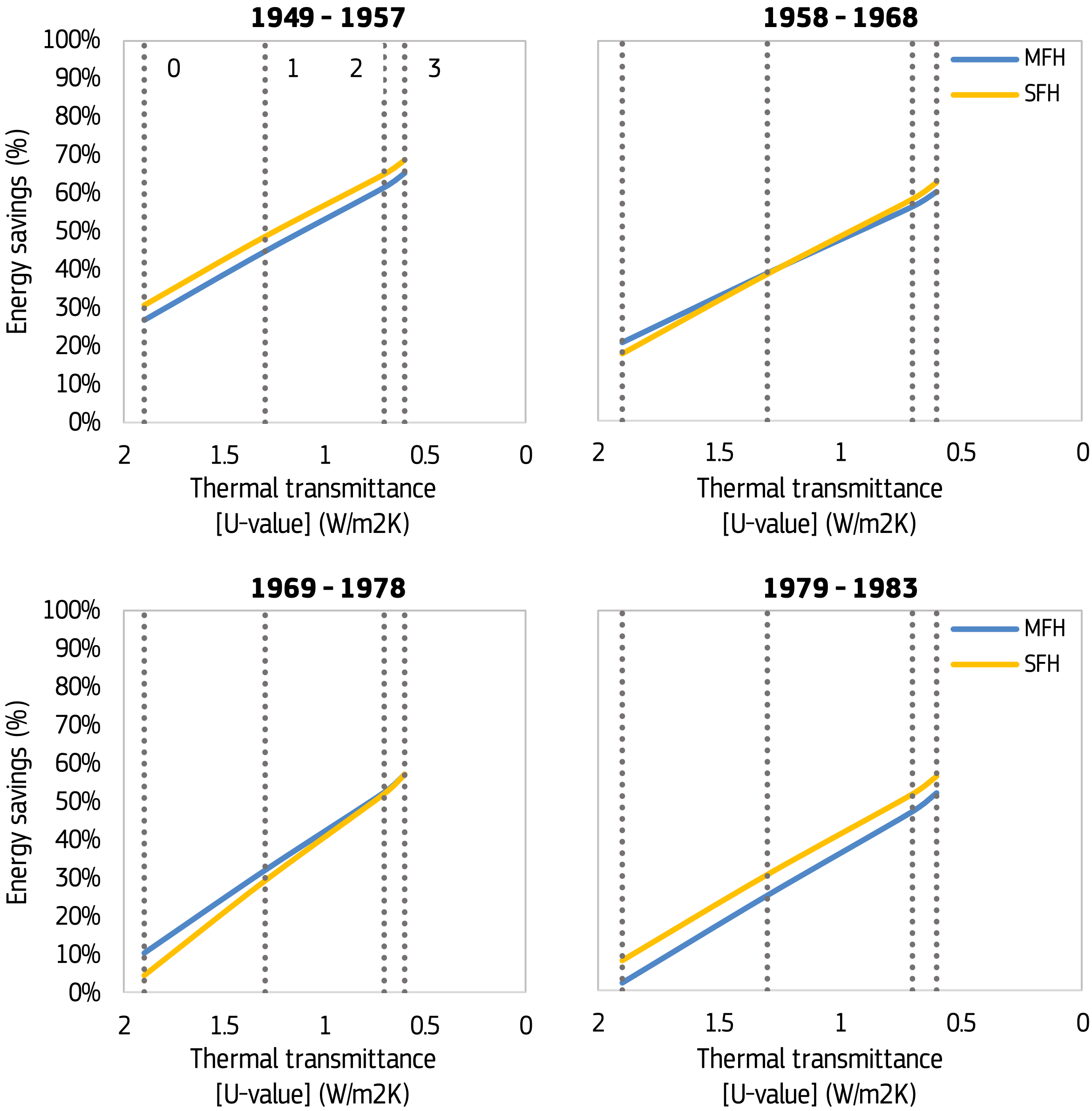

Figure 11 Heating savings for the German building stock for different building envelope improvement levels applied to MFH and SFH for the periods 1949-1957, 1958-1968, 1969-1978 and 1979-1983

Both Figure 10 and Figure 11 are best read across the x-axis (levels of renovation). We split the information of the graph into the types of dwellings —MFH (Multi-Family House) and SFH (Single Family House). The levels of renovation start from 0, signifying a shallow renovation of the façade, to 3 that is an ambitious level of upgrade — NZEB level. The main message of these figures is the linear correlation between the increase in the level of renovation and the resulting higher energy savings.

The y-axis shows the energy savings of the heating demand. When reading across the periods, the energy savings decrease. This is explained by the fact that only after the 1970s were thermal insulation restrictions in the building codes introduced.

In the Greek building stock we see large differences between MFH and SFH, especially at the shallow renovation levels — 0 and 1. As we progress to today and new building standards are introduced, the heating demand is levelised across the different building types.

One of the most important remarks from both figures is the potential of the old building stock to reduce heat demand — down to NZEB levels — if major renovations of the envelope (level 3) are applied. If we take a post-war MFH built between 1949-1957 in DE, when a level 3 envelope upgrade is applied the energy demand reduces to the same level as a MFH built during the period 1995–2001, which has undergone a level 2 envelope upgrade (Figure 12) .

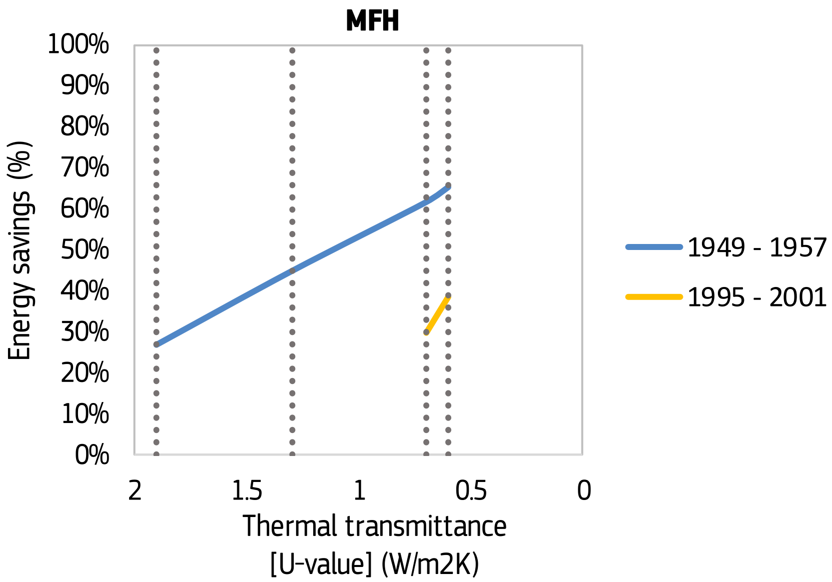

Figure 12 Heating savings for the MFH in Germany built in the periods 1949-1957 and 1995-2001

Moving on to cooling, only EL has a demand based on the quasi steady state model we are using in this work. In Figure 13, the savings on cooling demand of the Greek building stock are depicted.

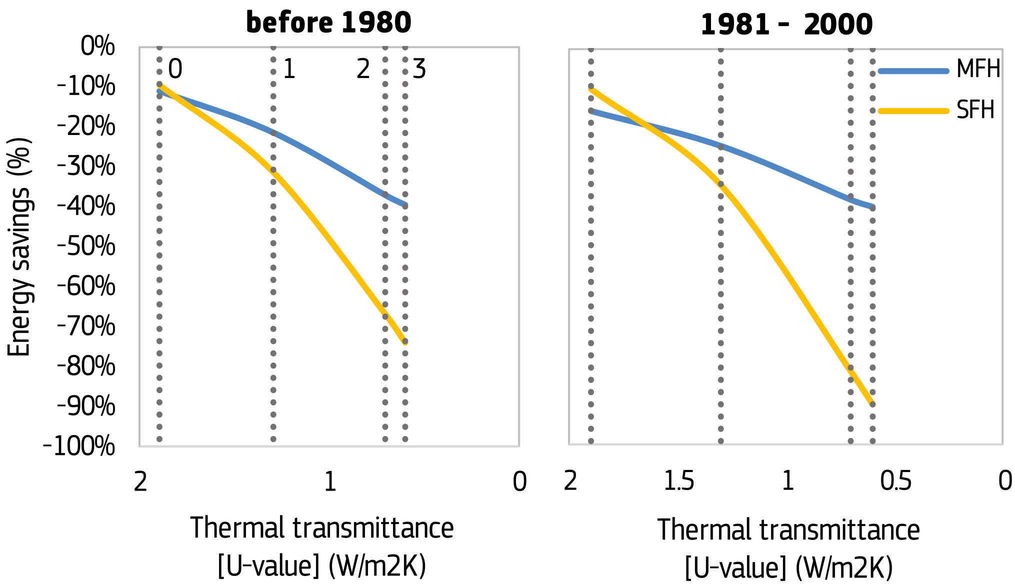

Figure 13 Cooling saving for the Greek building stock for different building envelope improvement levels applied to MFH and SFH for the periods 'before 1980' and 1981 – 2000.

Contrary to the heating demand, cooling savings respond differently to the increase of the envelope insulation levels. In Figure 13, this phenomenon is presented. In all cases, cooling demand rises even in shallow renovations. The increase of the cooling demand, between the reference and NZEB level, ranges between 40 to 90% for both MFH and SFH in EL.

This opposing trend in the heating and cooling needs, when the envelope insulation levels are increased, suggests that a trade-off should be reached. However, heating demand is dominating the overall energy demand — 10 times larger than cooling for the Greek building stock. This means that the renovation strategies should focus primarily on reducing the heating demand. Cooling becomes more relevant when it comes to thermal comfort standards for those months of the year where cooling degree days are present.

4.2.2 Heating and cooling energy consumption

In our study, the energy demand can be covered by the combination of a maximum of three systems for heating and DHW, one for cooling and possibly a mechanical ventilation system. In Table 6 we present two explanatory cases of combinations of systems considered as renovation options. For the heating and DHW needs, we define the fraction of the demand covered per system (α). In Annex 2, we present all combinations considered in this work (Table 9 and Table 10).

Table 6 Technical building system options. Two explanatory combinations

Cases	**EEM example a**	**EEM example b**
Heating system 1	Air heat pump	Condensing gas boiler
Heating system 2	Solar thermal	Instantaneous gas boiler
Production system	-	Photovoltaics
$\alpha_{DHW,1}$	0.4	0.1
$\alpha_{DHW,2}$	0.6	0.9
$\alpha_{DHW,3}$	-	-
$\alpha_{H,1}$[9]	1	1
$\alpha_{H,2}$	-	-
$\alpha_{H,3}$	-	-
Mechanical ventilation	Heat recovery system	-
Cooling system	Reverse air heat pump	Small Split (<5 kW)

After applying the technical building system combinations to the building stock we calculate the energy consumption. In Figure 14 we depict the energy consumption of the German building stock. We present the results grouped by primary heating system, type of dwelling and for the two extreme insulation cases (reference and level 3). The building year cohorts have been aggregated. We present the results in this way because heating is the dominant energy need as already discussed. We show the average final energy consumption per square meter for the part of the building stock without any envelope upgrade and for the fully insulated (level 3) shell — yellow and blue lines respectively. The y-axis further differentiates between the types of dwellings of the German stock. In all cases we observe that the level of insulation —level 3 — lower the final energy consumption for heating by at least half.

Looking into the different technical building system options for heating — primary system — (x-axis), we observe that the effect of the heating system in the energy consumption follows the same trend for the different types of buildings and levels of envelope upgrades. The air heat pump shows the smallest energy consumption followed by the DH and the gas condensing boiler. The micro-Combined Heat and Power (mCHP) is the most consuming option.

[9] H stands for space heating

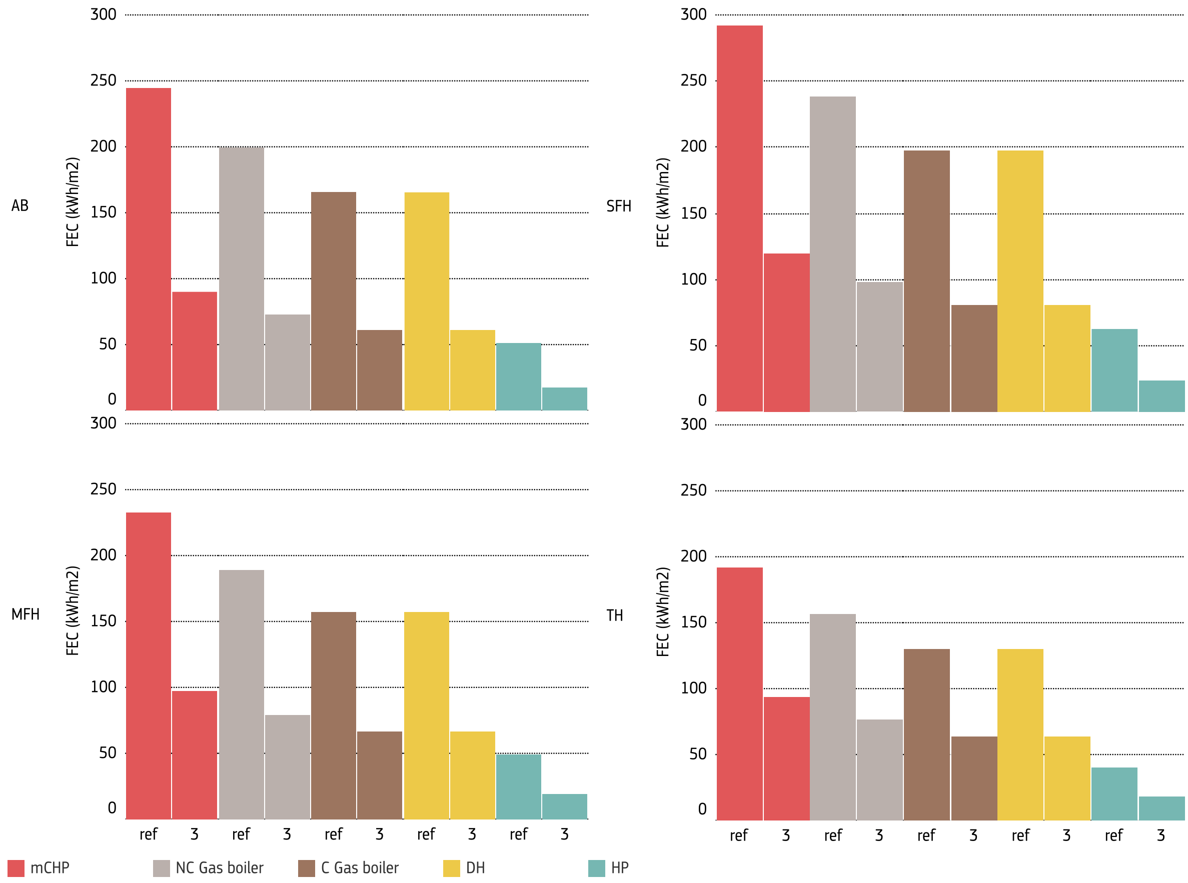

Figure 14 Energy performance of the German building stock for different primary heating systems and types (Final energy consumption in kWh/m^2)

We present the same results for the Greek building stock. Here, we also include the construction period breakdown. What is worth highlighting is the different consumption levels across the periods. This effect is due to the energy demand of the building (as presented in Figure 10). We observe that the second construction cohort (1981 – 2000) is the most consuming on average. This is true regardless of the heating system. However, an increase in the building envelope insulation together with highly efficient heating system, such as the air heat pump, smoothens these differences.

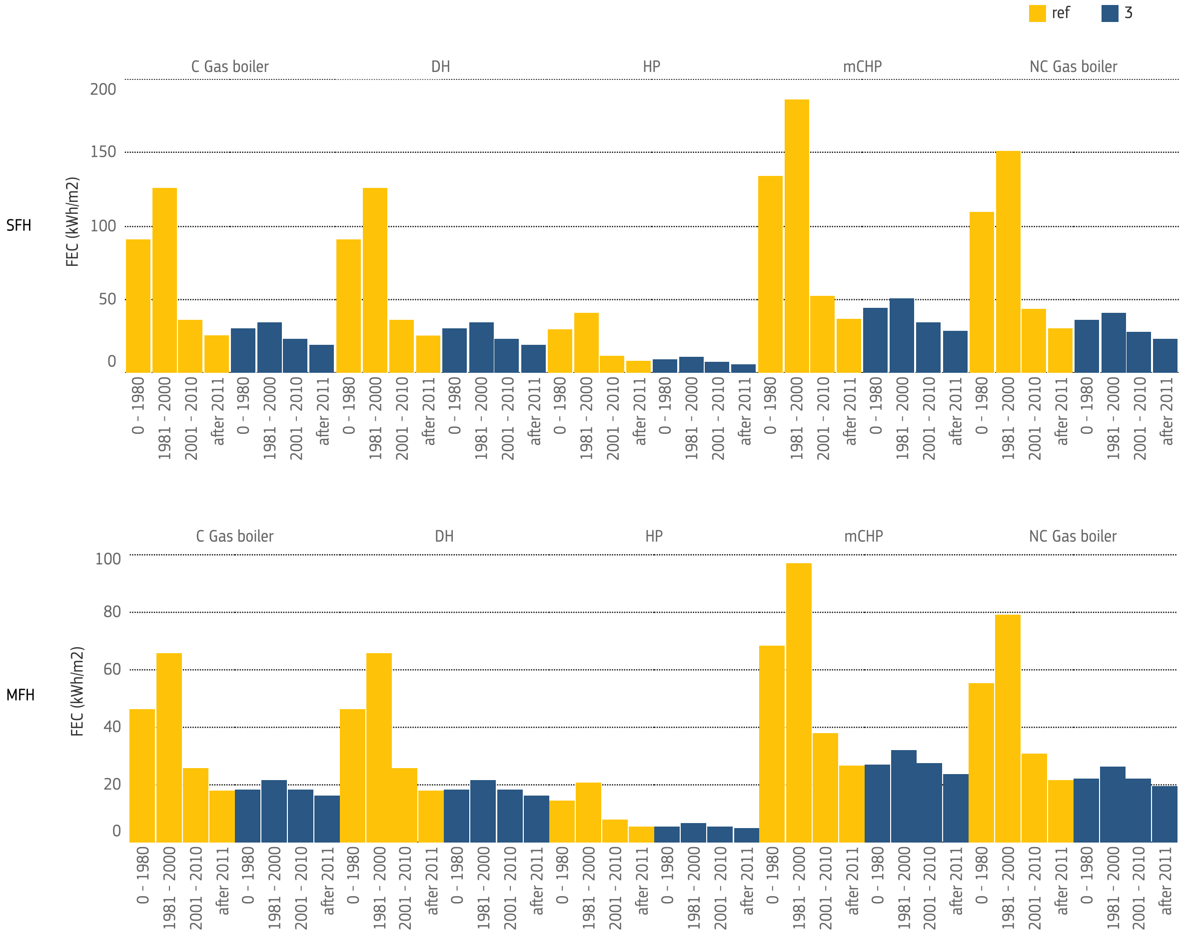

Figure 15 Energy performance of the Greek building stock for different primary heating systems, types and building year cohorts (Final energy consumption in kWh/m^2)

If we now check the FEC results based on the choice of cooling system, we observe the same trend as in the heating (Figure 10) for the Greek case. The performance of the building stock in terms of final cooling energy consumption is highly dependent on the selection of the system itself.

Moreover, the cooling consumption increases from the reference to the full insulated one driven by the thermal needs of the buildings stock — as already shown in the previous section by the energy demand graph (Figure 13).

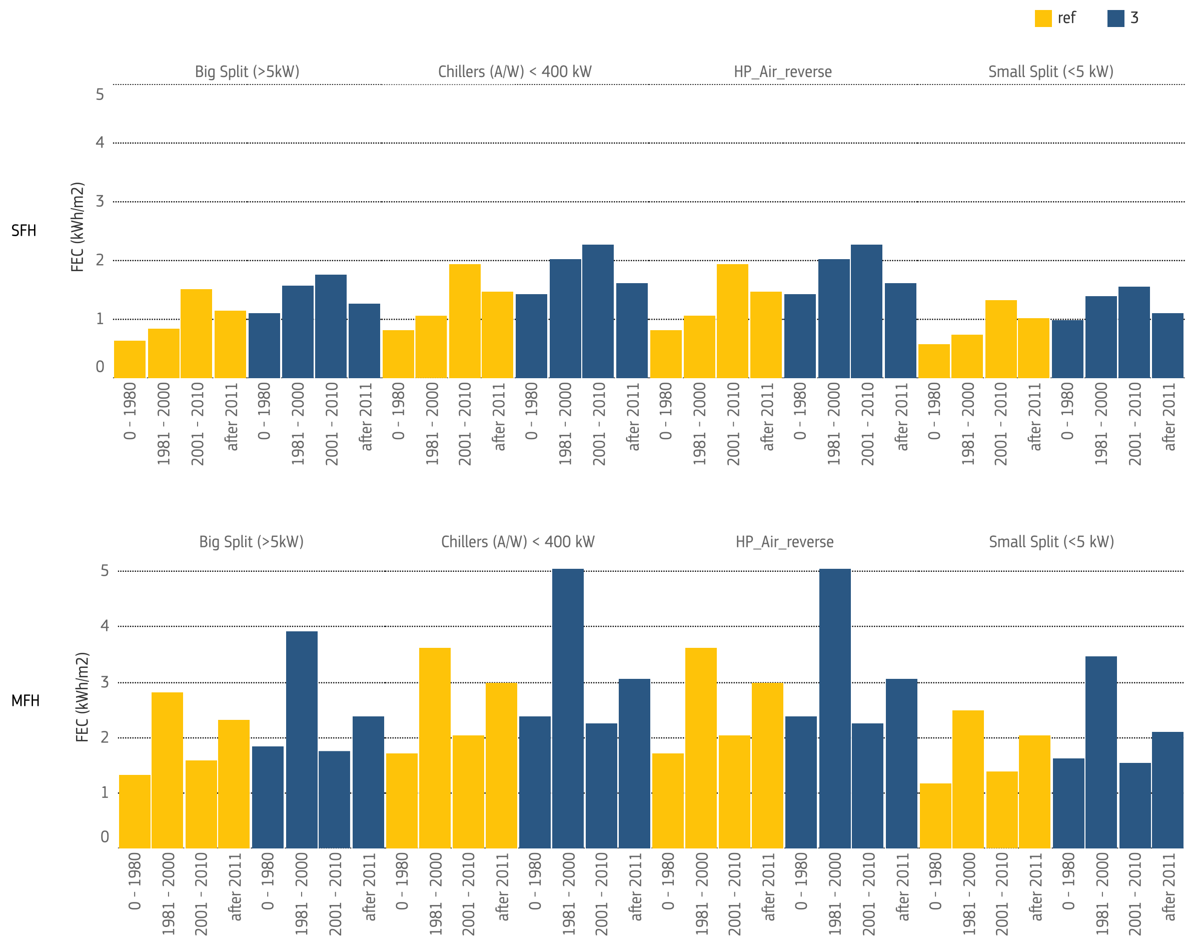

Figure 16 Energy performance of the Greek building stock for different cooling systems, types and building year cohorts (Final energy consumption in kWh/m2)

These results, both for the German and Greek cases, suggest that the assumption on the efficiency of the technical building system has a significant effect on the calculation of the final energy consumption — heating and cooling.

4.3 Cost-effective and cost optimal solutions

In this subsection we present the results of the CBA analysis. We, first, identify the cost-effective solutions, as described in our method, and then move on to select the cost optimal ones. Here, we present the performance, in terms of energy efficiency and costs, of the building stock when EEMs are applied.

4.3.1 Renovation options — Overview

In Figure 17 we show the results for Germany and Greece. The x-axis displays the primary energy consumption (PEC) and the y-axis the global costs (GC) of renovations per square meter. To get a general overview, we show all possible combinations for the renovation of the whole building stock. In total, 4 200 and 800 cases are computed for the German and Greek stocks respectively. Some general conclusions can be extracted. First, the PEC in the Greek stock is smaller than in Germany due to climatic conditions. Second, heat pumps turn out to be the cost-optimal solution for almost all building types in both stocks. Last, when it comes to the mCHP solution, it results in high energy consumption due to its low thermal efficiency. However, the electricity produced lowers the overall primary energy consumption making it competitive among the solutions proposed. Only when looking at the environmental parameters (CO2 emissions) does the mCHP perform worse (Section 4.3.4).

At the same time, costs are relatively low because of the assumption that mCHP operates under a net metering scheme. Both condensing (C) and non-condensing (NC) boiler options perform in between heat pumps and DH.

We should note here that for the DH option, we assume that the network is already in place even for the countries that this is not currently the case (e.g. EL). In other words, we consider the thermal substation and connection to the network in the investment cost (CAPEX). Regarding heat pumps, we have assumed a seasonal performance (see Annex 1 for assumptions — Table 8).

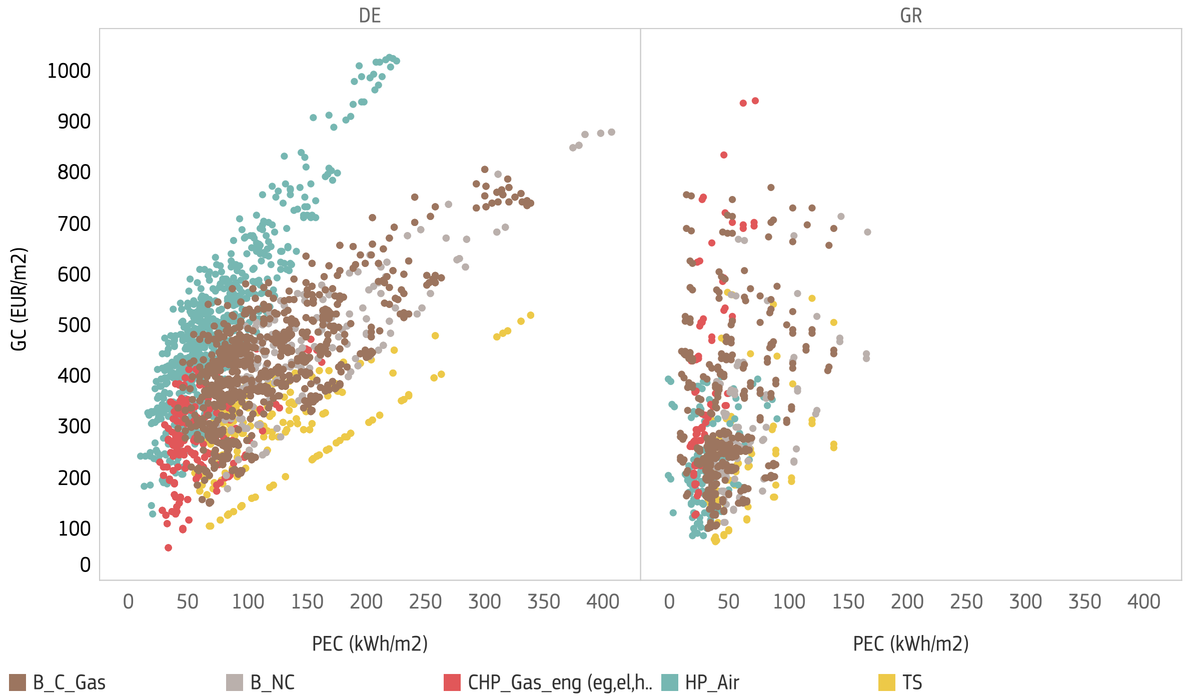

Figure 17 General overview of renovation solutions applied to the German and Greek building stock. Cost optimal range.

However, to better understand the effect of the EEMs we should look into specific building types. The analysis at this level of detail allows us to comprehend the trade-off between envelope upgrades and heating system installations.

4.3.2 Envelope and heating systems upgrades

The combined effect of both renovation strategies — envelope upgrades and heating systems — varies depending on the type of dwelling targeted, including its age. As a result, to understand the impact of these strategies we base our analysis on two specific typologies, MFH and SFH, for both DE and EL. Moreover, we split the results into building categories.

In Figure 18 and Figure 19, we show the mapping of renovation solutions taking into account primary energy consumption and global costs. We do so by highlighting the two extreme envelope cases — reference and NZEB levels. This way we can identify which of the two main strategies — envelope upgrade or primary heating system — should be prioritised. In addition, we have selected two year cohorts to highlight specific effects and conclusions drawn.

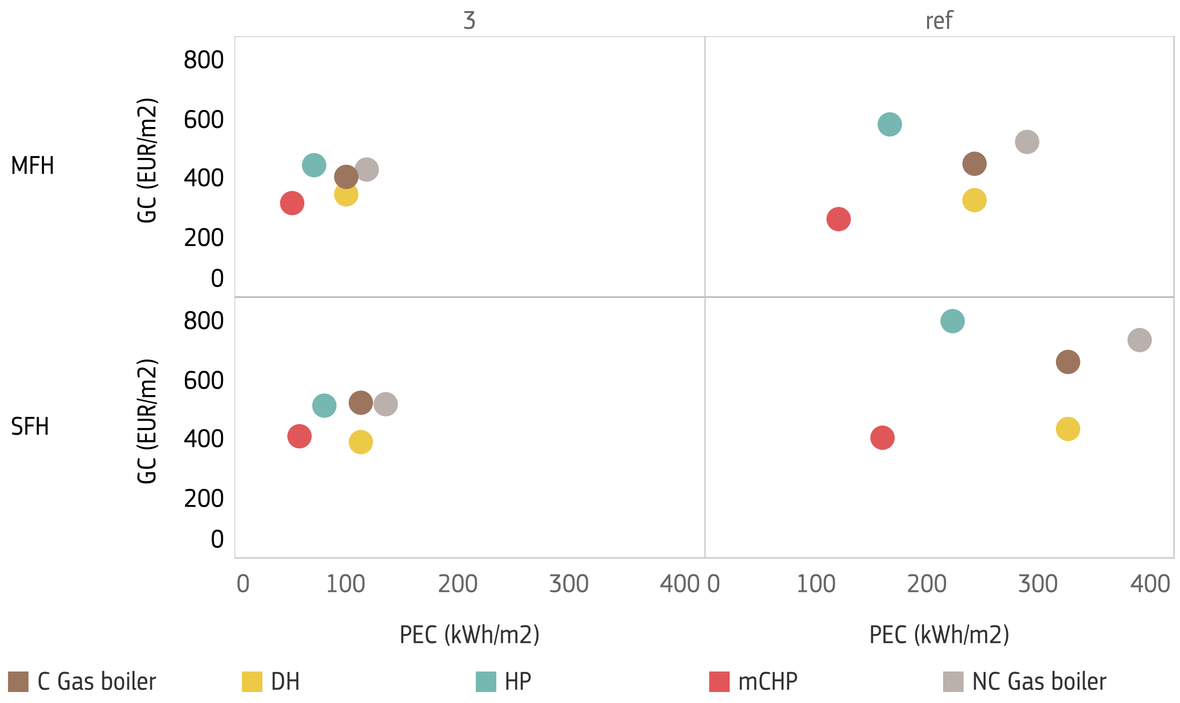

Figure 18 Combinations of envelope upgrade and heating system renovations. Primary energy consumption versus global costs for MFH and SFH dwellings built in the period 1949-1957. German building stock.

Following, for the German case, the improvement of the building envelope results in a reduction of not only primary energy consumption but of the global cost as well. The explanation of this effect lies with the high heating demand requirements of the German building stock dependant on the climatic conditions. In other words, the building envelope insulation is of extreme importance to achieve cost-effective primary energy reductions in Germany.

In Greece, the improvement of the envelope increases the global costs compared to the reference level in all cases. In Figure 19 we show this effect for the stock built between 1981 and 2000. The increase in the cost is caused by a smaller reduction in primary consumption in comparison to the German building stock.

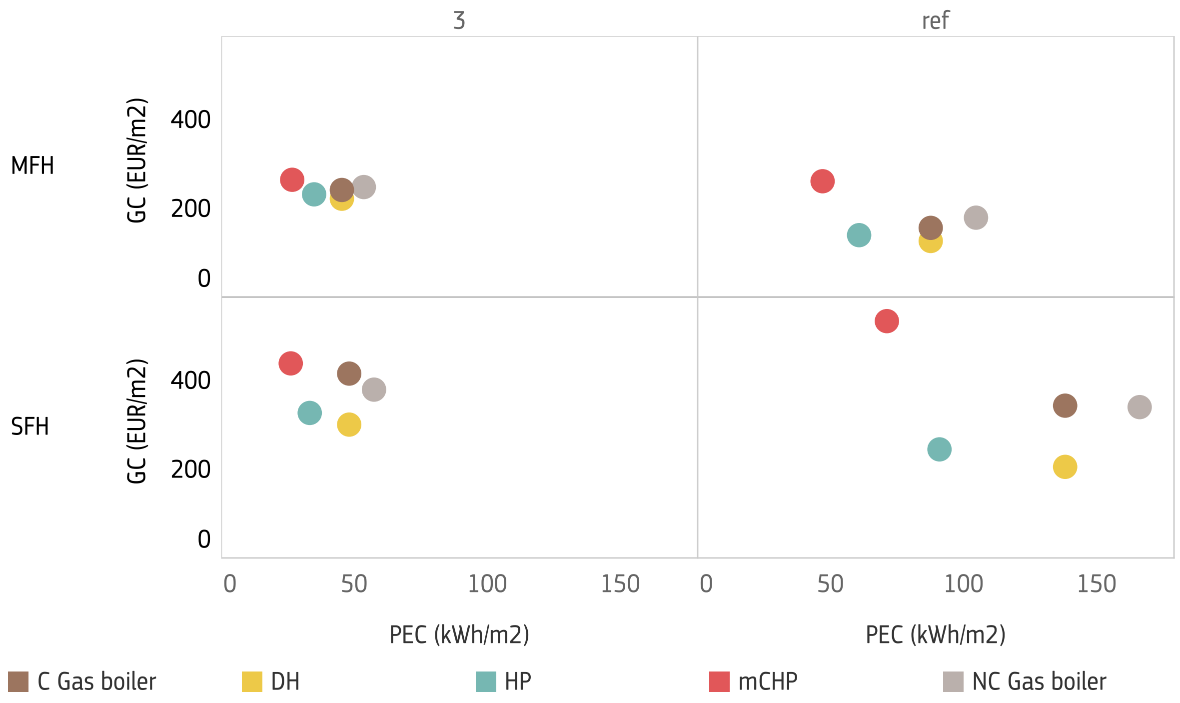

Figure 19 Combinations of envelope upgrade and heating system renovations. Primary energy consumption versus global costs for MFH and SFH dwellings built in the period 1981-2000. Greek building stock.

Observing the specific results, we cannot conclude what is the optimal strategy to renovate the Greek stock. Thus, we have to go into more detail in our analysis to understand the optimal level of envelope upgrades combined with heating systems solutions.

In Figure 20, we showcase a MFH built in Greece between 1981 and 2000 (left) and a MFH built in Germany between 1984 and 1994 (right) for all envelope upgrade levels and the two predominant heating system solutions — condensing gas boiler and air heat pump.

Two main conclusions can be derived: first, reading the graph vertically, on the left y-axis, we note that the reference case remains the cheapest option for the Greek case while in the German one the costs slightly increase. This is because a larger reduction in the heating demand (right y-axis) of the German case returns the cost of investments in the envelope renovation. Reading horizontally, the relative reduction across the different envelope upgrade levels reaches its maximum at level 1 for the Greek stock. So, from a cost-effective point of view it is less favourable to insulate the Greek building stock above this level.

Only in the case of mCHP, which shows a low thermal efficiency, the envelope upgrade reduces the global costs. Next, reading horizontally, the relative reduction across the different envelope upgrade levels reaches its maximum at level 1. So, for the Greek stock it is not cost-efficient to insulate the envelope above this level.

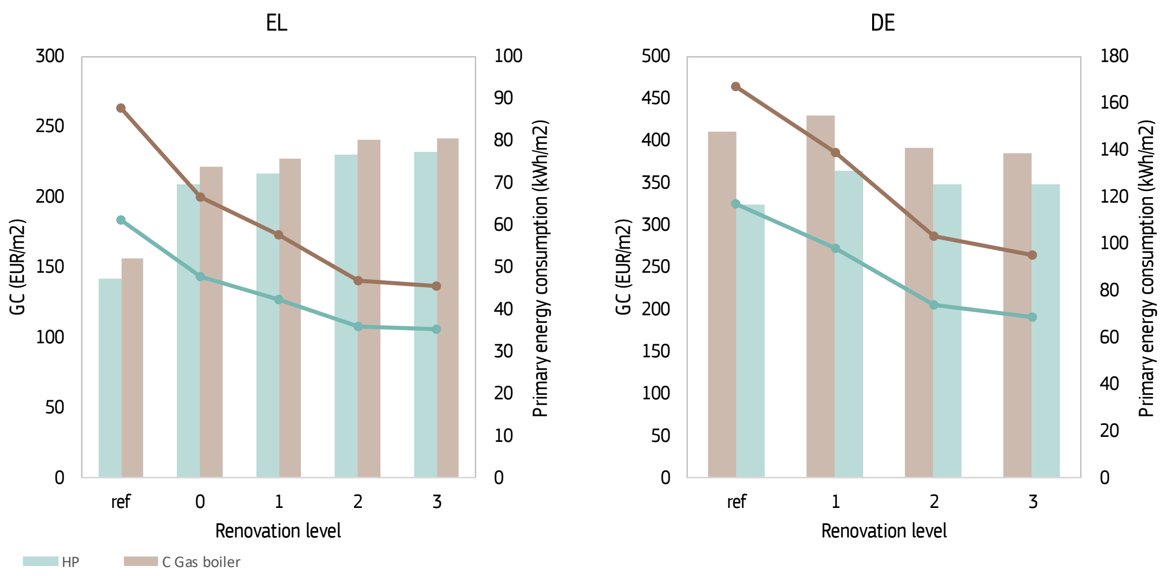

Figure 20 Combinations of envelope upgrades and heating system renovations. Primary energy consumption versus global cost. Greek MFH stock built between 1981 and 2000.

We can conclude that, as a general rule, additional envelope insulation — up to NZEB levels — is only cost-efficient for cases where the heating losses are large enough that cannot be covered by an efficient heating system alone. It could be argued that sustainable heating and cooling systems should be prioritised in mild climates like the Greek one.

4.3.3 The role of decentralised renewable solutions — Solar thermal and PV

Based on our assumptions solar thermal and solar PV show similar effects when it comes to primary energy consumption and global costs. The solar thermal solution is always used as a secondary system providing DHW needs, or a fraction of it depending on the case. The PV is delivering the electricity produced into the grid under a net metering approach. The effect of both renewables is the simultaneous reduction of both costs and primary energy consumption.

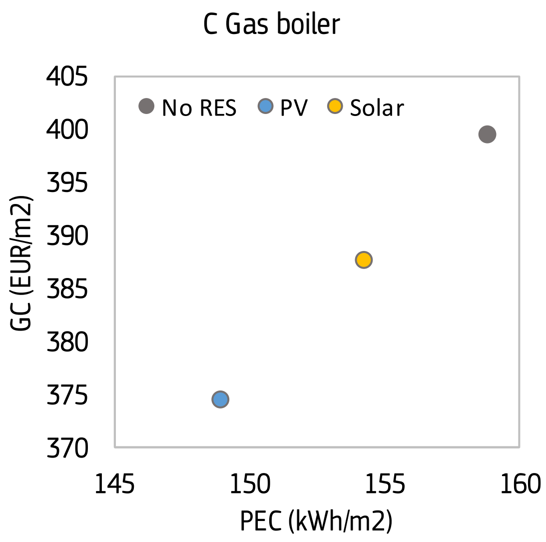

Figure 21 Effect of renewable energy sources in the CBA results

4.3.4 The impact of self-production — The case of mCHP

When it comes to the evaluation of mCHP solutions, we need to distinguish between its electricity and heat production. In our model we assume a net-metering approach for the electricity generated. In other words, the mCHP operates under a heat-driven strategy. Thus, it is sized based on the heating demand. In Figure 22 we present the case for a SFH built in Germany between 1979 and 1983 without any upgrade of the building envelope. We observe how the mCHP is the least efficient option and, as a result, leads to higher final energy consumption. However, in primary energy terms, when we deduct the electricity produced it becomes the most efficient solution. The same trend as for PEC is observed for CO_2 emissions.

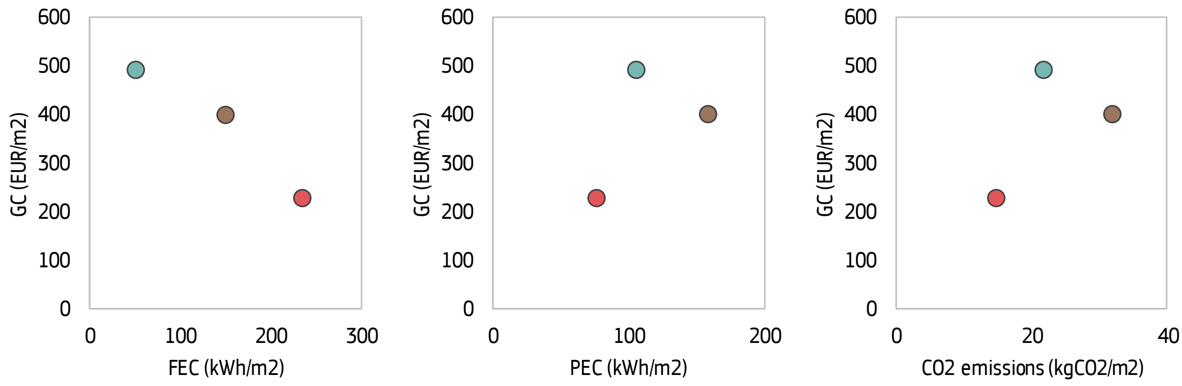

Figure 22 Comparison of FEC, PEC and CO2 emissions for the mCHP. SFH in Germany. 1979 – 1983. Reference case

4.3.5 GHG emission reductions

In Figure 23, we show the relation between global costs and CO_2 emissions. What is interesting to note here is that, CO_2 emissions for technologies that use electricity as the input fuel are dependent on the electricity fuel mix of MSs.

The CO_2 calculation in this work includes the emissions of all heating and cooling systems per case and the self-production systems. This means that we estimate the net CO2 emissions as the difference between consumed and produced energy flows. For example, in a dwelling with a condensing gas boiler and PV installation on the roof we calculate the CO2 emitted by the gas used and the CO2 avoided by the PV production.

Looking into specific solutions, certain phenomena can be observed. DH leads to high emission rates and is thus excluded from the cost effective area for the Greek case. The reason for that is that the national input fuel mix for district networks is highly reliant on fossil fuels (see Annex 3 for details). This makes their use highly inefficient in terms of CO_2.

In the case of mCHP, they lead to high CO2 emissions and thus a worse performance — driven by a low thermal efficiency — contrary to what we observed for the PEC (Figure 17). This is explained by the fact that the produced electricity is deducted in the PEC account.

It is worth noting that some solutions can lead to zero CO_2 emissions values. In those cases the presence of PV drives the CO2 balance closer to zero or even negative as a net metering approach is applied. This is particularly true when energy needs, mainly heating, are low as in the case of Greece.

As presented before, in both the German and the Greek case, heat pumps that were considered cost optimal in terms of primary energy consumption are not necessarily optimal in terms of CO_2 emissions. This is particularly true in the Greek case, as its national electricity fuel mix shows a higher CO_2 intensity factor — 623 gCO_2 / kWh_e than the one in Germany — 419 gCO_2 / kWh_e. As a result, gas-based technologies are better suited to reduce CO_2 emissions in Greece based on the current energy system fuel mix.

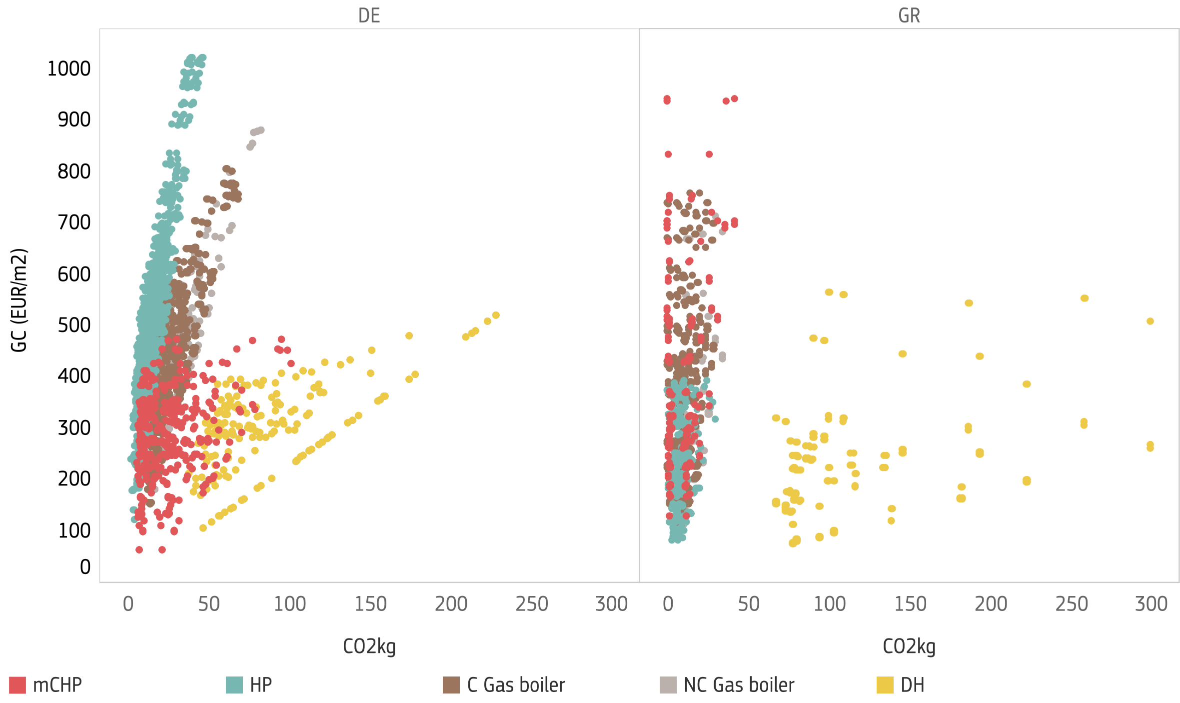

Figure 23 General overview of renovation solutions applied to the German and Greek building stock. Global costs and CO_2 emissions

To better illustrate the impact of the national energy mixes and how their development towards 2030 affects the renovation solutions of the building stock, we move on to specific examples for Germany and Greece. To make the analysis clearer we present the results for the two dominant heating systems: condensing boilers and heat pumps. In Figure 24 and Figure 25, we show the performance of the renovation strategies in terms of CO_2 for both 2020 and 2030. Our assumptions on carbon intensities for all fuels used can be found in Annex 3.

Moving on to the German case (Figure 24) we note that heat pumps are the cleaner and preferable option when it comes to reducing CO_2 emissions for both 2020 and 2030. In other words, the today's German electricity production is sufficiently clean to make heat pumps perform better than gas boilers. The CO2 gap between the two technologies intensifies when we apply the 2030 electricity mix of Germany.

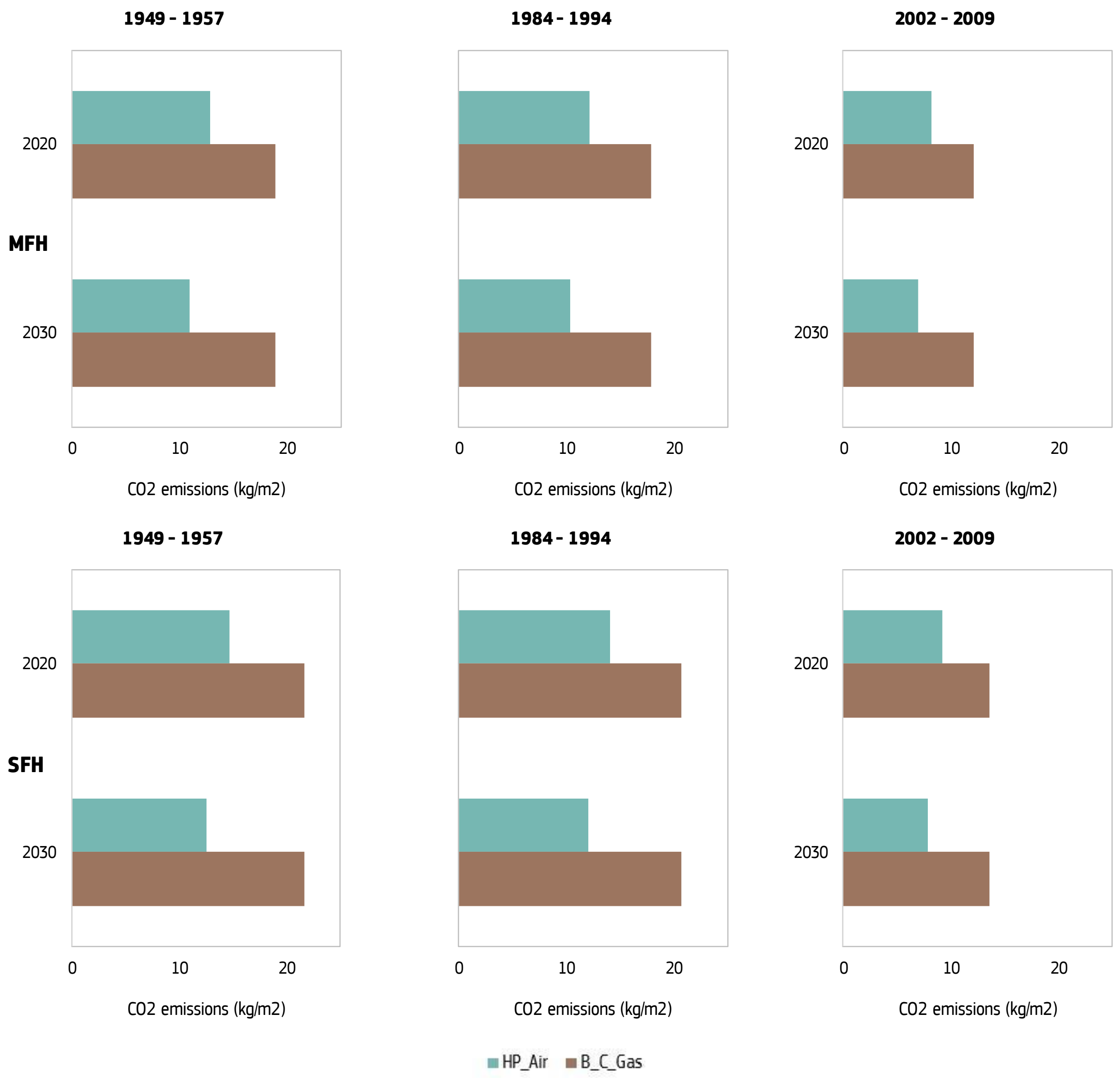

Figure 24 Combinations of envelope upgrade and heating system renovations. Global costs versus CO_2 emissions sorted by type of dwelling and building year cohort. German building stock

The situation for the Greek case is different (Figure 25). For the current electricity carbon intensity, heat pumps perform worse compared to gas boilers for all building types and years. However, this situation changes when we apply CO_2 emission factors for 2030, which depicts a cleaner electricity mix in the future. This effect for the Greek case can lead to undesirable lock-in effects if the energy system does not evolve as expected. Those lock-in effects can impact investment strategies and the uptake of renovation rates.

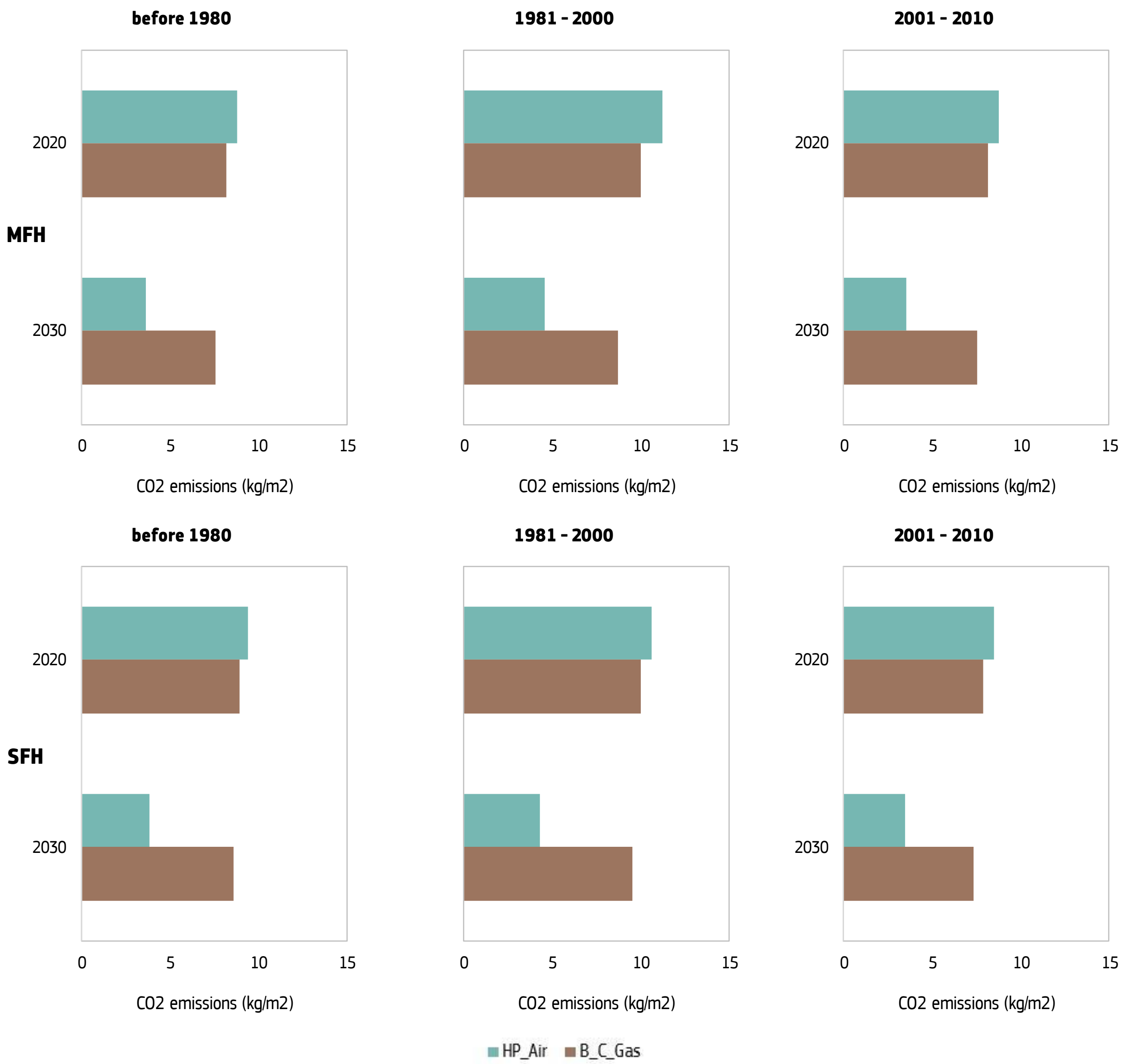

Figure 25 CO2 scenarios for heat pumps and condensing gas boilers as primary energy system in the Greek building stock. Level 3 annual values

5 Conclusions

The 2030 climate and energy goals of the EU include a 40% reduction of greenhouse gas emissions compared to 1990 levels; a 32% share of renewable energy consumption and 32.5% energy savings compared to 2005 levels (European Parliament & Council of the European Union, 2018). Due to its sheer size, to address the building sector is pivotal to achieve these goals and hence it has to be present in any decarbonisation strategy in the EU.

The EC, has acknowledged the renovation of buildings as a 'win-win' option for the EU economy (Saheb et al., 2015) and obliges Member States to pursue it following a cost-optimal approach for the establishment of minimum requirements and a cost-effective renovations of existing building stock. By 2050, the energy consumption of the residential sector should be reduced by 38% — compared to 2005 — following the baseline scenario of the EC (European Commission, 2018a). The EPBD and the EED have been designed to support the decarbonisation of the EU building stock among others (European Commission, 2018c). The implementation of these policy initiatives faces the complexity of a diverse EU building stock, both in terms of energy use and need, and age.

Within this policy context, we addressed the following question: *Which are the cost-effective ways to decarbonise the EU building sector through energy renovations?* Replying this, the study provided a method and a dataset to help the EC and eventually MSs identify cost-effective strategies to decarbonise their building stocks. Specifically, it allows examining the optimal level of energy efficiency measures in combination with low carbon heating and cooling solutions. To demonstrate the application of the method, two EU Member States (Germany and Greece) are examined and targeted renovation solutions are discussed.

This work first characterised the current state of the diverse EU building stock. The information, collected by several sources, was analysed and restructured to provide a harmonised and ready-to-use dataset. In other words, this work collected the up-to-date available data and created a dataset that, after processing and cleaning, is easy and ready to be used. This dataset was showcased for the two exemplary cases.

Next, the method developed assessed the combination of insulation measures and efficient heating and cooling supply technologies. The method uses the basic principles of Cost Benefit Analysis (CBA) from an economic perspective. It allows the evaluation of the energy performance of different energy renovation options and their global costs. Through its application, we identify the cost effective and cost optimal solutions in terms of, not only primary energy consumption, but also greenhouse gas emissions.

The novelty of this work lies with the development of the method that combines building shell and technical system upgrades to meet both heating and cooling needs in the building sector. Moreover, this study facilitates the comparison between MSs that has been proven challenging due to diverse national and regional approaches and the use of different parameters and methodologies. Phrasing it otherwise, it supports the benchmarking mechanism of the energy performance of building stocks that has been proven essential to monitor the impact of EU policies. Ultimately, the goal of this work was to provide the necessary tools and data to enhance energy policy advice on the optimal combination of cost-efficient energy renovations for the EU building stock.

Through the application of our method, first, we identified the single effect of the improvement of the building shell. We concluded that the older the building stock, the larger the difference between multi-family and single-family homes. In newer buildings, where building standards for thermal insulation are in place, these differences are smoothened. One of the most important outcomes is the potential of the old building stock to reduce its energy demand, for both heating and cooling, if major renovations of the envelope are applied.

We compared Member States under different climatic conditions. Our results confirm what is stated in the EPBD: a common strategy cannot be applied cost-effectively in all Member States. Thus, based on our results, northern European countries should pursue a highly insulated building stock. However, we found that in the south, priority should be given to sustainable heating and cooling systems, whereas building envelopes should be moderately insulated. To insulate buildings in the south does not reduce heating demand as significantly, and it increases cooling demand more than in northern Europe. In other words, it could be argued that sustainable heating and cooling systems should be prioritised in mild climates like the Greek one.

Regardless of the differences in the renovation strategies to be followed, we observed that the level of envelope insulation plays a key role in decreasing the heating demand and increasing the cooling one. This means that a trade-off should be pursued between envelope insulation levels that reduce the overall energy needs and efficient heating and cooling systems. Still, today, heating is the dominant energy need and, thus, is the main driver of the energy renovation strategies.

Concerning the selection of systems, when we analysed the cost-effective cases, heat pumps turned out to be the cost-optimal solutions for almost all building types in the building stocks examined. However, when referring to CO_2 reductions, the electricity fuel mix of the country highly affects the performance of those technologies running on electricity (e.g. heat pumps) and thus altering the cost-optimal solution. The results have shown that solutions that are cost optimal in terms of primary energy consumption are not necessarily cost optimal in terms of CO_2 emissions. This effect is clearly noticeable in the Greek case (MFH, 1981-2000) where for the primary energy consumption, heat pumps were cost optimal whereas condensing gas boilers led to the largest CO_2 emissions reduction. However, based on the expected carbon intensity reduction of the Greek electricity generation in 2030, heat pumps become the cost-optimal solution both in terms of energy and CO2 emissions.

In all German cases we tested, heat pumps remain the cost-optimal both for primary energy and CO_2 emissions and both for the current (2020) and future (2030) electricity generation mix. In other words, the today's German electricity production is sufficiently clean to make heat pumps perform better than gas boilers — the two most predominant technologies. The CO_2 gap between the two technologies intensifies when we apply the 2030 electricity mix of Germany. Overall, an expected cleaner electricity generation will reinforce the use of heat pumps both in terms of energy efficiency and carbon emissions.

Based on our outcomes, a holistic approach of the whole energy system in each MS should be considered when planning the decarbonisation of the building sector. In other words, the transformation of both the energy system and the building stock in particular, has to be designed in coordination to avoid lock-in effects in terms of investments, over investments less than cost-optimal energy efficiency renovations, and the shortening of the renovation cycles of buildings.

Following the above stated argument we should ask ourselves which is the strategy to improve the energy performance of the building stock. One thing is clear, we need to invest in energy efficiency but, *do we have to pursue the improvement of energy efficiency based on a demand reduction approach? — demand side — or, on the contrary, should we focus on improving the energy efficiency of the energy transformation? — supply side*. A synergy of both the demand and the supply side is the right answer. The balance between these two will be determined by climatic conditions and available technology solutions on a Member State level and, will determine the renovation strategies to be followed.

In both cases, the ultimately goal is the decarbonisation of the building stock. So, we should consider environmental aspects because as we showed the picture can be very different if we only examine costs and final energy consumption.

Future research questions to be addressed are:

- mapping the current state of the EU building stock in a harmonised way,
- identifying the cost-optimal energy renovation strategies for MSs,
- building national scenarios and possible decarbonisation pathways towards 2050,
- comparing these scenarios with the global EU policy scenarios (i.e. EUCO32325),
- assessing the rates of renovations and trends to achieve 2030 and 2050 goals,
- evaluating future climate conditions and energy market projections,
- releasing on the open source tool on Github.

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List of abbreviations and definitions

AB	Apartment Building
BSO	Building Stock Observatory
BPIE	Buildings Performance Institute Europe
C	Condensing
CAPEX	Capital expenditure
CAPEX	Capital expenditure
CBA	Cost Benefit Analysis
CO	Cost optimality
COP	Coefficient of Performance
DE	Germany
DH	District Heating
DHW	Domestic Hot Water
EC	European Commission
EEA	European Energy Agency
EED	Energy Efficiency Directive
EEM	Energy Efficiency Measure
EL	Greece
EP	Energy Performance
EPBD	Energy Performance of Buildings Directive
EU	European Union
GC	Global Cost
GHG	Greenhouse gas
HU	Hungary
IEA	International Energy Agency
IEE	Intelligent Energy Europe
LTS	Long-term Strategy
mCHP	micro Combined Heat and Power
MFH	Multi Family House
NC	Non condensing
NEEAP	National Energy Efficiency Action Plan
NPV	Net Present Value
NZEB	Nearly Zero-Energy Building
OPEX	Operating expenses
SFH	Single Family House
TH	Terraced House

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Annexes

Annex 1. Envelope level insulations and technical system details

Table 7 Envelope upgrade levels for DE, DK, EL and HU expressed in U-value (W/m2K)

Country	element	level 0	level 1	level 2	level 3
DE	Wall	0.8	0.5	0.3	0.2
DE	Roof	0.8	0.5	0.3	0.2
DE	Floor	0.8	0.5	0.2	0.2
DE	Window	1.7	1.5	1.2	1.0
DK	Wall	0.9	0.5	0.4	0.3
DK	Roof	0.4	0.4	0.3	0.2
DK	Floor	0.8	0.7	0.3	0.3
DK	Window	2.5	2.4	1.7	1.0
EL	Wall	1.9	1.3	0.7	0.6
EL	Roof	1.2	0.9	0.6	0.5
EL	Floor	3.0	1.9	0.5	0.4
EL	Window	4.3	3.6	2.7	2.6
HU	Wall	0.6	0.6	0.6	0.5
HU	Roof	0.7	0.6	0.4	0.2
HU	Floor	0.7	0.7	0.6	0.4
HU	Window	2.0	1.8	1.6	1.2

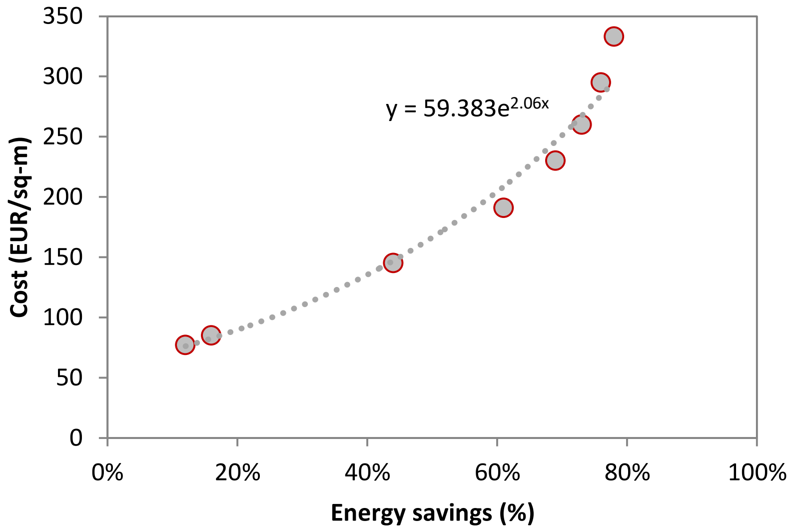

Figure 26 PRIMES cost assumption of envelope upgrades (Capros et al., 2018)

Table 8 Techno-economic parameters for the technical building systems

		Expenditure factors (Institut Wohnen und Umwelt GmbH, 2013)			Costs (Capros et al., 2018)		Type of fuel (Hofmeister & Guddat, 2017)	
Code of the technical building system	Description of the technical building system	level 0	level 1	level 2	CAPEX (EUR/kW)	Fixed O&M (€/unit/year)	fuel	LifeTime
B_NC	boiler, non-condensing	1.92	1.36	1.13	157	226	gas	20
B_C_Gas	boiler, condensing	1.31	1.13	1.06	195	226.0	gas	18
B_C_Oil	boiler, condensing	1.31	1.13	1.06	162	185.0	oil	18
B_WP	wood-pellets boiler	2.12	1.52	1.31	371.4	471.0	biomass	15
G_IWH_NC	gas-fired instantaneous water heater, non-condensing	1.27	1.24	1.20	134	226	gas	20
G_IWH_C	gas-fired instantaneous water heater, condensing	1.17	1.13	1.10	134	226	gas	20
E	direct electric heat generator	1.25	1.02	1.00	80	55	electricity	20
HP_Air	heat pump, heat source external air	0.50	0.37	0.30	714.3	135	electricity	18
HP_Ground	heat pump, heat source ground	0.52	0.31	0.21	1090	300	electricity	50
HP_ExhAir	heat pump, heat source exhaust air	0.36	0.33	0.31	940	120	electricity	18
HP_Water	heat pump, heat source ground water	2.96	1.92	1.40	1200	300	electricity	50
Stove	stove	4.44	3.39	2.44			coal	20
TS	district heating transfer station	1.34	1.13	1.06	252	0	derived heat	50
CHP_Gas_eng	combined heat and power generation - engine	1.67	1.67	1.67	1720.8	310	gas	15
CHP_Oil_eng	combined heat and power generation - engine	1.67	1.67	1.67	2145.0	310	gas	15
CHP_Gas_fc	combined heat and power generation - fuel cell	1.67	1.67	1.67	1240	500	gas	15
Solar	thermal solar plant	0.00	0.00	0.00	700	115	solar	25
PV	photovoltaics	0.00	0.00	0.00	1000	100	solar	25
HRS_Vent	mechanical heat recovery ventilation	0.50	0.80	0.90	100	20	electricity	20
Small Split (<5 kW)	cooling	0.20	0.20	0.20	329	46	electricity	12
Big Split (>5 kW, incl. ducted)	cooling	0.22	0.22	0.22	232	70	electricity	12
Chillers (A/W) < 400 kW	cooling	0.29	0.29	0.29	270	864	electricity	15
HP_Air_reverse	cooling	0.29	0.29	0.29	15.0	0.05	electricity	18
HP_Ground_reverse	cooling	0.43	0.43	0.43	120	0.05	electricity	50

Annex 2. Combinations of EEMs

Table 9 Technical building system combinations (1/2) (EPISCOPE project consortium, 2016)

Cases	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Heating system 1	B_NC	B_NC	B_NC	HP_Air	HP_Air	HP_Air	B_C_Gas	B_C_Gas	B_C_Gas	CHP_Gas_eng	CHP_Gas_eng	CHP_Gas_eng	TS
Heating system 2	-	-	-	Solar	Solar	-	Solar	Solar	Solar	-	-	-	-
Heating system 3	-	-	-	-	-	-	-	-	-	-	-	-	-
Production system	-	-	-	-	-	-	-	-	-	-	-	-	-
$\alpha_{DHW,1}$	1	1	1	0.4	0.4	1	0.6	0.6	0.6	1	1	1	1
$\alpha_{DHW,2}$	-	-	-	0.6	0.6	-	0.4	0.4	0.4	-	-	-	-
$\alpha_{DHW,3}$	-	-	-	-	-	-	-	-	-	-	-	-	-
$\alpha_{H,1}$	1	1	1	1	1	1	1	1	1	1	1	1	1
$\alpha_{H,2}$	-	-	-	-	-	-	-	-	-	-	-	-	-
$\alpha_{H,3}$	-	-	-	-	-	-	-	-	-	-	-	-	-
Mechanical ventilation	-	-	-	HRS_Vent	-	-	-	-	-	-	-	-	-
Cooling system	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	HP_Air_reverse	HP_Air_reverse	HP_Air_reverse	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	Small Split (<5 kW)

Table 10 Technical building system combinations (2/2) (EPISCOPE project consortium, 2016)

Cases	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Heating system 1	TS	TS	B_C_Gas	B_C_Gas	B_C_Gas	HP_Air	B_C_Gas	B_C_Gas	B_C_Gas	B_C_Gas	B_C_Gas	B_C_Gas
Heating system 2	-	-	G_IWH_C	G_IWH_C	G_IWH_C	-	-	-	-	G_IWH_C	G_IWH_C	G_IWH_C
Heating system 3	-	-	-	-	-	-	-	-	-	-	-	-
Production system	-	-	-	-	-	PV	PV	PV	PV	PV	PV	PV
$\alpha_{DHW,1}$	1	1	0.1	0.1	0.1	1	1	1	1	0.1	0.1	0.1
$\alpha_{DHW,2}$	-	-	0.9	0.9	0.9	-	-	-	-	0.9	0.9	0.9
$\alpha_{DHW,3}$	-	-	-	-	-	-	-	-	-	-	-	-
$\alpha_{H,1}$	1	1	1	1	1	1	1	1	1	1	1	1
$\alpha_{H,2}$	-	-	-	-	-	-	-	-	-	-	-	-
$\alpha_{H,3}$	-	-	-	-	-	-	-	-	-	-	-	-
Mechanical ventilation	-	-	-	-	-	-	-	-	-	-	-	-
Cooling system	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	HP_Air_ reverse	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW	Small Split (<5 kW)	Big Split (>5 kW, incl. ducted)	Chillers (A/W) < 400 kW

Annex 3. Calculation of the emission factors

The emission factors associated to the energy fuels have been retrieved from the results provided the PRIMES model under a EUCO2030 scenarios (E3MLab, 2018)

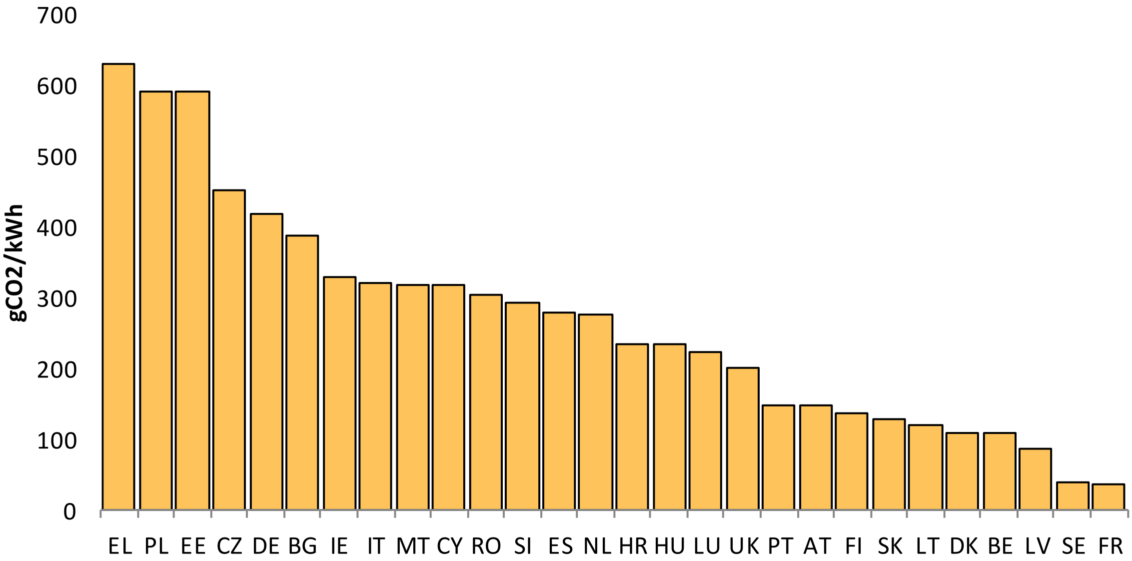

Figure 27 Carbon intensities for national electricity mixes. 2020

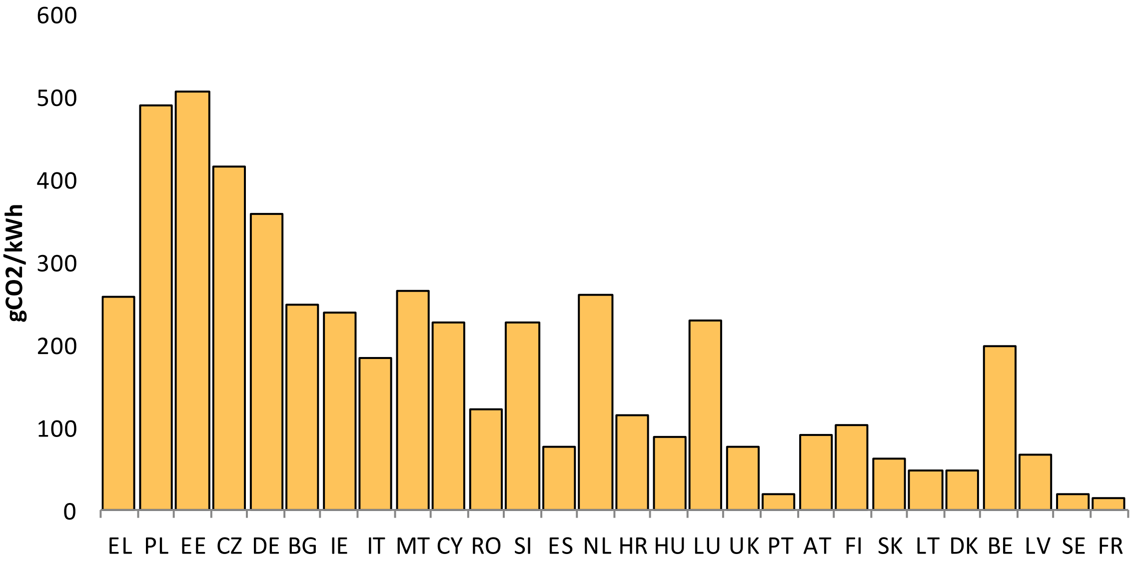

Figure 28 Carbon intensities for national electricity mixes. 2030

In the cases of coal, oil and natural gas we have considered the values provided by the IEA (International Energy Agency, 2016).

Table 11 CO_2 emission intensity per fuel

	Coal	**Oil**	**Natural gas**
CO_2 intensity (gr/kWh)	341	264	202

To calculate the electricity conversion factors from final to primary energy we use the Eurostat SHARES tool (Eurostat, 2019a)

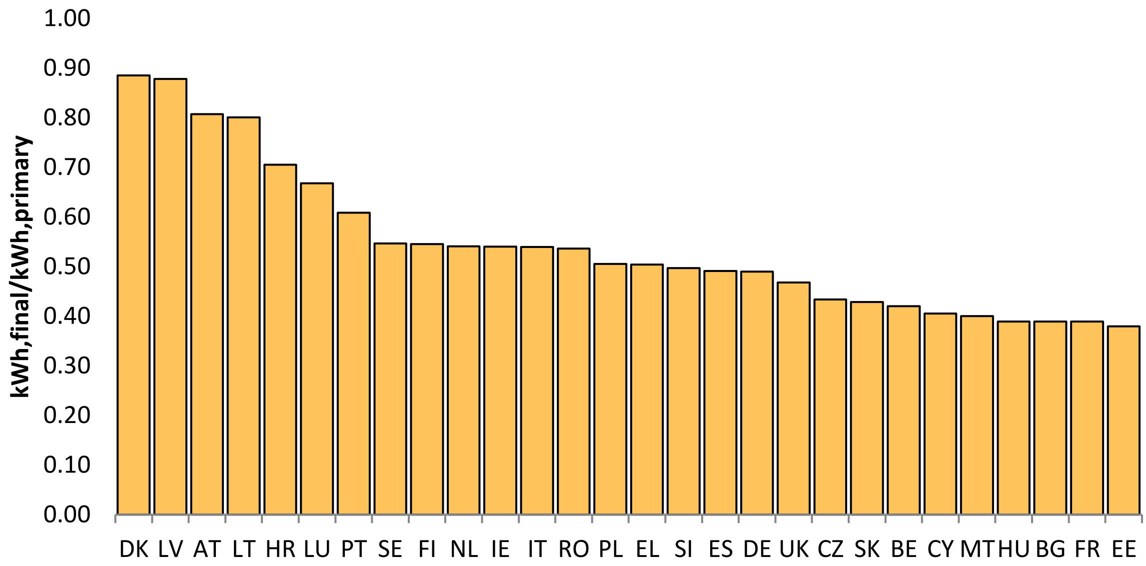

Figure 29. Electricity conversion factors

To calculate the emission factors associated to the derived heat carrier we have used the national energy balances provided in (Eurostat, 2019a). We have computed the heat flows produced by both DH and centralised CHP. In this last case, we have weighted the input fuels by the share of heat and electricity produced.

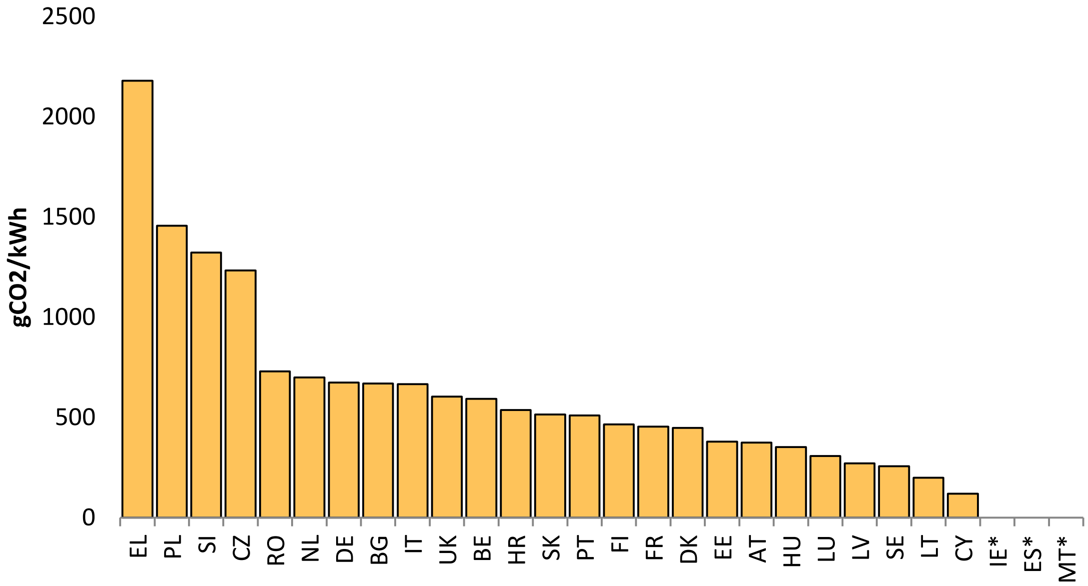

Figure 30 Carbon intensities for District heating and Combined Heat and Power

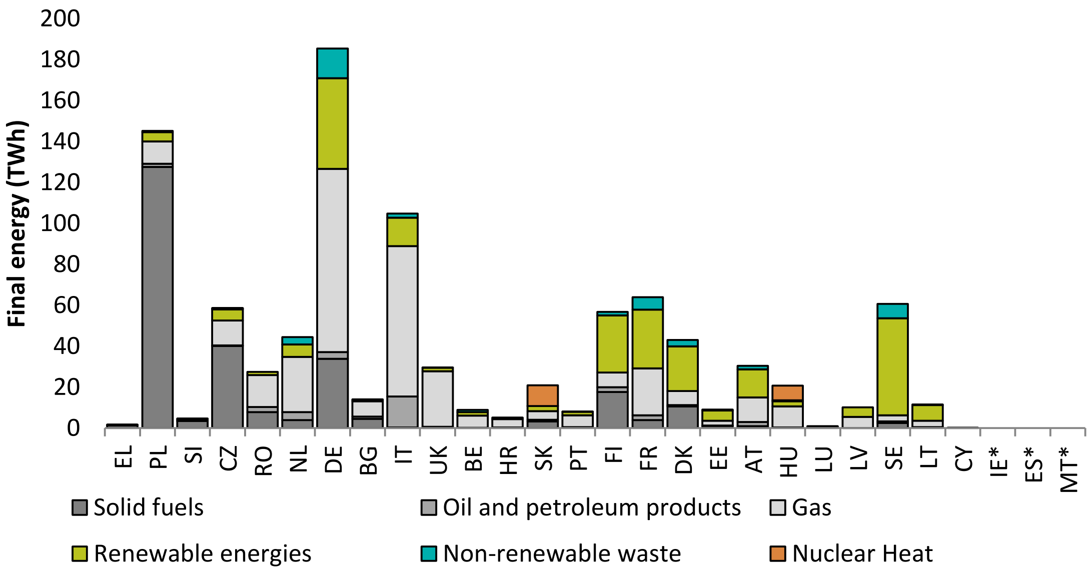

Figure 31 Fuel breakdown for derived heat and combined heat and power carriers

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