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Model-based case studies for assessing the Energy Efficiency First principle

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EXECUTIVE SUMMARY

Among other critical actions (ENEFIRST 2021b, 2021c), putting the **Energy Efficiency First** (EE1st) principle into practice requires quantitative evidence on the extent to which demand-side resources (e.g. building retrofits) in various contexts are generally preferable over supply-side resources (e.g. networks). These contexts range from municipal heat planning, over electricity network investment, up to the development of high-level policy strategies for Member States and the European Union (EU) at large. In previous quantitative work (2022b, 2022a), the ENEFIRST project demonstrated for the EU building sector that end-use energy efficiency measures can effectively reduce the need for energy supply infrastructures in transitioning to net-zero emission levels, while also bringing a variety of co-benefits or multiple impacts.

The present report provides additional **quantitative evidence on EE1st** by investigating five model-based **case studies**. The scope of these case studies is deliberately narrower compared with the EU-wide analysis, providing opportunity for a detailed evaluation of demand- and supply-side resource options in different contexts of building types (residential, non-residential), infrastructures (electricity, district heating, gas) and local conditions (weather, costs, etc.). The key findings of the five case studies are as follows:

❶ **Cumulated energy savings based on cost-optimal analysis** | If carried out within the next 10 years, single stage building renovations come with a lower cost than stepwise renovations. In both cases, exhausting the potential of deep renovation by achieving the highest energy saving is critical. The results support the instrument of renovation passports for building owners to enable informed renovation decisions.

❷ **Building retrofits and district heating systems** | District heating networks can be economically viable in scenarios with high refurbishment rates under different climate conditions and city typologies. The network's ability to combine multiple heat sources balances the impact of high fuel prices. Municipal heat planning can help lower total cost of heat and reduce the risk of energy poverty.

❸ **Heat pumps: Efficiency, CO_2 emissions and the value of flexible heat pumps** | By using buildings' thermal mass, residential heat pumps can provide additional flexibility to the power system. Depending on the building type, envelope, and location, the flexibility potential is between 18%-35% of the heat pump energy consumption. The economic profitability strongly depends on the regulation, fees, taxes, etc.

❹ **Strategic energy planning in commercial areas** | Thermal retrofits for office and education buildings can cost-effectively reduce the need for individual heat supply, distributed generation, heat networks, utility-scale generation, and seasonal heat storage. Advanced retrofit packages can possibly pay off within 13 to 14 years, making building retrofits a critical demand-side resource in the scope of the EE1st principle.

❺ **The trade-off between energy efficient household appliances and new electricity generation** | Efficient household appliances (e.g. refrigerators) can reasonably substitute for new renewable, fossil and hydrogen-based electricity generation. Cost-effective savings are in the range of 3.8%-19.4%, compared to an inefficient base case. Ecodesign standards and labelling are key instruments to achieve these savings.

In conclusion, **integrated energy systems modelling** is key to make the EE1st principle a reality. Practitioners can use model-based evidence to help formulate strategies and to put together a sound package of **policy instruments for EE1st** (ENEFIRST 2021b). At the same time, there remain critical challenges to quantitative modelling in the scope of EE1st – including the proper consideration and aggregation of multiple impacts, the selection of discount rates, and others (ENEFIRST 2022a, 2020b).

1 INTRODUCTION

The **Energy Efficiency First** (EE1st) principle suggests that demand-side resources should be prioritized whenever these provide greater value to society than alternative supply-side resources in meeting stated objectives (ENEFIRST 2020a). In practice, taking explicit account of the principle in energy system planning and policy formulation is a complex planning exercise. **Energy systems modelling** can help making these complexities tangible and thus enable decision-makers to make informed decisions on policy design, technology investment and system operation. However, as the topic of EE1st only recently entered the political and academic debate, there are only few model-based assessments that make explicit reference to the principle (ENEFIRST 2021a).

In a previous report, the ENEFIRST project (2020b) provided modellers and policymakers with a comprehensive **guidance on quantitative approaches** for assessing demand- and supply-side resources in the context of EE1st. In particular, the report pointed out what characterizes a quantitative assessment for EE1st. First, the EE1st principle requires an integrated appraisal of demand- and supply-side resources. Second, planning and policy objectives provide a common functional unit for these assessments. Third, cost-effectiveness is one important decision criterion for the selection and prioritization of resource options that can be assessed through cost-benefit analysis (CBA) and other appraisal techniques. Finally, the EE1st principle presupposes a societal perspective, which implies, inter alia, the inclusion of multiple impacts to represent the long-term societal welfare effects of different resources.

Against this conceptual background, a key step in the ENEFIRST project is to provide quantitative evidence on the EE1st principle. A suite of model-based assessments is supposed to demonstrate the distinct value of end-use energy efficiency, demand response and other demand-side resources for the European Union (EU) energy system with a view to economic costs and multiple impacts. More specifically, ENEFIRST carries out such assessments at **two levels of analysis**, as illustrated in **Figure 1**.

Level 1 | Energy system analysis for EU-27

- **Research question:** What level of end-use energy efficiency should be pursued for the EU building sector to provide the greatest societal value in transitioning to net-zero GHG emissions?
- **Spatial scope:** Member States
- **Timeframe:** 2020 – 2050

Level 2 | Local case studies for 3 Member States

- **Research question:** What level of demand-sider resources should be pursued for buildings in European municipalities to achieve local planning targets and substantial GHG emission reductions?
- **Spatial scope:** Urban areas (cities, neighborhoods)
- **Timeframe:** 2020 – 2050

Figure 1. Two levels of quantitative assessments for EE1st in the ENEFIRST project
Spain, Germany and Hungary as focus countries at Level 2 assessment

At **Level 1**, the project investigates the contribution of end-use energy efficiency in the building sector towards achieving European climate targets at the lowest cost in terms of monetary value and multiple impacts. EU Member States are modelled individually at national level and conclusions are aggregated for the EU-27 as a whole. The findings of this analysis are provided in dedicated reports. By assessing three model-based scenarios based on the performance indicator of energy system cost, the report ENEFIRST (2022b) demonstrates that society in the EU can be better off – in pure monetary terms – if end-use energy

efficiency in buildings was systematically prioritized over generators, networks and storage facilities. To obtain a more comprehensive picture of the true societal value of end-use energy efficiency in the building sector, the follow-up report ENEFIRST (2022a) substantiates the scenarios with bottom-up estimates of selected multiple impacts in the form of air pollution reductions and indoor comfort improvements.

This report addresses **Level 2** of quantitative assessments in the ENEFIRST project. The spatial scope is deliberately narrower compared with Level 1, providing opportunity for a detailed evaluation of demand- and supply-side resource options in different contexts of building types (residential, non-residential), infrastructures (electricity, district heating, gas) and local conditions (weather, costs, etc.).[1] An outline of these case studies is given in **Table 1**. The case studies are carried out for three selected EU countries: Germany (DE), Hungary (HU) and Spain (ES). In line with the policy-focused report ENEFIRST (2022c), these countries were selected as they represent jurisdictions with different climates, building sector composition and features, energy supply mixes, and political systems.

Table 1. Outline of the case studies

No.	Title	Objective
❶	Cumulated energy savings based on cost-optimal analysis	Identifying energy efficiency standards of residential buildings based on cost-optimal methodology under the consideration of the time when the renovation is performed, comparing single stage renovations and staged renovations.
❷	Building retrofits and district heating systems	Investigating the expected trade-offs between a DH system and retrofit strategies for buildings in achieving GHG emission reduction.
❸	Heat pumps: Efficiency, CO_2 emissions and the value of flexible heat pumps	Identifying the value of flexible heat pump operation in residential buildings where the building thermal mass is used as a heat storage
❹	Strategic energy planning in commercial areas	Exploring the potentials of retrofits for commercial buildings in reducing the need for individual heat supply, distributed generation, and district heating and cooling infrastructure, while reaching equivalent levels of emission reductions.
❺	The trade-off between energy efficient household appliances and new electricity generation	Investigating the trade-off between energy efficient household appliances and new electricity generation. Assessing the cost-effectiveness of appliances from private and societal viewpoints.

In the following, **Chapter 2** provides 8- to 12-page summaries for each case study. This includes their individual background and objective, methodologies, results, as well as discussions and conclusions. **Chapter 3** concludes this report with a summary of the case study findings, an overall perspective on the value of demand-side resources as alternatives to supply-side resources in energy system design and operation, as well as an outlook to policy design for implementing the EE1st principle in practice.

Note: The case studies ❶, ❷ and ❹ have been presented in a webinar series. The presentation files and recordings are available at: https://enefirst.eu/newsroom/webinar-series-operationalising-the-efficiency-first-principle-insights-into-3-modelling-case-studies/

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[1] The two levels of analysis thus address the topic of 'context dependency' discussed in the cost-benefit analysis literature (Ürge-Vorsatz et al. 2016; Chatterjee et al. 2018), that is, a loss of information about the variation of impacts resulting from aggregation at a larger geographic scale. An approach with a high level of geographic aggregation yields cost and benefit values that may not be useful to regional or local stakeholders, let alone individual cost-benefit considerations.

2 CASE STUDY REPORTS

This chapter presents dedicated summaries per case study. Each summary consists of the following sections: (1) background and objective, (2) methodology, (3) results, (4) discussion and conclusion. The case studies are introduced by case study headers (**Figure 2**) that indicate which building types (residential, non-residential), building end-uses (e.g. space heating) and energy supply infrastructures (e.g. power) are considered in the respective case study.

		(Case study title)			
Scope	Building types	Residential		Non-residential	
	Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
		Lighting	Process heating	Process cooling	Other
	Supply infrastructures	Power	District heating		Gas
Outline	Objective	…			
	Methodology	…			
	Key results	…			

Figure 2. Case study header

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(I)   Cumulated energy savings based on cost-optimal analysis

CASE STUDY #1	Cumulated energy savings based on cost-optimal analysis: what can we learn about optimal building stock decarbonization strategies			
Scope — Building types	Residential		Non-residential	
Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
	Lighting	Process heating	Process cooling	Other
Supply infrastructures	Power	District heating		Gas
Outline — Objective	Analysing key aspects of acceleration of the building stock's decarbonization based on the cost-optimal methodology: on one hand the effect of energy prices, and on the other hand the difference of single stage versus staged building renovation			
Methodology	We carried out the analysis in a five steps workflow, applying different models and methods and combining their results. The workflow relies on the cost-optimal methodology, combined with energy demand and optimization modelling.			
Key results	Optimized times for performing three-steps staged renovations are between 2021 and 2029, having the individual buildings roadmaps with an optimized duration between 5 and 8 years. This represents cumulated primary energy demand between 3.000 and 3.200 kWh/m² and global costs between 690 and 850 €/m².			

Background and objective[2]

Despite declaring targets and implementing programmes for increasing building renovation, European Member States have been very slow in the past years and decades in retrofitting their building stocks. Economic barriers are one of the main reasons for that. In previous studies, it was shown that the invested amount in renovation activity is directly linked to the achieved building energy efficiency standards and to the renovation approach – that can be single stage or staged renovation (Gillich et al. 2018). Until now, policy makers and academia have focused on the single stage approach and their cost-effectiveness (Stocker and Koch 2017; Mauro et al. 2015). However, empirical evidences have shown that in real-life, most renovation activities are carried out stepwise; meaning that the retrofit activity is performed in several stages over time (Cischinsky and Diefenbach 2018; Fehlhaber 2017). Moreover, in real-life the decision of deep renovation is a very individual one, and a study about citizens' motivations and barriers to engage on energy efficiency renovation showed that the decision of carrying out retrofit also depends on diverse personal socio-economic, geographical and cultural characteristics (Ipsos 2018).

In addition, the current Ukraine – Russian war and the strong increase of energy prices in a short period of time has generated a demand on carrying out measures to reduce the dependency on natural gas and oil from Russia and other potentially instable and undemocratic countries and regions. In this context there is still a dilemma between performing "short-term" measures in line with household's available budgets (which may be limited) or "long-term" well-planned measures. This means for example replacing the heating system, but not performing improvements on the building's envelope. Technically speaking the "short-term"

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[2] This case study is based on the paper Maia et al, 2022, submitted to the journal Smart Energy Systems in August 2022.

solution is often not the ideal one, as it may generate an inefficient operation of the heating system or risks of lock-in effects. Therefore, it is recommended to carry out renovation measures with the "long-term" approach. For example, following a building renovation roadmap, where the measures are performed on a single-stage or staged renovation approach, in a coordinated way in any case (Jafari and Valentin 2017). In the staged-renovation, however, investments may be higher over time and there is a risk of interruption (Maia et al. 2021). But, if properly planned and implemented, a high building energy efficiency can be guaranteed – even with the risk that not all necessary measures are carried out as initially planned.

Due to the seriousness of the current energy prices and energy security situation and the urgent need of building stock decarbonisation, we aim at analysing different aspects of accelerating the building stock decarbonisation: on one hand the effect of energy prices on the viability of different renovation measures, and on the other hand the difference of single stage versus staged building renovation. In this context, we also suggest the use of an indicator to take into consideration the time perspective, i.e. the timing of renovation measures and the resulting demand over time. When analysing cost-optimal single stage renovation, an indicator on the energy performance before and after the single-stage renovation is sufficient. However, in case of staged renovation this indicator would change after each renovation step. Therefore, in the current case study we introduce the cumulated primary energy demand over the whole period until 2050 (based on EU's decarbonisation target) as an indicator for assessing the energy demand of a building over a certain period of time. The following research questions are in the focus of this case study:

- What are opportunities and challenges of single-stage versus staged renovation activities and what is the difference of these approaches in terms of achieving (cumulated) energy savings and related global costs?
- What is the impact of energy prices on the cumulated primary energy and global costs in both single-stage versus staged renovation approaches?
- What are implications for the EE1st principle?

Methodology

The core calculation procedures are described in **Figure 3**. We start with a definition of reference buildings and possible, suitable renovation measures with different energy efficiency standards (step 1). Subsequently, we define different packages of renovation measures and then allocate them in staged renovation steps (step 2). Investment costs and energy demand (step 3) are calculated for each building roadmap, using the cost-optimality method (as defined in the EPBD – Energy Performance of Buildings Directive). Following a net-present value maximization algorithm (Maia et al, 2021), in step 4 we determine the optimal timing of renovation steps, before finally identifying the cumulated primary energy demand and global costs of staged renovation processes (step 5).

1	• Definition of the country-specific reference building (based on the TABULA database) • Definition of different energy efficiency standards
2	• Allocation of the different measures in a stepwise approach, including the package of measures per step
3	• Generation of building's stepwise roadmap: for different energy efficiency standards and per step, energy demand and global costs are calculated for each roadmap
4	• For each building roadmap, the optimized year of performing each step was calculated
5	• For the optimized year, the cumulated energy demand and cumulated global costs were calculated, based on cost-optimal analyses

Figure 3. Overview of the calculation procedures to assess cost-optimal and cost-effectiveness of energy renovation activities.
Source: adapted from (IEA 2017).

Reference building and renovation measures definition (STEP 1): The first stage of the methodology consists of defining the reference building. For the sake of this case study, the construction period that represents old buildings with low energy efficiency was chosen, i.e., a single-family house built before 1918. Here fore, the TABULA database (EPISCOPE project 2016) served as basis for the country-specific typology. Then, the renovation measures were defined as presented in **Table 2** and their energy efficiency standards represented by the insulation ranges, windows U-values and efficiency of the heating system. It was considered the replacement by a air-to-air heat pump with COP equal to 3.0. The combination of these measures and their different energy efficiency standards generates 54 possible combinations.

Table 2. Considered measures and their energy efficiency standards

Category	Measure	Measure parameter	Insulation range (cm)
Building envelope	Roof (or upper ceiling) insulation	Insulation thickness (cm)	30-10
Building envelope	Facade insulation	Insulation thickness(cm)	20-10
Building envelope	Floor (or cellar ceiling) insulation	Insulation thickness(cm)	20-10
Building envelope	Window/door replacement	U-value (W/K*m²)	0.7 and 0.95

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Table 3. Detailed information about the 54 variants (based on Table 2)

ID	Insulation thickness [cm] - External wall	Insulation thickness [cm] - Floor	Insulation thickness [cm] - Roof	U-value [W/(m²·K)] - External wall	U-value [W/(m²·K)] - Floor	U-value [W/(m²·K)] - Roof	U-value [W/(m²·K)] - Window	Heating system
1	10	10	15	0.29	0.25	0.18	0.7	Air-to-air heat pump
2	10	10	15	0.29	0.25	0.18	0.95	Air-to-air heat pump
3	10	10	20	0.29	0.25	0.14	0.7	Air-to-air heat pump
4	10	10	20	0.29	0.25	0.14	0.95	Air-to-air heat pump
5	10	10	25	0.29	0.25	0.12	0.7	Air-to-air heat pump
6	10	10	25	0.29	0.25	0.12	0.95	Air-to-air heat pump
7	10	15	15	0.29	0.18	0.18	0.7	Air-to-air heat pump
8	10	15	15	0.29	0.18	0.18	0.95	Air-to-air heat pump
9	10	15	20	0.29	0.18	0.14	0.7	Air-to-air heat pump
10	10	15	20	0.29	0.18	0.14	0.95	Air-to-air heat pump
11	10	15	25	0.29	0.18	0.12	0.7	Air-to-air heat pump
12	10	15	25	0.29	0.18	0.12	0.95	Air-to-air heat pump
13	10	20	15	0.29	0.15	0.18	0.7	Air-to-air heat pump
14	10	20	15	0.29	0.15	0.18	0.95	Air-to-air heat pump
15	10	20	20	0.29	0.15	0.14	0.7	Air-to-air heat pump
16	10	20	20	0.29	0.15	0.14	0.95	Air-to-air heat pump
17	10	20	25	0.29	0.15	0.12	0.7	Air-to-air heat pump
18	10	20	25	0.29	0.15	0.12	0.95	Air-to-air heat pump
19	15	10	15	0.21	0.25	0.18	0.7	Air-to-air heat pump
20	15	10	15	0.21	0.25	0.18	0.95	Air-to-air heat pump
21	15	10	20	0.21	0.25	0.14	0.7	Air-to-air heat pump
22	15	10	20	0.21	0.25	0.14	0.95	Air-to-air heat pump
23	15	10	25	0.21	0.25	0.12	0.7	Air-to-air heat pump
24	15	10	25	0.21	0.25	0.12	0.95	Air-to-air heat pump
25	15	15	15	0.21	0.18	0.18	0.7	Air-to-air heat pump
26	15	15	15	0.21	0.18	0.18	0.95	Air-to-air heat pump
27	15	15	20	0.21	0.18	0.14	0.7	Air-to-air heat pump
28	15	15	20	0.21	0.18	0.14	0.95	Air-to-air heat pump
29	15	15	25	0.21	0.18	0.12	0.7	Air-to-air heat pump
30	15	15	25	0.21	0.18	0.12	0.95	Air-to-air heat pump
31	15	20	15	0.21	0.15	0.18	0.7	Air-to-air heat pump
32	15	20	15	0.21	0.15	0.18	0.95	Air-to-air heat pump
33	15	20	20	0.21	0.15	0.14	0.7	Air-to-air heat pump
34	15	20	20	0.21	0.15	0.14	0.95	Air-to-air heat pump
35	15	20	25	0.21	0.15	0.12	0.7	Air-to-air heat pump
36	15	20	25	0.21	0.15	0.12	0.95	Air-to-air heat pump
37	20	10	15	0.16	0.25	0.18	0.7	Air-to-air heat pump
38	20	10	15	0.16	0.25	0.18	0.95	Air-to-air heat pump
39	20	10	20	0.16	0.25	0.14	0.7	Air-to-air heat pump
40	20	10	20	0.16	0.25	0.14	0.95	Air-to-air heat pump
41	20	10	25	0.16	0.25	0.12	0.7	Air-to-air heat pump
42	20	10	25	0.16	0.25	0.12	0.95	Air-to-air heat pump
43	20	15	15	0.16	0.18	0.18	0.7	Air-to-air heat pump
44	20	15	15	0.16	0.18	0.18	0.95	Air-to-air heat pump
45	20	15	20	0.16	0.18	0.14	0.7	Air-to-air heat pump
46	20	15	20	0.16	0.18	0.14	0.95	Air-to-air heat pump
47	20	15	25	0.16	0.18	0.12	0.7	Air-to-air heat pump
48	20	15	25	0.16	0.18	0.12	0.95	Air-to-air heat pump
49	20	20	15	0.16	0.15	0.18	0.7	Air-to-air heat pump
50	20	20	15	0.16	0.15	0.18	0.95	Air-to-air heat pump
51	20	20	20	0.16	0.15	0.14	0.7	Air-to-air heat pump
52	20	20	20	0.16	0.15	0.14	0.95	Air-to-air heat pump
53	20	20	25	0.16	0.15	0.12	0.7	Air-to-air heat pump
54	20	20	25	0.16	0.15	0.12	0.95	Air-to-air heat pump

Allocation of measures per step (STEP 2): There are basically two approaches for performing deep renovation – single stage (all measures performed at once) or staged renovation[3] (measures are performed in different steps). Then, for staged renovation it is needed to define the number of steps in which the performed measures will be broken down and the combination of measures per single step. This can also be understood as individual building renovation roadmap, as an energy assessor might develop it for a certain building together with the building owner. In the present study, this process is automatised.

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[3] We use the terms "stepwise" and "staged" renovations as synonyms, as they are also used in similar contexts in the literature.

Normally, the number of steps can vary between two and five. For example, a two steps roadmap can consist of first carrying out building envelope measures, and then, replacing the heating system and installing a local renewable energy generation source, as PV-cells. While a five-step roadmap would be performing each of the five measures listed in the **Table 2** separately. This would be the case if the renovation of one element is carried out only when the specific element has reached its lifetime, which would typically lead to separate timing of each step. However, it also needs to be considered that this leads to additional costs, while merging steps may lead to saving costs (e.g. the costs for the general construction site equipment, required more or less for each stage). Thus, a three-step roadmap is considered plausible by Maia et al. (2021). Having decided on the number of steps, there is still the issue to allocate the measures in a way that the steps are technically implementable and economically feasible (not representing a significant burden for building's owner). An exemplary three-steps roadmap (used in the analysis) is presented below:

Step 1   **Step 2**   **Step 3**

Upper ceiling insulation RES installation	→	External wall insulation Window replacement	→	Cellar ceiling insulation Heating system replacement
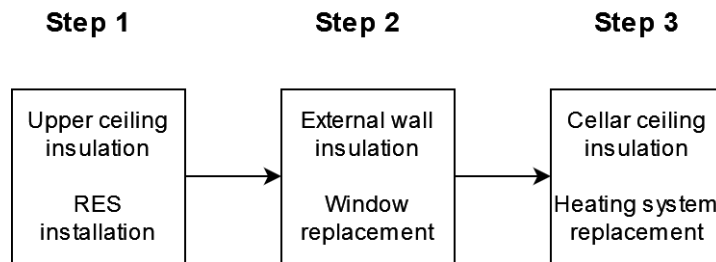
Figure 4. Three-steps roadmap

Energy demand and energy related investment costs (STEP 3): For the roadmaps 1 (single stage renovation) and 2 (staged renovation) specified in the step 2, the energy demand and the energy related investment costs for each step were calculated. The building energy demand calculation is a monthly-base steady-state calculation according to the German norm DIN 18999 that partly relies on the ISO 52000 series (Baunormlexikon 2018). The costs were estimated per measure (and package of measures) based on a literature review (Hummel et al. 2020).

Stepwise Optimization (STEP 4): In this step, the cost-optimum timing for performing each stage has been derived. The related optimization model is implemented according to Maia et al. (2021) as programming code in Python, using the Gurobi solver. The optimization considers 2020 as starting year, and 30 years of optimization period. This means that 2050 is the last year to perform an optimization. The model maximises the net present value of household's energy cash-flow (understood as annual budget minus energy related expenditures) and thus calculates the optimum time when each three steps will be performed according to the **Equation 4**.

$$\max NPV = \sum_{t}^{T} \frac{CF_t}{(1+r)^t} + \frac{L_t}{(1+r)^{tp}}$$
    Equation 1

NPV, energy-related net present value [EUR]; **CF**, cash-flow of energy related balance [EUR]; **L**, residual value of the retrofitting measures in year t [EUR]; **r**, interest rate [%]; **tp**, depreciation time [a]; **T**, optimisation period [a].

Cumulated energy demand versus cumulated global costs analysis (STEP 5): Combining the results from steps 3 and 4 allows the calculation of the cumulated primary energy demand (CPD) and global costs (GC).

$$CPD = \sum_{1}^{i} PED_i * p_i$$
    Equation 2

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CPD, cumulated primary energy demand [kWh/m²]; **PED**, primary energy demand during the period of step i [kWh/m²*yr]; **p**, time period of step i [a]; **i**, number of steps of the renovation roadmap. For single-step renovation, i = 1. In the present step-by-step model, i = 3. p is the time period between the implementation of step i and the next step (or the end of the optimization period, for the last step) [a].

$$GC = \sum_1^i IC_i + EC_i * p_i$$

GC, cumulated global costs [€/m²]; IC, investment costs [€/m²]; EC, energy running costs [€/m²]; p, time period of step i (as in **Equation 5**) [a]; i, number of steps of the renovation roadmap (as in Equation 5).

For the energy price scenario, following energy price for gas and electricity in Germany, in the period between 2020 and 2050 was considered:

Scenario I: constant increase over the time	Scenario II: abrupt increase between 2020 and 2030, then a drop with constant increase over the next years
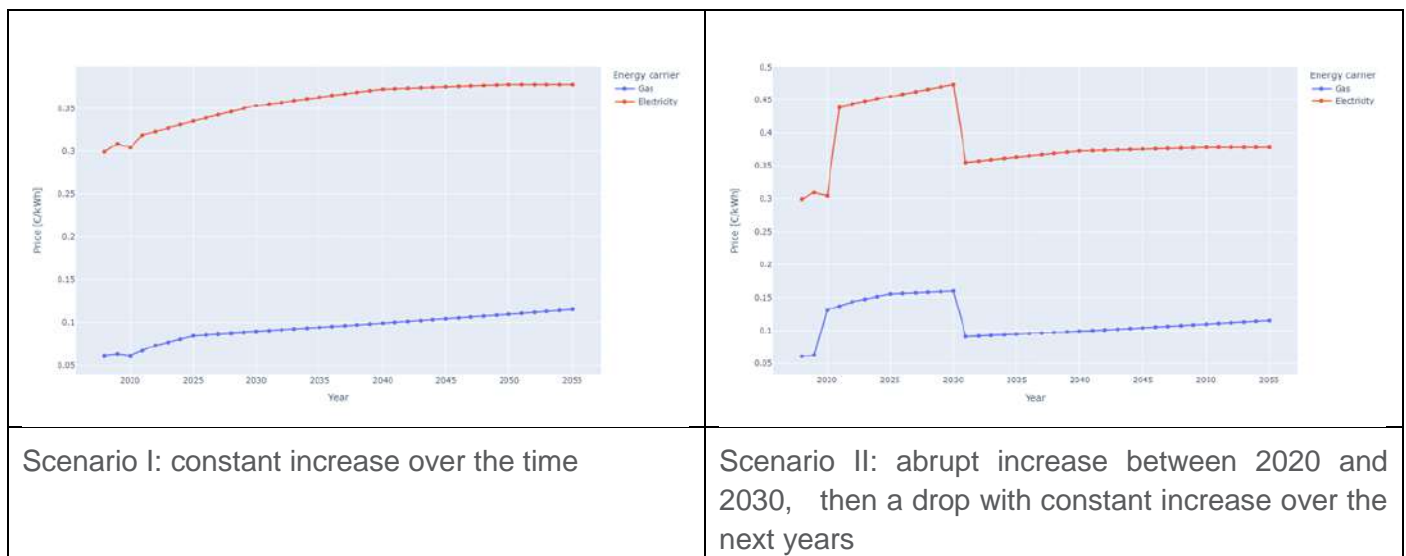
Figure 5. Energy price scenarios

Results

The **Figure 6** shows the primary energy demand for space heating [kWh/m².a] versus specific global costs [€/m²] for each of the 54 variants, that are the combinations of measures presented in the **Table 2** (the detailed parameters for each variant can also be seen above) for the selected building. The objective of the graph is to identify the cost-optimal variant. In this figure, it is considered that all measures are performed in a single stage renovation. In all variants, it was considered the replacement by a group source heat pump and the electricity price of 0,32[4] €/kWh. The **Figure 6** shows following patterns (referring to the ID of variants listed in Table 3):

- **Black marked variant (ID 20)**: the cost-optimal variant. For this variant the primary energy demand is 45 kWh/m².a and the specific global costs are 554 €/m². This variant consists of insulating the external wall with 15 cm (new U-value=0,20 W/m²K), the floor with 10 cm (new U-value=0,25 W/m²K), the roof with 15 cm (new U-value=0,18 W/m²K), and replacing the windows by a new one (U-value=0,95 W/m²K) (also shown in Annex I).

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[4] This assumption is based on the following source: average national electricity price for final consumers in Germany (Year 2021) https://ec.europa.eu/eurostat/databrowser/view/ten00117/default/table?lang=en including taxes and levie.

- **Red marked variant (ID 53):** the most energy efficient variant. This variant has the lowest primary energy demand of 38 kWh/m², however second highest specific global costs of 601 €/m². This variant consists of insulating the external wall with 20 cm (new U-value=0,16 W/m²K), the floor with 20 cm (new U-value=0,15 W/m²K), the roof with 25 cm (new U-value=0,12 W/m²K), and replacing the windows by a new one (U-value=0,7 W/m²K) (also shown in Annex I).

In general, between the different combinations of measures the primary energy demand difference is 11 kWh/m² (between 49 to 38 kWh/m²) (ID2 and ID53) and specific global costs difference of 51 €/m² between (605 and 554 €/m²) (ID17 and ID20). The external wall insulation has higher impacts on the primary energy demand (as explained below). The change in the energy price affects the specific global costs but not the primary energy demand (when maintaining the same heating system replacement option). The graph also shows that the results are affected by a clear pattern related to the difference in external wall insulation (10, 15 and 20 cm). Which is not the case for the other types of measure (defined in Table 2).
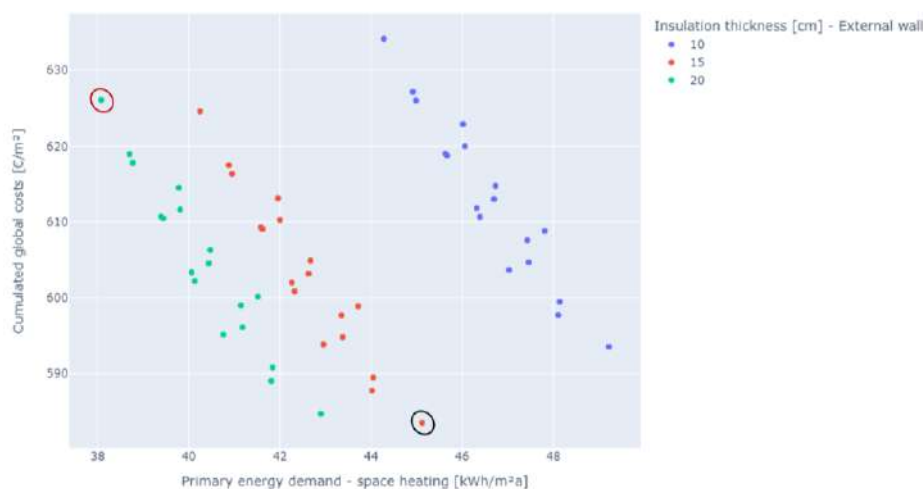
Figure 6. Cost-effectiveness variants of single-stage renovation

The next step carried out was the calculation of each three-step optimum time in the staged renovation. For that, firstly the combination of measures was allocated per step according to the roadmaps showed in the **Figure 4**. In the optimization model, an annual household budget of 6.000 EUR was assumed. Then, the annual household budget can slowly increase over time (depending on the energy costs and investment done), assuming financial savings of the disposal income. Below, the **Figure 7** presents the resulting optimum time of each step. The Figure 7 shows individual stepwise solutions for each of the 54 variants between 2020 and 2040 (being the optimisation period until 2050). The optimum time reflects different factors: the annual budget, the step investment costs, the energy prices (consequently, energy running costs) and building's material aging process. A maximum roadmap duration is 8 years and a minimum 5 years, being the steps performed between 2021 and 2029.
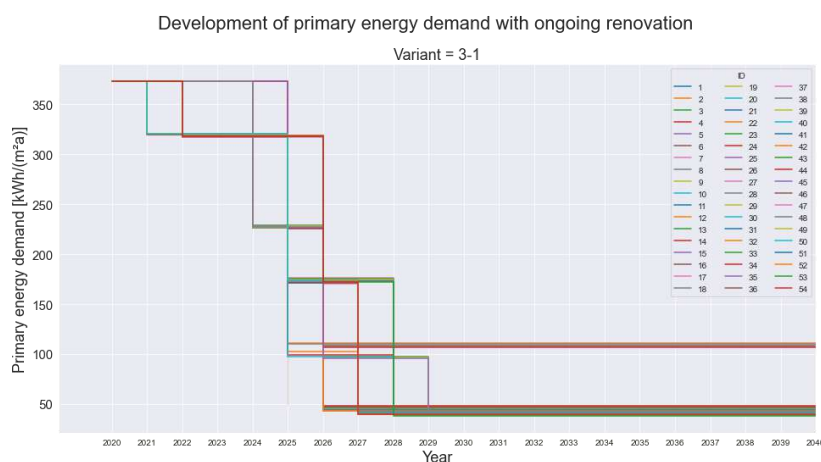
Figure 7. Optimized stage renovation, annual budget: 6.000 Euro

Finally, the **Figure 8** shows the results of the cumulated primary energy demand (kWh/m²) and global costs (€/m²) over the period of 30 years, taking into consideration the optimized time **Figure 7** and the primary energy demand calculated per step. In addition to the results for the 54 variants, the **Figure 8** also shows for the cost-optimal variant (ID20) from **Figure 6**, different single stage renovation scenarios. The scenarios consider that the single stage renovation is carried out immediately (year 0), in year 5, 10, 15 and 20. In general the results show that, in the single-stage approach, as faster the renovation is performed, the lower the global costs and cumulated primary energy demand. When comparing to the staged renovation, the variants are, in terms of cumulated primary energy demand, equivalent to the single stage performed in year 5 (about 3.000 kWh/m²). However, in terms of globals costs, they can vary between 700 €/m² (single-stage year 5) and 850 €/m² (single stage year 15). The cost optimal variant is similar in both single stage and staged approaches, having the staged renovation a slightly higher (about 50 €/m²) global costs.
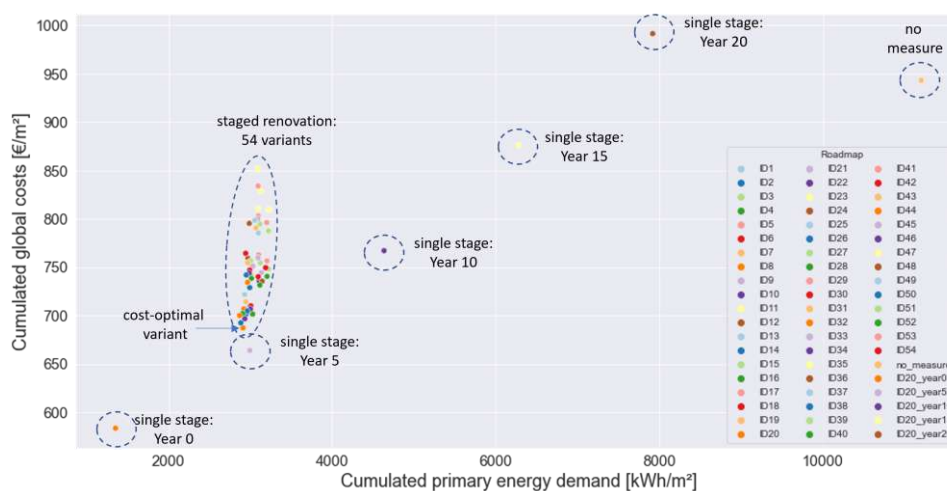
Figure 8. Cumulated primary energy demand and global costs, annual budget 6,000 Euro

The charts below show the sensitivity analysis that were performed, considering lower annual budget of 3.000 Euros (**Figure 9**) and increased energy prices (**Figure 10**). The **Figure 9** shows that the single-stage renovation remain equal. In the staged approach, however, the cumulated primary energy demand global costs are higher due to the delayed optimized year. This means that with lower annual budget available, the steps are carried out later and the roadmaps are in general longer. In this case, also a variant with lower investment costs (ID14) (more information in Annex I), then the cost-optimal one, has the lowest global costs and cumulated primary energy. This means that with lower budget, the cheaper variants (and consequently with lower energy efficient standards than others) are performed more rapidly.

Model-based case studies for assessing the Energy Efficiency First principle
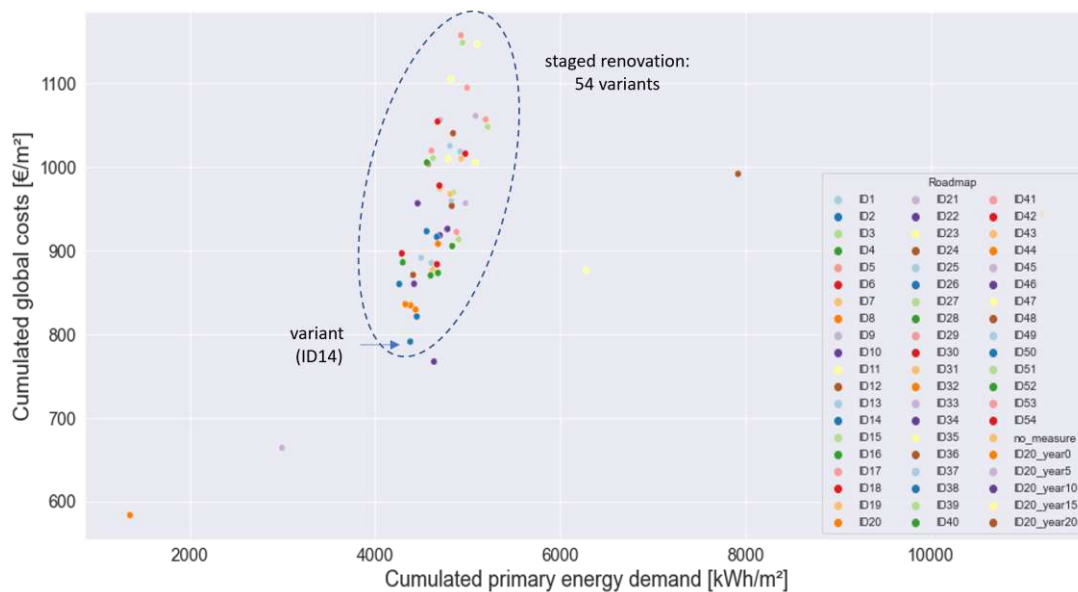
Figure 9. Cumulated primary energy demand and global costs, annual budget 3,000 Euro

The-Figure 10 shows the results when considering different energy prices. In this scenario it was considered an increase of the energy prices until 2030 and then a decrease (according to Figure 5 – scenario II). This scenario also affects the single-stage approach. In general, it is observed that in both approaches single-stage and staged the global costs are higher, however the cumulated energy demand not – because the optimized time is the same. When both gas and electricity prices increase and follow a trend, the optimised time is not affected. This would be different, if only the price of gas or electricity change. Another trend would be observed, if the prices of one of the energy carriers would change. Different as in the Figure 10, the staged renovation has global costs between single-stage renovation performed in the year 5 and 10.
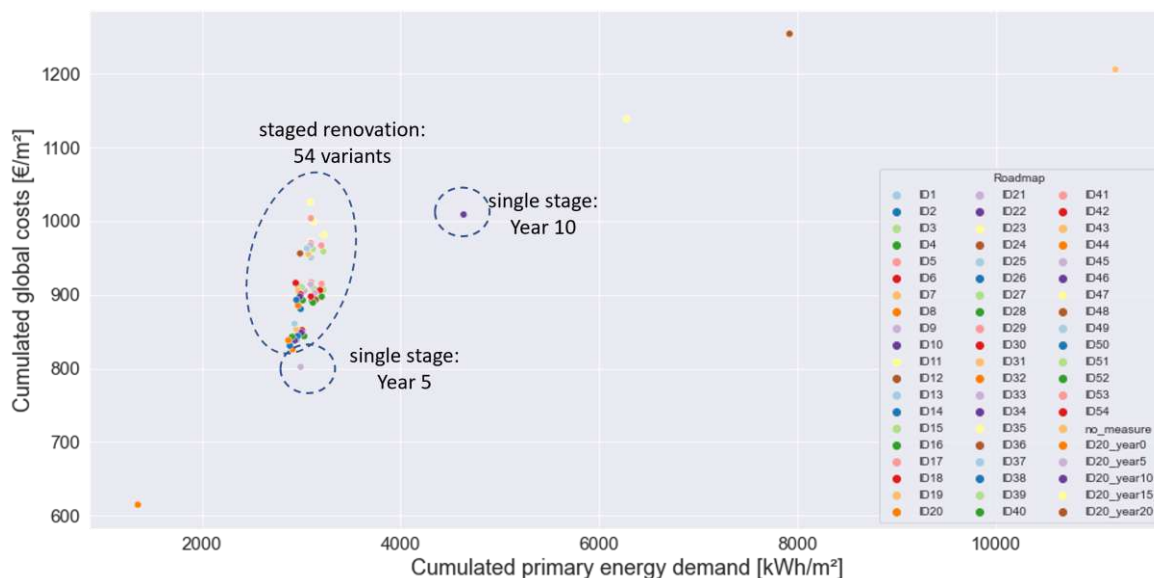
Figure 10. Cumulated primary energy demand and global costs, energy price increase

Discussion and conclusion

This case study discusses for different energy efficiency standards of renovation, the effects of the time perspective when the renovation is performed and which measures are performed by comparing the single-stage and staged renovation approaches. The main conclusions are that it depends on the right timing:

Model-based case studies for assessing the Energy Efficiency First principle

single stage renovation creates higher cumulated savings, if carried out fast (until 10 years). Between 10 and 15 years, there are some combinations of staged renovation that present lower cumulated global costs than the 15-year variant of single stage renovation (which may be attractive for homeowners, although the cumulated primary energy demand is about 1000 kWh/m² higher). However, the velocity of the renovation depends on the energy efficiency standards of the measures (and consequently their investments costs) and the annual budget available. The cost-optimal variant is not necessarily the best one, when considering the time perspective and building owner's budget restriction, especially when the main objective is to speed up renovation rates. Thus, properly planned renovation approaches are essential. This creates the need for renovation passports (individual building renovation roadmaps). At the same time, single stage renovation also needs to be promoted, but not as the only preferred option to achieve energy and climate targets. Performing optimal renovation is a security against energy prices volatility and help more building targeted achievement of EU decarbonisation goals.

(II) Building retrofits and district heating systems

CASE STUDY #2	The role of district heating solutions towards deep retrofitting of buildings in different urban settlements structures			
Scope — Building types	Residential		Non-residential	
Scope — Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
	Lighting	Process heating	Process cooling	Other
Scope — Supply infrastructures	Power	District heating		Gas
Outline — Objective	Identifying the expected trade-offs between a DH system and retrofit strategies for buildings in achieving GHG emission reduction. The scope of this study is on a meso-level with five cities located in different European climate zones			
Outline — Methodology	A Geographic Information System (GIS) model is used to estimate the heat distribution costs of DH for different heat density scenarios and decentral heat supply shares.			
Outline — Key results	The analysis shows that district heating networks are compatible with future scenarios with high refurbishment rates and deep building retrofits under different European climate conditions and city typologies.			

Background and objective

The buildings sector with final energy consumption in the EU-27 in 2018 of ca. 40% (Eurostat 2020b) represents the largest energy consumption sector in the European Union (EU). Space heating accounted for 64% of the energy consumption in the residential sector with renewables share of ca. 30% (including district heating) (Eurostat 2020a). Achieving the European targets on climate neutrality until 2050 set in the European Green Deal (European Commission 2019), requires significant reduction and changes in the current space heating demand and heat supply infrastructure. Energy Efficiency First (EE1st) should assist governments and local authorities in achieving these targets in a cost-optimal mix of demand- and supply-side resources. The EE1st principle as defined in the Governance Regulation 2018/1999 (European Union 2018c) requires that alternative cost-efficient energy efficiency measures for both demand- and supply-side should be included in both, energy planning activities as well as in policy and investment decisions. The development towards more energy efficient buildings, as well as the expansion of district heating (DH) networks, are generally considered to reduce Greenhouse gas (GHG) emissions, especially if the DH network is supplied by efficient Combined Heat and Power (CHP) plants (Åberg and Henning 2011; Milic et al. 2020). However, the combined effect of reduced heat demand due to building refurbishment and expansion of DH network, requires a more detailed approach in the assessment of the environmental impact reduction. There is no EU-wide legislation regarding DH systems, which are mostly operated and regulated by national and municipal laws. Nevertheless, EU legislation such as the Energy Efficiency Directive (EED) (European Union 2012) and the Renewable Energy Directive (RED II) (European Union 2018a) have the goal to increase the share of efficient DH systems. Both EED and RED have a clear focus on the supply-side efficiency without explicit consideration of the improvements on the demand-side by means of thermal renovations and other energy efficiency measures. The trends and future forecasts of the heating and cooling demands are largely influenced by the Energy Performance of Buildings Directive (EPBD) 2010/31/EU (European Union 2010b) and are mostly considered exogenous in the analysis of the

efficient heating and cooling supply. As defined in Article 2a of the revised EPBD 2018/844/EU (European Union 2018b), each Member State should establish a long-term renovation strategy (LTRS) to support the renovation of the national residential and non-residential building stock. Some of the requirements of the LTRS are to provide an overview of the national building stock, the identification of cost-effective approaches to renovation, and policies and actions to stimulate cost-effective deep renovation. Considering the EE1st principle would mean to explicitly reflect both aspects of supply and demand side energy efficiency measures. This is particularly relevant to DH systems, which have a long investment cycle of more than 30 years and require an integrated investment planning approach to achieve efficient heat supply and avoid unnecessary investments and infrastructure oversizing.

The study aims to identify the expected trade-offs between a DH system and retrofit strategies for buildings in achieving GHG emission reduction. To do so, a Geographic Information System (GIS) model is used to estimate the heat distribution costs of DH for different heat density scenarios and decentral heat supply shares. The scope of this study is on a meso-level (municipal planning) with a total of five cities located in different European climate zones (PVSITES Consortium 2016). The main selection criteria of the analysed cities and modelled areas were the current DH market share, climate zone, population density, and transferability potential. The DH market share varies from 10% (Milan) up to 92% (Helsinki). The total population within the case studies varies between 0.31 million inhabitants (Karlsruhe) up to 1.76 million (Warsaw), with population densities between 1,800 inh/km² (Karlsruhe) and 7,700 inh/km² (Milan). In **Table 4** some general characteristics of the analysed case studies and their DH networks are presented.

Table 4. General characteristics of the analysed case studies and their DH networks
Sources: City of Helsinki (2019); Galindo Fernandez et al. (2021); Mataszsz (2019); PGNIG (2019); Stadtwerke Karlsruhe (2020)

Case study	Karlsruhe	Budapest	Milan	Warsaw	Helsinki
Total population [Mil. inhabitants]	0.31	1.75	1.35	1.76	0.63
Population density [inh/km²]	1,800	3,351	7,700	3,460	2,986
Total area [km²]	173,5	525,5	181,8	517,2	213,8
Built-up area [km²]	58,8	193,0	101,1	247,7	102,4
Climate zone	4	3	1&2	3	5
Heating Degree Days 2019	2,650	2,293	1,859	2,764	4,142
DH market share [%]	30%	30%	10%	80%	92%
DH installed capacity [MWth]	800	2,345	901	5,329	3,630
DH heat production [GWh]	900	2,184	1,226	9,472	7,200
DH network length [km]	222	460	317	1,735	1,390
Liner heat density [MWh/m]	4.05	4.75	3.87	5.46	5.18
DH density [km/ 1000 inh]	0.71	0.26	0.23	1.02	2.2

Methodology

The applied methodology can be summarized in three main steps. In the **first step**, the analysed heat demand scenarios and related building refurbishment costs are calculated. In the **second step**, district heating related costs such as distribution, operation and heat generation costs are calculated for each case study and heat demand scenario. Varying scenarios were modelled by applying different connection rates and shares of heat supplied by DH. In the **third step**, to calculate the total costs of heat supply for a

specific year, the decentral costs of heat are calculated. To compare costs between investments made at different points in time and to be able to compare different types of costs such as district heating supply, building refurbishment, and decentral heat supply, all costs in the analysis are annualised.[5] For the analysis, the results from Invert/EE-Lab[6], NetHEAT[7] and Enertile[8] energy system models were used. **Figure 11** presents an overview of the methodology used for this case study.
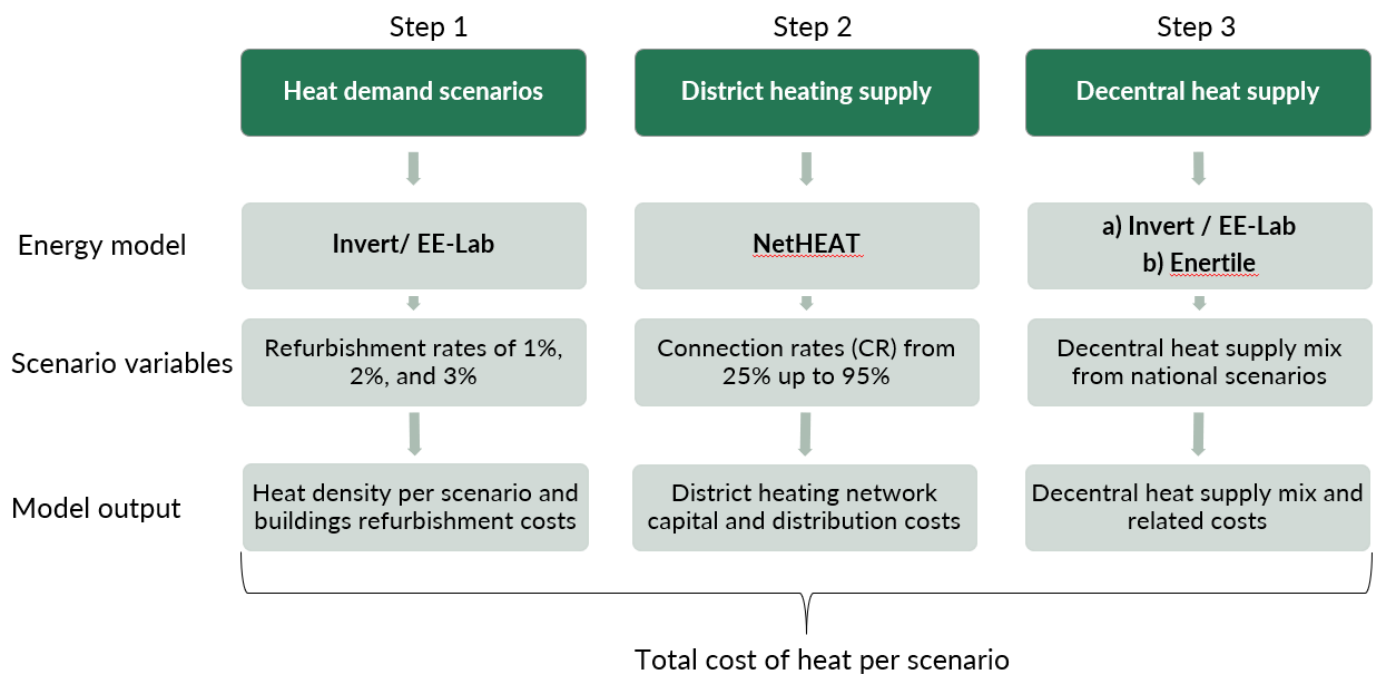
Figure 11. Overview of applied methodology, energy models, scenario variables, and model outputs for case study #2

In the first step, the Hotmaps toolbox[9] calculation module - Demand Projection - was used to calculate the heat demand scenarios and the development of the heat demand densities on a hectare level. The methodology relies upon the Invert/EE-Lab Model, which is a dynamic bottom-up simulation tool that evaluates the effects of different policy packages on the total energy demand, energy carrier mix, CO2 reductions and costs for space heating, cooling, hot water preparation and lighting in buildings.

In this analysis *three different demand projection scenarios* were calculated for varying average refurbishment rates of 1%, 2%, and 3% of the total gross floor area being renovated annually until the year 2050. *The 1% refurbishment rate scenario* considers a cumulated refurbishment of ca. 40% for the period between 2015 and 2050, indicating that mainly buildings with poor building envelope quality are considered, as larger energy savings can be achieved. *The 2% refurbishment rate scenario* considers a cumulated refurbishment rate of 100%, where all the buildings built before the year 2015 undergo a building refurbishment until 2050. *The higher refurbishment rate of 3%* assumes that also buildings with better building envelope quality are increasingly renovated and the reduction in heat demand happens faster. For

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[5] Considering the methodology to derive social discount rates and applied discount rates by government agencies, the social discount rates in the EU member states varied between 1 and 7% (Steinbach and Staniaszek 2015). For all case studies 3% social discount rate were applied to evaluate the total costs and benefits of the energy system.
[6] Invert/EE-Lab website: https://www.invert.at/ (last accessed on 11.01.2022)
[7] NetHEAT website: https://irees.de/netheat/ (last accessed on 11.01.2022)
[8] Enertile website: https://www.enertile.eu/enertile-en/ (last accessed on 11.01.2022)
[9] Hotmaps Toolbox website: https://www.hotmaps.eu/map (last accessed on 11.01.2022)

all the scenarios it is assumed that the current efficiency policies remain in place and that they are effectively implemented. The energy efficiency policy mix corresponds to the current packages in place, which in most countries is a mix of regulatory approaches, economic support, and energy taxation.

In the second step, for each of the simulated refurbishment scenarios, the capital distribution costs as well as the operating costs of the DH networks were calculated by using the NetHEAT Model. The model utilizes several different publicly available datasets to determine the suitable DH regions, type of area, number of buildings, and DH pipe length as a function of the road length, where the DH network is built.

A minimum heat density of 25 GWh/km² was used as a benchmark value in the model to identify the suitable district heating regions (DHR). Afterwards, the number of residential and non-residential buildings was identified. The number of buildings is determined based on the OpenStreetMap (OSM) dataset (OpenStreetMap, 2021b). It is observed that the building dataset in OSM identifies many objects as buildings. As this number includes many objects such as individual and parking garages, allotments, warehouses, and depots, etc., an additional filter is required to identify and select the residential and non-residential buildings. By applying a filter on the area and type of buildings from the OSM dataset, most of the residential and non-residential buildings are selected. If the type of building is not provided, the filter focuses on the buildings where a housing address is available, the building footprint area is larger than 50 m², or another information such as commissioned year, number of floors, etc. are provided.

The length of the streets and roads where the DH pipeline can be built are determined based on the Urban Atlas (UA) dataset and OSM data (Copernicus Land Monitoring Service 2018b; OpenStreetMap 2021). From the UA dataset a selection category "other roads and associated land" is used, which includes the secondary and local roads, whereas for the OSM data the key highway is used, where the values of residential, living, and service streets are selected. The total road length where the DH pipeline is build is identified as a function of the DH connection rate. This length represents the DH main distribution pipeline. Additional to the main distribution pipeline, sub-distribution (or house connection) pipeline is calculated by assuming average 10m per connection of each building connection pipeline.

Since the DH pipeline construction costs are not the same everywhere within the city boundaries (e.g. differences between inner city and outer city areas), to identify different types of city areas the 'imperviousness dataset' from the Copernicus land monitoring service is used (Copernicus Land Monitoring Service 2018a).The 'imperviousness dataset' defines the soil sealing density in a range from 0-100% for each hectare raster cell. 100% sealing density implies that the area is fully covered with buildings and roads. The model assumes that the higher the sealing density, the higher are the specific construction costs for building a DH network in that area. For areas with a continuous urban fabric and a sealing density of more than 80%, the highest costs coefficients are considered. Whereas for the areas with a medium to low urban fabric and sealing density below 50%, the lowest specific costs are considered
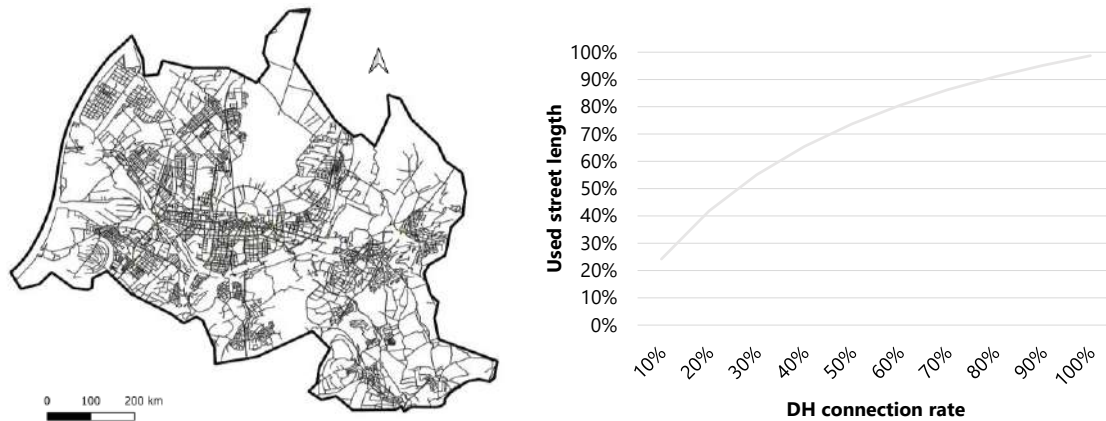
Figure 12. Identified streets (left) and the share of used street length as a function of the DH connection rate (right)
Sources: Jochum et al. (2017); OpenStreetMap (2021)

Referring to the classification done by Persson and Werner (2011), where the building density is used as an intermediate parameter to estimate cost levels, the continuous urban fabric relates to the inner-city areas, discontinuous urban fabric to outer-city areas and medium to low fabric relates to park areas. For each type of area, a country specific construction cost constant C_1 (€/m) and construction cost coefficient C_2 (€/m²) are calculated by using Heat Roadmap Europe heat distribution costs data (Persson et al. 2019) and country specific Eurostat indices for labour and construction prices (Eurostat 2022f, 2020c), **Table 5** presents the calculated cost coefficients for each case study based on the land area type. The highest specific costs based on the applied methodology are observed in Helsinki, whereas the lowest are observed in Budapest. The cost coefficients are adjusted by using country specific data for the labour costs in the construction sector and construction price index in 2019. The cost coefficients are kept constant over the years and no additional economic indicator such as inflation, labour price development, etc. were considered.

Table 5. Cost coefficients per area type and case study
Sources: Eurostat (2022f); Eurostat (2020c); Persson et al. (2019)

Land area type	Continuous urban fabric		Discontinuous dense urban fabric		Medium to low urban fabric	
Cost coefficient	C_1 (€/m)	C_2 (€/m²)	C_1 (€/m)	C_2 (€/m²)	C_1 (€/m)	C_2 (€/m²)
Karlsruhe	419	3,238	352	2,572	229	2,191
Budapest	167	1,293	141	1,026	91	874
Milan	253	1,957	213	1,554	138	1,324
Warsaw	183	1,411	154	1,120	100	954
Helsinki	442	3,418	372	2,714	241	2,312

In **Equation 4**, the capital distribution cost (C_d) calculation is presented, where Q_s is the annual heat demand (MWh/a), L is the trench length (m), a is the annuity, and d_a is the average pipe diameter (m) calculated based on **Equation 5,** where $\dot{m}$ is the mass flow rate (kg/s), ρ is the water density (kg/m³), and v is the average flow velocity (m/s). The calculated operation and maintenance costs (C_{op}) consist of fuel (C_f), electricity (C_e), and other operation and maintenance costs (C_o) as presented in **Equation 6**, where ql represents the heat distribution losses (MWh), pf is the price of heat generation cost (€/MWh), e is the electricity consumption for pumping (MWh), and pe is the electricity price. The heat distribution losses are calculated as presented in **Equation 7**, where $Upipe$ is the effective average heat transfer coefficient

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(W/m²K), r is the pipe diameter (m), ΔTm is the difference between the average heat supply and return temperature and the soil temperature (K), L is the pipe length (m), and τ are the annual DH operation hours. The effective average heat transfer coefficient (U_{pipe}) is calculated for each raster cell as a function of the DH pipe diameter and average thermal conductivity of old and new type of DH pipes (Duić et al. 2017; Grosse et al. 2017; Eurostat 2022f, 2020c).

$$C_d = \frac{a * (C_1 + C_2 * d_a)}{\frac{Q_S}{L}} \ (\text{€}/MWh)$$

Equation 4

$$d_a = \sqrt{\frac{\dot{m}}{3600 * \pi * \rho * v}} * 2 \ (m)$$

Equation 5

$$C_{op} = C_f + C_e + C_o = \frac{q_l * p_f}{n_a} + e * p_e + C_o$$

Equation 6

$$q_l = \frac{U_{pipe} * 4\pi * r * \Delta T_m * L}{1,000,000} * \tau$$

Equation 7

A generic DH fuel mix is assumed for the analysed case studies as presented in **Figure 13**. Wholesale fuel prices from a system perspective (excluding taxes, surcharges, CO_2 prices, and additional costs) were considered and based on HRE dataset (Duić et al. 2017).The investments in the heat generation units are calculated based on Grosse et al. (2017) dataset for Germany, adjusts for each case study by using national costs coefficients such as labour costs index in the construction sector and price level index for machinery and equipment (Eurostat 2022f, 2020c).
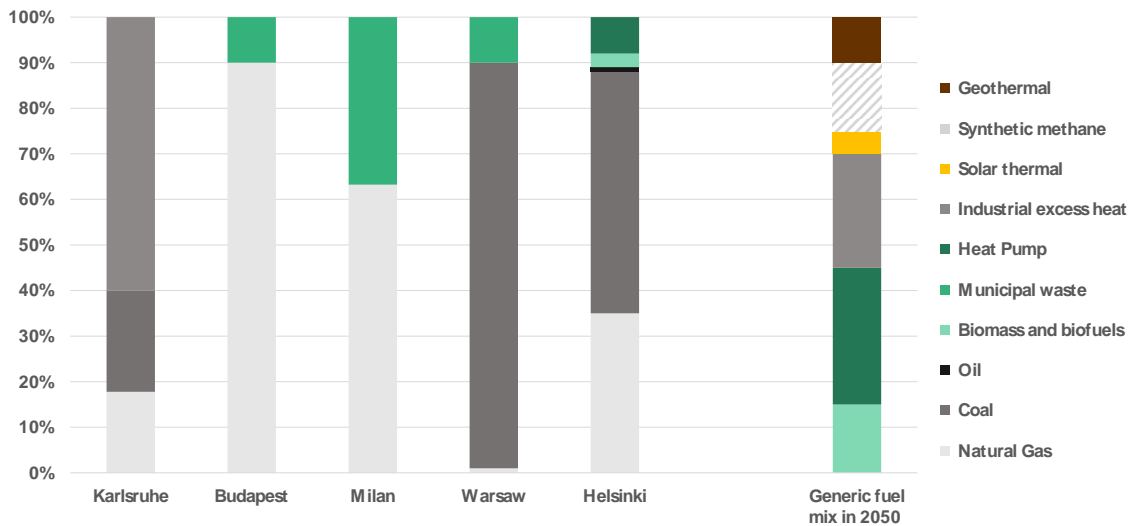
Figure 13. Current DH fuel mix and assumed generic fuel mix in 2050

Hydrogen has a potential to become a major energy carrier, which can assist many sectors in their sustainable energy transition, either through direct usage or as a main component of synthetic Methane obtained through power-to-gas production. However, there are many uncertainties such as technology learning curves, cost developments and policy support (DNV GL 2017), which makes hydrogen and synthetic methane price forecasts very unpredictable. **Figure 14** presents an overview of different price forecasts for synthetic methane in selected studies. The price range in the studies differs due to various

indicators such as production location (Germany, Europe or Middle East and North Africa (MENA)), type of power generation (wind onshore and offshore, photovoltaic) and additional costs such as grid and distribution costs.
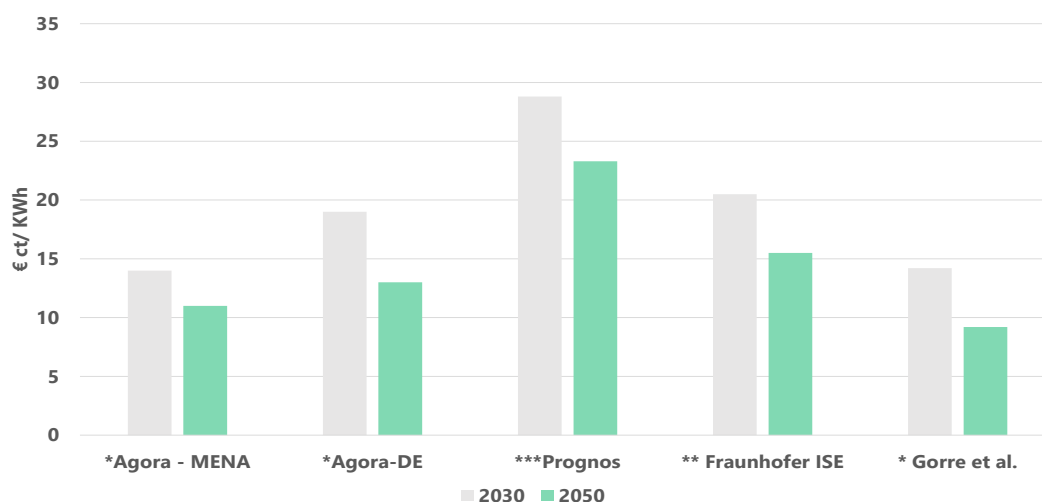
* Production costs only
** Import prices for Germany (DE), production in MENA-Region
*** End-user prices, production in MENA-Region

Figure 14. Synthetic methane prices in 2050 based on different studies and costs assumptions
Sources: Grosse et al. (2017); Hank et al. (2020); Jochum et al. (2017); Kreidelmeyer et al. (2020); Maier and Deutsch (2018)

In the third step, to compare the total costs of heat supply for each scenario, the costs of decentral heat must be calculated as well. The methodology to determine the costs of decentral heat supply can be summarized in the following tasks:

- The *total heated floor area of residential and non-residential buildings* is defined based on the scenarios and calculated by the Hotmaps tool
- The *share of single-family and multi-family houses* of the residential floor area as well as the share of *offices, education, health, wholesale and retail, hotels and restaurants, and other* non-residential buildings are defined based on the country specific average values (Esser et al. 2019)
- For nine decentral heat supply units (gas boiler, biomass boiler, direct electric heaters, coal boiler, oil boiler, air-to-air heat pump, air-to-water heat pump, ground source heat pump, and solar thermal), the specific heat supply costs in €/m² are calculated for a typical average building size of each building category defined in step 2.
- The supply share of each decentral unit was determined based on the ENEFIRST scenarios presented in D3.3 (ENEFIRST 2022b) and calculated with the Invert-EE/Lab model
- Total decentral heat supply costs for each scenario and decentral heat supply share are calculated.

The share of the decentral heat supply technologies is calculated for each case study based on the HighEFF scenario presented in deliverable D3.3 of the ENEFIRST project (ENEFIRST 2022b). It is assumed that the scenarios and applied assumptions, which are presented on a country level, can be replicated on a local one as well. **Figure 15** presents the current and future share of decentral heat supply share per technology in 2050 for each case study.

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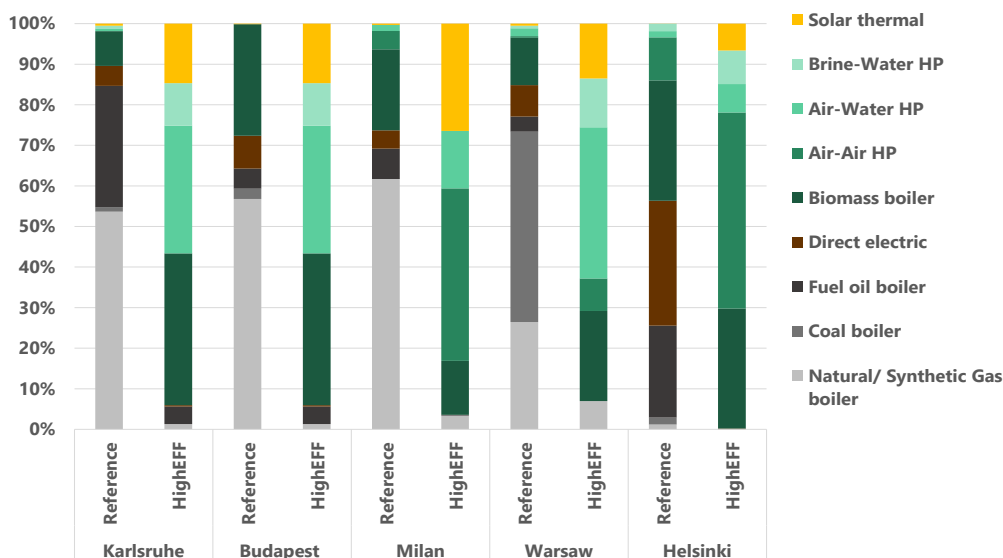
Figure 15. Own calculation based on ENEFIRST HighEFF scenario
Source: ENEFIRST (2022b)

Results

The results shed light on the DH development in the analysed scenarios and the DH impact on the total cost of heat supply in 2050 for each of the case studies. For each heat demand scenario with 1%, 2%, and 3% refurbishment rates, regions with minimum 25 GWh/km² are identified and defined as district heating regions (DHR). Within these regions, varying DH connection rates (CR) from 25% up to 95% were simulated. Consequently, the results of the DH development are presented in a span between minimum, average, and maximum value for each indicator in the simulated 1%, 2%, and 3% scenario and varying CR.

Figure 16 presents the DH pipe length and the DH share of the total heat supply in 2050. It is observed that in the case studies with the highest current share of DH – i.e. Warsaw and Helsinki - there is a reduction of the DH supply in all scenario variations due to the lower heat demand and constraint of 25 GWh/km² as a minimum heat demand density suitable for DH supply. On the other hand, in Milan in each scenario variation an increase in the share of the DH supply is observed, whereas for Karlsruhe and Budapest for the 3% refurbishment scenario the DH share sinks with the averages still above the current DH share. An increase of the DH length is observed in each scenario for the case studies in Budapest and Milan, whereas in each scenario there is a reduction of the total DH length in Warsaw and Helsinki.

Model-based case studies for assessing the Energy Efficiency First principle
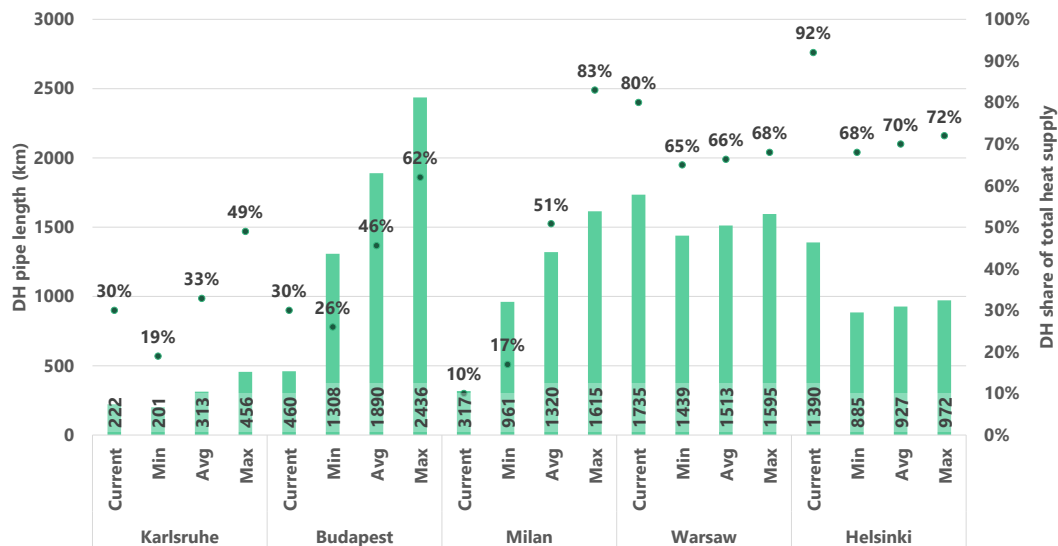
Figure 16 Development of the DH pipe length (one-way) and the share of total heat supplied by DH in 2050

Figure 17. presents the share of linear heat densities per hectare and the total linear heat densities (incl. house connection pipeline) within the analysed DHR. It is observed that for almost all scenario variations the linear heat densities are above 2 MWh/m, which is considered as a general rough benchmark assessment value (Nussbaumer et al. 2020) below which the conditions for DH development are considered as unfavourable from today's economic perspective.
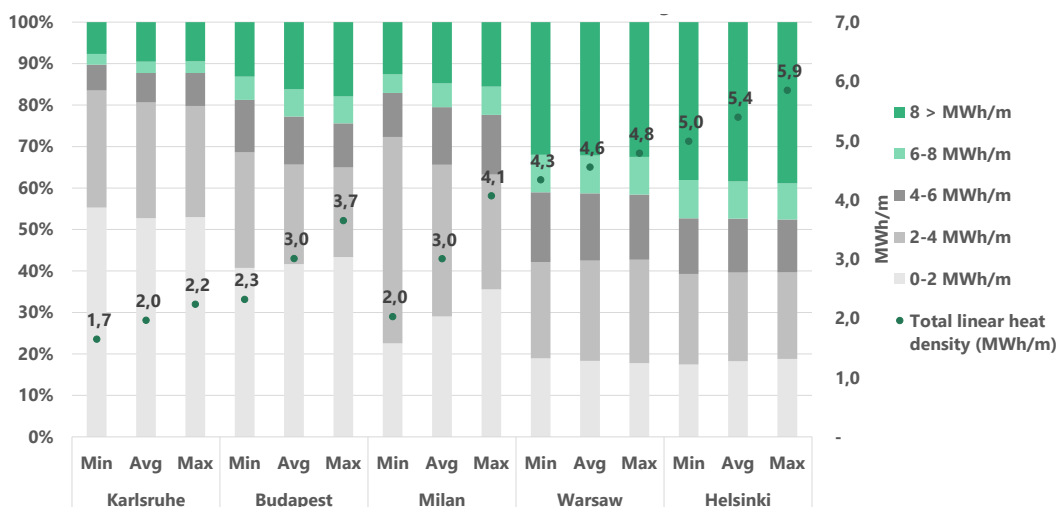
Figure 17. Linear heat densities (MWh/m) within the suitable DHR (min 25GWh/km²) for the simulated heat demand scenarios and varying DH connection rates

The capital distribution costs presented in **Figure 18**, are correlated to the linear heat densities. Hence, the highest costs are observed in the case studies with the lowest linear heat densities. The lowest capital distribution costs are observed in Warsaw, Budapest, and Helsinki, followed by Milan and Karlsruhe, which, due to the low heat densities, have the highest capital distribution costs.
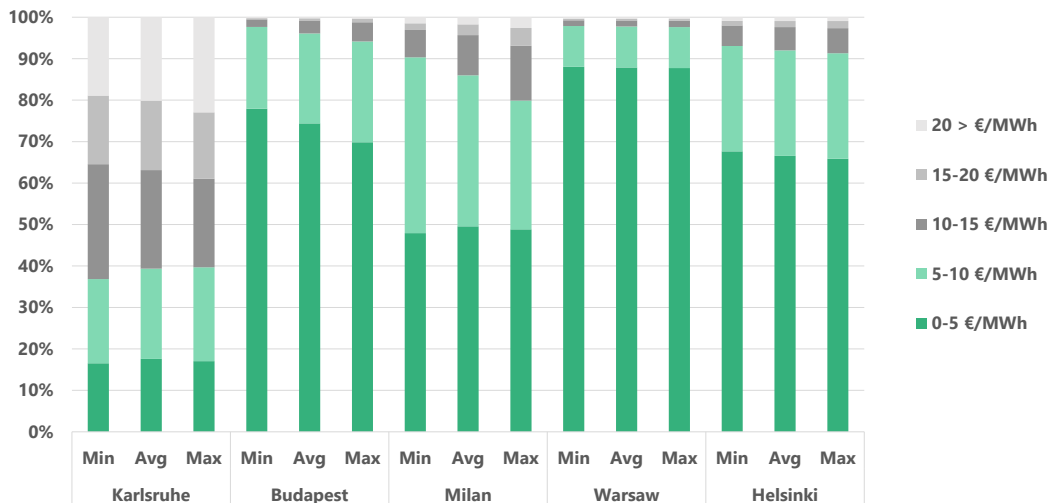
Figure 18. Capital distribution costs within the suitable DHR (min 25GWh/km²) for the simulated heat demand scenarios and varying DH connection rates

In **Figure 19** the price development of the capital distribution and operation costs are presented. It is observed that in all scenarios a price increase can be expected due to the lower heat densities. The average price increase lies between 23% and 27% for all the case studies, except Milan, where the average price increase is at ca. 40%. For the scenarios with lower demand reductions and high connection rates, a price increase between 12% (Warsaw) and 26% (Milan) is expected.
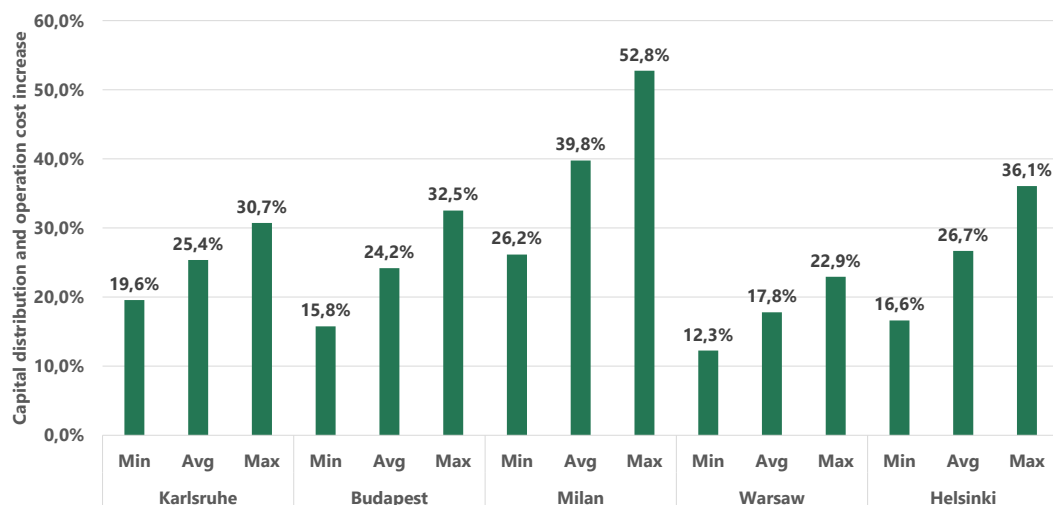
Figure 19. DH capital distribution and operation costs development

Despite the expected increase in DH prices, maximizing the connection rates in the identified DHR leads to lower total costs of heat supply in comparison to the scenarios without any DH network. Figure 20 presents the total costs of heat supply in Milan in 2050. In all scenarios, higher shares of DH lead to lower total costs of heat supply. In the scenario variations with CR of 95%, high DH shares of more than 80% can be achieved. Although these high shares might be economically feasible, it will be very hard to achieve them since the current DH share is about 10%.

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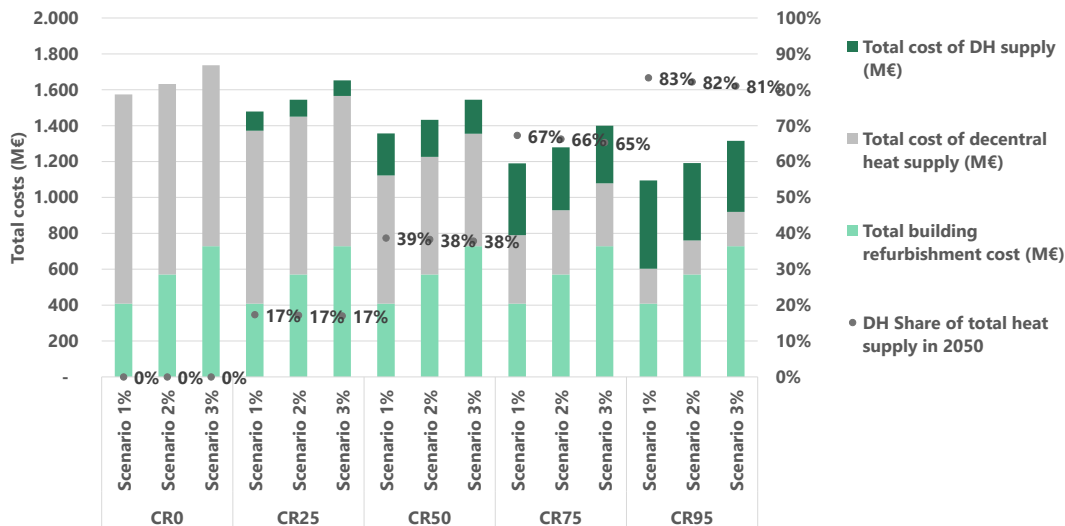
Figure 20. Total costs of heat supply in Milan for the modelled scenarios and varying DH connection rates (CR) within the suitable DHR

Figure 21 presents the total costs of heat in Helsinki (left) and Warsaw (right) in 2050. In both case studies if the restriction of 25 GWh/km² as a suitable DHR is applied, it reduces the share of DH supply below the current level. By reducing this restriction and including regions with lower heat density, higher shares for slightly higher costs can be achieved. Nevertheless, in the case study of Helsinki this would still lead to lower shares of DH supply of about 80%, compared to the current one of 92%. For the case study of Warsaw, without the restriction, about 83% of the total heat demand can be supplied by DH, which is slightly higher than the current share of 80%. Although higher DH shares can certainly be reached, in the analysed scenario worlds with reduced heat demand densities this would lead to high total cost, and it cannot be justified from an economic perspective.
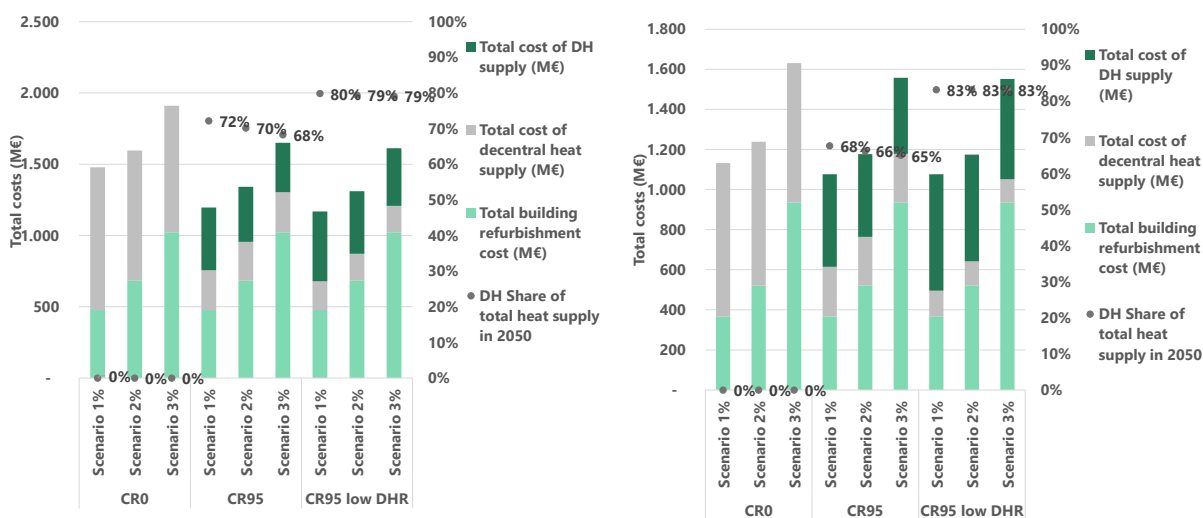
Figure 21 Total costs of heat supply in 2050 in Helsinki (left) and Warsaw (right) for the modelled scenarios and varying DH connection rates (CR) within the suitable DHR

Discussion and conclusion

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The analysis shows that DH networks are compatible with future scenarios with high refurbishment rates and deep building retrofits under different European climate conditions and city typologies. The span of the analysed scenarios varies between average 1% refurbishment rate, which represents the current status-quo, a 2% refurbishment rate, which is the goal of the EU Renovation Wave initiative (European Commission 2020) and goes up to a 3% refurbishment rate, which could be observed as an extreme. Even in the scenarios with very high refurbishment rates of 3%, a high percentage of the built-up area between 23% and 68%, depending on the city typology, are within suitable DHR with at least 25 GWh/km² annual heat density.

Due to the future reduced heat densities, an average increase of the DH cost between 14% to 35% can be expected, depending on the scenario and case study. Nevertheless, maximizing the DH CR in the identified DHR leads to lower total costs of heat in almost all the analysed case studies. The share of DH, which can be supplied in a cost-effective manner varies between 49% (Karlsruhe) and 83% (Milan). Although more case studies and typologies for smaller cities need to be analysed, it is to be expected that for smaller cities with low population and heat densities such as Karlsruhe, the share of DH, which can be supplied in a cost-effective manner, will be much lower in comparison to the larger cities with more densely populated built-up areas. For those cities with already high shares of DH, such as Warsaw and Helsinki, it might be reasonable to reduce the network in some areas with future low heat demand, which would reduce the share of DH in the total heat supply.

Natural gas and other fossil fuels play a major role in the current heat supply fuel mix in all the analysed case studies. Although it is expected that hydrogen and synthetic fuels will play an important role in assisting many sectors in their sustainable energy transition, replacing such a large share of fossil fuels with synthetic ones, would most certainly drastically increase the total cost of heat supply in the building sector as well, since the production of synthetic fuels is still associated with very high costs. Technology learning curves, cost development, production location, type of power generation, etc. are some of the factors influencing the synthetic fuels future prices and it is very unlikely to expect end-user prices below 200 €/MWh in 2050, which is several times more expensive than what households and other actors in the building sector currently pay for their fossil fuel space heating related consumption. Such high energy costs could lead to an increase in the share of population that cannot afford to heat their homes sufficiently and aggravate the energy poverty in the EU. Investment in buildings' envelope energy efficiency measures and connecting more buildings to DH could act as a safeguard against such high future prices and reduce the risk of energy poverty. One of the major strengths of the DH networks is the ability to combine several heat sources such as fossil/ synthetic fuels, geothermal heat, large-scale solar thermal, heat pumps, industrial excess heat etc. and hence, balance the impact of high fuel prices.

To ensure that in 2050 a climate neutral and economic heat supply of the building stock is available, a strategic approach on a municipal level is necessary. Municipal heat planning activities can ensure that the EE1st principle is applied properly, which will lead to lower total costs of heat and reduce the risk of energy poverty. As a reoccurring activity, it can monitor the development of fuel prices and react promptly if the energy transition is not on track to reach its sustainability targets. Additionally, it will improve the knowledge and data quality of the current building stock, which would lead to more accurate models and scenario results.

(III)   Heat pumps: Efficiency, CO₂ emissions and the value of flexible heat pumps

CASE STUDY #3	Heat pumps: Efficiency, CO₂ emissions and the value of flexible heat pumps			
Scope	Building types	Residential		Non-residential	
	Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
		Lighting	Process heating	Process cooling	Other
	Supply infrastructures	Power	District heating		Gas
Outline	Objective	This case study aims to identify the value of flexible heat pump operation in residential buildings where the building thermal mass is used as a heat storage			
	Methodology	A simplified building physics model of four building types was used to determine the buildings time constant and thermal inertia. Three building refurbishment packages and related U-values for each building component were considered in the model.			
	Key results	If the building thermal mass is used as a heat storage, depending on the building type, envelop, and geographical location, between 18% and 35% of the heat pump consumption can be used to provide flexibility to the power system.			

Background and objective

Electrifying space heating and hot water demand in buildings can contribute to reduction in the CO₂ emissions and provide flexibility to the power market by integrating higher shares of variable renewable energy. Imbalances in the power grid from the integration of variable renewable power plants are usually counteracted by fossil fuel power plants which provide expensive flexibility services. Power-to-heat (P2H) technologies such as heat pumps can allow flexible usage patterns by using either water-based thermal storage or the buildings thermal mass. The buildings sector represents the largest energy consumption sector in the European Union (EU) with final energy consumption in 2018 of ca. 40% (Eurostat 2020a, 2020b). Space heating, cooling, and hot water demand account to ca. 2/3 of this demand and can provide very high and predictable Demand Response (DR) capacities.

Through the Energy Efficiency Directive (2012/27/EU) (European Union 2012), the EU addressed the opening of the power markets for DR services. As an example, Article 15.8 of the Directive establishes access of the consumers to the energy markets, by requiring that regulators, transmission, and distribution system operators adjust the technical modalities to allow market participation for DR services. A study of the progress of DR in the EU in 2016 (Bertoldi et al. 2016) concludes that no Member State has succeeded in incorporating all the elements of the Directive. Despite the progress of DR services in the EU power markets in recent years, the flexibility potential, maturity of the technologies, and its cost-effectiveness are still largely unknown (Kohlhepp et al. 2019).

This case study aims to identify the value of flexible heat pump operation in residential buildings where the building thermal mass is used as a heat storage. It strives to identify the level of CO₂ emissions for heating a house in the EU27 with a heat pump and the cost saving potentials of the flexible dispatch for the

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electricity system. To do so, a simplified building physics model is used to estimate the required installed capacity of the heat pump and to identify the building thermal mass characteristics. Four residential building categories located in four cities representing the major European climate zones were selected.

Methodology

The applied methodology of this study can be summarized in five main steps, as shown in **Figure 22**. In the **first step,** four building types and three envelope refurbishment packages were modelled by using a simplified building physics model. In the **second step,** the daily mean outside air temperatures for Stockholm, Barcelona, Budapest, and Frankfurt in the year 2010 were selected. 2010 was selected as one of the coldest years in the past 30 years in Europe whereas the locations represent the four major European climate zones (PVSITES Consortium 2016). Since most of the current heat pumps in the building stock constitutes of air-air heat pumps (European Heat Pump Association 2022), the study focuses on the building thermal mass as a heat storage. To do so, in the **third step**, the building thermal time constant and inertia were calculated for each building type, refurbishment package, and location. In the **fourth step,** to forecast the heat pump market share and final energy demand until 2050, an EU27 scenario was selected. Finally, in the **fifth step**, countries were classified based on their predominant climate zone and the locations of the modelled buildings.
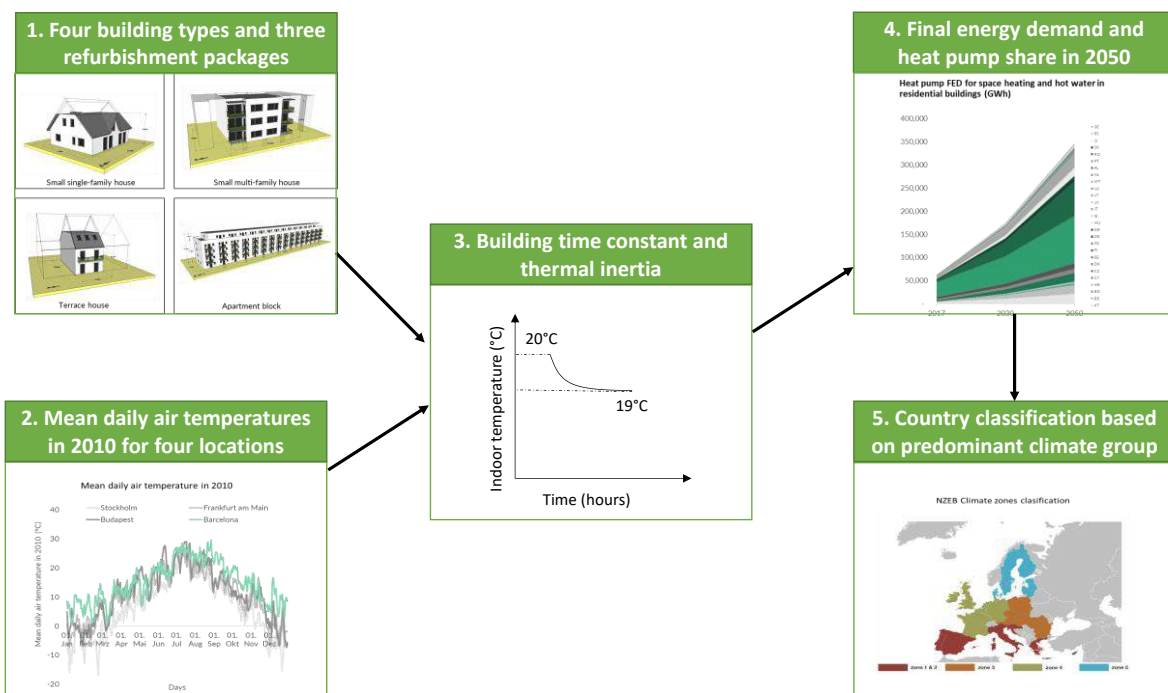
Figure 22. Overview of applied methodology for case study #3

Simplified building physics models of a small single-family house, terraced house, small multi-family house, and apartment block as presented in **Figure 23** were created. Three building refurbishment packages and related U-values for each building component were considered in the model. The renovation packages and respective U-values differ between the countries. Package 1 represents average U-values for buildings built before 1948, package 2 for buildings built after 2010, and package 3 for low-energy buildings. Although the low-energy building definition can vary between the countries, the same U-values of the building components were used on each location.
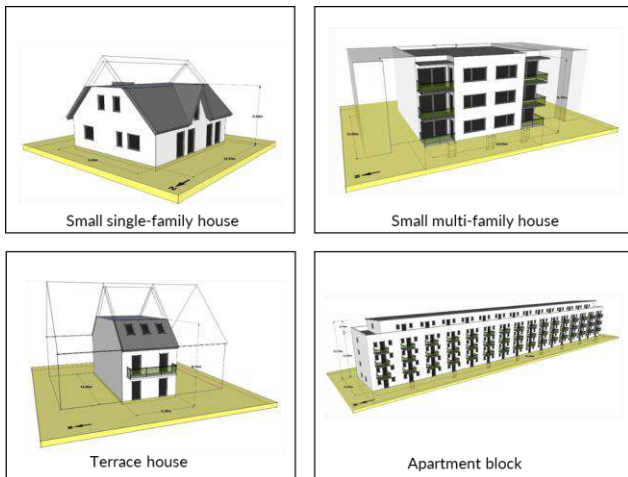
	Single -family and terraced house				Small multi-family house and apartment block		
	Germany (Frankfurt am Main)				**Germany (Frankfurt am Main)**		
U-value (W/m²K)	Package 1	Package 2	Package 3	U-value (W/m²K)	Package 1	Package 2	Package 3
Walls	1.76	0.22	0.1	Walls	1.55	0.29	0.1
Roofs	1.55	0.17	0.1	Roofs	0.98	0.23	0.1
Floors	1.23	0.26	0.1	Floors	0.83	0.32	0.1
Windows	2.8	1.2	0.8	Windows	2.9	1.2	0.8
	Sweden (Stockholm)				**Sweden (Stockholm)**		
Walls	0.6	0.18	0.1	Walls	0.6	0.18	0.1
Roofs	0.29	0.13	0.1	Roofs	0.4	0.13	0.1
Floors	0.28	0.15	0.1	Floors	0.3	0.15	0.1
Windows	2.34	1.3	0.8	Windows	3.2	1.3	0.8
	Spain (Barcelona)				**Spain (Barcelona)**		
Walls	3.98	0.48	0.1	Walls	2.46	0.48	0.1
Roofs	3.4	0.45	0.1	Roofs	2.87	0.48	0.1
Floors	1.43	0.88	0.1	Floors	1.07	0.71	0.1
Windows	4.73	3	0.8	Windows	5.1	3.37	0.8
	Hungary (Budapest)				**Hungary (Budapest)**		
Walls	0.94	0.22	0.1	Walls	1.1	0.22	0.1
Roofs	1.25	0.21	0.1	Roofs	0.54	0.21	0.1
Floors	1.04	0.44	0.1	Floors	0.75	0.22	0.1
Windows	3.5	1.5	0.8	Windows	3.5	1.5	0.8

Figure 23. Modelled building types and applied U-values for each building envelope refurbishment package
Sources: Klauß and Maas (2003); Pezzuto et al. (2018)

The building time constant was calculated based on the DIN V 18599-2 (DIN V 18599-2 2011). The higher the time constant, the longer it takes for the building room temperature to decrease, if the heat pump is turned off to provide flexibility to the power market. In **Equation 8** the calculation of the building time constant is presented, where C_w is the building's effective heat capacity and H the overall heat losses from transmission, ventilation, and infiltration (*H depends on the building envelope*). **Equation 9** presents the 'cool down' time t_z, i.e. the time after which the setpoint temperature of the setback would be reached in the case where the heat pump is turned off. In the equation τ presents the building time constant as calculated in **Equation 8**, T_T the indoor set temperature, T_N the indoor set temperature during the setback, and T_V the temperature level against which the temperature drop takes place. This temperature depends on the daily mean outdoor temperature and the refurbishment standard of the building. If the 'cool down' time for a reduction by one degree Celsius of the room temperature is shorter than 2 hours, the heat pump can provide flexibility only for one hour at a time. If the 'cool down' time is longer than 2 hours, the heat pump can provide flexibility for two hours at a time. It is assumed that the heat pump can be turned off maximum 3 times in one day. Hence, the total flexibility can vary maximum between 3 and 6 hours in one day. **Figure 24** presents the logic behind using the building thermal mass as a heat storage providing flexibility to the power market related to the time constant and the respective 'cool down' times according to the indoor temperature.

$$\tau = \frac{C_w}{H} \ (hours)$$

Equation 8

$$t_z = \tau * \ln\frac{T_T - T_V}{T_N - T_V} \ (hours)$$

Equation 9

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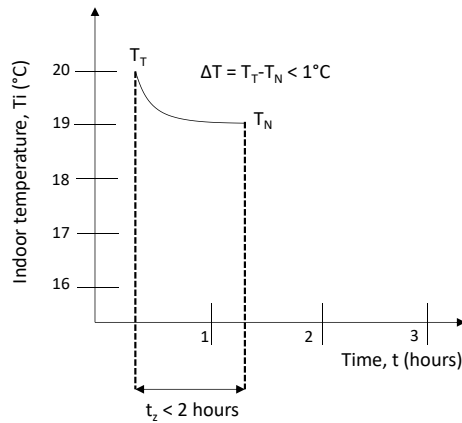
If **t_z < 2** hours, then flexibility provided at maximum 3 hours per day (3*1 hour each)
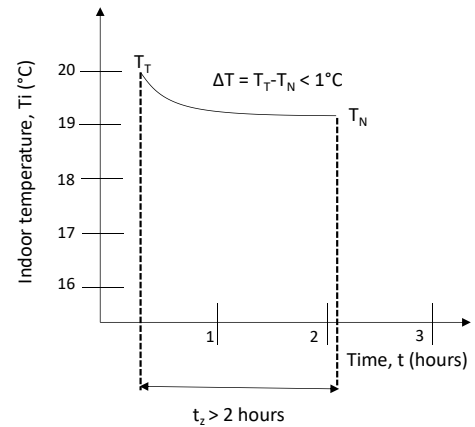
If **t_z > 2** hours, then flexibility provided at maximum 6 hours per day (3*2 hour each)

Figure 24. Calculation logic of the maximum flexibility provided by the building thermal mas depending on the 'cool down' time according to the indoor temperature

In the considered scenario (ENEFIRST 2022b), a reduction of the current space heating and hot water demand in the EU27 from 1,531 TWh in 2017 to 757 TWh in 2050 is foreseen. The space cooling demand increases from the current 13.6 TWh in 2017 to 42.3 TWh in 2050. The heat pumps share of the space heating and hot water demand increases from the current 4.1% (63 TWh) to 45.8% (346 TWh) in 2050. **Figure 25** presents the considered development of heat pump final energy demand for space heating and hot water (on the left) and space cooling (on the right) in residential building in the EU27 for the period between 2017 and 2050.
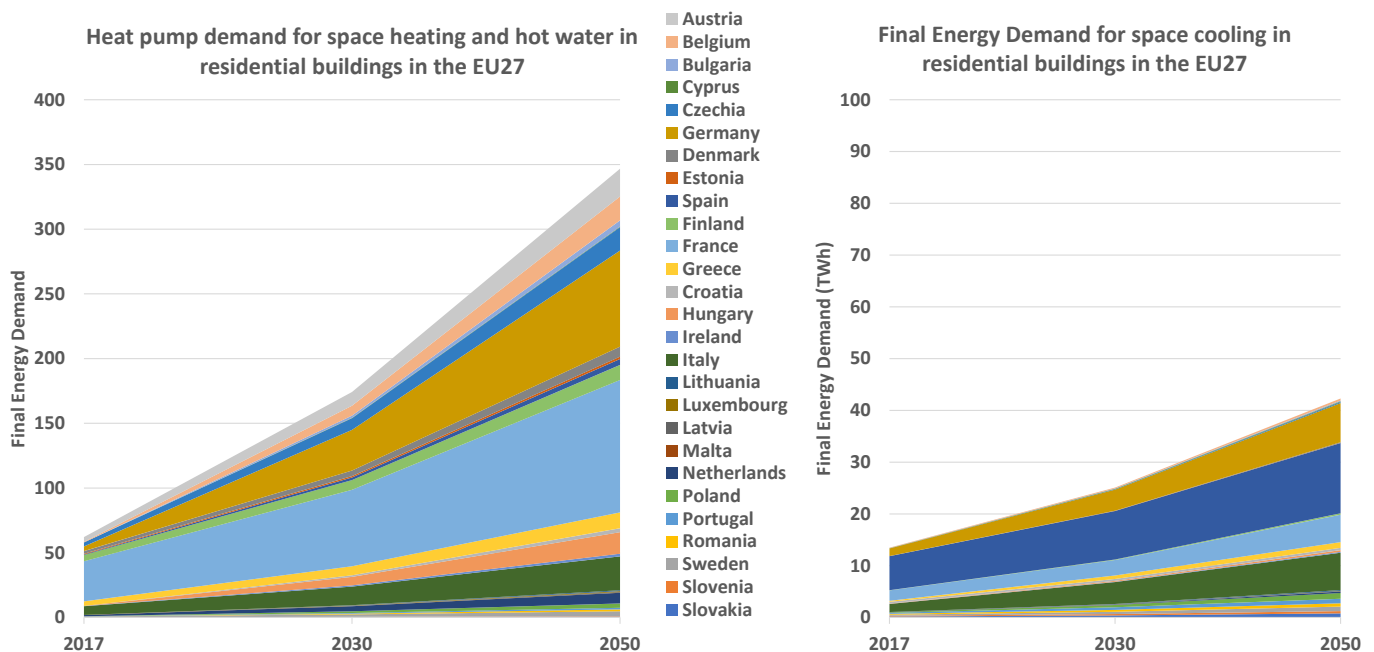
Figure 25. Heat pump final energy demand for space heating and hot water in residential buildings in the EU27 (left) and final energy demand for space cooling (right)
Source: ENEFIRST (2022b)

Figure 26 presents the considered daily mean temperatures in 2010 for the analysed locations (left) in and the NZEB Climate zones classification (right). The four selected locations (Stockholm, Frankfurt, Budapest, and Barcelona) represent the four major European climate zones. Although within the countries there can be several climate zones, to simplify the calculation, the NZEB climate zones classification was applied.

The countries in Zone 1&2 are represented by the modelled buildings in Barcelona, Zone 3 countries are represented by Budapest, Zone 4 countries by Frankfurt, and Zone 5 countries by Stockholm. It is assumed that what applies for the analysed cities can be transferred on a national level in the countries which belong to the respective climate zones.
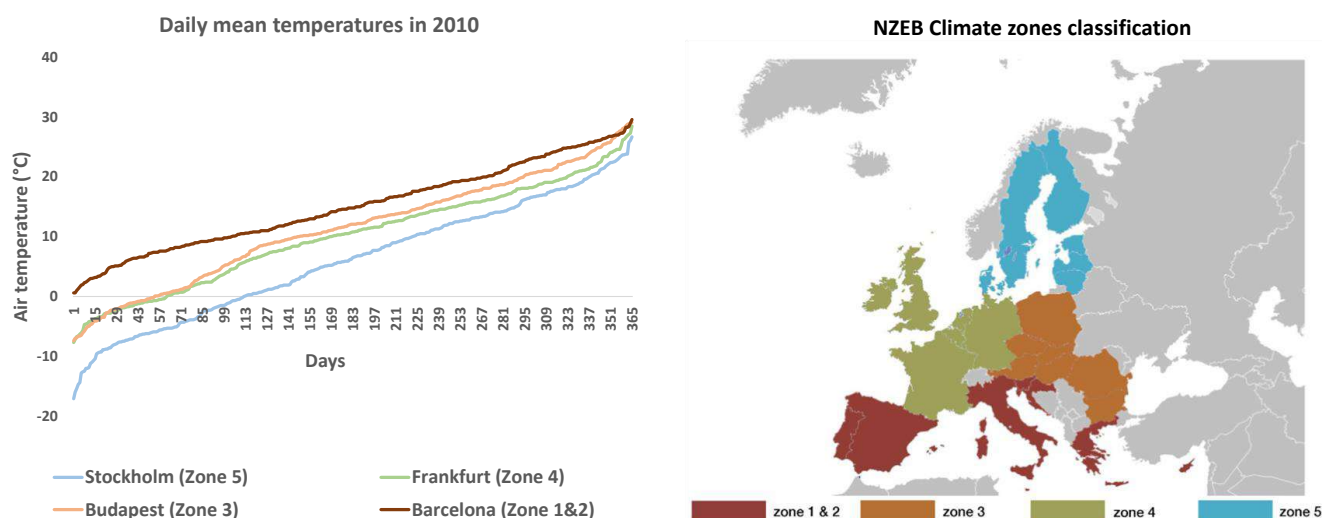
Figure 26. Daily mean temperatures in 2010 (left) and NZEB country climate zones classification
Source: Klein et al. (2002); PVSITES Consortium (2016)

Results

Figure 27 presents the average annual heat capacities (left), the building time constant (middle), and the average indoor temperature cool down time (right) for the analysed building types, renovation rates, and considered building locations and respective daily mean temperatures. The mean value of the average cool down time varies between 2 hours for single-family houses and 3.7 hours for apartment blocks. Since very large shares of the buildings in the countries are not or only partially refurbished, it must be noted that these values only represent the 48 modelled buildings presented in Figure 23 (4 buiding types * 3 renovation packages * 5 cities) and are not representative of the whole building stock.
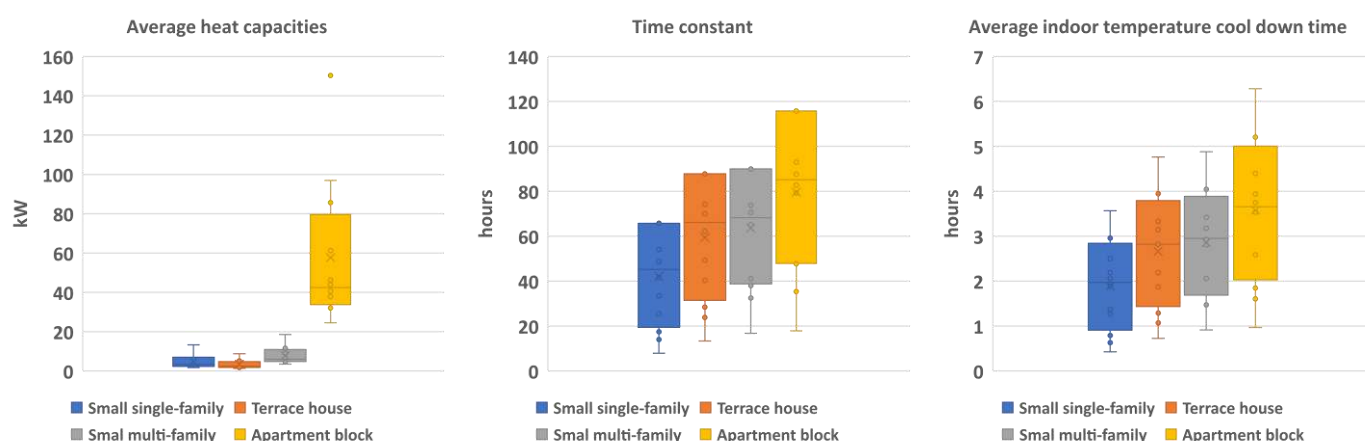
Explanation: box = interquartile range (IQR); middle line in the box = median value; x = mean value; circle = outlier; whiskers = minimum and maximum value

Figure 27. Average annual heat capacities (left), building time constant (middle) and average indoor temperature cool down time (right)

Figure 28 presents the share of final energy demand for space heating and hot water in the analysed EU scenario. In the EU27 the heat pump share increases from ca. 3.6% in 2017 to 39.3% in 2050. In most of the countries a drastic increase in the heat pump share between 2030 and 2050 is expected.

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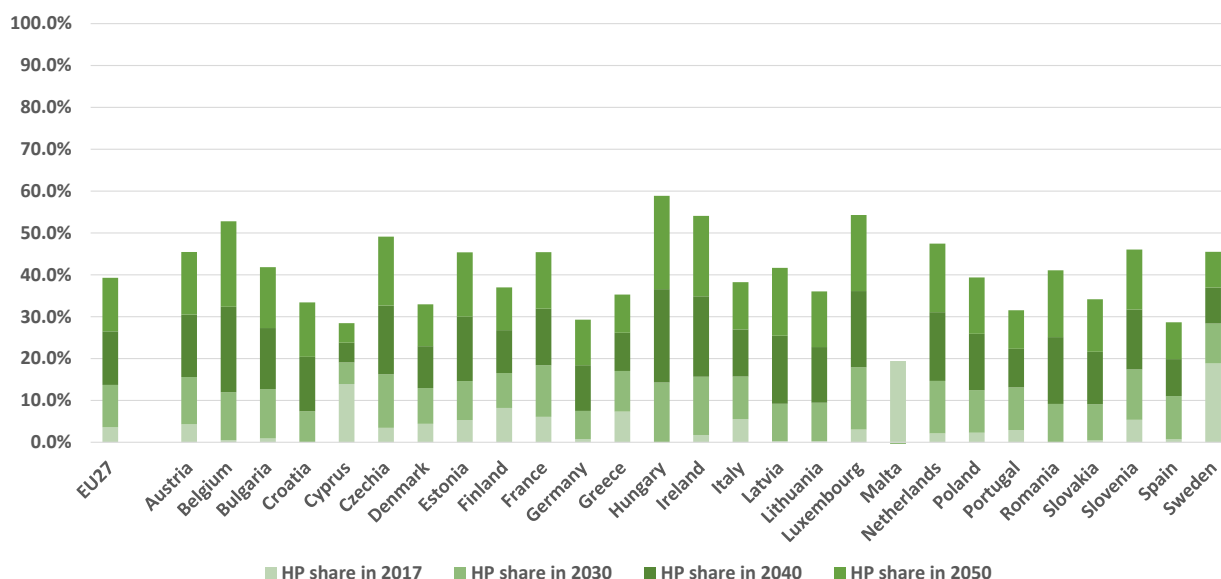
Figure 28. Heat pump share of the final energy demand for space heating and hot water in the analysed EU scenario

By using the building thermal mass as a heat storage, depending on the building type, envelop, and geographical location, between 18% and 35% of the heat pump consumption can be used to provide flexibility to the power system. **Figure 29** presents the total adjustable electrical energy (left) and adjustable power (right). For the analysed scenario an estimated flexibility potential between 26.9 TWh and 32.01 TWh of the electricity consumption providing 8.4 GW to 10.03 GW flexible power capacity were identified for the EU27 in the year 2050. 'Low potential' means an average 18% of the heat pump demand to be flexible, while 'high potential' assumes an average 26% of the total building heat demand consumption is flexible.
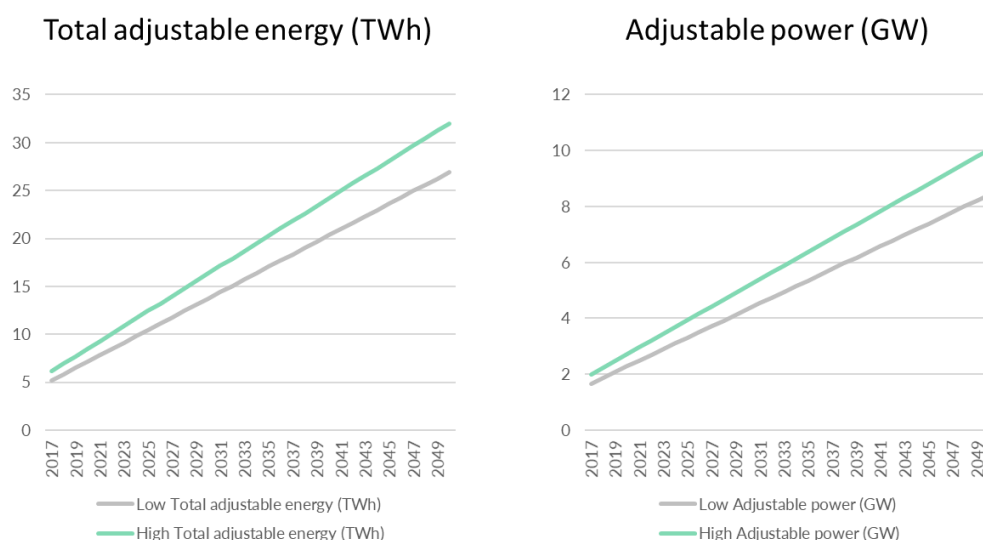
Figure 29 The total estimated adjustable electrical energy (left) and adjustable power (right) in the EU27 residential buildings

The estimated revenues and the total cost of the flexibility potential for one MW installed capacity are presented in **Table 6**. The estimation of the revenues relies upon an average saved electricity costs across the EU27 (European Commission et al., 2022) and an average full load hours based on the average heating degree and cooling degree days for the period between 2000 and 2020 (Eurostat 2022e). By

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multiplying the average full load hours and the saved electricity costs, annual revenues of around 7,200 € /MW can be expected.

Table 6. Estimated revenues and total cost of ownership

Estimated revenues		Estimated total cost of ownership	
EU Average HDD (2000-2020)	3,065	Hardware: Control box	0 – 850 €/building
EU Average CDD (2000-2020)	90	Software: Network connection	0 – 170 €/building
Approx. maximum flexibility	6 h/ day	Interest rate	2%
Average full load hours	1,113 hours	Annuity	20 years
Average saved electricity costs	6.46 €/MWh	Average heat pump capacity	10 kW$_e$/building
Annual revenue	**7,189 €/MW**	**Total cost of ownership**	**1,200-6,200 €/MW**
Estimated savings = 1,000 – 6,000 €/MW			

The estimated total cost of ownership consider both hardware and software costs (European Commission et al. 2022). In the hardware cost, an additional control box to connect the heat pump and the utility is foreseen. Whereas the software costs consider the network connection and the administrative costs. Since most of the newly sold heat pumps are so called „smart grid ready" (Bundesverband Wärmepumpe (BWP) e.V. 2022) and there are on-going pilot projects which aim to connect the residential heat pump to the utility without a control box, the total cost of ownership are in the range of 1,200 €/MW (only software related costs) and 6,200 €/MW (software and hardware). An average heat pump electric capacity of 10 kW$_{el}$ is foreseen, meaning that 100 residential heat pumps need to be connected to reach 1 MW of flexibility.

Although some margin opportunity from flexible residential building heat pumps between 1,000 – 6,000 €/MW is calculated, the profitability will strongly depend on the investments in the smart local grid substations, fees, taxes, and other additional costs which might reduce the calculated savings.

Figure 30 shows the CO_2 intensity of electricity consumption in 2019 per country (Hein and Buck 2020) and the CO_2 emissions savings of using heat pumps instead of condensing natural gas boilers. For the calculation it is assumed that the heat pumps have an average COP of 2.5 whereas the condensing natural gas boilers have an average efficiency of 98%. Higher emissions from using heat pumps instead of condensing natural gas boilers under these conditions can be observed in several EU Member States such as Estonia, Poland, and Cyprus where the heat pump related CO_2 emissions are higher by 30%, whereas for Czechia, Greece, and Bulgaria the higher heat pump related emissions are much lower between 1% and 6%.

Figure 30. CO$_2$ intensity of electricity consumption in 2019 | CO2 emissions savings from using heat pump (average COP of 2.5) in comparison to condensing natural gas boilers (205 g/kWh)
Sources: own representation based on Hein and Buck (2020)

Discussion and conclusion

If the building thermal mass is used as a heat storage, depending on the building type, envelop, and geographical location, between 18% and 35% of the heat pump consumption can be used to provide flexibility to the power system. The larger the building, the longer it takes to cool down. Although, apartment blocks offer higher flexibility than single-family houses per floor area, the room temperature within the apartments will differ. Hence, it must be noted that some apartments will cool down much faster than others within the same apartment block (e.g. apartments in the corners have more walls exposed to the outdoor temperature). This effect has not been considered in this analysis.

For water-based systems, wherever technically feasible, the addition of a thermal water storage could potentially increase the share and provide even higher flexibilities. The focus of this study lies only on the utilisation of the building thermal mass. The rationale behind this decision is to consider the flexibility potential of air-to-air heat pumps which constitutes the largest market share of the currently installed heat pumps.

Aggregated on an EU27 level in 2050, based on the analysed EU scenario and future heat pump share, flexibility potential between 26.9 TWh and 32.01 TWh of the electricity consumption providing 8.4 GW to 10.03 GW flexible power capacity were identified. Replacing condensing natural gas boilers with air-air heat pumps brings substantial CO$_2$ emissions savings in most of the Member States (based on the CO$_2$-intensity of electricity consumption in 2019). This should improve in the future with the growing share of RES for electricity. Some estimated cost saving potential from flexibility in residential heat pumps is expected, although it strongly depends on fees, taxes, and other additional investments in local grid substations.

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(IV)   Strategic energy planning in commercial areas

CASE STUDY #4	Strategic energy planning in commercial areas: balancing local heat supply with building retrofit measures			
Scope — Building types	Residential		Non-residential	
Scope — Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
	Lighting	Process heating	Process cooling	Other
Scope — Supply infrastructures	Power	District heating		Gas
Outline — Objective	Exploring the potentials of thermal retrofits for commercial buildings in reducing the need for individual heat supply, distributed electricity generation, and district heating and cooling infrastructure while reaching equivalent levels of emission reductions.			
Outline — Methodology	Definition of one archetype commercial area of 20 buildings with country-specific weather conditions and technology cost. Use of open-source optimization model for analysing system technology configurations and their cost-effectiveness.			
Outline — Key results	Advanced building retrofits for commercial areas can cost-effectively reduce the need for investments in and operation of heat supply, networks and storage units. Light retrofits are not cost-effective in light of the high fixed cost for retrofit works.			

Background and objective

The commercial and public services sector is responsible for a significant share of 13.4% of final energy consumption in the EU (Eurostat 2022a). It consists of commercial buildings like offices, restaurants and supermarkets as well as public buildings like schools and administration buildings. Much of this energy is used in existing buildings that are generally characterized by low energy performance (Esser et al. 2019). Meanwhile, there is the urgent need to decarbonise energy used in service sector buildings with a view to the EU's commitment of net-zero greenhouse gas (GHG) emissions by 2050 (European Union 2021). In this context, thermal retrofits of buildings reduce the need for investments and operation of individual heat supply (e.g. biomass boilers), distributed generation (e.g. photovoltaics), networks (e.g. district heating), utility-scale generation (e.g. heat pump), and storage (e.g. seasonal heat storage). As the EE1st principle suggests, end-use energy efficiency measures and other demand-side resources should be screened and adopted whenever they provide greater value than supply-side resources (ENEFIRST 2020b).

Urban planning authorities as well as investors require a comprehensive view of net-beneficial opportunities to improve the performance of buildings at district scales against investments in energy generators, networks, and storage. In technical terms, the study of optimal energy systems configurations is a multi-scale and multi-objective problem that requires modelling tools with high spatiotemporal resolution to account for variable patterns of building demand and resource availability. Previous research in this context has demonstrated advanced modelling techniques. Harrestrup and Svendsen (2014) show that for a district heating system in the Copenhagen area, it is slightly more cost-beneficial to invest in comprehensive building retrofits before investing in new renewable district heating supply (waste, geothermal energy). Delmastro and Gargiulo (2020) demonstrate that demand- and supply-side resources reciprocally boost each other, where demand reductions facilitate the transition to cleaner heat, not only by reducing peak capacity but also by proving increased flexibility (e.g. improved building thermal mass, see case study #4).

In sum, existing studies emphasize the need for considering both demand- and supply-side resources in the optimisation of local energy system design and operation. At the same time, this existing literature features two major shortcomings. For one thing, the vast majority of studies analyses only residential buildings while disregarding buildings in the commercial and public services sector. The latter are characterized by more heterogeneous building properties (e.g. wall types) and occupancy behaviour (e.g. lighting schedules), as well as poorer data availability which, overall, tends to make their analysis more challenging than in the case of residential buildings. For another, studies tend to provide evidence on single case study areas which impedes the generalizability of model-based outcomes and conclusions across regions or countries.

Against this background, the objective of this case study is to provide insights on the potentials and constraints that building retrofits can provide in the design of urban energy systems in commercial areas. It explores the synergies and trade-offs between five types of technology or resource options: (a) thermal retrofit measures for different building components (e.g. triple glazing of windows); (b) individual heat supply (e.g. biomass boilers); (c) distributed electricity generation (e.g. photovoltaics); (d) centralised district heating and cooling (DHC) networks with corresponding supply, network and storage infrastructure; and (e) waste heat integration (e.g. from data centres).

For generalization purposes, one archetypical commercial area is examined for three countries Germany (DE), Hungary (HU) and Spain (ES). This area is inspired by real-life buildings and topography. It is characterized as a municipally owned office park erected in the 1970s consisting of offices, canteens, laboratories, server rooms and schools. Across the three countries, the area differs in terms of weather conditions (ambient temperature, solar radiation, etc.), technology costs (e.g. roof insulation), and energy carrier prices (e.g. grid electricity). Three scenarios are analysed per country that represent different levels of ambition and constraints for building retrofits. Based on these given retrofit packages, a multi-objective energy system optimization model with high spatiotemporal resolution is used to determine technically feasible combinations of generators, networks and storage along a cost-optimal path towards significant reductions in greenhouse gas emissions. The outcomes of this analysis can help urban planning authorities and investors to assess the order of magnitude of net-benefits that building retrofits can deliver in reaching the same outcomes as energy supply solutions in the context of the EE1st principle.

Methodology

The case study objective requires a detailed characterization of building retrofits, along with the spatiotemporal and temperature-dependent patterns of energy use and energy supply via boilers, heat networks, storage units and other supply-side resources. Before turning to the modelling approach, this section specifies the case study area as well as the building retrofit measures and scenarios investigated. The archetype case study area is a municipally owned office park of 25 ha erected in the 1970s that is inspired by the real-world office park 'Technologiepark Karlsruhe' in Germany.[10] It consists of 21 buildings between 1 and 7 floors. A variety of companies in the services sector occupies the site with an overall use-mix in terms of gross floor area of 75% offices, 12% labs, 7% schools, 6% canteens, and 1% server rooms (**Figure 31**). Residential uses are not considered in the case study area.

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[10] Location: 49°1'14.3832"N 8°26'31.0776"E

No.	Type	Conditioned floor area (m² | %)	Gross floor area (m² | %)
#1	● Office	25,948 m² | 24.2%	37,972 m² | 23.0%
#2	● Lab	11,955 m² | 11.2%	19,438 m² | 11.8%
#3	● Office	8,653 m² | 8.1%	14,070 m² | 8.5%
#4	● School	6,647 m² | 6.2%	10,808 m² | 6.5%
#5	● Canteen	6,571 m² | 6.1%	10,017 m² | 6.1%
#6	● Office	4,878 m² | 4.6%	6,798 m² | 4.1%
#7	● Office	4,876 m² | 4.5%	6,795 m² | 4.1%
#8	● Office	4,456 m² | 4.2%	6,793 m² | 4.1%
#9	● Office	4,855 m² | 4.5%	6,767 m² | 4.1%
#10	● Office	4,327 m² | 4.0%	6,596 m² | 4.0%
#11	● Office	4,212 m² | 3.9%	6,420 m² | 3.9%
#12	● Office	3,209 m² | 3.0%	5,870 m² | 3.6%
#13	● Office	3,259 m² | 3.0%	5,299 m² | 3.2%
#14	● Office	2,690 m² | 2.5%	4,375 m² | 2.6%
#15	● Office	2,655 m² | 2.5%	4,317 m² | 2.6%
#16	● Office	2,606 m² | 2.4%	4,237 m² | 2.6%
#17	● Office	1,758 m² | 1.6%	2,859 m² | 1.7%
#18	● Office	1,060 m² | 1.0%	1,723 m² | 1.0%
#19	● Office	888 m² | 0.8%	1,444 m² | 0.9%
#20	● Server room	844 m² | 0.8%	1,373 m² | 0.8%
#21	● Office	839 m² | 0.8%	1,364 m² | 0.8%
		107,186 m² | 100.0%	165,337 m² | 100.0%

Figure 31. Characterization of case study area

Three scenarios are developed per country, each reflecting different building retrofit packages for reducing building energy consumption, including insulation of roofs, walls, floors and window replacement (**Table 7**).

Table 7. Renovation packages per scenario
Source: TABULA/EPISCOPE (2017), Fernández Boneta (2013)

	Scenario	Retrofit measures by building component | U-value | Specific cost			
		Roof	Wall	Floor	Windows
DE	DE_Existing	Concrete ceiling with 5 cm insulation 0.51 W/(m²K) | 0.0 (EUR/m²)	Concrete panels 1.10 W/(m²K) | 0.0 (EUR/m²)	Concrete base with 2 cm insulation 0.77 W/(m²K) | 0.0 (EUR/m²)	Plastic frame with double glazing 3.00 W/(m²K) | 0.0 (EUR/m²)
	DE_Standard	+12 cm insulation 0.19 W/(m²K) | 159.3 (EUR/m²)	+12 cm insulation 0.23 W/(m²K) | 91.7 (EUR/m²)	+8cm insulation 0.28 W/(m²K) | 53.4 (EUR/m²)	Double glazing, argon filled, low emissivity 1.30 W/(m²K) | 313.1 (EUR/m²)
	DE_Advanced	+30 cm insulation 0.09 W/(m²K) | 177.7 (EUR/m²)	+24 cm insulation 0.13 W/(m²K) | 110.4 (EUR/m²)	+12 cm insulation 0.21 W/(m²K) | 77.4 (EUR/m²)	Triple glazing, argon filled, low emissivity 0.80 W/(m²K) | 354.0 (EUR/m²)
ES	ES_Existing	Wooden joints 1.92 W/(m²K) | 0.0 (EUR/m²)	Cavity wall 1.33 W/(m²K) | 0.0 (EUR/m²)	Wooden joints 1.13 W/(m²K) | 0.0 (EUR/m²)	Single glazing 5.70 W/(m²K) | 0.0 (EUR/m²)
	ES_Standard	+2 cm insulation and gravel 0.60 W/(m²K) | 103.3 (EUR/m²)	+3 cm insulation 0.64 W/(m²K) | 73.8 (EUR/m²)	No improvement 1.13 W/(m²K) | 0.0 (EUR/m²)	Double glazing 1.84 W/(m²K) | 496.6 (EUR/m²)
	ES_Advanced	+6 cm insulation and greenery 0.15 W/(m²K) | 124.6 (EUR/m²)	+5 cm insulation 0.42 W/(m²K) | 86.3 (EUR/m²)	No improvement 1.13 W/(m²K) | 0.0 (EUR/m²)	Triple glazing 0.80 W/(m²K) | 580.0 (EUR/m²)
HU	HU_Existing	Concrete ceiling 0.44 W/(m²K)	Concrete panels 0.70 W/(m²K) | 0.0 (EUR/m²)	Concrete base 0.48 W/(m²K) | 0.0 (EUR/m²)	Wooden frame with double glazing 2.50 W/(m²K) | 0.0 (EUR/m²)
	HU_Standard	+10 cm insulation 0.21 W/(m²K) | 104.0 (EUR/m²)	+5 cm insulation 0.37 W/(m²K) | 56.6 (EUR/m²)	+10 cm insulation 0.24 W/(m²K) | 53.4 (EUR/m²)	Double glazing, argon filled, low emissivity 1.60 W/(m²K) | 212.5 (EUR/m²)
	HU_Advanced	+24 cm insulation 0.12 W/(m²K) | 117.0 (EUR/m²)	+16 cm insulation 0.18 W/(m²K) | 67.3 (EUR/m²)	+20 cm insulation 0.16 W/(m²K) | 77.4 (EUR/m²)	Triple glazing, argon filled, low emissivity 1.00 W/(m²K) | 275.0 (EUR/m²)

- In the **EXISTING scenarios**, municipal decision-makers opt for maintaining the relatively poor thermal performance of the building stock from the 1970s and to only upgrade the energy supply system of conversion, distribution and storage towards significantly lower greenhouse gas emissions. This represents a situation where the EE1st principle is not taken into account since building retrofits as a significant demand-side resource are essentially disregarded from the system planning process.
- The **STANDARD scenarios** represent a situation where moderately ambitious retrofit packages are applied to the building stock. In view of split incentives, lack of awareness and other imaginable barriers, decision-makers are selecting conservative refurbishment options that effectively lead to energy savings and which also reduce the capacities needed and operation of supply-side resources. As such, some consideration is given to having a balance of demand- and supply-side resources.

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- Finally, the **ADVANCED scenarios** consist of highly ambitious renovation packages for the building envelopes. Roofs, walls, floors are equipped with thick layers of insulation that reduce the thermal transmittance (U-value) and thus lead to significant energy savings. In response, the need for boilers, networks, storage units and other supply-side resources is minimized. These scenarios thus represent a situation where the EE1st principle is thoroughly taken into account by all decision-makers.

Renovation packages and corresponding U-values (W/m^2K) are defined and characterized based on the TABULA building typology (TABULA/EPISCOPE 2017). While relevant in practice, this analysis does not consider the dedicated potentials of different façade surface finishes, shading, green façade and other energy modulation measures (Sarihi et al. 2021). The costs of retrofit measures ($EUR/m^2_{component}$) are based on country-specific data collected in the ENTRANZE project (Fernández Boneta 2013). Construction price indices (Eurostat 2022b) are used to refer this data to EUR$_{2020}$ price levels.

To implement these scenarios, the City Energy Analyst (CEA) model is used (Happle et al. 2020; Fonseca et al. 2016; Fonseca and Schlueter 2015). CEA is a python-based open-source model framework for the analysis and optimization of energy systems in neighbourhoods and city districts. Based on geo-referenced data of neighbourhoods and hourly temporal resolution, it allows to analyse building energy demand, solar radiation as well as the energy, carbon and financial features of building retrofit and infrastructure options. All simulations in this case study are carried out using CEA version 3.27.

CEA uses a building-by-building simulation approach to compute the hourly temperature and energy requirements for space conditioning, domestic hot water and electricity in buildings (Happle et al. 2020; Fonseca and Schlueter 2015). Starting from a set of generic building archetypes, each building is modelled using its real location and geometry with user-defined construction properties (e.g. roof thermal properties) and occupant-building-interactions (e.g. lighting schedules). The model calculates energy needs based on an hourly single-zone resistance-capacitance model as a function of (a) heat losses from ventilation and transmission and (b) heat gains from occupancy, solar radiation and electrical appliances. The effective indoor temperature of buildings is set to 21°C. Solar heat gains of buildings are based on a dedicated engine that takes into account mutual shading between buildings.

Renewable energy potentials are endogenously calculated in CEA using dedicated physical models (Fonseca et al. 2016). This includes solar potentials (rooftop solar collectors, photovoltaic and photovoltaic thermal panels), ambient heat (ground source and water source heat pumps) and waste heat (servers, industrial processes, sewage). Aside from renewable energy sources, the model also represents condensing boilers (biogas, natural gas), combined heat and power technologies (combined gas cycle turbine, fuel cells), thermal storage (daily and seasonal thermal storage), substations and heat exchangers, circulation pumps, as well as chillers and cooling tower for cooling purposes. The representation of district heating and cooling networks is a key feature of CEA. These networks can integrate a variety of sources and sinks of heat (e.g. ambient heat). Layout and diameter of possible thermal networks are determined automatically in the model based on a minimum spanning tree algorithm and mass flow simulation.

The extent to which these resource potentials are adopted is subject to a multi-objective optimization problem in CEA (Fonseca et al. 2016). Rather than determining a single optimum in terms of least costs, the model calculates a set of technically feasible system configurations of different production, network and storage units along a Pareto-optimal frontier of minimum total annual costs and GHG emissions. The model uses a 'greenfield' approach, i.e. it considers a single target year and does not explicitly consider technology stock turnover as well as existing and written-off assets in the case study area. Total annual costs are defined as the sum of capital costs, operation and maintenance, as well as fuel costs. This multi-objective and multi-period (hourly) optimization problem is subject to constraints of resource availability, technology operation and network configuration and is formulated as a mixed-integer non-linear program.

The evaluation perspective taken is that of a benevolent municipal planner with unrestricted leverage on investment decisions in buildings and energy supply. As such, the optimization allows the trade-off between alternative system configurations in terms of costs and emission reductions to be made explicit.

The model essentially requires four types of input data (Fonseca et al. 2016; Fonseca and Schlueter 2015):

- **Building properties data** | CEA comes with a set of default time series and schedules of occupancy, minimum ventilation rates, and temperature and humidity set points for buildings. It also includes standard specific hourly consumption values for appliances, lighting, server-rooms and cold-rooms. This data is used together with the country- and scenario-specific building envelope data described above.
- **Weather data** | Location-specific time-series of ambient temperature, relative humidity, and solar transmissivity are needed. Weather files used for the simulations represent a typical meteorological year for Frankfurt (DE), Budapest (HU) and Málaga (ES) and are obtained from EnergyPlus (2022).
- **Technology data** | Energy conversion and distribution technologies are characterised by various techno-economic metrics. To account for national characteristics beyond the default numbers in CEA, data on technology conversion efficiencies [%], technical lifetimes [a] and specific costs [EUR/MW] are obtained from the country-specific datasheets in Kranzl et al. (2021).[11] Consumer prices [EUR/kWh] as well as carbon intensities [gCO_2-eq/kWh] for electricity, natural gas and biomass are derived from the EU-wide scenario analysis in ENEFIRST (2022b).
- **Topography data** | CEA provides geo-referenced data of buildings and their surroundings, based on the geographic database OpenStreetMap. This includes building properties such as footprint area, height, window to wall ratios, and year of construction according to the case study area described above. As such, the level of energy service demand in terms of conditioned floor space is the same across scenarios and countries. CEA also endogenously provides information about sewage lines, roads, and characteristics of soil and water bodies such as type and stratification, which are relevant for the estimation of resource potentials in the model.

Results

Figure 32 presents the final energy demand by end-use for the sum of the buildings in the case study area. Across the countries, thermal retrofit measures lead to significant reductions in final energy demand for space heating and also cooling as transmission and ventilation losses are lowered. In the case of DE, the retrofit packages reduce space heating demand by -59.2% (DE_STANDARD) and -73.3% (DE_ADVANCED). Demand for appliances slightly increases due to mechanical ventilation. Sanitary hot water demand is nearly the same across countries and scenarios. In sum, the retrofit measures reduce overall final energy demand by 27-33% (DE), 11-19% (ES), and 20-33% (HU).

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[11] Note that CEA endogenously determines the coefficient of performance (COP) of water source and ground source heat pumps as a function of the temperature of heat sources and sinks (Fonseca et al. 2016).
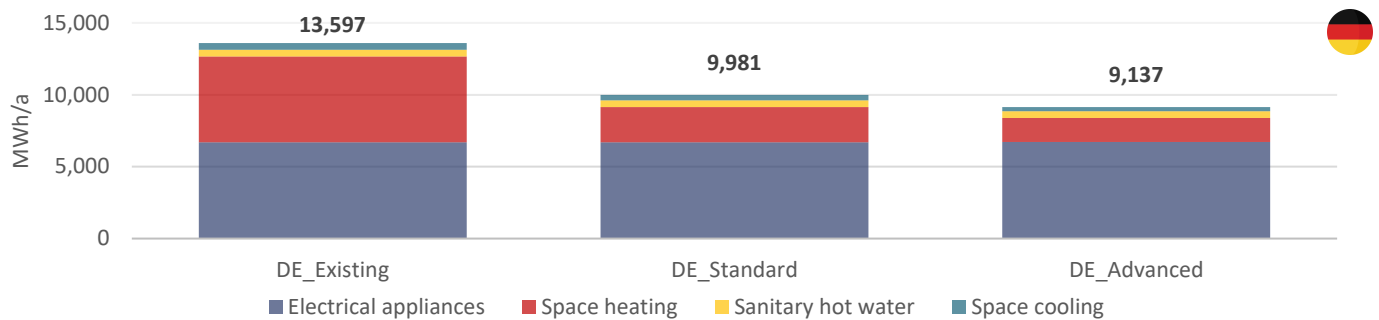
	Scenario	Electrical appliances	Space heating	Sanitary hot water	Space cooling
DE	DE_EXISTING	6,684.6 [MWh/a]	5,965.9 [MWh/a]	473.7 [MWh/a]	473.1 [MWh/a]
	DE_STANDARD	6,706.0 [MWh/a]	2,435.3 [MWh/a]	472.1 [MWh/a]	367.4 [MWh/a]
	DE_ADVANCED	6,724.7 [MWh/a]	1,653.2 [MWh/a]	471.5 [MWh/a]	287.6 [MWh/a]
ES	ES_EXISTING	6,684.6 [MWh/a]	1,525.6 [MWh/a]	474.4 [MWh/a]	4,873.2 [MWh/a]
	ES_STANDARD	6,786.6 [MWh/a]	877.8 [MWh/a]	472.0 [MWh/a]	3,864.7 [MWh/a]
	ES_ADVANCED	6,801.2 [MWh/a]	531.6 [MWh/a]	470.9 [MWh/a]	3,174.5 [MWh/a]
HU	HU_EXISTING	6,684.6 [MWh/a]	5,612.4 [MWh/a]	472.8 [MWh/a]	512.4 [MWh/a]
	HU_STANDARD	6,694.1 [MWh/a]	3,122.6 [MWh/a]	472.2 [MWh/a]	396.5 [MWh/a]
	HU_ADVANCED	6,713.7 [MWh/a]	1,354.9 [MWh/a]	471.6 [MWh/a]	305.3 [MWh/a]

Figure 32. Final energy demand by end-use
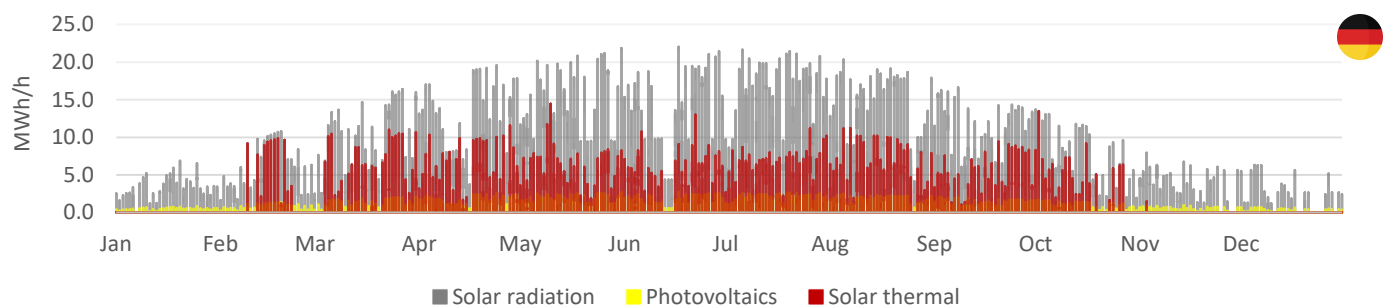
	Scenario	Area available	Solar radiation	Photovoltaics	Solar thermal
DE	DE_EXISTING				
	DE_STANDARD	24,487.2 [m²]	24,263.1 [MWh/a]	3,301.6 [MWh/a]	6,469.8 [MWh/a]
	DE_ADVANCED				
ES	ES_EXISTING				
	ES_STANDARD	24,487.2 [m²]	59,969.7 [MWh/a]	7,376.3 [MWh/a]	15,412.2 [MWh/a]
	ES_ADVANCED				
HU	HU_EXISTING				
	HU_STANDARD	24,487.2 [m²]	32,541.4 [MWh/a]	4,523.3 [MWh/a]	8721.1 [MWh/a]
	HU_ADVANCED				

Figure 33. Solar generation potentials for case study area

The CEA model endogenously determines the potentials for solar energy and other renewable energy sources. **Figure 33** shows the solar radiation as well as the generation potential from photovoltaics and solar thermal installations. While CEA also features façade-installed solar panels, in this case study only rooftop-installed panels were considered. The total roof space available in the case study area is 24,487 m², i.e. an area of about 156 x 156 m. Annual solar radiation onto roofs ranges between 24,263 MWh (DE) and 59,969 MWh (ES). As such, there are significant electrical and thermal generation potentials from

photovoltaic and solar thermal panels, respectively. Note that the CEA model takes into account that the solar cell performance decreases with increasing temperatures, which explains why the solar yield by unit of radiation is not constant across the countries. Overall, photovoltaics and solar thermal panels compete for limited roof space in the case study area. Which of these technology potentials is actually adopted depends on the multi-objective optimization logic in CEA.

Before analysing how much of the potentials can be feasibly integrated, **Figure 34** illustrates the district heating network planning feature of CEA. Based on a minimum spanning tree algorithm and a mass flow simulation, the model determines a technically feasible thermal hydraulic network for all buildings in the case study area. In the case of the case study area in Germany, the model suggests trench lengths in the district heating network of 0.7–103.5 m, mass flow rates of 3.3–96.3 kg/s, and peak velocities of the pressurised hot water of 1.8–2.5 m/s. Similar to the solar potentials described above, this represents a technical rather than an economic potential for grid-bound heating and cooling supply. Which of the buildings are actually connected to the network is again subject to the optimization logic of CEA.

Figure 34. Network layout at nominal operating conditions for district heating in Germany and district cooling in Spain

Following the estimation of energy savings and technology potentials, CEA determines Pareto-optimal configurations of individual heat supply units as well as decentralized district heating and cooling infrastructure. **Figure 35** presents the outcomes of this multi-objective optimization for total annual cost (capital, operation & maintenance costs, fuel costs) and greenhouse gas emissions, divided by country and scenario. Each dot in the charts represents one individual technically feasible energy supply configuration for meeting energy service needs in the case study area. These charts can be interpreted in two ways.

When drawing a vertical line, it turns out that the building retrofit measures in the STANDARD and ADVANCED scenarios enable more effective GHG emission reductions for the same level of total annual cost. For example in Germany, for a total annual cost of 4.0 m EUR/a, the magnitude of greenhouse gas emissions is in the range of 700 tCO_2-eq/a (DE_ADVANCED) to 1600 tCO_2-eq/a (DE_STANDARD). This is because low-cost renewable energy potentials in the case study areas in the form of solar, ambient heat and waste heat are physically limited. Any excess energy needs require imports from beyond the system boundaries in the form of electricity and natural gas that come with average CO_2 emissions.

When drawing a horizontal line in **Figure 35**, the graphs show that building retrofits effectively reduce total annual cost of energy supply for the same level of GHG emissions. In the context of EE1st, arguably, this interpretation is more significant than the vertical interpretation because the principle aims to compare demand- and supply-side resources with a view to the equivalent decision outcomes, such the same magnitude of GHG savings (ENEFIRST 2020b). Sticking with the example of Germany, a GHG emission level of about 800 tCO_2-eq/a requires total annual cost for energy supply between 3.6 m EUR/a (DE_ADVANCED) and 5.6 m EUR/a (DE_EXISTING). Most fundamentally, this is because a building envelope with poor thermal performance leads to greater variable cost than an energy-efficient one, e.g. for purchasing electricity to drive a heat pump. What is more, poor thermal performance in buildings also leads

Model-based case studies for assessing the Energy Efficiency First principle

to higher fixed capital costs because, in order to meet building energy needs, greater capacities for heat generation, networks and storage are needed than if the building were energy-efficient.
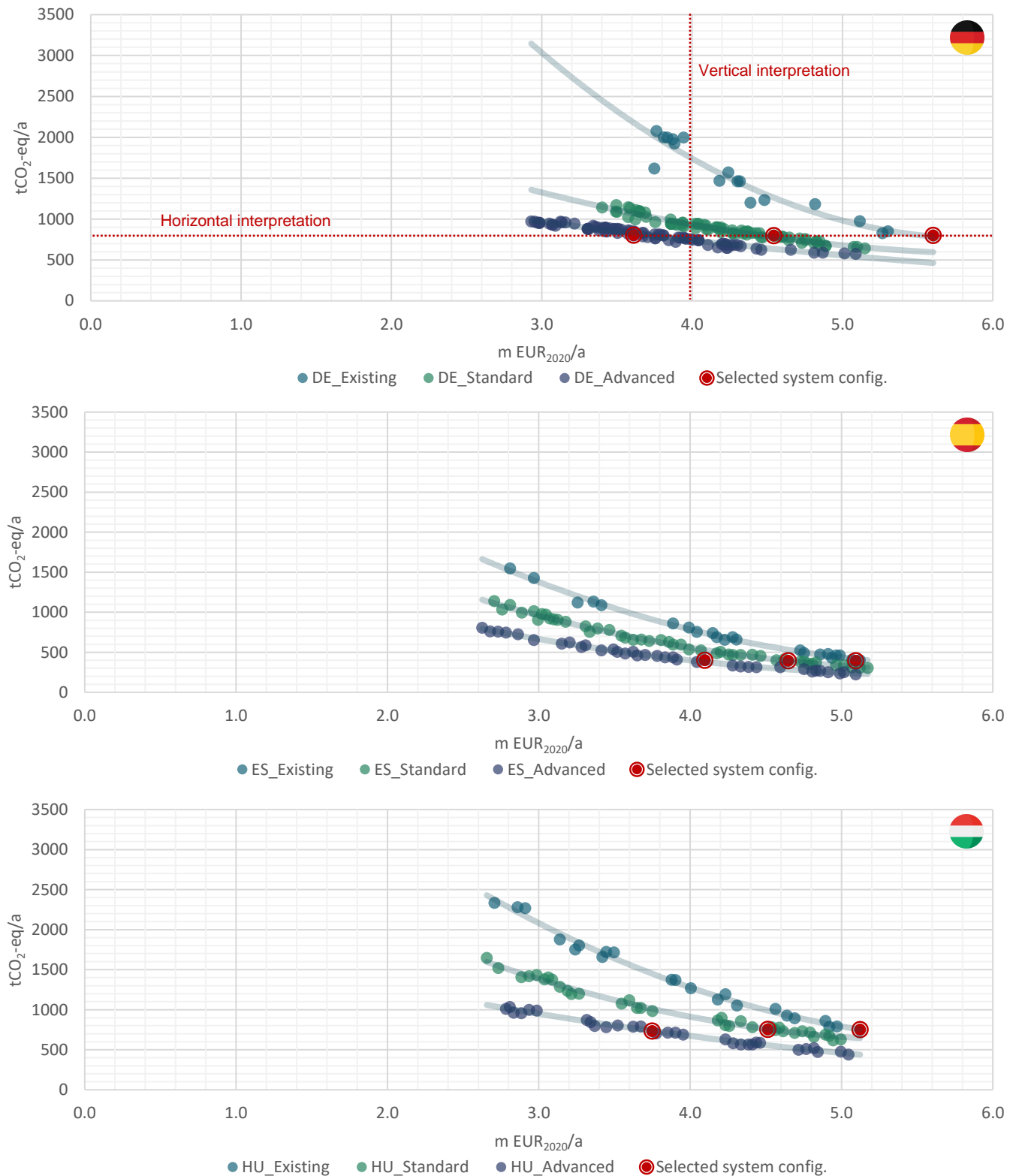
Figure 35. Multi-objective optimization of energy supply system configurations for total annual cost and greenhouse gas emissions

Total annual cost = sum of capital, operation and maintenance, and fuel costs for individual and centralized heat supply | Costs of building retrofits not included here; selected system configurations are subject to economic analysis below

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What is not shown in **Figure 35** is whether the system configurations are cost-effective when factoring in the cost of the building retrofit measures. For this purpose, three resource configurations are selected per country that are characterised by essentially the same levels of GHG emissions. In **Figure 36**, these system configurations are characterised in terms of their installed capacities for heating (DE, HU) and cooling (ES). Based on the model's optimization logic, centralized heating and cooling via local networks is significant across all three countries. Technologies deployed range from biomass-based cogeneration, over solar technologies to heat pumps and storage units. Across the scenarios, building retrofits clearly reduce the need for individual and centralized heating and cooling supply. Another observation is that the higher the retrofit ambition, the more centralized generation is replaced by individual heat supply in buildings.
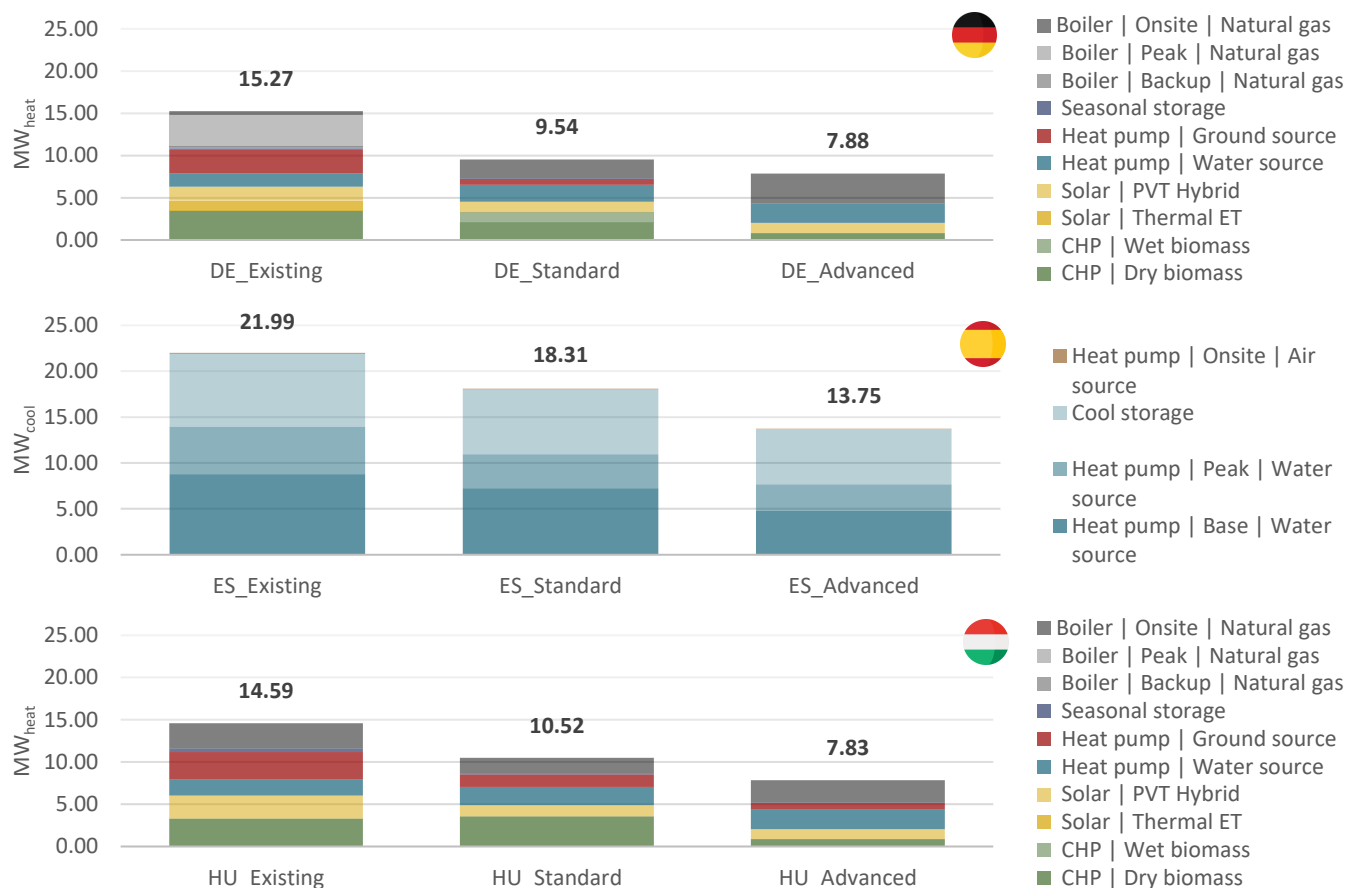
Figure 36. Heating and cooling generation capacity for selected system configurations
PVT = Photovoltaic-thermal hybrid panels, ET = solar thermal evacuated tube collector, CHP = combined heat and power

The ultimate question in the context of EE1st is whether the retrofit measures and ensuing energy savings are net-beneficial. **Table 8** provides an economic analysis of the retrofit packages based on three basic indicators (Konstantin and Konstantin 2018).[12] In the case of DE and HU, only the ADVANCED retrofit packages are cost-effective while the STANDARD ones are not. This can be attributed to the high share of fixed costs in building retrofits that have to be offset by reduced energy cost. As for ES, none of the two packages are cost-effective. As indicated before (Sarihi et al. 2021), insulation is much more effective in

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[12] The net present value (NPV) compares the initial investment of the retrofits with the discounted future returns in the form of reduced cost for energy supply. It has to be greater than zero for the investment to be cost-effective. The discounted payback period (DPBP) represents the number of years needed for the retrofits to pay back. The internal rate of return (IRR) has to be higher than the discount rate for the retrofit measures to be cost-effective.

reducing heating compared to cooling demand. This warrants closer investigation of energy modulation measures (e.g. green façades) for reducing cooling demand in warm-summer Mediterranean climate. Moreover, it should be noted that Southern countries like Spain and Italy include very different climate zones. The renovation packages can then be cost-effective in the coldest climate zones.

Table 8. Economic analysis of building retrofit options

NPV = Net present value, DPBP = Discounted payback period, IRR = Internal rate of return | Assumptions: 5% discount rate, 20 [a] lifetime for building retrofit measures

	Scenario	Emission level	NPV	DPBP	IRR
	DE_EXISTING	797.7 [tCO$_2$-eq/a]	-	-	-
	DE_STANDARD	795.8 [tCO$_2$-eq/a]	-225,732.2 [EUR/a]	28.9 [a]	2.8%
DE	DE_ADVANCED	801.0 [tCO$_2$-eq/a]	+470,698.6 [EUR/a]	13.2 [a]	8.4%
	ES_EXISTING	393.1 [tCO$_2$-eq/a]	-	-	-
	ES_STANDARD	391.4 [tCO$_2$-eq/a]	-432,905.3 [EUR/a]	>50.0 [a]	<1%
ES	ES_ADVANCED	399.5 [tCO$_2$-eq/a]	-39,800.5 [EUR/a]	21.2 [a]	3.5%
	HU_EXISTING	750.0 [tCO$_2$-eq/a]	-	-	-
	HU_STANDARD	753.4 [tCO$_2$-eq/a]	-92,586.3 [EUR/a]	23.3 [a]	4.0%
HU	HU_ADVANCED	732.7 [tCO$_2$-eq/a]	+316,282.9 [EUR/a]	14.6 [a]	7.5%

Discussion and conclusion

Local planning for low-carbon energy systems involves a trade-off between saving and supplying energy. Building retrofits reduce the magnitude of energy needed and thus also the generation capacities and the cost for energy supply. However, retrofits involve significant capital expenditures. This case study finds that there is clear scope for the EE1st principle in local energy planning for commercial areas. Deep retrofits can be more cost-efficient in meeting equivalent greenhouse gas reductions than light retrofits or strategies focusing exclusively on supply side investment. In this archetype case study, advanced retrofit packages pay off within 13 to 14 years in countries with temperate continental climate. At the same time, EE1st should not be equated with end-use energy efficiency. Heat pumps, cogeneration and efficient district heating overall are a key requirement for achieving significant greenhouse gas reductions in commercial areas – supply-side energy efficiency is a critical component of the principle. As with every model-based analysis, these results should be taken with caution. The problem is not only uncertainties, but also the capabilities of the model setup as well as conceptual issues in counting costs and benefits. This issues are extensively discussed in ENEFIRST (2022b).

(V) The trade-off between energy efficient household appliances and new electricity generation

Scope					
CASE STUDY #5		**The trade-off between energy efficient household appliances and new electricity generation**			
	Building types	Residential		Non-residential	
	Building end-uses	Space heating	Water heating	Space cooling	Electr. appliances
		Lighting	Process heating	Process cooling	Other
	Supply infrastructures	Power	District heating		Gas
Outline	Objective	Investigating the trade-off between energy efficient household appliances (e.g. refrigerators) and new electricity generation (e.g. onshore wind power). Assessing the cost-effectiveness of efficient appliances from private and societal viewpoints.			
	Methodology	Development of long-term marginal cost curves that allow for comparing the cost and electricity savings potentials of energy efficient appliances with the specific cost of new renewable, fossil and hydrogen-based electricity generation.			
	Key results	Efficient household appliances can be a reasonable substitute for new electricity generation. Cost-effective savings are in the range of 3.8%-19.4% compared to a base case of inefficient appliances, with payback times between 4.6 to 6.6 years.			

Background and objective

Electrical appliances and lighting are a significant end-use, accounting for about 57% of electricity use in the households sector (Eurostat 2021). Accordingly, the EU policy framework has a significant emphasis on making electrical appliances more efficient and thus achieving economy-wide energy savings. The Ecodesign Directive (European Union 2009) establishes a framework for energy performance criteria manufacturers of appliances must meet to legally bring their product to the market. It is complemented by the Energy Labelling Regulation (European Union 2017, 2010a) that aims at providing transparent energy and environmental information for consumers to make an informed choice between products on the market. Together, by 2020, Ecodesign and labelling have effectively reduced electricity use across the EU-27 by 12%, compared to a situation without these measures (European Commission 2021).

Meanwhile, the expansion of renewable energies in the power system is moving forward – a process that has been accompanied by significant cost reductions for key technologies. To illustrate, in 2021 alone, utility-scale photovoltaics (PV) has experienced a year-on-year cost reduction of 13% (Taylor et al. 2022). In the context of the EE1st principle, this raises the question of whether, and to what extent, energy efficient appliances should be systematically prioritized over new electricity generation. As the principle suggests, a kilowatt-hour generated and transmitted is equivalent to a kilowatt-hour saved – so the economic balance between end-use energy efficiency and electricity generation becomes an important matter to investigate.

The objective of this case study is to investigate the trade-off between saving or supplying electricity for electrical appliances in the household sector. It relies on cost curves that allow for comparing the cost and electricity savings potentials of efficient appliances with the cost of new electricity generators. As for savings options, the focus is on 'white goods', including refrigerators, freezers, washing machines, dryers,

dishwashers and ovens. Generation technologies include variable renewables (e.g. rooftop PV), fossil generators (e.g. combined cycle gas turbine), and emerging backup generators that are critical in a net-zero future (e.g. hydrogen-fired gas turbine). The trade-off is assessed from two perspectives, a societal and a private one. Results are presented for the countries of Germany (DE), Spain (ES), and Hungary (HU), taking into account local characteristics in terms of weather, price levels and technology availability.

Methodology

This work compares new electricity generation and end-use energy efficiency technologies by examining their levelized energy generation cost on the supply side with the generation equivalent cost on the demand side of the power system. The concept of levelized energy generation cost (LEC), also known as levelized cost of electricity (LCOE), is widely used to compare the costs of generation technologies with different generation and cost structures (Kost et al. 2021; Konstantin and Konstantin 2018). The LEC represents the specific generation cost in EUR/kWh.[13] It is calculated by comparing the upfront capital expenditure (CAPEX) plus the discounted operating expenses (OPEX) incurred over the lifetime with the discounted value of energy generated (**Equation 10**). OPEX are composed of fixed costs that do not depend on the output level (e.g. maintenance) and variable costs that directly depend on the output level (e.g. fuel costs).Table **9** presents the generation technologies and their techno-economic characteristics used for the calculation of the LEC. Fundamental data is derived from Kost et al. (2021) and DeVita et al. (2018). Note that full load hours (h/a) and CAPEX (EUR) are given in ranges. In this table, these ranges represent cross-country differences (DE, ES, HU) as well as ranges within a country. The actual LEC thus varies between the lower and upper estimates. Full load hours of generators are a critical variable. For PV and wind, annual yield is based on the Renewables.ninja database. In turn, the annual generation of a thermal power plant depends on the respective demand and the technology competitiveness in power markets. In the course of increasing generation from renewables and rising CO_2 certificate prices, the yield of conventional power plants are expected to decrease continuously until 2050 (Kost et al. 2021).

Discount rates are determined for each technology by applying the parameter of weighted average costs of capital (WACC) for each investment. The WACC consists of a share for interest rate on debt and the return on equity. Large power plants operated by large investors have a higher WACC due to the expected return of the investor compared to small and medium size projects that are constructed by private persons or business partnerships. In addition, the return on equity expected by investors for technologies with lower maturity (e.g. offshore wind) are higher compared with established technologies (Kost et al. 2021; Konstantin and Konstantin 2018). All costs stated in this case study refer to real, rather than nominal values (EUR_{2020}). Fuel prices and CO_2 certificate costs are based on (ENEFIRST 2021a).

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[13] The method is not suitable for determining the profitability of a specific technology. This requires financial calculations that take into account all income and expenditure with a dedicated cash flow model. Moreover, the LEC does not take into account the price of the electricity produced within an energy system in a given hour of the year (Kost et al. 2021).

Equation 10 Levelized energy generation cost (LEC)

$$LEC_{i,j} = \frac{CAPEX_{i,j} + \sum_{t=1}^{n} \frac{OPEX_{i,j}}{(1 + r_{i,j})^{t_j}}}{\sum_{t=1}^{n} \frac{E_{i,j}}{(1 + r_{i,j})^{t_j}}}$$

$$OPEX_{i,j} = C_{O\&M,fix,i,j} + C_{O\&M,var,i,j} + C_{fuel,i,j} + C_{ETS,i,j}$$

Equation 11 Generation equivalent cost

$$GEC_{i,j} = \frac{\alpha_{i,j} * (I_{i,j} - I_{i,j,base})}{E_{i,j} - E_{i,j,base}}$$

$$\alpha_{i,j} = \frac{r_{i,j}}{1 - (1 + r_{i,j})^{-n_j}}$$

Variables		Unit
LEC	= Levelized energy generation cost	[EUR/kWh]
GEC	= Generation equivalent cost	[EUR/kWh]
α	= Capital recovery factor	[1/a]
$CAPEX$	= Capital expenditure	[EUR]
$OPEX$	= Operating expenses	[EUR]
E	= Electricity generation or use	[kWh]
$C_{O\&M,fix}$	= Fixed operation and maintenance	[EUR]
$C_{O\&M,var}$	= Variable operation and maintenance	[EUR]
C_{fuel}	= Fuel costs	[EUR]
C_{ETS}	= CO_2 certificate costs	[EUR]
r	= Discount rate	[%/a]
t	= Time step	[a]
n	= Technology lifetime	[a]

Indices		
i		= Country
j		= Technology
$base$		= Base case

Table 9. Techno-economic properties of new electricity generators

Source: Kost et al. (2021); DeVita et al. (2018); https://www.renewables.ninja/ | Ranges represent cross-country and intra-country differences | CCGT = combined cycle gas turbine, OCGT = open cycle gas turbine; PV = photovoltaics; CH₄ = synthetic methane; H₂ = hydrogen; CAPEX = capital expenditure; OPEX = operating expense | [a] System > 30 kWp | [b] System ≤ 30 kWp

Technology	Efficiency	WACC	Technical lifetime	Full load hours (2020)	Full load hours (2050)	CAPEX	OPEX fix	OPEX var
			[a]	[h/a]		[EUR$_{2020}$/kW]		[EUR/kWh]
Biogas power plant	40.0%	3.2%	25	3000–7000	3000–7000	2340–5000	20	0.004
Biomass power plant	40.0%	3.2%	25	3000–7000	3000–7000	2810–5000	20	0.004
CCGT | CH₄	60.0%	9.0%	30	-	80–250	750–1100	20	0.003
CCGT | H₂	60.0%	9.0%	30	-	300–1000	750–1100	20	0.003
CCGT | Natural gas	60.0%	5.8%	30	3000–8000	1000–4000	750–1100	20	0.003
Hard coal power plant	46.0%	6.2%	30	2000–6200	1500–2000	1410–2000	22	0.004
Lignite power plant	45.0%	6.2%	40	4500–7300	1500–2000	1500–2200	32	0.0045
OCGT | CH₄	40.0%	9.0%	30	-	80–250	380–600	20	0.003
OCGT | H₂	40.0%	9.0%	30	-	150–500	380–600	20	0.003
OCGT | Natural gas	40.0%	5.8%	30	500–3000	1000–2000	380–600	20	0.003
PV rooftop large [a]	85.0%	2.5%	30	1300–1860	1300–1860	750–1400	21.5	-
PV rooftop small [b]	85.0%	2.2%	30	1300–1860	1300–1860	940–1600	26	-
PV utility scale	85.0%	2.5%	30	1300–1860	1300–1860	500–800	13.3	-
Wind offshore	100.0%	5.2%	25	3320–4780	3320–4780	2810–4000	70	0.008
Wind onshore	100.0%	3.0%	25	2400–4190	2400–4190	1310–2000	20	0.008

In order to compare new electricity generation to energy-efficient technologies, a generation equivalent cost (GEC) is calculated by dividing the upfront capital costs by the annual energy savings throughout the expected life of the appliance to yield a cost in EUR/kWh (EECA 2019) (**Equation 11**). Annual capital costs are determined by multiplying the upfront capital expenditure with the capital recovery factor or annuity factor α, which is a function of the discount rate and the technology lifetime.

There are various mature energy efficient technologies that can provide reductions in energy demand. Five product groups are prominent in this case study: refrigerators, freezers, washing machines, laundry dryers, and electric ovens. For each of these product groups, four options are defined (**Table 10**). The *base case*

represents an average EU product in terms of functionality and dimensions. The remaining options are more energy efficient, but require higher acquisition cost that is paid back over later years with lower energy costs. Prices in **Table 10** represent observed retail prices incl. value added tax (VAT).[14] Prices are collected for the EU as a whole and turned into country-specific numbers using purchasing power parities (Eurostat 2022g). To refer all prices to 2020 levels, consumer price indices are used (Eurostat 2022d).

Table 10. Techno-economic properties of energy saving options

[a] Base case: average EU product, LLCC: least life cycle cost according to Ecodesign preparatory studies, Mid-point: interpolation between LLCC and BAT, BAT: best available technology | [b] Range between countries DE, ES, HU | [c] Observed retail price, incl. VAT. Prices referred to EUR_{2020} price levels using purchasing power parities and consumer price indices.

Product group	Option [a]	Lifetime	Ownership rate [b]	Default price [b,c]	Energy use	Source
		[a/unit]	[Units/household]	[EUR$_{2020}$/unit]	[kWh/unit/a]	
Refrigerator Single door refrigerator | Net volume 250 l	Base case	16.0	1.00 – 1.16	438 – 484	119.0	VHK/ARMINES 2016
	LLCC			521 – 576	79.0	
	Mid-point			601 – 665	62.0	
	BAT			815 – 902	55.0	
Freezer Upright freezer | Net volume 200 l	Base case	16.0	0.75	438 – 484	232.0	VHK/ARMINES 2016
	LLCC			521 – 576	162.0	
	Mid-point			601 – 665	144.5	
	BAT			815 – 902	127.0	
Washing machine Standard machine | 220 cycles per year | Average loading 3.3 kg	Base case	12.5	0.80 – 0.90	454 – 497	184.8	Boyano et al. 2017a
	LLCC			540 – 591	170.0	
	Mid-point			623 – 683	138.6	
	BAT			845 – 925	96.1	
Laundry dryer Condenser dryer | 107 cycles per year | 4.4 kg load per cycle	Base case	12.0	0.25 – 0.45	442 – 489	447.0	Maya-Drysdale et al. 2019; European Commission 2021
	LLCC			526 – 582	339.0	
	Mid-point			607 – 672	285.0	
	BAT			823 – 912	231.0	
Dishwasher Household dishwasher | 280 cycles/year | 13 place settings	Base case	12.5	0.60 – 0.75	454 – 497	268.8	Boyano et al. 2017b
	LLCC			540 – 591	210.0	
	Mid-point			623 – 683	190.4	
	BAT			845 – 925	128.8	
Electric oven 54 l capacity	Base case	19.0	1.00	432 – 481	107.0	Mudgal et al. 2011; European Commission 2021
	LLCC			514 – 573	97.6	
	Mid-point			593 – 661	88.2	
	BAT			804 – 896	69.3	

Table 11. Evaluation perspectives for calculation of generation equivalent cost and its cost-effectiveness

[a] = Value added tax + renewable taxes + capacity taxes + environmental taxes + nuclear taxes | [b] Weighted average cost of capital as per Kost et al. (2021)

		Societal perspective	Private perspective
Generation equivalent cost	Observed retail price	✓	✓
	Value added tax	✗	✓
	Discount rate	2%	10%
Levelized energy generation cost	Electricity generation costs	✓	✓
	Network costs	✓	✓
	Taxes, fees, levies and charges [a]	✗	✓
	Discount rate	2%	WACC [b]

The ownership rate represents the average number of appliances per household. Country-specific values are collected from the ODYSSEE-MURE database (2022). The general assumption in this case study is

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[14] In practice, the price of an appliance largely depends on the retailer, the trade channels, the brand and also the time (e.g. in case of special sales) (Boyano et al. 2017a).

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that households use appliances until the end of their technical lifetime. As a result, the situation of premature replacement of inefficient appliances is disregarded and the only focus is on new appliances that replace scrapped ones. The number of new appliances is estimated for a representative set of 1,000 households by country by multiplying the ownership rate with the inverse of the technoloy lifetime. In other words, a normal distribution of appliance failure is assumed where each year $1/a$ of the stock is replaced.

To give consideration to different evaluation perspectives in the scope of the EE1st principle, the LEC is calculated from a private and a societal perspective (**Table 11**). The private perspective is concerned with the profitability of the savings options for the individual household. Taxes are included as actual cash flows incurred. These price components, same as network costs in the electricity price, are taken from Eurostat (2022c). Time preferences and subjective risk are taken into acount through a financial discount rate of 10% for households, based on Capros et al. (2021). In turn, the societal perspective considers costs and benefits to society. Taxes are omitted from the societal perspetive as they represent transfer payments that do not affect the real value of a product (ENEFIRST 2020b).[15]

Results

Figure 37 shows the generation equivalent cost (EUR_{2020}/kWh) for the different product groups of refrigerators, freezers, washing machines, laundry dryers, dishwashers, and electric ovens. This represents the specific cost for saving an additional kWh of electricity relative to the base case, as defined above in **Table 10**. The product options are displayed by energy label.[16] As can be seen from the charts, each product group features multiple energy efficient alternatives that provide the same functionality as the base case while using less electricity. From the societal perspective (2% discount rate, excl. VAT), generation equivalent cost ranges from 0.05 EUR/kWh (laundry dryer with A label in HU) to 0.58 EUR/kWh (electric oven with label A+ in ES). Cross-country differences in price levels for appliances are taken into account, as a result of which ES features the higher average prices than DE and HU. What is also evident in **Figure 37** is that taking the Private perspective results in higher cost because, in this case study, this involves a higher discount rate of 10% and adds VAT to the product retail price. Compared to the societal perspective, the private perspective increases costs by a factor of 1.9x (ES, 18% VAT) to 2.6x (HU, 27% VAT). As a result, generation equivalent cost from the private perspective across DE, HU and ES is in the range from 0.13 EUR/kWh to 1.32 EUR/kWh. As to be shown further below, some of these options are thus not cost-effective when compared to the levelized cost of electricity.

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[15] Note that this split is simplistic with regard to both perspectives. The private perspective of households is governed by more complex variables beyond monetary costs, e.g. hidden costs for finding and installing a more energy-efficient product, and possibly hidden benefits such as new functionalities or better design. In turn, the societal perspective should ideally include uncompensated costs and benefits that inviduals impose on one another, e.g. negative externalities from fuel combustion.

[16] At present, there are two scales of the energy label in circulation. The Energy Labelling regulation (European Union 2017) was adopted in 2017, replacing the former Energy Labelling Directive (European Union 2010a). The new regulation reintroduces the original A-G scale for future labels. Among the technology options considered, this rescaling concerns the product groups of refrigerators, freezers, washing machines, and dishwashers.
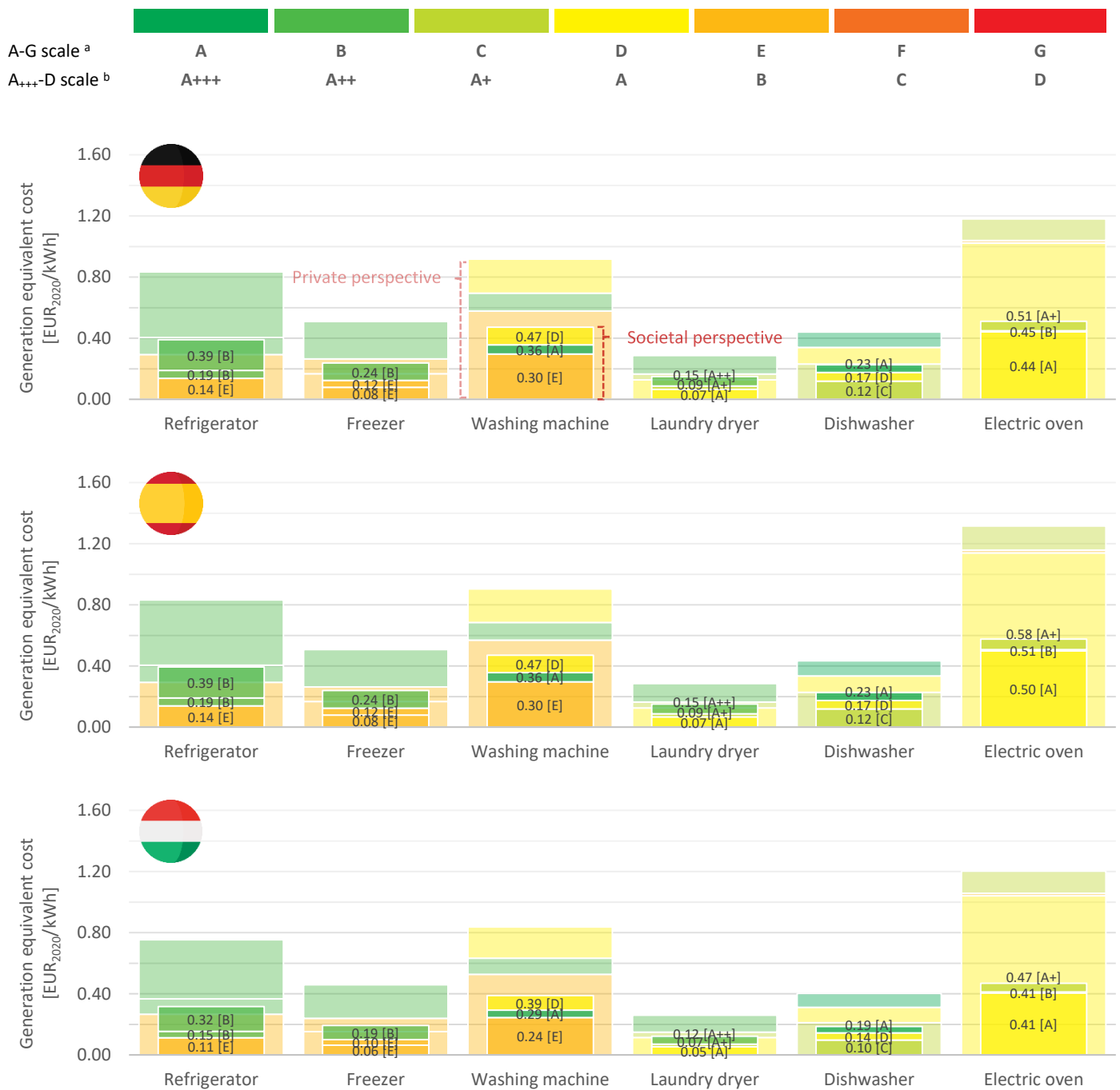
Figure 37. Generation equivalent cost of energy-efficient appliances by energy label

[a] Energy Labelling Regulation (European Union 2017) | [b] Energy Labelling Directive (European Union 2010a) | Private perspective: 10% discount rate, unit price incl. VAT; Societal perspective: 2% discount rate, unit price excl. VAT
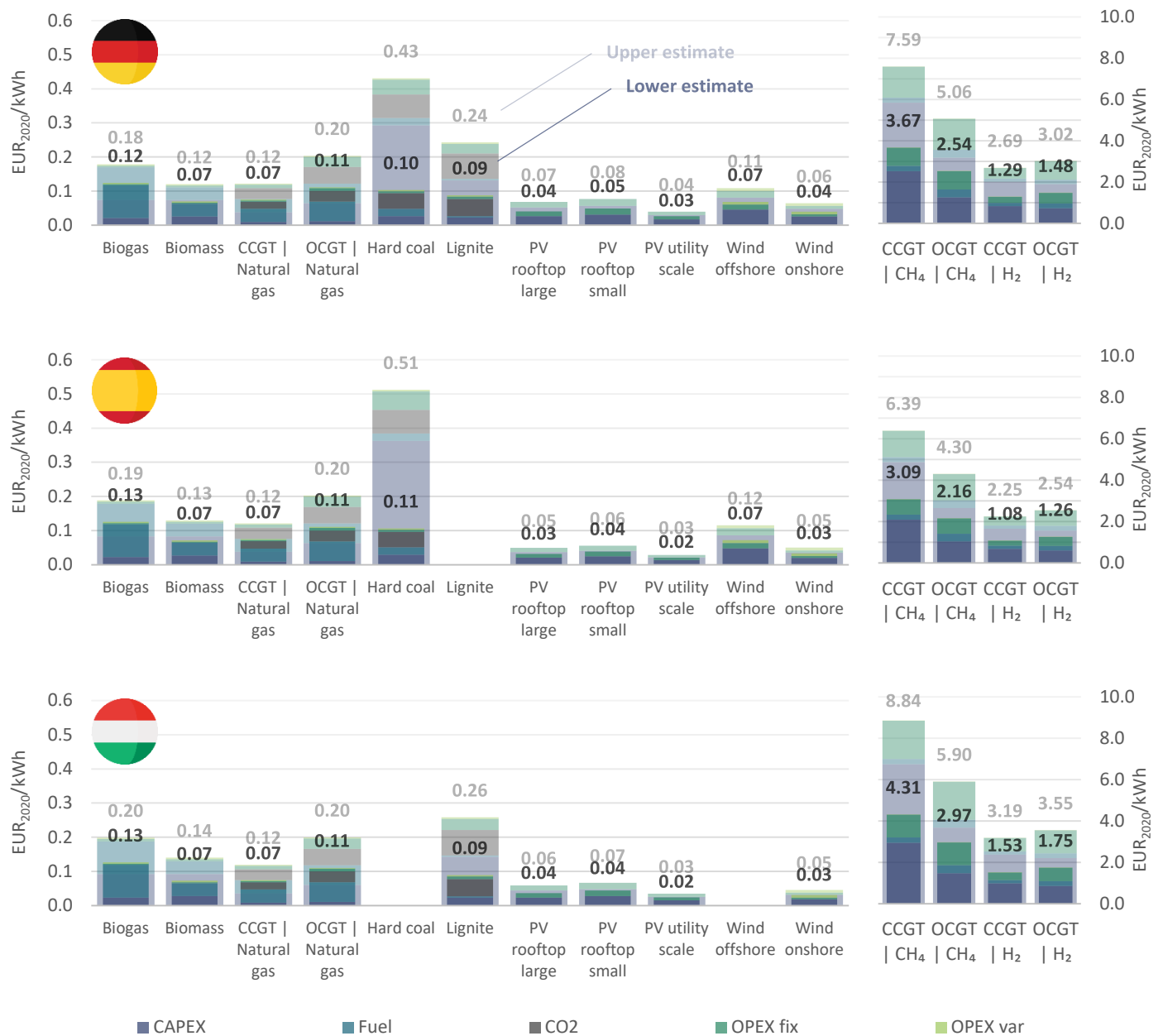
Figure 38. Levelized energy generation cost by technology and cost component

Private perspective (discount rate = WACC, no taxes and levies, network costs not shown here) | Upper estimate involves higher fuel cost and lower generation yield | CCGT = combined cycle gas turbine, OCGT = open cycle gas turbine; PV = photovoltaics; CH_4 = synthetic methane; H_2 = hydrogen

As regards generation, **Figure 38** shows the levelized energy generation cost (LEC) by technology and cost component. Costs are displayed for a lower estimate (low energy carrier prices, high full load hours) and, conversely, a higher cost estimate. For variable renewables (PV, wind) the LEC is generally in the range of 0.02 to 0.12 EUR/kWh and thus generally lower than most of the energy savings options identified above. The cost for conventional dispatchable generators ranges from 0.07 (biomass) to 0.51 EUR/kWh (hard coal). Finally, there is a range of dispatchable backup generators needed in a system with shares of renewables, including combined cycle and open cycle gas turbines fuelled by synthetic methane and hydrogen. Generation from these assets comes at exorbitant cost from 1.08 to 8.84 EUR/kWh, which is why most scenarios consider these assets only as peaking plants for times with high residual load.
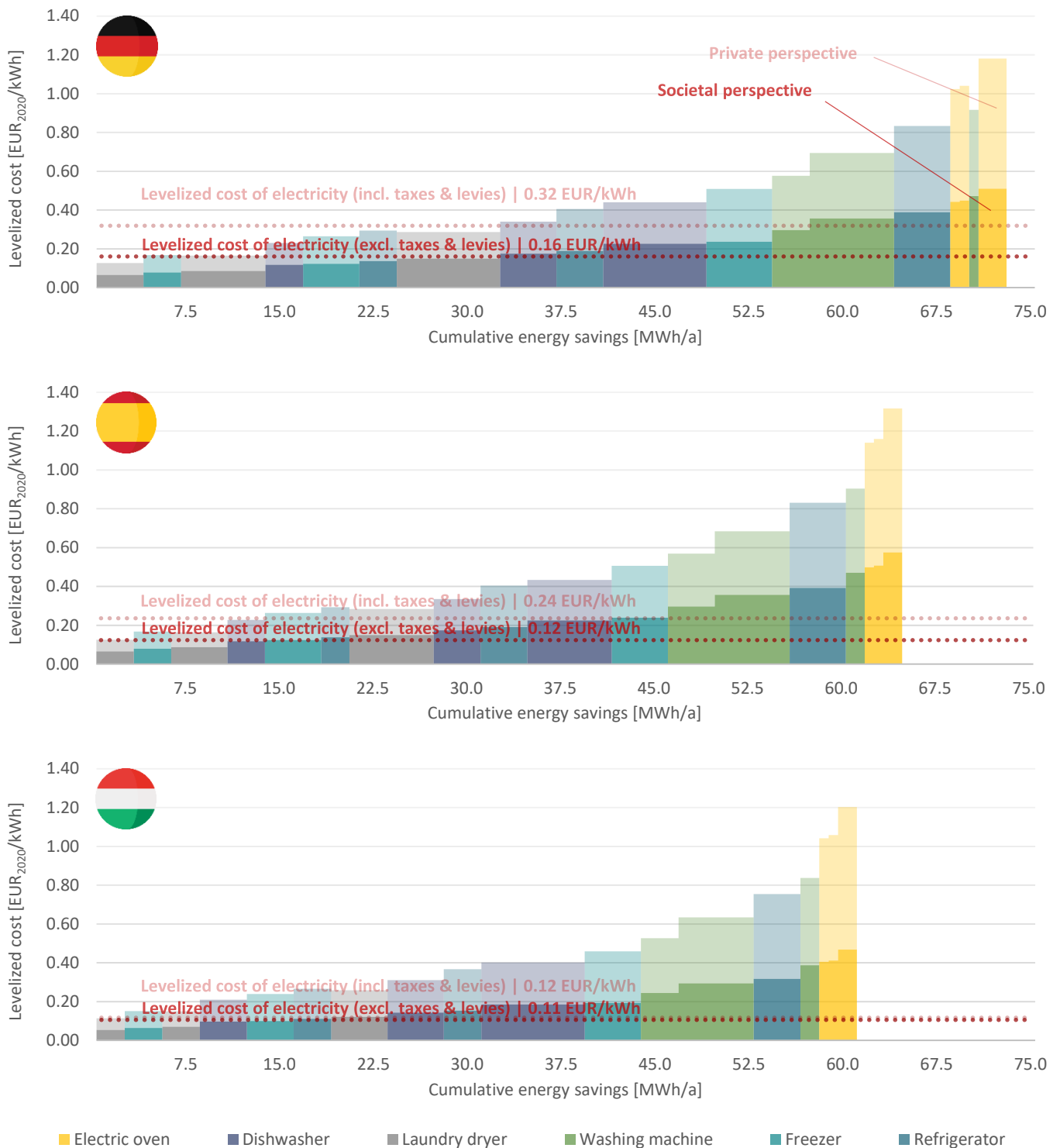
Figure 39. Equivalent cost curve of energy saving options for 1,000 households
Set of 1,000 households per country | Levelized cost of electricity consists of generation and network costs

When comparing **Figure 37** (GEC) with **Figure 38** (LEC), it is apparent that the cost of saving electricity by means of energy efficient appliances is in a very similar range than the cost of generating electricity from variable renewables and dispatchable generators. Investing in energy efficient appliances will thus not always provide cheaper means of substituting for thermal generation and lowering GHG emissions than new renewable generation. Meanwhile, actual market operations in a high-renewable system have daily and seasonal variability that must be managed. In addition, the LEC values shown here do not include the network costs, which can be significant depending on the locational value of the technologies. An optimal

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renewable electricity system will thus require a combination of additional renewable capacity and investment in energy efficiency technologies.

To get a more accurate picture of cost-effectiveness of the energy efficiency measures, **Figure 39** presents equivalent cost curves for the energy saving options examined. Detailed data is provided in **Table 12**. The variety of generation technologies is here represented by a uniform levelized cost of electricity that is computed from the country-specific projections in the EU Reference Scenario (Capros et al. 2021). Besides the generation component, it also includes network costs as well as – depending on the perspective (**Table 11**) – taxes, fees, levies and charges. The cost curves show that energy efficient appliances are available at reasonably competitive cost in both the private and the societal perspective. Low-cost options with significant savings potentials compared to the respective base case are freezers (e.g. upgrade from G to E label), laundry dryers, and dishwashers. Total achievable energy savings for the assumed set of 1,000 households are highest in DE (34.4 MWh/a) and lowest in HU (29.0 MWh/a). This is due to the differences in ownership rates ($Units/household$) across the countries, which results in different numbers of appliances that, on average, are replaced each year.

Table 12. Analysis of cost-effective energy savings options
[a] SOC = Societal perspective (2% discount rate, excl. taxes and levies), PRIV = Private perspective (10% discount rate, incl. taxes and levies)

Country	Unit	DE		ES		HU	
Perspective [a]		SOC	PRIV	SOC	PRIV	SOC	PRIV
Appliances replaced per 1,000 households	[Units/a]	340	340	318	318	304	304
Total achievable savings relative to base case	[MWh/a]	34.4	34.4	30.7	30.7	29.0	29.0
Cost-effective savings	[MWh/a]	13.8	13.8	9.2	9.2	8.9	2.3
% of achievable savings	[-]	40.2%	40.2%	30.1%	30.1%	30.5%	7.8%
% reduction to base case	[-]	-19.4%	-19.4%	-14.5%	-14.5%	-14.7%	-3.8%
Average savings cost	[EUR/kWh]	0.10	0.20	0.09	0.17	0.07	0.11
Incremental investment relative to base case	[EUR/household]	16.34	20.18	9.39	11.45	7.64	1.75
Avoided energy cost	[EUR/household/a]	2.21	4.41	1.15	2.19	0.93	0.27
Average simple payback time	[a]	7.4	4.6	8.2	5.2	8.2	6.6

By comparing the generation equivalent cost against the levelized cost of electricity, the cost-effectiveness of the energy saving options can be assessed. From the societal perspective – i.e. using a 2% discount rate and excluding taxes & levies – cost-effective savings potentials are in the range of 8.9-13.8 MWh/a, corresponding to 30.1%-40.2% of achievable savings. Relative to their respective base case technologies (**Table 10**), the cost-effective options save 14.5%-19.4% of electricity. Cost-effective savings from the private perspective (10% discount rate, incl. taxes & levies) are in the same range, with the exception of HU where the share of taxes & levies in the levelized cost of electricity is considerably low, while the VAT on appliances is at a high level of 27%. Overall, to adopt the cost-effective technologies, the average household is faced with acquisition cost between 1.75 and 20.18 EUR in addition to the price of the base case technology. These investments are offset by savings in energy costs, resulting in simple payback times from the private perspective between 4.6 and 6.6 years.

Discussion and conclusion

This case study demonstrates that there is opportunity for readily available energy efficient appliances to substitute for some electricity generation, thereby helping reduce the cost for meeting energy service needs. The largest and most attractive opportunities are from adoption of efficient laundry dryers, freezers and dishwashers, summing up to cost-effective savings between 3.8% to 19.4% compared to a base case

of inefficient appliances. For an average household, the simple payback time for these opportunities is in the range of 4.6 to 6.6 years. Implementation times for switching to efficient appliances are short relative to building new renewable generation, meaning that such measures can make large, near-term, low cost and low-risk contributions to achieving GHG reductions in the power system (EECA 2019).

With respect to the EE1st principle, it is evident that an optimal and cost-effective highly renewable electricity system will require a combination of additional renewable capacity and investment in energy efficient technologies. Policymaking and planning should devote appropriate attention to electricity efficiency measures alongside renewable capacity expansion. Ecodesign, labelling and other policies will thus have to remain critical elements of the EU's energy and climate policy framework. This case study also shows the importance to make fair comparisons where the whole supply cost is considered (e.g. here considering the network costs in addition to the generation costs).

Meanwhile, this case study features simplifications, particularly with regard to the generation equivalent cost of energy efficient appliances. The true cost of these appliances depends on a multitude of variables not explicitly investigated in this study, including their actual utilization in terms of operating hours per year, individual consumer preferences and budget constraints, up to potential rebound effects (e.g. choosing larger appliances compared to the replaced ones). In addition, the analysis provides an indication of how the electricity system will work on average and, as such, does not properly take into account the daily and seasonal variability of wind and solar generation. This warrants a more granular modelling approach using detailed energy systems modelling.

3 CONCLUSION

EE1st is a striking principle of energy system planning, investment and policymaking as it seeks to deliver a balanced deployment and operation of demand- and supply-side resources with a view to GHG reductions, security of supply and other societal objectives. In practice, taking explicit account of EE1st in system planning and corresponding policy design is challenging due to complex system interactions and long-term uncertainties. **Energy system models** play a vital role in making these complexities and uncertainties tangible and in enabling decision-makers to make informed decisions on future technology investment, system operation and policy design. Yet, given the novelty of the concept of EE1st in the political and academic debate, at present there are only few studies that make explicit reference to the EE1st principle.

This report set out to provide **quantitative evidence on the EE1st principle** by investigating five model-based **case studies** with different scopes in terms of building types, building end-uses (residential, non-residential) and supply infrastructures (electricity, gas, district heating) considered. Moreover, the five case studies use a variety of dedicated modelling techniques, including geographic information systems, cost-benefit analysis, building physics modelling, cost-supply curves, and others. This diverse set-up allows for a detailed appraisal of different questions relevant to the EE1st principle – such as the economic trade-off between building retrofits and heat supply systems or the demand response potential of domestic heat pumps. The key findings of the case studies can be summarized as follows:

❶ **Cumulated energy savings based on cost-optimal analysis** | This analysis discusses the time perspective of building's retrofitting under the consideration of different energy efficiency standards by comparing cumulated primary energy demand and global costs for 54 combinations variants. In the analysis, two approaches about how the deep renovation is carried out are also compared: staged versus single-stage renovation approaches. The sensitivity analysis considered different energy price scenarios and annual household budget. The main conclusions are that it depends on the right timing: single stage renovation creates higher cumulated savings when perfomed later, while staged renovation present lower cumulated global costs if single stage renovation is not done early in the period under consideration. To speed up the building stock decarbonisation financial support and incentives are an essential element, as the results showed that with lower budget also less energy efficient combination of measures would be preferred, therefore with higher cumulated primary energy over the analysed period

❷ **Building retrofits and district heating systems** | The analysis highlights that district heating networks are compatible with future scenarios with high refurbishment rates and under different European climate conditions and city typologies. To ensure that in 2050 a climate neutral and economic heat supply of the building stock is available, a strategic approach on a municipal level is necessary. Municipal heat planning activities can ensure that the EE1st principle is applied properly, which will lead to lower total costs of heat and reduce the risk of energy poverty. As a recurring activity, it can monitor the development of fuel prices and react promptly if the energy transition is not on track to reach its sustainability targets. Additionally, it will improve the knowledge and data quality of the current building stock, which would lead to more accurate models and scenario results.

❸ **Heat pumps: Efficiency, CO_2 emissions and the value of flexible heat pumps** | If the building thermal mass is used as a heat storage, depending on the building type, envelop, and geographical location, between 18% and 35% of the heat pump consumption can be used to provide flexibility to the power system. Aggregated on an EU27 level in 2050, based on the analysed scenario and future heat pump share, flexibility potential between 26.9 TWh and 32.01 TWh of the electricity consumption providing 8.4 GW to 10.03 GW flexible power capacity were identified. Some estimated cost saving potential from

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flexibility in residential heat pumps is expected, although it strongly depends on fees, taxes, and other additional investments in local grid substations.

❹ **Strategic energy planning in commercial areas** | Ambitious thermal retrofits for office and education buildings can cost-effectively reduce the need for investments in and operation of individual heat supply, distributed generation, heat networks, utility-scale generation, and seasonal heat storage facilities. Advanced retrofit packages pay off within 13 to 14 years in countries with temperate continental climate. Light retrofits are not necessarily cost-effective in light of the high fixed cost for retrofit works that do not pay off in the form of savings in heat supply cost. As such, this case study finds clear scope for the EE1st principle in local energy planning for commercial areas. This calls for an integrated planning of demand- and supply-side resources in making commercial areas fit for significant GHG reductions, e.g. in the context of the comprehensive assessments for heating and cooling (EED, Art. 14) and the long-term renovation strategies in the (EPBD, Art. 2a) (ENEFIRST 2021b).

❺ **The trade-off between energy efficient household appliances and new electricity generation** | This case study demonstrates that there is opportunity for readily available energy efficient appliances to substitute for some electricity generation, thereby helping reduce the cost for meeting energy service needs. The largest and most attractive opportunities are from adoption of efficient laundry dryers, freezers and dishwashers, summing up to cost-effective savings between 3.8% to 19.4% compared to a base case of inefficient appliances. Implementation times for switching to efficient appliances are short relative to building new renewable generation, meaning that such measures can make large, near-term, low cost and low-risk contributions to achieving GHG reductions in the power system. With respect to the EE1st principle, it is evident that an optimal and renewable electricity system will require a combination of both, additional renewable capacity and energy efficient appliances. Policymaking should devote appropriate attention to electricity efficiency measures alongside renewable capacity expansion.

To conclude, as argued throughout the ENEFIRST project (2021b, 2020b), **integrated energy systems modelling** that recognises the economic interplay between demand- and supply-side resources is a key factor to make the EE1st principle a reality. Such quantitative evidence is critical in various contexts of strategic energy planning, such as EU-wide impact assessments, local heating and cooling plans, utility network planning, cost-optimality calculations for building codes, and others (ENEFIRST 2022a). Policymakers and other practitioners can use model-based evidence to help put together and calibrate a sound **package of policy instruments for EE1st** – including planning guidelines, utility remuneration schemes, dynamic pricing, public funding instruments, and more (ENEFIRST 2021b, 2021c).

At the same time, one has to keep in mind the practical **limitations of quantitative energy systems modelling**. Most fundamentally, every model-based projection of the future is subject to uncertainties (e.g. fuel price dynamics) that, ideally, should be quantified in probabilistic terms to provide a range of possible futures. More specifically, there is a number of key issues that warrant particular attention when carrying out quantitative assessments in the context of the EE1st principle – including the selection of discount rates, the use of models with high spatio-temporal resolution, the proper consideration of multiple impacts (e.g. indoor comfort gains in energy efficient buildings), and others (ENEFIRST 2020b). As discussed in a dedicated ENEFIRST report (2022a), a particularly important issue is how to aggregate multiple impacts for decision-makers to assess the relative merits of resource options and thus to decide what options should be prioritized, invested in, or otherwise supported.

4 REFERENCES

Åberg, M.; Henning, D. (2011): Optimisation of a Swedish district heating system with reduced heat demand due to energy efficiency measures in residential buildings. In *Energy Policy* 39 (12), pp. 7839–7852. DOI: 10.1016/j.enpol.2011.09.031.

Baunormlexikon (2018): DIN V 18599-9 | 2018-09 Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung - Teil 9: End- und Primärenergiebedarf von stromproduzierenden Anlagen. Available online at https://www.baunormenlexikon.de/ http://files/1713/942b0d0c-0d01-4a08-8625-395876dfb6b0.html.

Bertoldi, Paolo; Zancanella, Paolo; Boza-Kiss, Benigna (2016): Demand response status in EU Member States. JRC Science for Policy Report. Luxembourg: Publications Office of the European Union.

Boyano, A.; Cordella, M.; Espinosa Martinez, M.; Villanueva, A.; Graulich, K.; Rüdenauer, I. et al. (2017a): Ecodesign and Energy Label for Household Washing machines and washer dryers. Preparatory study. Final report. Luxembourg: Publications Office of the European Union (JRC Technical Reports).

Boyano, A.; Moons, H.; Villanueva, A.; Graulich, K.; Rüdenauer, I.; Alborzi, F. et al. (2017b): Ecodesign and Energy Label for Household Dishwashers. Preparatory study. Final report. Luxembourg: Publications Office of the European Union (JRC Technical Reports).

Bundesverband Wärmepumpe (BWP) e.V. (2022): SG Ready-Label. Available online at https://www.waermepumpe.de/normen-technik/sg-ready/, checked on 7/13/2022.

Capros, P.; DeVita, Alessia; Florou, A.; Kannavou, M.; Fotiou, T.; Siskos, P. et al. (2021): EU Reference Scenario 2020. Energy, Transpart and GHG Emissions. Trends to 2050. Brussels: European Commission.

Chatterjee, Souran; Ürge-Vorsatz, Diana; Thema, Johannes; Kelemen, Agnes (2018): Synthesis Methodology. Deliverable D2.4 of the COMBI Project. Brussels: COMBI Project.

Cischinsky, Holger; Diefenbach, Nikolaus (2018): Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand, p. 179. Available online at http://files/354/Cischinsky und Diefenbach - Datenerhebung zu den energetischen Merkmalen und M.pdf.

City of Helsinki (2019): Helsinki Energy Challenge. Available online at https://energychallenge.hel.fi/results-helsinki-energy-challenge, checked on 8/8/2022.

Copernicus Land Monitoring Service (2018a): Imperviousness density. Available online at https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness.

Copernicus Land Monitoring Service (2018b): Urban Atlas. Available online at https://land.copernicus.eu/local/urban-atlas, checked on 8/8/2022.

Delmastro, Chiara; Gargiulo, Maurizio (2020): Capturing the long-term interdependencies between building thermal energy supply and demand in urban planning strategies. In *Applied Energy* 268, p. 114774. DOI: 10.1016/j.apenergy.2020.114774.

DeVita, Alessia; Kielichowska, Izabela; Mandatowa, Pavla (2018): Technology pathways in decarbonisation scenarios. Brussels: ASSET Project.

DIN V 18599-2 (2011): Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – Part 2: Net energy demand for heating and cooling of building zones Performance.

DNV GL (2017): DNV GL Energy Transition Outlook – Oil and Gas, p. 76.

Duić, Neven; Štefanić, Nedeljko; Lulić, Zoran; Krajačić, Goran; Pukšec, Tomislav; Novosel, Tomislav (2017): EU28 fuel prices for 2015, 2030 and 2050. In *Heat Roadman Europe 2050* (695989).

EECA (2019): Energy Efficiency First. The Electricity Story. Overview Report. Wellington: Energy Efficiency and Conservation Authority (EECA).

ENEFIRST (2020a): Defining and contextualizing the E1st principle. Deliverable D2.1 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 5/5/2020.

ENEFIRST (2020b): Review and guidance for quantitative assessments of demand and supply side resources in the context of the Efficiency First principle. Deliverable D3.1 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 3/3/2021.

ENEFIRST (2021a): Concept development for a model-based assessment of the E1st Principle. Deliverable D3.2 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 12/19/2021.

ENEFIRST (2021b): Guidelines on policy design options for the implementation of E1st in buildings and the related energy systems. Deliverable D4.3 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 11/26/2021.

ENEFIRST (2021c): Priority areas of implementation of the Efficiency First principle in buildings and related energy systems. Deliverable D4.1 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 9/9/2021.

ENEFIRST (2022a): Energy Efficiency First and Multiple Impacts: integrating two concepts for decision-making in the EU energy system. Deliverable D3.4 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 7/14/2022.

ENEFIRST (2022b): Quantifying Efficiency First in EU scenarios: implications for buildings and energy supply. Deliverable D3.3 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 3/31/2022.

ENEFIRST (2022c): Report on in depth policy design analysis as a prerequisite for EE1st implementation. Deliverable D5.1 of the ENEFIRST project. Brussels: ENEFIRST Project. Available online at http://enefirst.eu, checked on 7/14/2022.

EnergyPlus (2022): Weather Data. Available online at https://energyplus.net/weather, checked on 3/29/2022.

Esser, Anne; Dunne, Allison; Meeusen, Tim; Quaschning, Simon; Wegge, Denis; Hermelink, Andreas et al. (2019): Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU. Final report. Brussels: European Commission.

European Commission (2019): The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. COM/2019/640. Brussels: European Commission.

European Commission (2020): A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. COM/2020/662 final. Brussels: European Commission.

European Commission (2021): Ecodesign Impact Accounting. Annual Report 2020. Overview and Status Report. Luxembourg: Publications Office of the European Union.

European Commission; Directorate-General for Energy; Antretter, M.; Klobasa M.; Kühnbach, M.; et al. (2022): Digitalisation of energy flexibility.

Model-based case studies for assessing the Energy Efficiency First principle

European Heat Pump Association (2022): EHPA Stats. Available online at http://www.stats.ehpa.org/hp_sales/cockpit/, checked on 1/19/2022.

European Union (2009): Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products. In *Official Journal of the European Union* (L 285), pp. 10–35.

European Union (2010a): Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products. In *Official Journal of the European Union* (L 153), pp. 1–12.

European Union (2010b): Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. In *Official Journal of the European Union* (L 153), pp. 13–35.

European Union (2012): Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. In *Official Journal of the European Union* (L 315), pp. 1–56.

European Union (2017): Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU. In *Official Journal of the European Union* (L 198), pp. 1–23.

European Union (2018a): Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. In *Official Journal of the European Union* (L 328), pp. 82–209.

European Union (2018b): Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. In *Official Journal of the European Union* (L 156), pp. 75–91.

European Union (2018c): Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. In *Official Journal of the European Union* (L 328), pp. 1–77.

European Union (2021): Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). In *Official Journal of the European Union* (L 243), pp. 1–17.

Eurostat (2020a): Energy consumption in households - Statistics Explained. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households, checked on 3/29/2021.

Eurostat (2020b): Energy statistics - an overview - Statistics Explained. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption, checked on 3/29/2021.

Eurostat (2020c): Price level indices for machinery and equipment, 2020, checked on 10/6/2021.

Eurostat (2021): Disaggregated final energy consumption in households. Code NRG_D_HHQ. Available online at https://ec.europa.eu/eurostat/data/database, checked on 10/21/2021.

Model-based case studies for assessing the Energy Efficiency First principle

Eurostat (2022a): Complete energy balances. Code NRG_BAL_C. Available online at https://ec.europa.eu/eurostat/data/database, checked on 5/18/2022.

Eurostat (2022b): Construction cost (or producer prices), new residential buildings - annual data. Code STS_COPI_A. Available online at https://ec.europa.eu/eurostat/data/database, checked on 4/5/2022.

Eurostat (2022c): Electricity prices components for household consumers - annual data (from 2007 onwards). Code NRG_PC_204_C. Available online at https://ec.europa.eu/eurostat/data/database, checked on 8/11/2022.

Eurostat (2022d): Harmonised index of consumer prices (HICP). Code PRC_HICP_AIND. Available online at https://ec.europa.eu/eurostat/data/database, checked on 5/10/2022.

Eurostat (2022e): Heating and cooling degree days - statistics - Statistics Explained. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Heating_and_cooling_degree_days_-_statistics, checked on 7/13/2022.

Eurostat (2022f): Labour cost levels by NACE Rev. 2 activity. Code lc_lci_lev. Available online at https://ec.europa.eu/eurostat/data/database, checked on 8/18/2022.

Eurostat (2022g): Purchasing power parities (PPPs), price level indices and real expenditures for ESA 2010 aggregates. PRC_PPP_IND. Available online at https://ec.europa.eu/eurostat/data/database, checked on 7/12/2022.

Fehlhaber, Daniel (2017): PhD Dissertation: Bewertung von Kosten und Risiken bei Sanierungsprojekten, p. 186. Available online at http://files/694/Bewertung von Kosten und Risiken bei Sanierungsprojekten.pdf.

Fernández Boneta, Maria (2013): Cost of energy efficiency measures in buildings refurbishment: a summary report on target countries. D3.1 of WP3 from Entranze Project. Brussels: ENTRANZE Project (Policies to Enforce the Transition to Nearly Zero Energy Buildings in the EU-27)).

Fonseca, Jimeno A.; Nguyen, Thuy-An; Schlueter, Arno; Marechal, Francois (2016): City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. In *Energy and Buildings* 113, pp. 202–226. DOI: 10.1016/j.enbuild.2015.11.055.

Fonseca, Jimeno A.; Schlueter, Arno (2015): Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. In *Applied Energy* 142, pp. 247–265. DOI: 10.1016/j.apenergy.2014.12.068.

Galindo Fernandez, Marina; Bacquet, Alexandre; Bensadi, Soraya; Morisot, Paul; Oger, Alexis (2021): Integrating renewable and waste heat and cold sources into district heating and cooling systems Case studies analysis, replicable key success factors and potential policy implications External study performed by Tilia for the Joint Research Centre.

Gillich, Aaron; Sunikka-Blank, Minna; Ford, Andy (2018): Designing an 'optimal' domestic retrofit programme. In *Building Research & Information* 46 (7), pp. 767–778.

Grosse, R.; Christopher, B.; Stefan, W.; Geyer, R.; Robbi, S. (2017): Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU. In *1831-9424* EUR28859 (EUR28859). DOI: 10.2760/24422.

Hank, Christoph; Sternberg, André; Köppel, Nikolas; Holst, Marius; Smolinka, Tom; Schaadt, Achim et al. (2020): Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. In *Sustainable Energy and Fuels* 4 (5), pp. 2256–2273. DOI: 10.1039/d0se00067a.

Happle, Gabriel; Fonseca, Jimeno A.; Schlueter, Arno (2020): Impacts of diversity in commercial building occupancy profiles on district energy demand and supply. In *Applied Energy* 277, pp. 1–25. DOI: 10.1016/j.apenergy.2020.115594.

Harrestrup, M.; Svendsen, S. (2014): Heat planning for fossil-fuel-free district heating areas with extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark. In *Energy Policy* 68, pp. 294–305. DOI: 10.1016/j.enpol.2014.01.031.

Hein, Fabian; Buck, Matthias (2020): The European Power Sector in 2019: Up-to-Date Analysis on the Electricity Transition.

Hummel, M.; Büchele, R.; Müller, Andreas; Aichinger, E.; Steinbach, Jan; Kranzl, Lukas et al. (2020): The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe. In *Energy and Buildings*, p. 110454. DOI: 10.1016/j.enbuild.2020.110454.

Ipsos (2018): Uncover the underlying motivations and barriers for energy efficient renovations Report for European Climate Foundation.

Jafari, Amirhosein; Valentin, Vanessa (2017): An optimization framework for building energy retrofits decision-making. In *Building and Environment* 115, pp. 118–129.

Jochum, Patrick; Mellwig, Peter; Lempik, Julia; Pehnt, Martin; Böttcher, Saskia; Oehsen, Amany von et al. (2017): Ableitung eines Korridors für den Ausbau der erneuerbaren Wärme im Gebäudebereich - Anlagenpotenzial, pp. 0–234.

Klauß, Swen; Maas, Anton (2003): Entwicklung einer Datenbank mit Modellgebäuden für energiebezogene Untersuchungen, insbesondere der Wirtschaftlichkeit.

Klein, Tank; A.M.G; Coauthors (2002): Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. In *Int. J. of Climatol.* (22), pp. 1441–1453.

Kohlhepp, Peter; Harb, Hassan; Wolisz, Henryk; Waczowicz, Simon; Müller, Dirk; Hagenmeyer, Veit (2019): Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. In *Renewable and Sustainable Energy Reviews* 101 (February 2018), pp. 527–547. DOI: 10.1016/j.rser.2018.09.045.

Konstantin, Panos; Konstantin, Margarete (2018): Power and Energy Systems Engineering Economics. Cham: Springer International Publishing.

Kost, Christoph; Shammugam, Shivenes; Fluri, Verena; Peper, Dominik; Davoodi Memar, Aschkan; Schlegl, Thomas (2021): Levelized Cost of Electricity. Renewable Energy Technologies. Freiburg: Fraunhofer Institute for Solar Energy Systems (ISE).

Kranzl, Lukas; Forthuber, Sebastian; Fallahnejad, Mostafa; Büchele, Richard; Fleiter, Tobias; Mandel, Tim et al. (2021): Renewable space heating under the revised Renewable Energy Directive. Final report. ENER/C1/2018-494. Brussels: European Commission.

Kreidelmeyer, Sven; Dambeck, Hans; Kirchner, Almut; Wünsch, Marco (2020): Kosten und Transformationspfade für strombasierte Energieträger. Available online at www.prognos.com.

Maia, Iná; Kranzl, Lukas; Müller, Andreas (2021): New step-by-step retrofitting model for delivering optimum timing. In *Applied Energy* 290, p. 116714. DOI: 10.1016/j.apenergy.2021.116714.

Maier, Urs; Deutsch, Matthias (2018): Die zukünftigen Kosten strombasierter Brennstoffe: Schlussfolgerungen aus Sicht von Agora Verkehrswende und Agora Energiewende.

Mataszsz (2019): Data on the hungarian district heating sector 2019. Available online at http://marefateadyan.nashriyat.ir/node/150.

Mauro, Gerardo Maria; Hamdy, Mohamed; Vanoli, Giuseppe Peter; Bianco, Nicola; Hensen, Jan L. M. (2015): A new methodology for investigating the cost-optimality of energy retrofitting a building category. In *Energy and Buildings* 107, pp. 456–478. DOI: 10.1016/j.enbuild.2015.08.044.

Maya-Drysdale, Larisa; Høgh Iversen, Niklas; Gydesen, Annette; Skov Hansen, Peter Martin (2019): Review study on household tumble driers. Final report. Luxembourg: Publications Office of the European Union.

Milic, Vlatko; Amiri, Shahnaz; Moshfegh, Bahram (2020): A systematic approach to predict the economic and environmental effects of the cost-optimal energy renovation of a historic building district on the district heating system. In *Energies* 13 (1). DOI: 10.3390/en13010276.

Mudgal, Shailendra; Tinetti, Benoît; Hoa, Eric; Audard, Guillaume; Robertson, Chris; Goodman, Paul; Pitman, Stephen (2011): Preparatory Studies for Ecodesign Requirements of EuPs (III). Lot 22 Domestic and commercial ovens (electric, gas, microwave), including when incorporated in cookers. Paris: BIO Intelligence Service.

Nussbaumer, Thomas; Thalmann, Stefan; Jenni, Andres; Ködel, Joachim (2020): Handbook on Planning of District Heating Networks. Bern: EnergieSchweiz.

ODYSSEE-MURE (2022): MURE Database on Energy Efficiency Measures in the European Union. Available online at https://www.measures.odyssee-mure.eu/energy-efficiency-policies-database.html#/, checked on 10/8/2020.

OpenStreetMap (2021): Key:highway. OpenStreetMap Wiki. Available online at https://wiki.openstreetmap.org/wiki/Key:highway, checked on 4/20/2021.

Persson, Urban; Werner, Sven (2011): Heat distribution and the future competitiveness of district heating. In *Applied Energy* 88 (3), pp. 568–576. DOI: 10.1016/j.apenergy.2010.09.020.

Persson, Urban; Wiechers, Eva; Möller, Bernd; Werner, Sven (2019): Heat Roadmap Europe: Heat distribution costs. In *Energy* 176, pp. 604–622. DOI: 10.1016/j.energy.2019.03.189.

Pezzuto, Simon; Zambotti, Stefano; Croce, Silvia; Zambelli, Pietro; Popovski, Eftim; Steinbach, Jan et al. (2018): Hotmaps Project, D2.3 WP2 Report – Open Data Set for the EU28, 2018.

PGNIG (2019): Sprawozdanie zarzadu z działalności PGNIG S.A. i grupy kapitałowej PGNIG za rok 2019.

PVSITES Consortium (2016): D2.2 European climate zones and bio-climatic design requirements (August 2016), pp. 1–31. Available online at https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ac7b5027&appId=PPGMS.

Sarihi, Soad; Mehdizadeh Saradj, Fatemeh; Faizi, Mohsen (2021): A Critical Review of Façade Retrofit Measures for Minimizing Heating and Cooling Demand in Existing Buildings. In *Sustainable Cities and Society* 64, p. 102525. DOI: 10.1016/j.scs.2020.102525.

Stadtwerke Karlsruhe (2020): Umwelterklärung 2020.

Steinbach, Jan; Staniaszek, Dan (2015): Discount rates in energy system analysis. Discussion Paper. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI).

Stocker, E.; Koch, D. (2017): Cost-Effective Refurbishment of Residential Buildings in Austria. In Fernando Pacheco-Torgal, Claes-Göran Granqvist, Bjørn Petter Jelle, Giuseppe Peter Vanoli, Nicola Bianco, Jarek Kurnitski (Eds.): Cost-Effective Energy Efficient Building Retrofitting: Materials, Technologies, Optimization and Case Studies. Amsterdam: Elsevier, pp. 489–513.

TABULA/EPISCOPE (2017): National Building Typologies. Available online at https://episcope.eu/building-typology/, checked on 4/5/2022.

Taylor, Michael; Ralon, Pablo; Al-Zoghoul, Sonia; Jochum, Matthias; Gielen, Dolf (2022): Renewable Power Generation. Costs in 2021. Abu Dhabi: International Renewable Energy Agency (IRENA).

Ürge-Vorsatz, Diana; Kelemen, Agnes; Tirado-Herrero, Sergio; Thomas, Stefan; Thema, Johannes; Mzavanadze, Nora et al. (2016): Measuring multiple impacts of low-carbon energy options in a green economy context. In *Applied Energy* 179, pp. 1409–1426. DOI: 10.1016/j.apenergy.2016.07.027.

VHK/ARMINES (2016): Preparatory/review study. Commission Regulation (EC) No. 643/2009 with regard to ecodesign requirements for household refrigeration appliances and Commission Delegated Regulation (EU) No. 1060/2010 with regard to energy labelling of household refrigeration appliances. Final report. Luxembourg: Publications Office of the European Union.