

Quantifying Energy Efficiency First in EU scenarios: implications for buildings and energy supply



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EXECUTIVE SUMMARY

The **Energy Efficiency First (EE1st) principle** aims to consider and prioritise demand-side resources (end-use energy efficiency, demand response, etc.) whenever they deliver more value than supply-side resources (generation, networks, storage, etc.) in achieving the same objectives. This study set out to provide quantitative evidence on EE1st by investigating the level of end-use energy efficiency measures in the building sector that would provide the greatest benefit for the European Union (EU) in transitioning to net-zero greenhouse gas (GHG) emissions by the year 2050.

By using a suite of **energy system models**, three **scenarios** are investigated (LOWEFF, MEDIUMEFF, HIGHEFF), each of them reaching the net-zero target. The scenarios differ regarding the ambition level for building retrofits, energy-efficient appliances and other energy efficiency measures in residential and non-residential buildings. These differences, in turn, affect the deployment of energy generators and networks for electricity, district heating, and hydrogen. As such, this analysis helps determine the extent to which society is better off – in pure monetary terms – if end-use energy efficiency in buildings was prioritized over generators, networks and storage facilities, in line the EE1st principle.

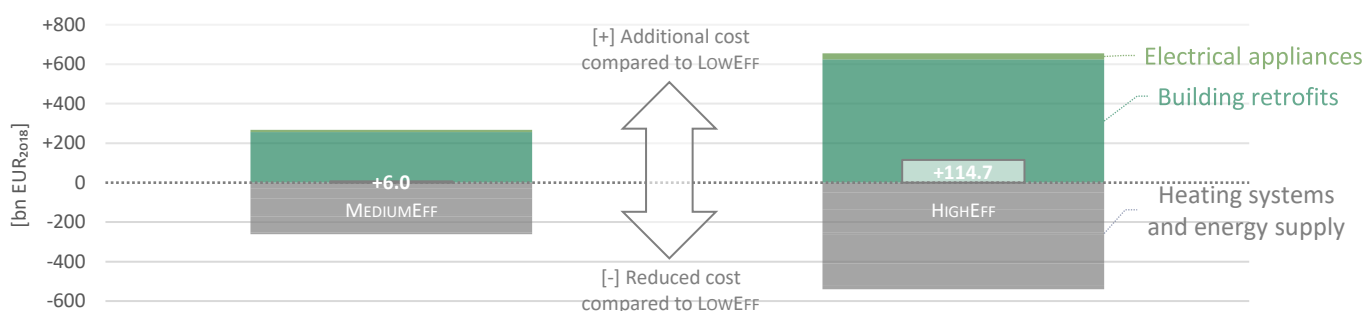


Figure 1. Energy system cost compared to LOWEFF scenario for the EU-27 over the period 2020–2050.

Energy system cost including capital, fuel, maintenance, greenhouse gas emissions allowance costs | Energy supply including electricity generation/networks/storage, district heating generation/networks/storage, hydrogen generation

The findings suggest that energy efficiency in buildings is critical to achieve net-zero GHG emissions by 2050. The LOWEFF scenario (-21.1% reduction in final energy demand for buildings in 2050 vs. 2020 levels) represents the **conservative lower end of reasonable ambition levels** for end-use energy efficiency in buildings with a view to net-zero emissions. This level of ambition is significantly above the business-as-usual pathway of the EU Reference Scenario (-10.4% final energy demand in 2050 vs. 2020) (Capros et al. 2021). According to the central indicator of energy system cost (**Figure 1**), the more ambitious scenarios MEDIUMEFF (-30.2% final energy demand in 2050 vs. 2020) and HIGHEFF (-35.5% final energy demand in 2050 vs. 2020) are generally not cost-effective in comparison to LOWEFF.

However, there is ample reason to support these **ambition levels beyond the LOWEFF scenario**. For one thing, the differences in energy system cost are small in magnitude – e.g. the additional annual cost in HIGHEFF vs. LOWEFF corresponds to less than 0.03% of the EU’s gross domestic product. For another, this study did not anticipate the recent spike in **energy prices** as of 2021–2022, which would justify higher ambition levels for energy efficiency (Eichhammer 2022). The same applies to the inclusion of indoor comfort gains, reduced air pollution and other **multiple impacts**. As demonstrated in a follow-up report (ENEFIRST 2022), their consideration significantly enhances the attractiveness of energy efficiency and thus provides further support for the EE1st principle. In practice, the scenarios set out in this study require an ambitious package of planning and policy instruments. Another branch of reports in the ENEFIRST project (2021d, 2021c, 2021b) provides a detailed account of policy design options for EE1st.

1. INTRODUCTION

The **Energy Efficiency First (EE1st) principle** has lately gained traction in the political debate in the European Union (EU). After its definition in the Governance Regulation (European Union 2018c, Art. 2.18), the proposal for a recast of the Energy Efficiency Directive (EED) by the European Commission (2021d, Art. 3) specifies the scope of its application. The principle shall henceforth apply to all energy systems, processes of public procurement, and energy transformation, transmission and distribution systems (Wilson 2021; ENEFIRST 2021b). Implementing EE1st and thus prioritising demand side resources (end-use energy efficiency, demand response, etc.) whenever these cost less or deliver more value than default energy infrastructure (generation, networks, storage, etc.) (ENEFIRST 2020a) requires actions across sectors. This is particularly relevant with a view to the EU objective of a minimum 55% reduction in greenhouse gas (GHG) emissions by 2030 and **net zero GHG emissions** by 2050, as set out in the European Climate Law (European Union 2021).

Buildings are a key sector in this setting. The **building sector** accounts for 40% of the EU-27's final energy demand in 2019, two thirds of which are used in the households sector and the remainder in commercial and public buildings (Eurostat 2022a). Altogether, buildings are responsible for approximately 36% of GHG emissions in the EU (European Union 2018b). Space heating is the major end-use, accounting for 77% of building energy use in the EU-27 – way ahead of water heating, appliances and lighting, process heating and other end-uses (Fleiter et al. 2017). The high energy use for space heating is partly because 75% of the EU's building stock is energy inefficient compared to legislation on energy performance. This also reflects in a low retrofit rate – on average, the total building stock's primary energy consumption reduces by only 1% per year through energy retrofits (Esser et al. 2019).

To pursue the ambition of net-zero emissions in the building sector, there are two major options. On the one hand, end-use energy efficiency, energy service sufficiency and demand response are what is known as **demand-side resources** in the context of EE1st (Mandel et al. 2022; ENEFIRST 2020a). These technologies and actions reduce the quantity or temporal pattern of energy use. Constructional heat insulation measures and energy-efficient appliances are important demand side resources in the building sector with substantial potential (IEA 2020). On the other hand, the emissions of heat and electricity use for buildings must be reduced by using technologies that produce no or significantly lower emissions than fossil energy generation methods. Referred to as **supply-side resources**, this includes on-site equipment (e.g., biomass boiler), but also all conversion, network, and storage infrastructures needed to supply energy carriers to end-users. Especially for the building end-use of heating, various supply-side decarbonisation options are debated. These range from electrification via heat pumps, to district heating, direct use of biomass, solar thermal and other renewable energy sources, to hydrogen and hydrocarbon-based synthetic combustibles (Stephanos and Höhne 2018; Andreu et al. 2019).

Energy systems modelling is a significant tool to quantify the trade-off between demand and supply side resources for long-term transition processes in the context of the EE1st principle (ENEFIRST 2020b). By determining cost-optimal transitions by a range of alternative scenarios, it can assist decision-makers in making informed decisions on future technology investment, system operation as well as policy design. In practice, various studies investigate scenarios for the EU energy system towards climate-neutrality by 2050 (Tsiropoulos et al. 2020; D'Aprile et al. 2020; IEA 2021). However, only few studies make explicit the **societal trade-off between saving and supplying energy in the building sector**, according to the notion of the EE1st principle. For example, at subnational level, Harrestrup and Svendsen (2014) find that for a district heating system in the Copenhagen area, it is slightly more cost-effective for society to invest in comprehensive thermal retrofits in the local building stock before deploying new renewable heat supply.

In addition, existing studies tend to have a number of **methodological limitations** that reduce their value for system planning, technology investment and policy formulation in the context of EE1st. First, studies tend to use models with low levels of **temporal, spatial and technical detail**, which may underestimate the need for generation and network capacity and, conversely, the system benefits of demand side resources (ENEFIRST 2020b). Second, studies for the building sector are typically limited to space heating as an important but not the sole **end-use in buildings**. Electrical appliances, lighting, and other end-uses hold energy efficiency potentials that should not be disregarded (European Commission 2021a). Finally, studies are often limited to the monetary costs of demand and supply side resources (e.g. Dranka et al. 2020). **Multiple impacts** like health benefits or employment gains are often disregarded, although their inclusion can significantly alter the outcome of model-based assessments (Ürge-Vorsatz et al. 2016).

Against this background, the objective of this study is to provide **quantitative evidence on the EE1st principle** by investigating the level of end-use energy efficiency measures in the building sector that would provide the greatest benefit for the EU in transitioning to net-zero GHG emissions by 2050. By applying a suite of detailed energy system models, the study investigates **three scenarios**: LOWEFF, MEDIUMEFF, and HIGHEFF. Each of these scenarios is geared to reach the 2050 target of net-zero GHG emissions in the EU.¹ In particular, the LOWEFF scenario represents the lower end of possible ambition levels for end-use energy efficiency in buildings, which is more ambitious than current trends. However, the scenarios differ in terms of the ambition level for end-use energy efficiency in residential and non-residential buildings – including building retrofits, energy-efficient appliances and other measures. These differences, in turn, affect the investments into and operation of energy conversion and network capacities for power, district heating, and hydrogen.

In this study, **energy system cost** is the central performance indicator, indicating the sum of all capital costs, operation and maintenance costs, and fuel costs for energy use in buildings and related energy supply. It thus indicates the extent to which society is better off – in pure monetary terms – if end-use energy efficiency in buildings on the demand side was prioritized over generators, networks and storage facilities on the supply side. In a follow-up ENEFIRST report (2022), the analysis will be substantiated with quantitative appraisal of selected **multiple impacts**, including avoided air pollution damage as well as indoor comfort gains. This is to account for the non-monetary benefits of demand- and supply-side resources in the context of the EE1st principle and thus to ensure a fair comparison between them.

This report is structured as follows. **Chapter 2** outlines the scenarios, energy system models and key performance indicators used in this study. This **methodology** is more thoroughly described in a previous ENEFIRST report (2021a). **Chapter 3** presents the quantitative **results** of the model-based analysis, covering both cross-sectoral findings as well as sectoral features in buildings, electricity supply, district heating supply, and hydrogen supply. **Chapter 4** discusses the **policy implications** of the study with a view to the revision of the EED and other legislations. It also points out the **methodological limitations** of the study. Finally, **Chapter 5** concludes this report and provides an outlook to further research.

¹ In keeping with the terminology used in ENEFIRST (2020b), the three scenarios correspond to the normative paradigm of quantitative assessments for EE1st. That is, they investigate what resource options should be adopted under given framework conditions to reach an anticipated vision of the future – in this case, net-zero GHG reductions by the year 2050. In turn, the scenarios do not show what resources could or are likely to be adopted over time in response to socio-economic conditions and policy measures, referred to as the exploratory paradigm to EE1st.

2. METHODOLOGY

The methodology of this model-based assessment is thoroughly described in ENEFIRST (2021a). In the following, we briefly recapitulate the target scenarios ([Chapter 2.1](#)), energy system models ([Chapter 2.2](#)), and key performance indicators ([Chapter 2.3](#)) used in this analysis.

2.1 Target scenarios

We analyse three scenarios, representing different **decarbonisation pathways** for the European energy system by the year 2050. Each of these scenarios is set to reach the 2050 target of net-zero emissions. However, the scenarios differ in terms of the ambition level on end-use energy efficiency measures in residential and non-residential buildings and the associated deployment of energy conversion and network capacities for power, district heating, and hydrogen ([Figure 2](#)):

- The Low Efficiency in Buildings (**LOWEFF**) scenario assumes building decarbonisation primarily via the use of renewable energy sources. It reflects a future where EE1st is not comprehensively applied. This implies that the renovation rates are not increased above the current levels and renovation depth is only moderately improved. Still, the scenario results in final and primary energy savings compared to the base year 2020;
- The Medium Efficiency in Buildings (**MEDIUMEFF**) scenario is characterized by a balanced deployment of energy efficiency measures in buildings and supply-side generation and network infrastructures. Renovation rates are doubled compared to the LOWEFF scenario and also renovation depth is increased;
- The High Efficiency in Buildings (**HIGHEFF**) scenario considers end-use energy efficiency measures in buildings as the most favourable decarbonisation option for the European energy system by 2050. Renovation rates are increased further and a strong focus is put on deep renovation to achieve substantial energy savings.

		SCENARIOS		
		Low Efficiency in Buildings (LOWEFF)	Medium Efficiency in Buildings (MEDIUMEFF)	High Efficiency in Buildings (HIGHEFF)
Decision objectives	2020 to 2050	Meet energy service demand	2030	2050
			<ul style="list-style-type: none"> ▪ ≥55% reduction GHG emissions (1990) ▪ ≥32% share for renewable energy ▪ ≥32.5% improvement in energy efficiency 	Net-zero GHG emissions according to European Climate Law
BUILDINGS	Thermal efficiency	Moderate component requirements and renovation rates	Enhanced component requirements and renovation rates	Ambitious component requirements and renovation rates
	Appliance efficiency	Moderate minimum energy performance standards	Enhanced minimum energy performance standards	Ambitious minimum energy performance standards
ENERGY SUPPLY	Individual heat supply	Optimized capacity expansion & operation Balanced deployment of solar thermal, heat pumps, etc.		
	Energy sufficiency	Equal indoor temperatures, floor space, technology ownership, appliance use intensity, etc.		
	Fuel prices	Fuel prices for crude oil, natural gas, hard coal according to <i>Sustainable Development</i> scenario (IEA World Energy Outlook 2019)		
	Other energy demand	Energy demand in industry & transportation according to <i>1.5TECH</i> scenario (Clean Planet for All study)		
	Electricity supply	Optimized capacity expansion & operation No CCS, coal phase-outs, declining biomass, power transmission based on TYNDP-2018		
	District heating supply	Optimized capacity expansion & operation Limited potential for solar thermal, geothermal, biomass		
	Hydrogen supply	Optimized capacity expansion & operation 20% share of hydrogen & synthetic methane in building gas demand in 2050; high import prices		

Figure 2. Outline of scenario narratives in energy system analysis

Source: ENEFIRST project

Comparing the three scenarios with documents and existing scenarios, it turns out that the LOWEFF scenario is more ambitious than the 2020 Reference Scenario ('PRIMES-2020') (Capros et al. 2021). The targets outlined in the Renovation Wave strategy (European Commission 2020a) and scenarios modelled in the climate target impact assessment (European Commission 2020b) are in between the ambition levels of the MEDIUMEFF and HIGHEFF scenarios. Overall, the comparison with other scenarios of energy efficiency in the building stock shows that other studies delivered scenarios with lower ambition than our LOWEFF scenario and also scenarios with higher energy savings than our HIGHEFF scenario. Thus, we did not design the scenarios as extreme scenarios. We will refer back to this topic in [Chapter 4.1](#).

In sum, the scenarios allow to assess the **societal value of end-use energy efficiency in the building sector** as an important demand-side resource in view of EU's long-term target of net-zero greenhouse gas emissions. As further described in [Chapter 2.3](#) below, we use the term 'societal' in this context to emphasize we are not focusing on the costs for certain investors, households or other agents. Rather, we put the perspective of the energy system and costs and benefits occurring to the society as a whole in the focus of the analysis. However, we are aware that the exact system boundary of the 'societal value' is not always easy and clear to draw. In [Chapter 4](#), we discuss this point as well. In the context of the EE1st principle, this analysis thus helps ascertain the difference in terms of monetary costs between a very comprehensive implementation of the principle in the building sector and a more limited and less ambitious implementation that follows established practices of system planning and investment. In addition to these monetary costs there are additional multiple impacts of energy efficiency measures that are dealt with in a dedicated follow-up report (ENEFIRST 2022).

2.2 Energy system models

Four **bottom-up energy system models** are coupled in this assessment to calculate the scenarios:

- **INVERT** estimates investment decisions in residential and non-residential buildings, focusing on space heating, domestic hot water and space cooling. It is based on disaggregated building stocks for the different EU Member States and calculates cost-optimal pathways based on a combination of various retrofitting measures for the building envelope and heating systems.
- **FORECAST** represents long-term appliance adoption behaviour in residential and non-residential buildings. It covers large electrical appliances (e.g., refrigerators), information and communication technologies (e.g., televisions), lighting, small appliances (e.g., coffee machines), as well as cooking equipment (e.g., stoves).
- **ENERTILE** optimizes the investments into all major energy supply infrastructures, including power plants, cogeneration plants, power-to-heat, variable renewable energies, hydrogen supply, synthetic methane supply, cross-border transmission grids, and storage technologies. The model determines a cost-optimal portfolio of technologies, while determining the utilization of these for all hours of each year.
- **NETHEAT** calculates costs related to the expansion and operation of district heating infrastructure and derives the optimal district heating infrastructure associated with different input data and restrictions. Using a hectare-level resolution for all EU countries, it captures specific local situations with regard to heat demands.

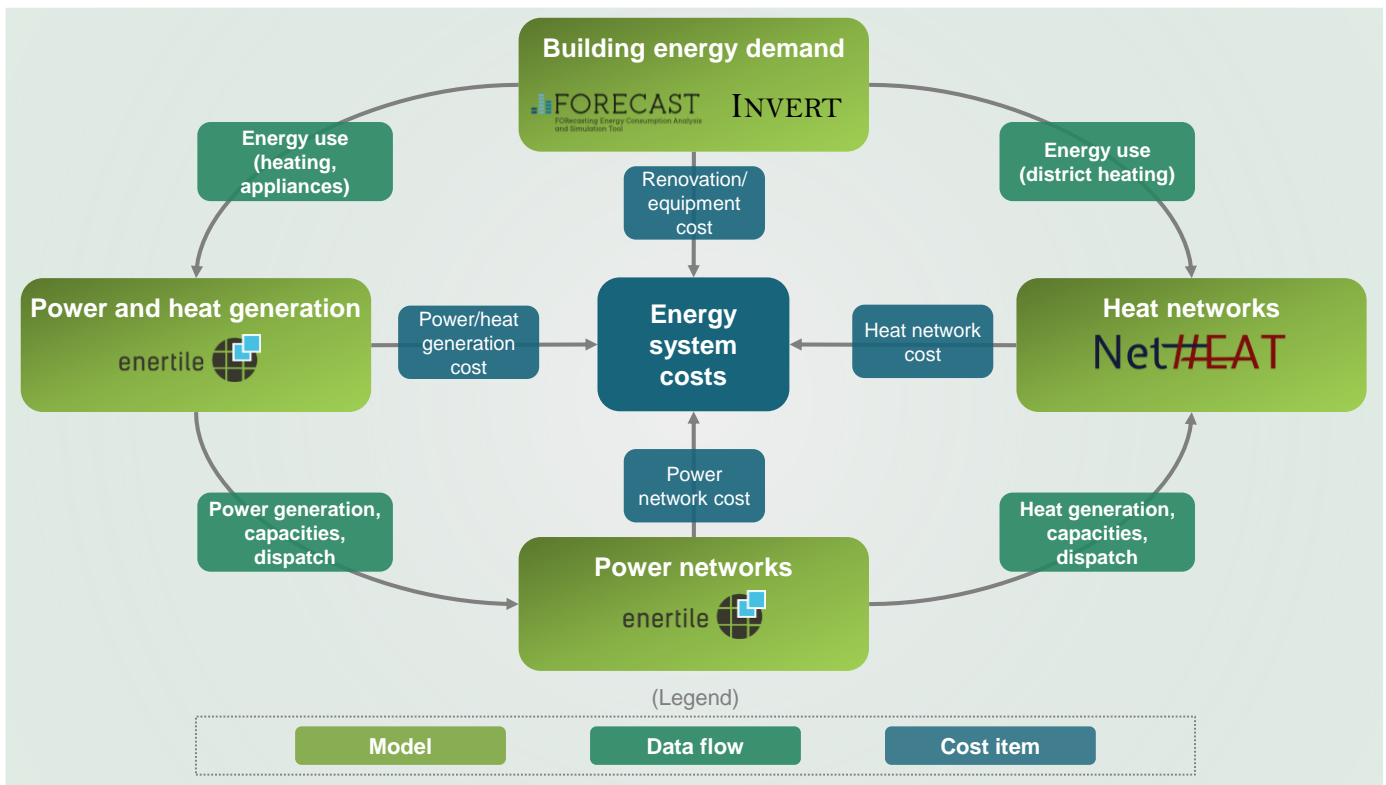


Figure 3. Coupling of models and calculation of energy system cost

Source: ENEFIRST (2021a)

Using these models allows to compare the scenarios in terms of energy system cost, GHG emissions, energy demand and other indicators. The way the models are coupled to determine the central indicator of energy system cost is illustrated in **Figure 3**, with each of the models providing individual cost items. Overall, by soft-coupling these bottom-up models, the model-based assessment features a **comprehensive coverage of the major end-uses** (space heating, water heating, space cooling, electrical appliances, lighting, cooking) in residential and non-residential buildings. On the supply side, operation and investment of **electricity, district heating, and hydrogen systems** are explicitly modelled.

2.3 Key performance indicators

The three scenarios are compared by a set of **key performance indicators**:

- **Energy system cost** | Costs for resource options per sector and cost type (see details below)
- **Energy demand** | Final energy demand used by sector, energy carrier, and end-use;
- **Energy supply** | Annual generation of electricity, heat and hydrogen as well as installed capacities;
- **CO₂ emissions** | Direct CO₂ emissions. Note that all scenarios are set to achieve net-zero GHG emissions in 2050. However, the transition until 2050 differs and thus the total carbon budget;
- **Market development** | Technology ramp-up (e.g. heat pumps) in terms of sales/market shares.

Energy system cost is the central indicator in this assessment. It reflects the value of energy efficiency in buildings regarding its interlinkages with the supply sector, indicating the extent to which society is better off – in pure monetary terms – if energy efficiency was prioritized in energy planning and operation. The indicator consists of various cost items (**Figure 4**) that are computed by the models.

Σ ENERGY SYSTEM COST (EUR₂₀₁₈)

	Capital costs ¹	Fuel costs ²	O&M costs	Other costs
Buildings	<ul style="list-style-type: none"> Building renovation Heating equipment Electrical appliances & lighting equipment 	<ul style="list-style-type: none"> Wholesale costs for natural gas, fuel oil, coal, biomass 	<ul style="list-style-type: none"> Maintenance costs for heating systems 	-
Electricity supply	<ul style="list-style-type: none"> Generation plants Electricity storage facilities Electricity networks 	<ul style="list-style-type: none"> All relevant fuel costs (wholesale) 	<ul style="list-style-type: none"> Import/export cost Fixed & variable O&M costs of supply assets (incl. ancillary services) 	<ul style="list-style-type: none"> EU emissions allowance costs (ETS)
District heating supply	<ul style="list-style-type: none"> Boilers & cogeneration plants Heat storage facilities Heat networks 	<ul style="list-style-type: none"> All relevant fuel costs (wholesale) 	<ul style="list-style-type: none"> Fixed & variable O&M costs of supply assets 	<ul style="list-style-type: none"> EU emissions allowance costs (ETS)
Hydrogen supply	<ul style="list-style-type: none"> Hydrogen electrolyzers Methanation facilities 	-	<ul style="list-style-type: none"> Import/export cost Fixed & variable O&M costs of supply assets 	-

¹ 2% discount rate for transforming capital expenditures into annual capital costs (“annuities”)
² Excl. taxes (valued added tax, environmental taxes, renewable taxes, nuclear taxes, etc.)

Figure 4. Cost items for calculation of energy system costs by sector

Source: ENEFIRST project

This model-based assessment is carried out from a **societal perspective**. This has a number of implications for energy system cost: (i) a 2.0% discount rate is used to calculate capital costs (“annuities”) and to discount payment years; (ii) taxes and subsidies are omitted to the extent possible as they are transfer payments and do not reflect an increase or decrease in societal welfare; (iii) selected multiple impacts (e.g. air pollution) are estimated in an upcoming ENEFIRST report (2022) and will be dealt with separately there.

2.4 Output reporting

This report focuses on the findings for the EU-27 as a whole. Disaggregated outputs at the Member State are available from the **ENEFIRST SCENARIO EXPLORER (Figure 5)**:



Interactive **dashboard** and disaggregated outputs by Member State



Easy access and handling in **MS Excel**



Available from <https://enefirst.eu/>

Figure 5. Overview of the ENEFIRST SCENARIO EXPLORER

The SCENARIO EXPLORER is a Microsoft Excel-based database that features detailed model outputs by indicator (e.g., final energy demand) and Member State (e.g., Austria). It also contains an interactive **dashboard** that allows for a detailed appraisal of the outputs. The Scenario Explorer is available from the ENEFIRST website. Note that the SCENARIO EXPLORER does *not* allow to simulate **variants of the scenarios** (e.g., with different energy prices) or to perform sensitivity analysis. The calculations needed for each scenario are indeed very intensive in computation resources, especially for the detailed simulation of the energy systems.

Summary | Chapter 2 | Methodology

To conclude, this analysis covers a set of three model-based **scenarios** (LOWEFF, MEDIUMEFF, HIGHEFF). Each of these is geared to reach the 2050 target of **net-zero emissions** in the EU-27, but features different **ambition levels for end-use energy efficiency** in residential and non-residential buildings. The models Invert, Forecast, Enertile and NetHEAT are coupled to ascertain these effects. Energy system cost is used as the central performance indicator to determine in which scenario the EU is best off in monetary terms.

3. RESULTS

In the following, we present the quantitative results of the model-based analysis. We begin with cross-sectoral findings on emissions and energy system cost (Chapter 3.1). Then, we turn to sectoral features in buildings (Chapter 3.2), electricity supply (Chapter 3.3), district heating supply (Chapter 3.4), and hydrogen supply (Chapter 3.5).

3.1 Cross-sectoral results

The findings presented in the following generally involve all energy use in the building sector – including residential, commercial and public buildings – as well as all energy use in electricity, district heating and hydrogen supply. Note that differences among the scenarios result exclusively from **different ambition levels for end-use energy efficiency in buildings**. Trends in the industry and transportation sectors, along with assumptions on technology costs and constraints in energy supply, are held constant between the scenarios to ensure that the results are comparable (ENEFIRST 2021a).

Figure 7 presents an overview of **direct greenhouse gas emissions** in the three scenarios.² These emissions are expressed as CO₂ equivalents, thus taking into account the global warming potential of methane (CH₄) and nitrous oxide (N₂O) as other significant greenhouse gases. Compared to 2020 levels, emissions from direct combustion in buildings (e.g. fuel oil) as well as energy supply for final use across all end-use sectors (buildings, industry, transportation) in 2050 are reduced by 98.2% (LOWEFF), 98.8% (MEDIUMEFF), and 99.3% (HIGHEFF). In response to the ambitious building sector efficiency levels in HIGHEFF, emissions are reduced earlier than in the other two scenarios. When looking at the carbon budget, i.e. the sum of emissions in the period 2020–2050, there are minor deviations of -2.9% (MEDIUMEFF) and -6.4% (HIGHEFF) compared to LOWEFF.

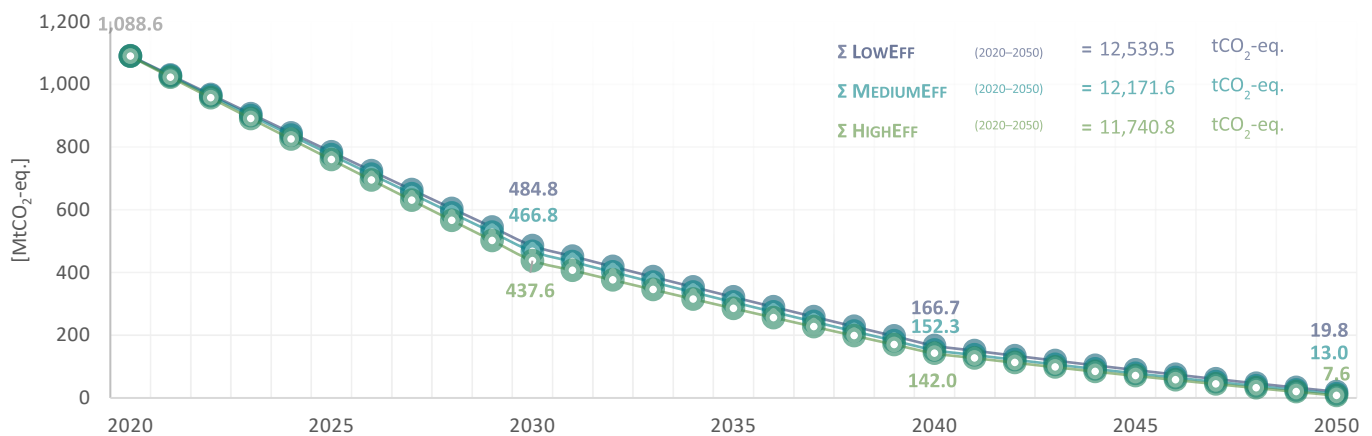


Figure 6. Direct greenhouse gas emissions from buildings and energy supply in EU-27 (2020–2050)

Direct emissions excluding upstream emissions | Emissions in buildings comprise direct combustion of fuels. Emissions from electricity and heat supply are total emissions for final use across all end-use sectors (buildings, industry, transportation)

² Direct emissions arise the conversion from primary, secondary and final energy to useful energy. Upstream or indirect emissions – arising, for example, in the production of energy technologies – are beyond the scope of this analysis.

As can be seen from **Figure 7a**, cutting energy production particularly from lignite and coal is a key prerequisite to follow a net-zero emissions pathway. In 2050, there remain some emissions from oil (incl. synthetic hydrocarbons from power-to-gas), biomass, and gas (incl. natural gas, biomethane, hydrogen, and synthetic methane). From **Figure 7b** is apparent that electricity and heat supply are almost fully decarbonised in 2040, with the remainder of emissions primarily arising within the building sector up until 2050. Overall, these results indicate that there are **different technically viable pathways** to reach net-zero emission levels by 2050. These pathways have different implications with regard to levels of energy demand and supply as well as energy system cost.

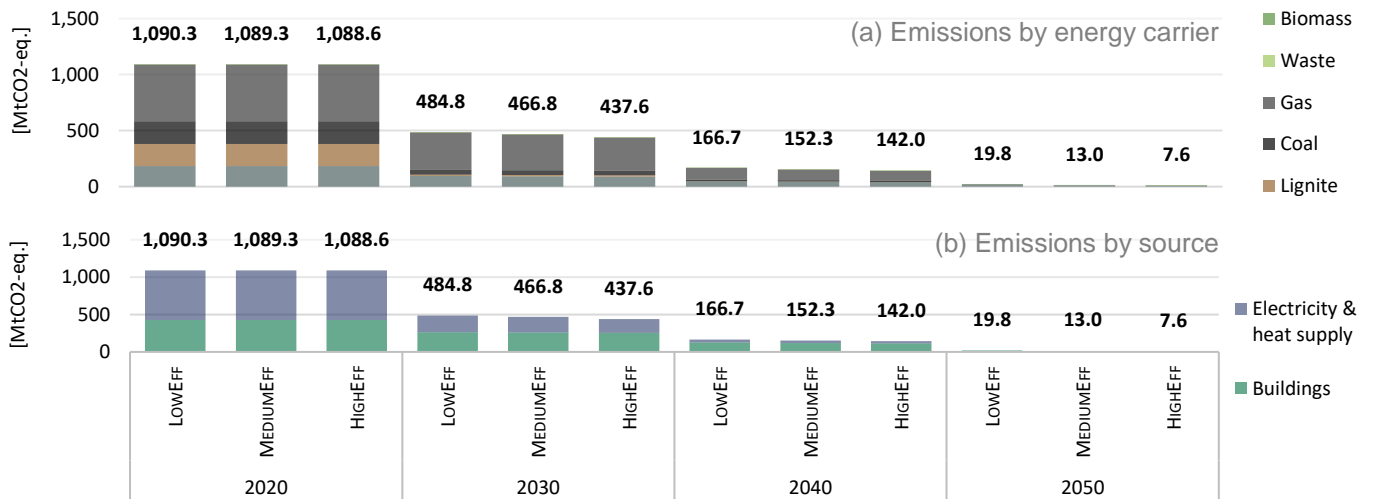


Figure 7. Disaggregated direct greenhouse gas emissions in EU-27 (2020–2050)

Direct emissions excluding upstream emissions | Emissions in buildings comprise direct combustion of fuels. Emissions from electricity and heat supply are total emissions for final use across all end-use sectors (buildings, industry, transportation)

The performance of the three scenarios in terms of the central indicator of **energy system cost** (**Chapter 2.3**) is presented in **Figure 8**. These numbers are expressed (i) in *cumulative* terms, i.e. the sum of energy system cost over the period 2020–2050 using an annual discount rate of 2.0%; and (b) in *differential* terms, i.e. compared to the cost of the LOWEFF scenario. This differential perspective helps highlight the dedicated effects of building sector efficiency in MEDIUMEFF and HIGHEFF on cost.

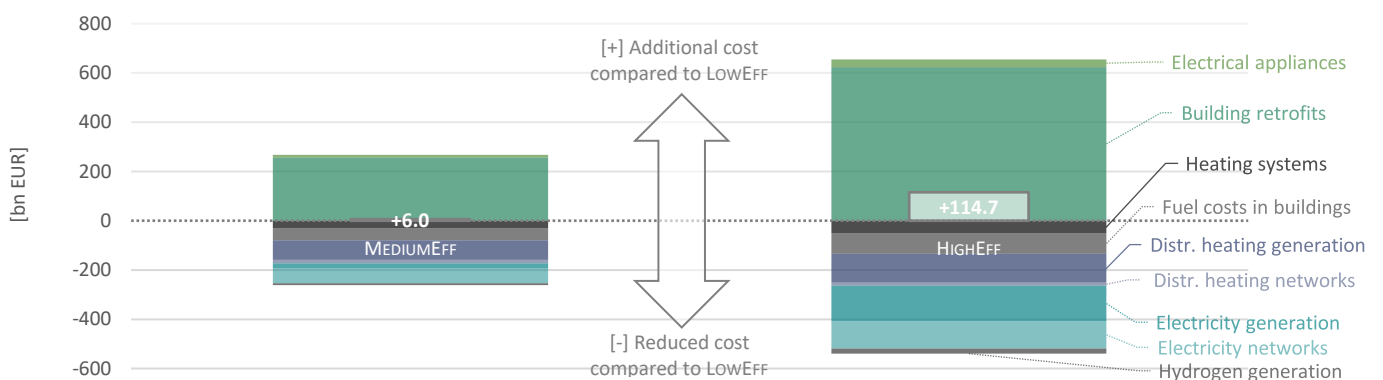


Figure 8. Cumulative differential energy system cost compared to LOWEFF for EU-27 (2020–2050) by cost item

Fuel costs in buildings including natural gas, coal, oil, biomass for direct combustion

This chart is revealing in three ways. First, it indicates that the higher ambition levels for building sector energy efficiency in MEDIUMEFF and HIGHEFF are **not necessarily cost-effective in energy system cost terms** compared to the more moderate ambition levels of LOWEFF. Cumulative differential cost amounts to +6.0 bn EUR (MEDIUMEFF) and +114.7 bn EUR (HIGHEFF) over the period 2020–2050, equivalent to *annual* differential cost of +0.2 bn EUR/a (MEDIUMEFF) and +3.8 bn EUR/a (HIGHEFF). Both scenarios thus incur additional cost in reaching essentially the same **objective of net-zero greenhouse gas emissions** by 2050. However, as discussed before (ENEFIRST 2021a), the indicator of energy system cost does not factor in the variety of multiple impacts in the realms of comfort gains, air pollution reduction, and others. How the inclusion of these impacts may alter the outcome of this analysis will be discussed in **Chapter 4**. The quantitative effect of selected multiple impacts on energy system will be demonstrated in a dedicated follow-up report (ENEFIRST 2022).

Second, it is clear that improving **building sector efficiency** – both for building retrofits and for replacing inefficient electrical appliances – incurs **significant cost** in the form of capital costs.³ The ensuing energy savings, described further below, lead to **reduced energy system cost** for heating systems, electricity generation, and other cost items. These cost items are more explicitly depicted in **Figure 9**.

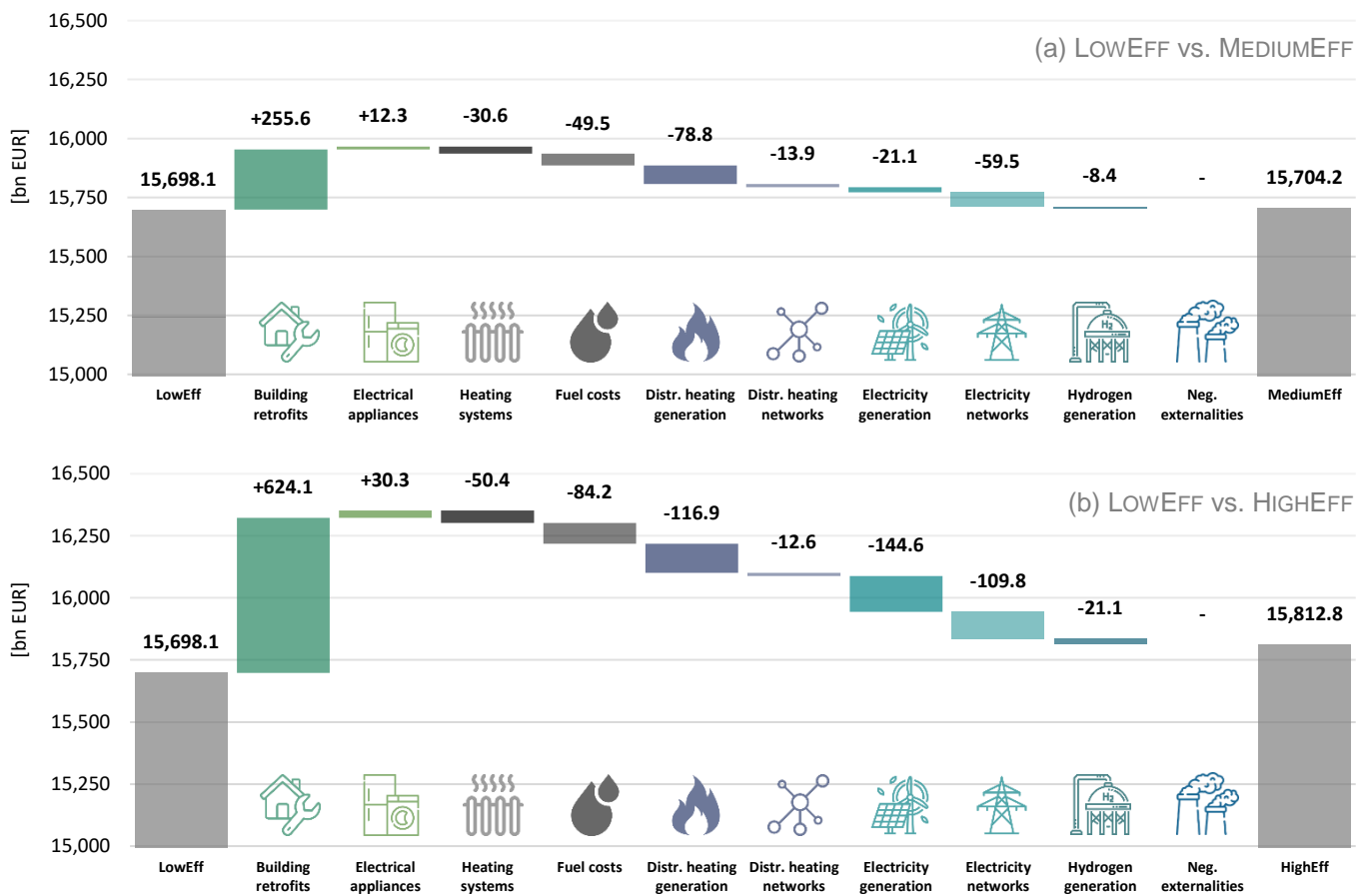


Figure 9. Decomposition of cumulative differential compared to LowEff for EU-27 (2020–2050)

³ Capital costs are the initial capital expenditures ('investments') of the efficiency measures converted into annual instalments ('annuities'), As such, investments made before 2050 are only partially considered (ENEFIRST 2021a).

Fuel costs in buildings including natural gas, coal, oil, biomass and exclude hydrogen and synthetic methane | Damage cost from negative externalities from air pollution and greenhouse gas emissions to be presented in ENEFIRST (2022)

As described further below, when improving the efficiency of the building stock, individual heating systems in buildings require smaller capacities (e.g., for heat pumps), which is reflected in capital cost savings (-30.6 to -50.4 bn EUR). Likewise, buildings have lower fuel costs for natural gas, fuel oil, coal and biomass (-49.5 to -84.2 bn EUR). With regard to energy supply, end-use energy efficiency also leads to significant cost savings for the generation and distribution of electricity (-80.7 to -254.4 bn EUR) and district heating (-92.7 to -129.5 bn EUR). Another cost driver is the supply of hydrogen (-8.4 to -21.1 bn EUR), which is used for both direct use in buildings as well as reconversion in power plants, cogeneration plants and district heating boilers. In sum, the additional capital costs for building retrofits and energy-efficient appliances in MEDIUMEFF compared vs. LOWEFF amount to +267.9 bn EUR and are almost entirely offset by savings in energy supply of -261 bn EUR over the period 2020–2050, i.e. a ratio of 97.7%. In HIGHEFF vs. LOWEFF, costs (+654.4 bn EUR) and savings (-539.7 bn EUR) result in a savings ratio of 82.5%. There is thus a **clear trade-off between saving and supplying energy**.

Third, the numbers in **Figure 9** indicate that the **aggregate cost volume** across the three scenarios is at a very similar level. Despite the significant differences in ambition levels for building sector efficiency, the scenarios end up at a cumulated cost volume between 15.7 (LOWEFF) and 15.8 *trillion* EUR (HIGHEFF) over the period 2020–2050. This corresponds to average annual cost between 523.3 (LOWEFF) and 527.1 bn EUR/a (HIGHEFF), or a relative standard deviation of 0.41% between the three scenarios. This demonstrates that **energy system cost will be substantial in the mid and long term until 2050** – regardless of whether building sector efficiency has absolute priority over supply-side resources or not.⁴ If performance requirements for energy use in buildings are moderate, as exemplified in the LOWEFF scenario, the supply side will need to deploy and operate larger capacities for electricity, district heating and hydrogen supply in order to reach the net-zero target by 2050. In turn, more efficient energy use in buildings, as depicted by MEDIUMEFF and HIGHEFF, leads to cost savings on the supply side but incurs substantial capital costs for the energy efficiency measures.

Overall, the results show that the differences between the scenarios are small with respect to both the explicit decision objective of net-zero emissions by 2050 and – implicitly – the ensuing carbon budget over this period, as well as energy system cost. Most, but not all, of the extra costs due to increased end-use energy efficiency investments in MEDIUMEFF and HIGHEFF are compensated by savings in energy supply costs. Before turning to general conclusions, the following sections present detailed **sectoral findings** for buildings, electricity supply, district heating supply, and hydrogen supply.

⁴ Note that these are total numbers that do not relate to the cost volume accruing anyway until 2050 for power plants, networks and other technologies. In other words, the numbers do not reflect the *additional* cost for reaching net-zero greenhouse gas emission levels compared to any scenario following a business-as-usual pathway.

3.2 Buildings

Table 1. Main results for buildings

Key results	LowEff	MediumEff	HighEff
Building energy demand in 2050 in [TWh]	3,488.2	3,060.2	2,812.2
• of which heating & cooling [TWh]	2,498.4	2,099.5	1,865.4
• of which electrical appliances [TWh]	989.7	960.7	946.8
Total energy savings compared to 2020 [%]	-21.1%	-30.2%	-35.5%
Building renovation rate (2050-2020) [%/a]	0.7%	1.4%	1.7%



The models INVERT and FORECAST were used to provide the projections for residential and non-residential buildings. **Figure 10** provides the breakdown of **final energy demand** by end-use. In response to the constraints for building components and appliances assumed in the scenarios, final energy demand in 2050 decreases between 21.1% (LOWEFF) and 35.5% (HIGHEFF) relative to 2020. In 2050, space and water heating account for 64.2% (LOWEFF) to 57.3% (HIGHEFF) of final energy demand.

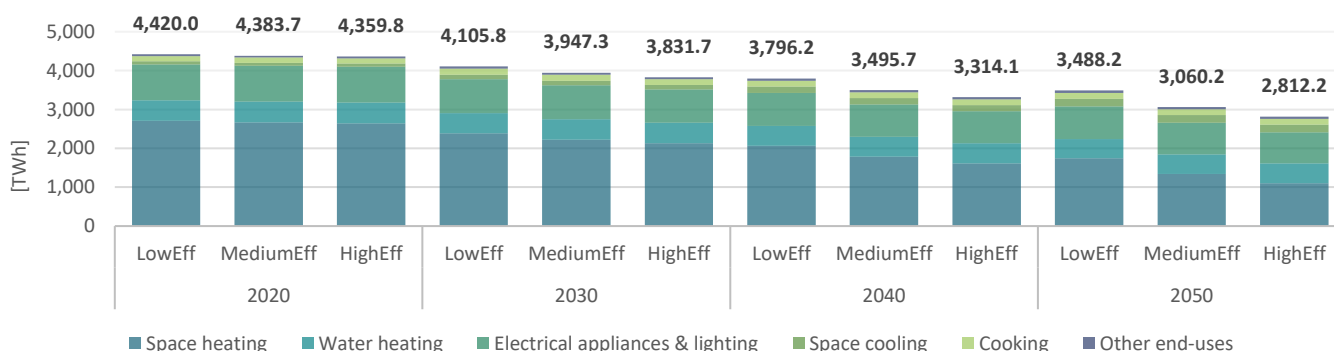


Figure 10. Final energy demand by end-use in EU-27

The different ambition levels for the energy performance of building components are also clearly apparent in **Figure 11**. While the moderate requirements in LOWEFF lead to a **final energy demand for heating and cooling** of 2498.4 TWh in 2050, the HIGHEFF scenario ends up at 1865.4 TWh. The reduction is especially pronounced in the heat supplied with heat pumps (-292.7 TWh in HIGHEFF in 2050 vs. LOWEFF) and district heating (-215 TWh). Overall, in 2050 heat pumps in all scenarios cover the highest share of heat demand (about 40%), followed by district heating (20% in the LOWEFF scenario and 16% in HIGHEFF) and biomass. The latter is mainly restricted by the absolute biomass resource potential, which was set to about 300 TWh. Since this potential is fully exploited, the share of biomass in the year increases from 11% in the LOWEFF scenario to 17% in the HIGHEFF scenario. The share of solar heat in the year 2050 is 11% in LOWEFF and 13% in HIGHEFF).

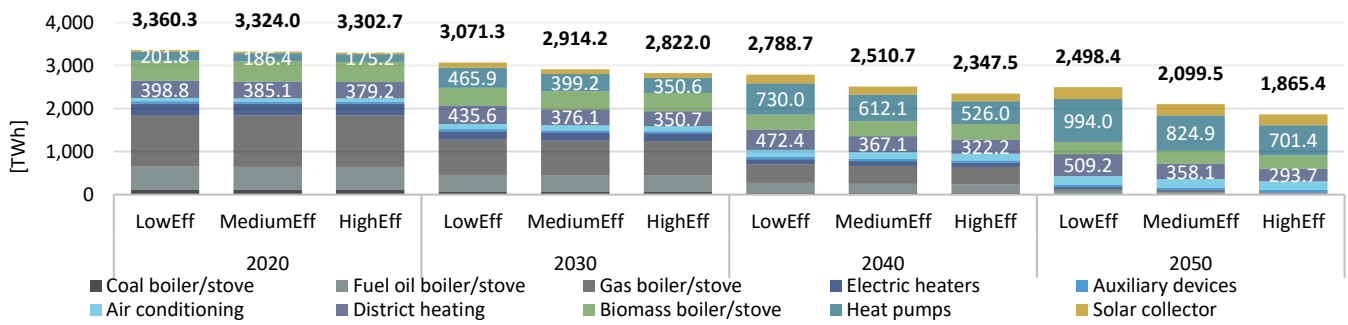


Figure 11. Final energy demand for heating and cooling technology in EU-27

Reduced final energy also reflects in the **nominal capacities** for heating technologies (Figure 12). Across all scenarios, there is a significant increase in heat pump capacity in buildings, reaching 833.9 (LOWEFF) to 719.0 GW (HIGHEFF) in 2050. Final energy savings in HIGHEFF vs. LOWEFF in 2050 reduce heat pump capacity needed by 114.9 GW (13.8%). As will be demonstrated further below, these differences in final energy demand and capacities needed have clear implications for the magnitude of energy supply.

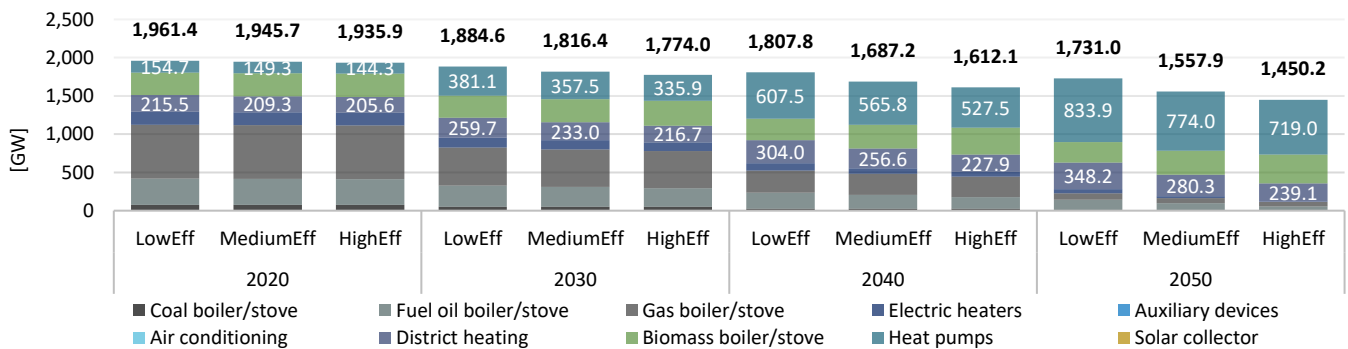


Figure 12. Nominal capacities of heating technologies in EU-27

If we now turn to the **energy efficiency of heat pumps** in particular (Figure 13), it can be seen that better energy performance of the building envelope enhances the seasonal coefficient of performance (SCOP) of heat pumps in the EU-27. While the SCOP is 3.2 in the LOWEFF scenario, it reaches 3.5 in HIGHEFF. The modelling approach in the model Invert/Opt considers the fact that the SCOP of heat pumps depends on the supply temperature level of the heating system in a specific building. Renovation of buildings lowers heat demand while – not necessarily – changing the radiators or other forms of heat emission system. This leads to the fact that the supply temperature can be decreased after renovation. The model thus calculates higher SCOP values of buildings after renovation. The displayed SCOP values represent a weighted average of the model results over the full spectrum of buildings and climatic zones in the EU building stock. Overall, this is a clear example of the importance to consider the interactions between end-use energy efficiency and building energy supply equipment.



Figure 13. Seasonal coefficient of performance of heat pumps in EU-27 in 2050

In the scenarios, reductions in final energy demand are less pronounced for **electrical appliances, cooking, and other end-uses** (Figure 14). The reduction relative to 2020 levels ranges from 6.6%

(LOWEFF) to 10.4% (HIGHEFF). This is not because energy efficiency potentials are limited per se for these end-uses. Instead, the FORECAST model used for these projections features data gaps with regard to the specific costs of individual appliances, particularly for those in non-residential buildings. Ultimately, we modelled energy efficiency improvements only for those appliances for which reliable cost was available, which results in modest reductions until 2050. Also note that direct rebound effects and affluence effects (e.g., increased ownership rates) are taken into account in the model, which counteracts energy efficiency improvements.

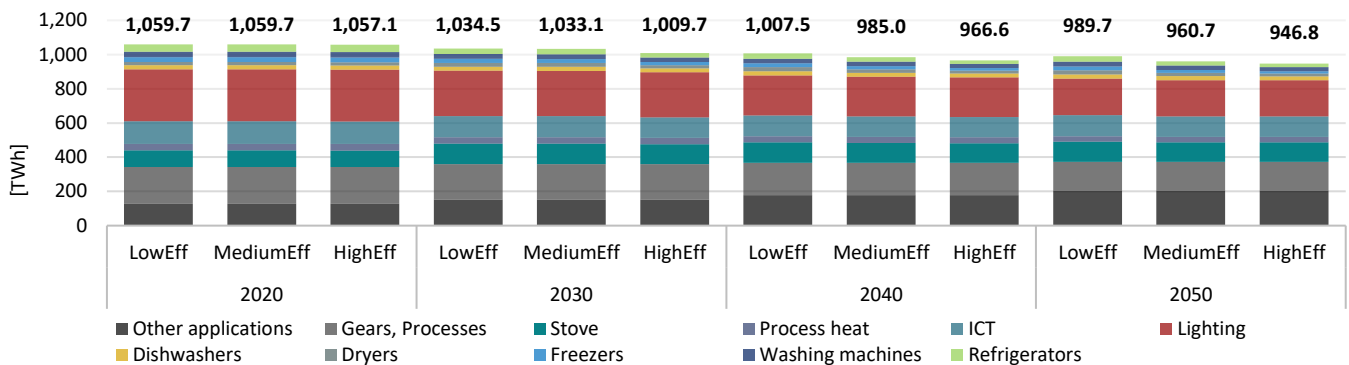


Figure 14. Final energy demand for electrical appliances and lighting by technology in EU-27

How these overall differences in final energy demand affect energy system cost is presented in **Figure 15**. It is apparent that building retrofits require substantial **additional capital costs** relative to the LOWEFF scenario, amounting to +348.3 bn EUR (MEDIUMEFF) and +850.7 bn EUR (HIGHEFF) of cumulative cost between 2020 and 2050. In line with the observations above, lower capacities needed for heating equipment involve minor savings in capital costs for heating systems of -42.7 bn EUR (MEDIUMEFF) and -70.3 bn EUR (HIGHEFF). This suggests that there is some scope for the EE1st principle within the system boundaries of buildings in the sense that there is a trade-off between the ambition level of building retrofits and the corresponding capacity of heat pumps and other heating equipment needed. However, the mere savings in capital costs for heating equipment by far do not offset the capital costs required for retrofits. From Figure 15, it is also well visible how end-use energy efficiency leads to savings in fuel costs within the building sector relative to LOWEFF, ranging from -70.7 bn EUR (MEDIUMEFF) to -120.5 bn EUR (HIGHEFF). As described above in **Chapter 2.3**, this only comprises energy carriers that are directly converted onsite, i.e. natural gas, coal, fuel oil and biomass. All secondary energy carriers (electricity, district heat, hydrogen) and their individual costs are reported in **Sections 3.3–3.5**.

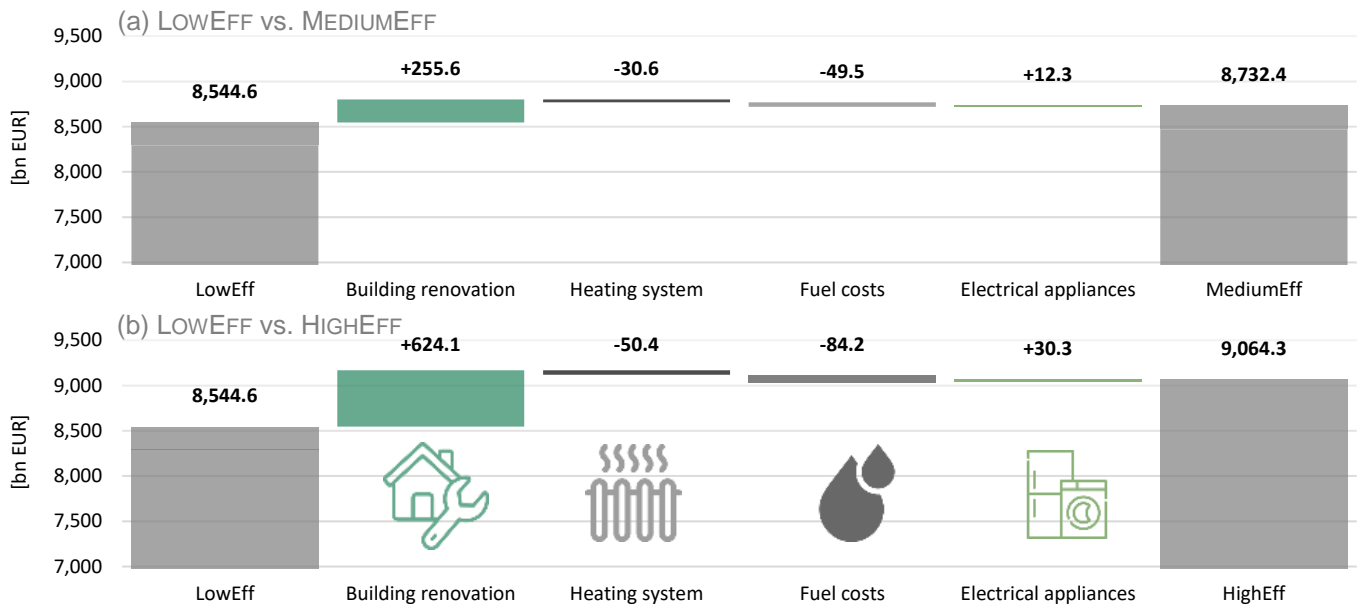


Figure 15. Decomposition of cumulative differential cost in the building sector relative to LOWEFF for EU-27 (2020–2050)

Taken together, these results suggest that building retrofits are a **significant cost driver** within the building sector. As shown in the cross-sectoral results in [Chapter 3.1](#), at least for the HIGH EFF scenario, this does not necessarily pay off from an energy system cost viewpoint, as the savings in various costs for energy supply do mostly, but not completely, offset the **incremental capital costs** for the improvements in energy efficiency over the period 2020–2050. This illustrates the amount of capital needed to finance building retrofits and other energy efficiency measures in the building sector, and how this compares to the **direct benefits** of these investments when considering a whole system perspective. Part of these benefits happen at individual level (e.g., reduction in energy bills), and part of them at the system level (e.g., reduction in the supply-side investments). The trade-off observed at the system level can then be significantly different from the trade-off in the view of a building owner. This difference provides a clear rationale for public policies to help aligning the building owner’s perspective with the whole system perspective. This is a key area of action in the scope of the EE1st principle (ENEFIRST 2021b).

3.3 Electricity supply

Table 2. Main results for electricity supply

Key results	LowEff	MediumEff	HighEff
Gross electricity generation in 2050 [TWh]	6,151.4	5,978.5	5,865.0
Installed generation capacities in 2050 [GW]	2,711.8	2,613.1	2,535.2
Cross-border transmission network capacity in 2050 [GW]	722.1	686.9	674.7
Total cumulative cost (2020–2050) [bn EUR]	5,939.8	5,859.1	5,685.4
Total cost difference compared to LowEff [%]	-	-1.4%	-4.3%



The ENERTILE model was used to quantify electricity generation as well as its transmission and distribution. **Figure 16** shows electricity demand in the form of a **load duration curve** for the EU-27 in 2050.⁵ This represents the entire power system, i.e. not only the building sector demand but also transportation, industry and other loads. The scenarios generally share a common level of minimum load that results from stable loads across the sectors (e.g., industrial applications). In turn, due to the different end-use energy efficiency levels in buildings, peak load reduces by -7.7% (MEDIUMEFF) and -12.3% (HIGHEFF) compared to LOWEFF.

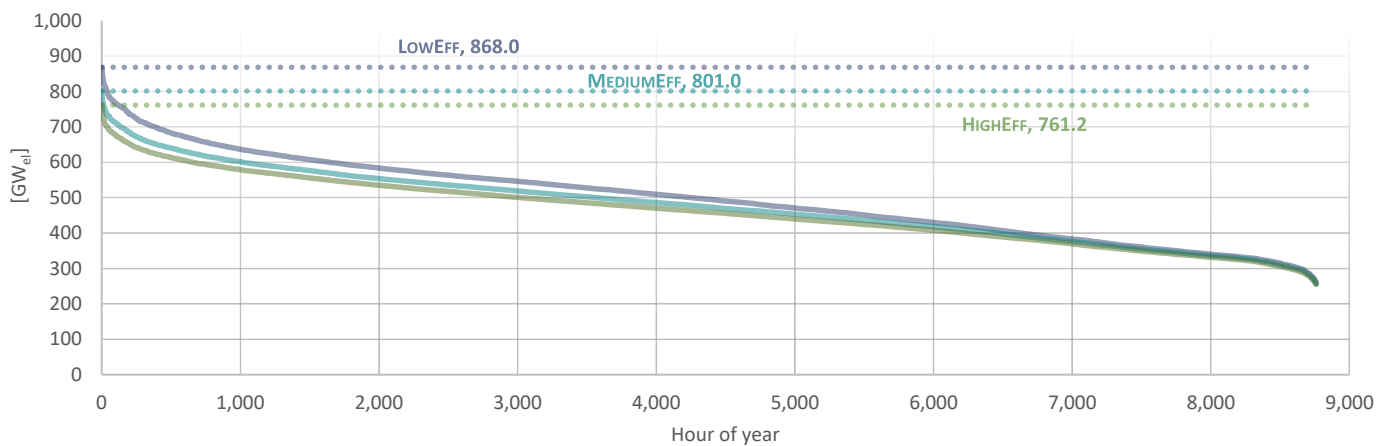


Figure 16. Electrical load duration curve in EU-27 in 2050

Electrical load for entire EU power system, including buildings, transportation, industry, and other loads (e.g. electrolyzers)

The differences in electrical load are also reflected in the **installed generation capacities**. As shown in **Figure 17**, end-use energy efficiency in buildings reduces the need for **variable renewable electricity generation capacity**. This is especially the case for field photovoltaics (-11.2% in HIGHEFF relative to LOWEFF in 2050) and wind onshore (-9.6%). The remaining technologies all reach their assumed capacity

⁵ A load duration curve is a way to display the electricity demand over the 8,760 hours of one year. For constructing the load duration curve, electricity demand is re-ordered in descending order according to its load level (IEA 2014).

limit by 2050, regardless of the scenario: wind offshore (300.0 GW), PV roof (364.4 GW), CSP (51.1 GW), run-of-river hydro (66.2 GW), and geothermal power plants (5.8 GW).

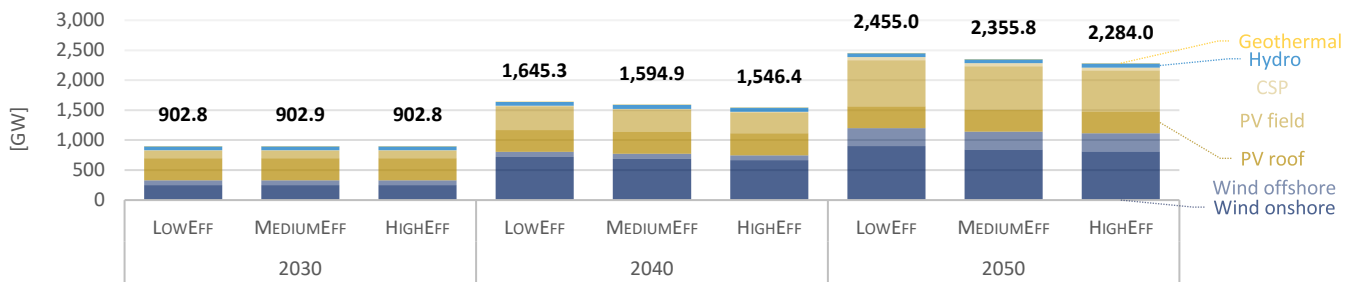


Figure 17. Installed electricity generation capacity by variable renewable technology

PV = photovoltaics; CSP = Concentrated solar power

Besides variable renewables, there will remain a need for **dispatchable generators** until 2050, as presented in **Figure 18**. Interestingly, the ambition level for end-use energy efficiency in buildings is projected to hardly affect the total capacity for these technologies in 2050 (-2.8% in HIGHEFF versus LOWEFF). This can be attributed to the different load curves in the individual scenarios, which take into account weather conditions, ramp rates and other constraints. Note that effect of demand response is undervalued in this assessment, of which a more comprehensive representation is likely to reduce the need for dispatchable generators.⁶ Hydrogen-fired power plants are already present in 2030 and reach installed capacities of 91.0 GW (HIGHEFF) to 119.8 GW (LOWEFF) by 2050. Another observation is that battery storage capacity increases in response to the level of end-use energy efficiency in buildings, amounting to 14.0 GW (LOWEFF), 27.7 GW (MEDIUMEFF), and 37.4 GW (HIGHEFF).

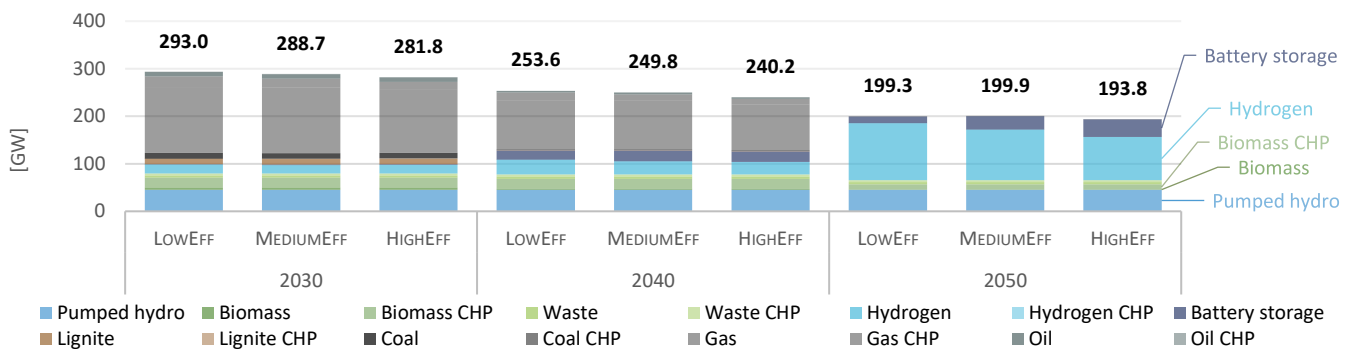


Figure 18. Installed electricity generation capacity by dispatchable generator in EU-27

CHP = combined heat and power

The ENERTILE model also computes the installed capacities for **cross-border electricity transmission networks**, as displayed in **Figure 19**. When compared with near-term levels in 2030 as projected by the Ten Year Network Development Plan (ENTSO-E 2018; ENEFIRST 2021a), there is a significant increase

⁶ In this study, the model ENERTILE represents load shifting for individual heat pumps in buildings as well as large-scale heat pumps in district heating networks. Based on the final energy demand for heating in buildings, the model determines the practical potential for load shifting through heat pumps and their hourly dispatch. Assumptions on technical feasibility, consumer acceptance, and other relevant inputs are not varied among the scenarios.

in capacity by 2050 across all three scenarios. According to these numbers, on average, there is a need for additional cross-border capacity between 24.1 GW per year (HIGHEFF) to 26.5 GW per year (LOWEFF). In 2050, capacity in HIGHEFF is reduced by -6.6% versus LOWEFF.

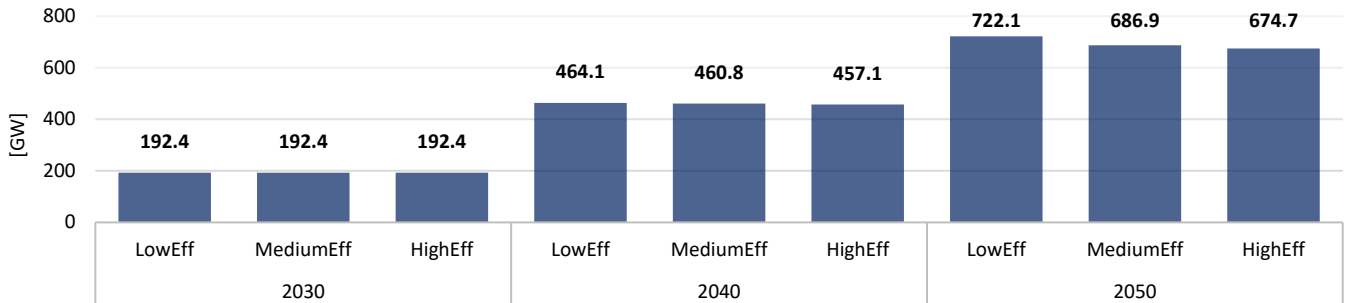


Figure 19. Installed cross-border electricity transmission network capacity

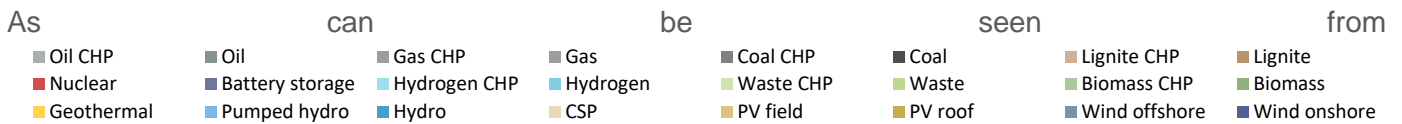


Figure 20, gross electricity generation significantly increases by 2050. Across all scenarios, variable renewable generators (photovoltaics, wind, hydro, geothermal) are the backbone of the power system, supplying between 89.9% (HIGHEFF) to 90.5% (LOWEFF) of generation. Fossil generators are completely phased out by 2050, with dispatchable generation provided by biomass- and hydrogen-fired power plants as well as energy storage. In accordance with the scenario storylines (see ENEFIRST 2021a), nuclear power remains a significant technology until 2050. In sum, total generation in 2050 is -2.8% (MEDIUMEFF) and -4.7% (HIGHEFF) lower compared to LOWEFF.

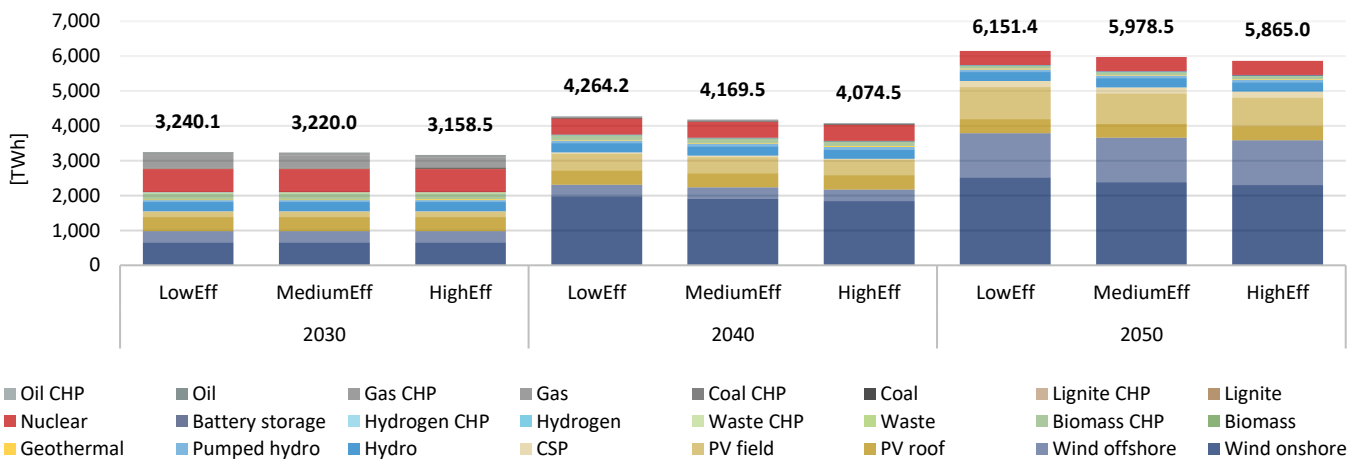


Figure 20. Gross electricity generation by technology in EU-27

CHP = combined heat and power; CSP = concentrated solar power; PV = photovoltaics

Figure 21a presents the **hourly operation** of these generators in response to different electrical loads for a winter day in the EU-27 in 2050. Besides the category of ‘other demand’ (e.g., industrial applications), heat pumps are a significant load on this day. As more thoroughly explained in Bernath et al. (2019), the ENERTILE model optimizes the operation of decentralised heat pumps and large heat pumps in district heating systems in response to outside temperature, heat storage availability and the marginal price of electricity. In other words, heat pumps are assumed to be available for demand response purposes, which is visible in the concurrence of variable renewable electricity generation around noon, and the utilization of heat pumps. **Figure 21b** shows the hourly system operation for a summer day. Generation from

photovoltaics, wind power and other variable renewables largely coincides with electricity demand for hydrogen electrolyzers, methanation facilities and other demand. Some excess generation is used for charging pumped hydro and battery storages. Curtailment of some excess renewables is also present. The overall differences across the scenarios correspond to the general trends on installed capacities and generation above: end-use energy efficiency in buildings reduces energy demand and thus the need for electricity supply.

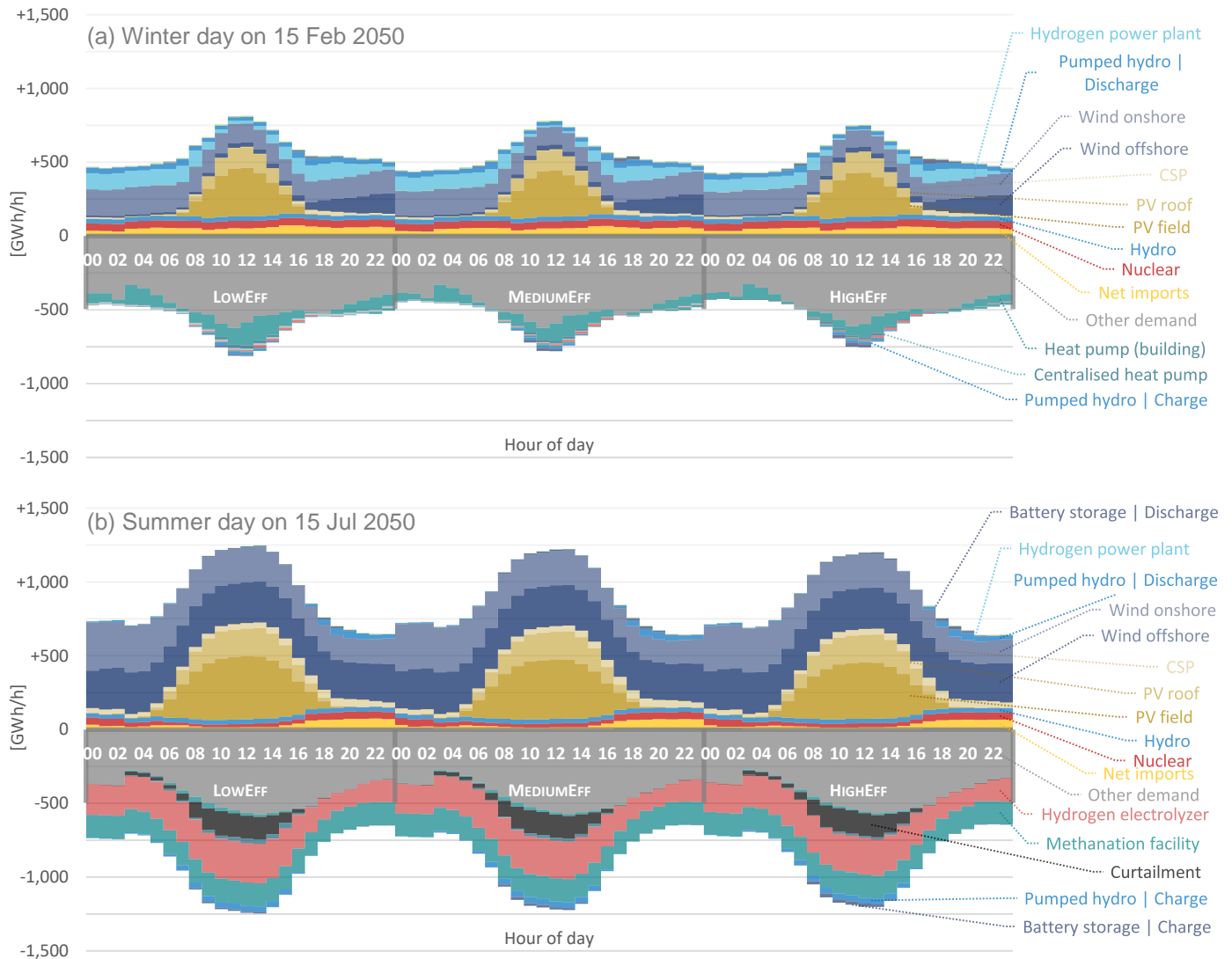


Figure 21. Hourly operation of electrical generators and loads for EU-27 in 2050

Other demand including all other loads in buildings, transportation and industry

The overall **cost balance for electricity supply** is set out in **Figure 22**. In sum, compared to the LOWEFF scenario, cumulative cost for electricity supply over the period 2020–2050 is clearly reduced in both MEDIUMEFF (-80.7 bn EUR) and HIGHEFF (-254.4 bn EUR). Significant cost drivers are the capital costs for generation and networks. As for generation, the savings in capital costs are primarily due to the lower capacities needed for onshore wind power and field photovoltaics. With regard to networks, the majority of capital costs is due to distribution, rather than transmission lines (data not shown here). However, the magnitude of these cost differences appears very low when compared to the overall cost volume incurred for electricity supply over the period 2020–2050. This overall cost volume ranges between 5,939.8 bn EUR or 198.0 bn EUR/a (LOWEFF) and 5,685.4 bn EUR or 189.5 bn EUR/a year (HIGHEFF), i.e. a relative

standard deviation of 2.2% between the three scenarios. This underlines the overall importance of the power system for a transition towards net-zero greenhouse gas emissions by 2050. The building sector can contribute to reducing energy system cost within the power system, but substantial costs will have to be incurred regardless of subtle differences in ambition levels for end-use energy efficiency in buildings.

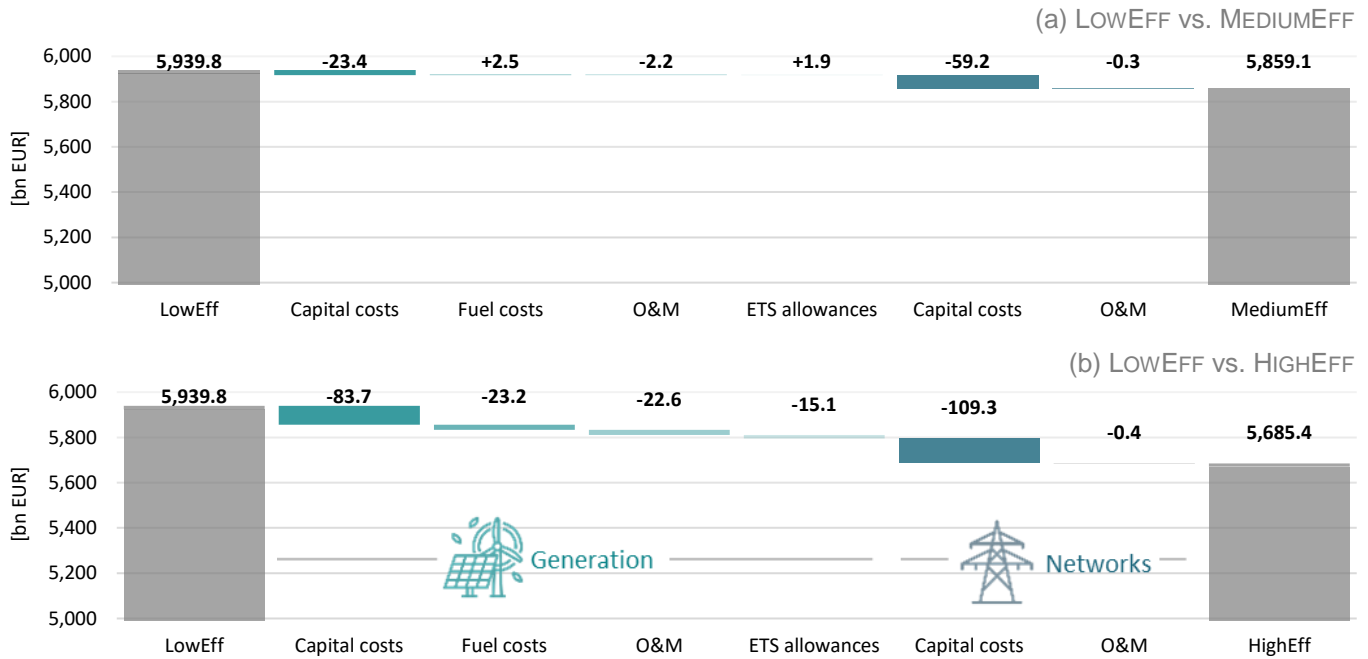


Figure 22. Decomposition of cumulative differential cost in electricity supply relative to LOWEFF for EU-27 (2020–2050)

Overall, these results indicate that there is certainly **scope for the EE1st principle in electricity supply**. Investments in end-use energy efficiency on the demand side of the energy system clearly reduce capital costs, fuel costs and other cost items for electricity generators and networks. It is also apparent that, regardless of the ambition level for end-use energy efficiency, the transition of the electricity system from fossil and nuclear fuels to renewable energies and net-zero GHG levels involves substantial energy system cost in the order of trillions for the period from 2020 to 2050. Nevertheless, higher level of energy end-use efficiency can help reduce the pressure on the needs to develop renewable energy capacities. This can result in complementary positive impacts, such as on land-use.

3.4 District heating supply

Table 3. Main results for district heating supply

Key results	LowEff	MediumEff	HighEff
Heat generation in 2050 [TWh]	562.7	395.8	324.7
Installed generation capacities in 2050 [GW]	293.6	207.8	172.6
Heat network length 2050 [thousand km]	305.6	263.7	265.6
Total cumulative cost (2020–2050) [bn EUR]	758.0	665.4	628.5
Total cost difference compared to LowEff [%]	-	-12.2%	-17.1%



As set out in **Section 3.2** above, the three scenarios also have clear implications for district heating demand. Based on its optimization logic, the ENERTILE model determines the district heating supply mix and related cost for each EU Member State. The NetHEAT model calculates the expansion and associated cost of district heating systems. **Figure 23** provides the aggregate **heat load duration curve** for the EU-27 in 2050, covering buildings and industry applications. The enhanced thermal performance of buildings clearly leads to a reduction in peak load by -30.5% (MEDIUMEFF) and -43.5% (HIGHEFF) compared to LOWEFF. Minimum load is between 6.0 GW (HIGHEFF) and 10.5 GW (LOWEFF).

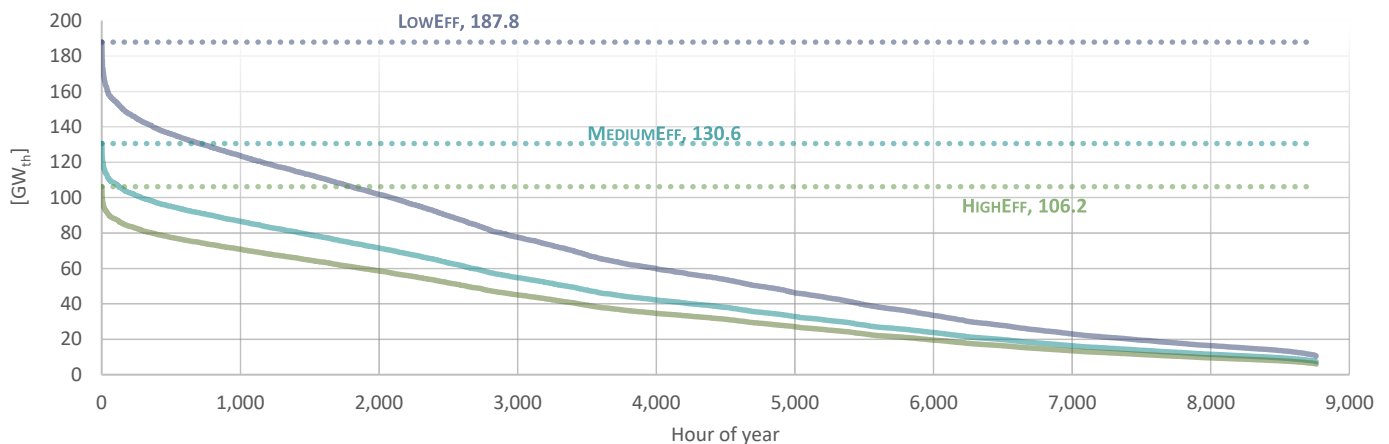


Figure 23. Thermal load duration curve in EU-27 in 2050

Heat load for entire EU, including buildings and industry

Reduced thermal load involves smaller capacities needed on the supply side. **Figure 24** shows the **installed capacities for variable renewable district heating technologies**, i.e. solar thermal and geothermal energy. Across the three scenarios, these technologies reach a total installed capacity of 15.6 GW by 2050. As more thoroughly described in ENEFIRST (2021a), this reflects assumed potential restrictions at a country level which were not varied across the scenarios. In practice, solar thermal and geothermal energy involve close-to-zero variable costs and are thus readily deployed for district heating supply in the cost-based logic of the ENERTILE model, regardless of the ambition level for building retrofits.

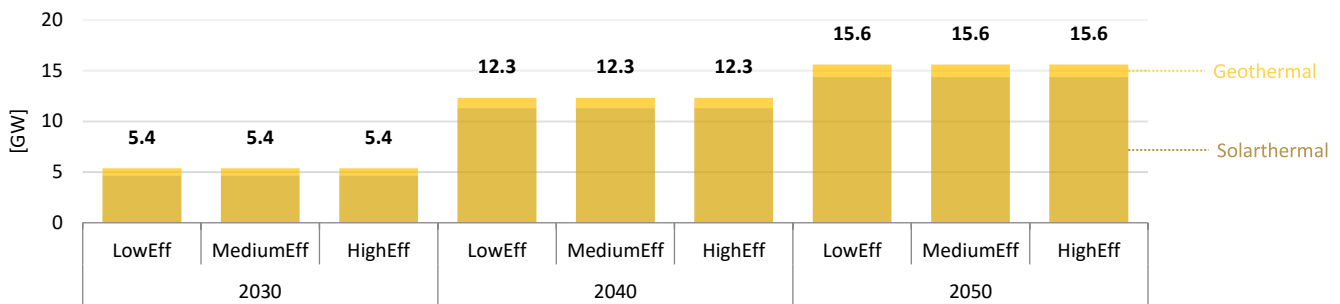


Figure 24. Installed heat generation capacity by variable renewable technology

The bulk of district heating supply capacity is provided by **dispatchable supply technologies** that operate primarily when supply from solar thermal and geothermal energy is low. **Figure 25** shows the breakdown of these dispatchable generators. District-scale heat pumps are the predominant technology in this setting, with installed capacities reaching 81.5 GW (HIGHEFF) to 154.7 GW (LOWEFF) in 2050. Another interesting finding are the large capacities for hydrogen-fuelled boilers that account for 21.5% (HIGHEFF) to 28.9% (LOWEFF) of the dispatchable capacities in 2050. When linked to the generation data in **Figure 26** below, it turns out that these hydrogen boilers are primarily deployed to operate at peak load in district heating systems. Their capacity factors ⁷ range from 2.8% (HIGHEFF) to 4.7% (LOWEFF), meaning that these assets are idle for most of the year. This low utilization again supports the idea of the EE1st principle in the sense of prioritizing demand-side resources to avoid superfluous generation assets.

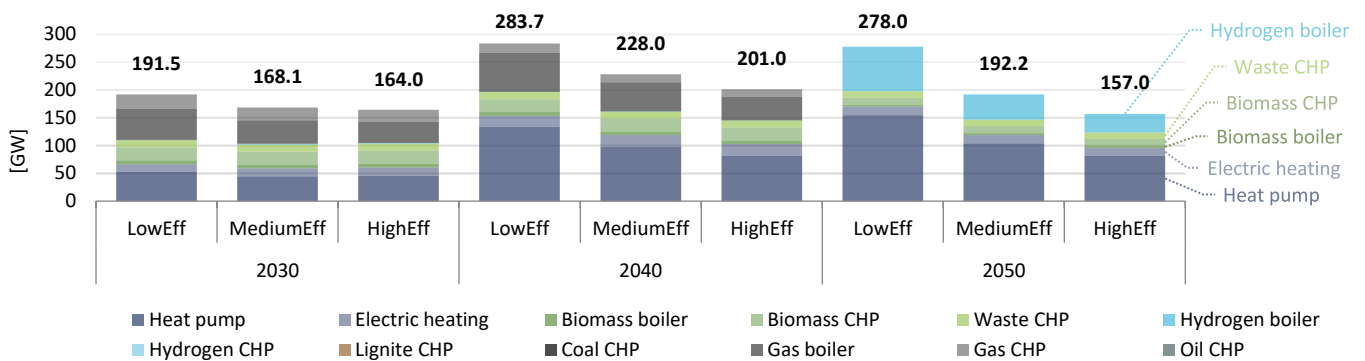


Figure 25. Installed heat generation capacity by dispatchable generator in EU-27

CHP = Combined heat and power

As shown in **Figure 26**, building retrofits also significantly reduce the **amount of heat supplied**. Total generation in 2050 is -29.6% (MEDIUMEFF) and -42.3% (HIGHEFF) lower compared to the LOWEFF scenario. Variable renewables (solar thermal, geothermal) provide 5.6% to 9.7% of this energy in 2050, the remainder is supplied by dispatchable technologies. District-scale heat pumps supply 75.9% (LOWEFF) to 66.9% (HIGHEFF) of heat. Hydrogen is also used for heat generation (2.6% to 5.9% in 2050).

⁷ The capacity factor, or load factor, is defined as the annual output of a system divided by the output that would have been achieved if the system had run at the nominal capacity for the full year (8,760 hours) (Blok and Nieuwlaar 2016).

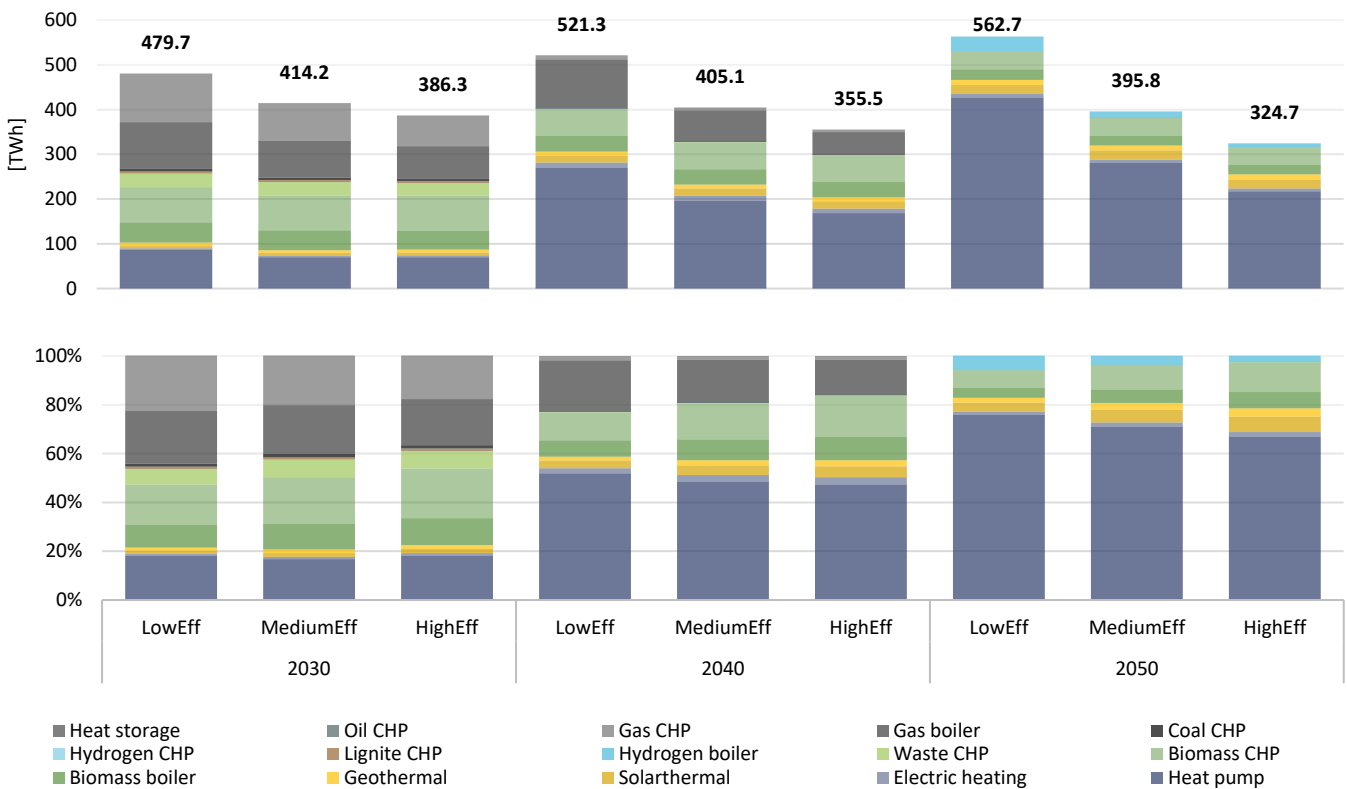


Figure 26. District heating generation by technology in EU-27

CHP = Combined heat and power

Figure 27 provides an example of the aggregate hourly operation of district heating systems in the EU-27 for a winter day with high thermal load in 2050. Solar thermal systems provide some heat around midday, which is complemented by centralised heat pumps and biomass boilers. Hydrogen boilers are a key technology to serve the high thermal load on that day. The dispatch of seasonal heat storage to cover load peaks is clearly visible. Overall, the annual generation also reflects in hourly operation.

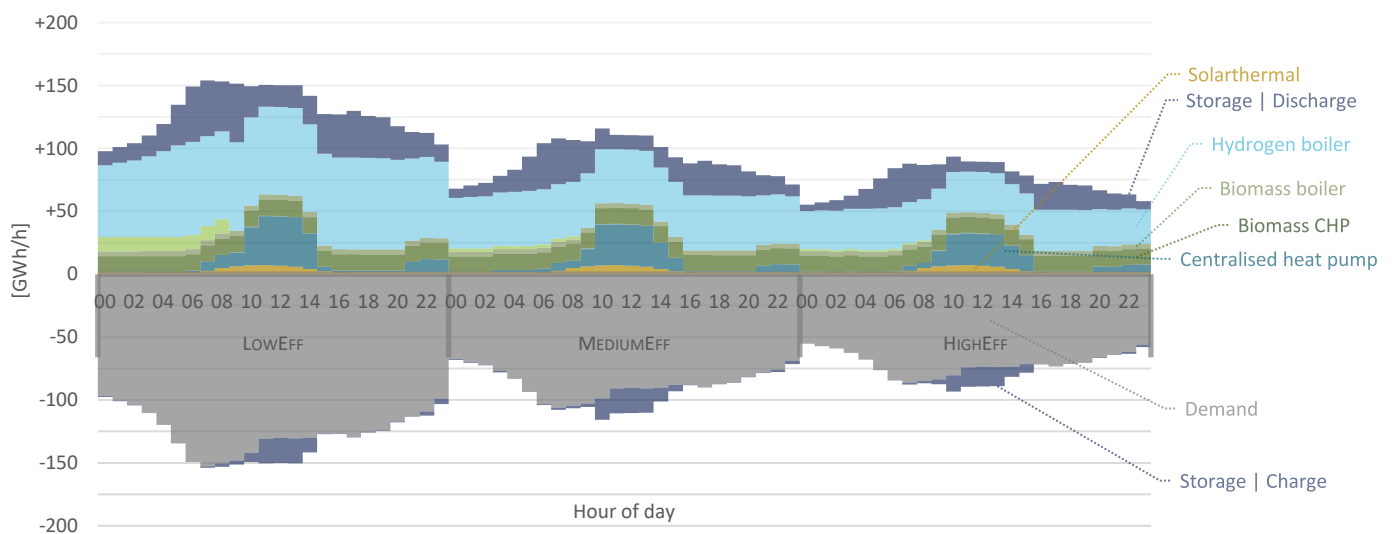


Figure 27. Hourly operation of heat generators and loads for EU-27 in 2050

Winter day on 15 Feb 2050

Before turning to the cost balance for district heating, **Figure 28** displays the projected district heating **network length** along with the **number of buildings** connected. Compared to current levels, the total network length increases between 56.6% (HIGHEFF) and 80.2% (LOWEFF) by 2050, similar to the number of buildings connected (+67.3% to +95.7% compared to current levels). In a net-zero future, district heating networks are thus a key asset. Combining these numbers with the annual generation (**Figure 26**) yields the **heat density** for district heating networks. These densities range from 1.84 (LOWEFF) to 1.22 (HIGHEFF) MWh per year and network meter in 2050. In response to the building retrofits, on average, the utilization of district heating networks in 2050 is thus -33.6% lower in HIGHEFF compared to LOWEFF.

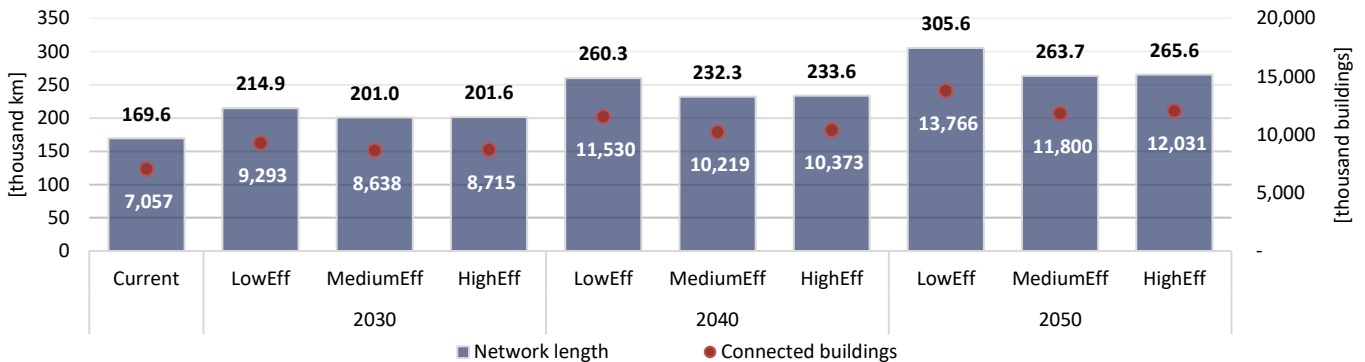


Figure 28. District heating network length [thousand km] and number of connected buildings in EU-27

Figure 29 presents the overall **cost balance** for district heating supply in the three scenarios. Cumulative energy system cost for the period 2020–2050 ranges from 623.5 bn EUR or 20.8 bn EUR/a (HIGHEFF) to 750.5 bn EUR or 25.0 bn EUR/a (LOWEFF). Relative to LOWEFF, ambitious renovation rates thus lead to cost savings of 12.1% (MEDIUMEFF) and 16.9% (HIGHEFF) by 2050. Generation makes up 75.6% to 78.1% of district heating cost, with fuel costs accounting for the major portion, followed by costs for emission certificates (Other costs) and capital costs. Network costs are almost entirely made up of capital costs.

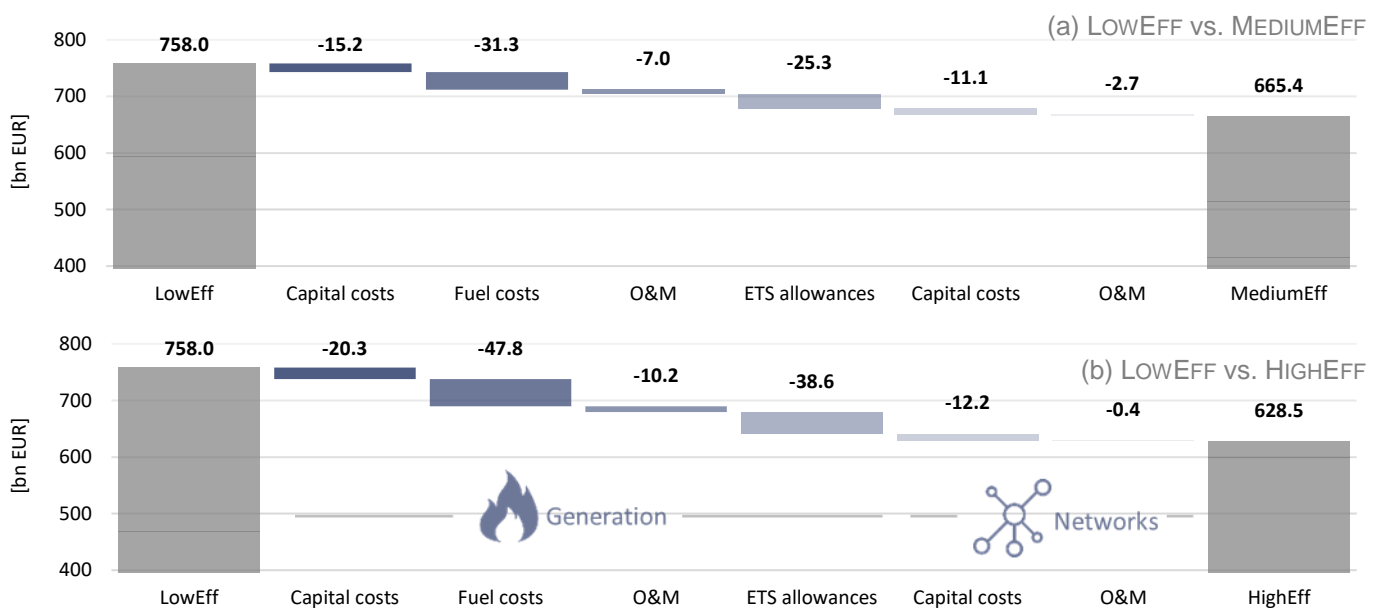


Figure 29. Decomposition of cumulative differential cost in district heating supply relative to LOWEFF for EU-27 (2020–2050)

Taken together, these results show that buildings retrofits do not only reduce the energy system cost for electricity supply, but also for district heating supply, thus again supporting the notion of EE1st.

3.5 Hydrogen supply

Table 4. Main results for hydrogen supply

Key results	LowEff	MediumEff	HighEff
Hydrogen generation in 2050 [TWh]	636.7	610.4	597.7
Hydrogen net imports+/exports- in 2050 [TWh]	+104.7	+103.6	+102.3
Electrolyzer capacity in 2050 [GW]	303.4	290.2	281.7
Total cumulative cost (2020–2050) [bn EUR]	455.7	447.3	434.6
Total cost difference compared to LowEff [%]	-	-1.8%	-4.6%



Produced by means of low-carbon electricity and electrolysis, hydrogen can be stored and reconverted to power via gas turbines or fuel cells. Another application is the use as a feedstock in industrial processes. Finally, combined with carbon dioxide, **hydrogen** can be converted to other sources of energy such as **methane**. These are easy to store and can thus be readily used in conventional combustion processes (Stephanos and Höhne 2018). **Figure 30a** presents the balance of supply and demand for hydrogen in the scenarios. Two major effects from the different ambition levels for energy efficiency in the building sector are visible. First, building sector efficiency involves a minor reduction in ‘Other hydrogen demand’, i.e. the direct use of hydrogen in buildings, industry and transportation. The differences result from the ambition levels for end-use energy efficiency in buildings: the better the thermal performance of the buildings, the less hydrogen is required for heating purposes in hydrogen boilers or fuel cells. Second, hydrogen savings do not only materialize for direct use in buildings, but also with regard to reconversion in power plants and district heating boilers. Hydrogen use for electricity and heat supply in 2050 compared to LOWEFF is reduced by -33.7% (MEDIUMEFF) and -51.0% (HIGHEFF).

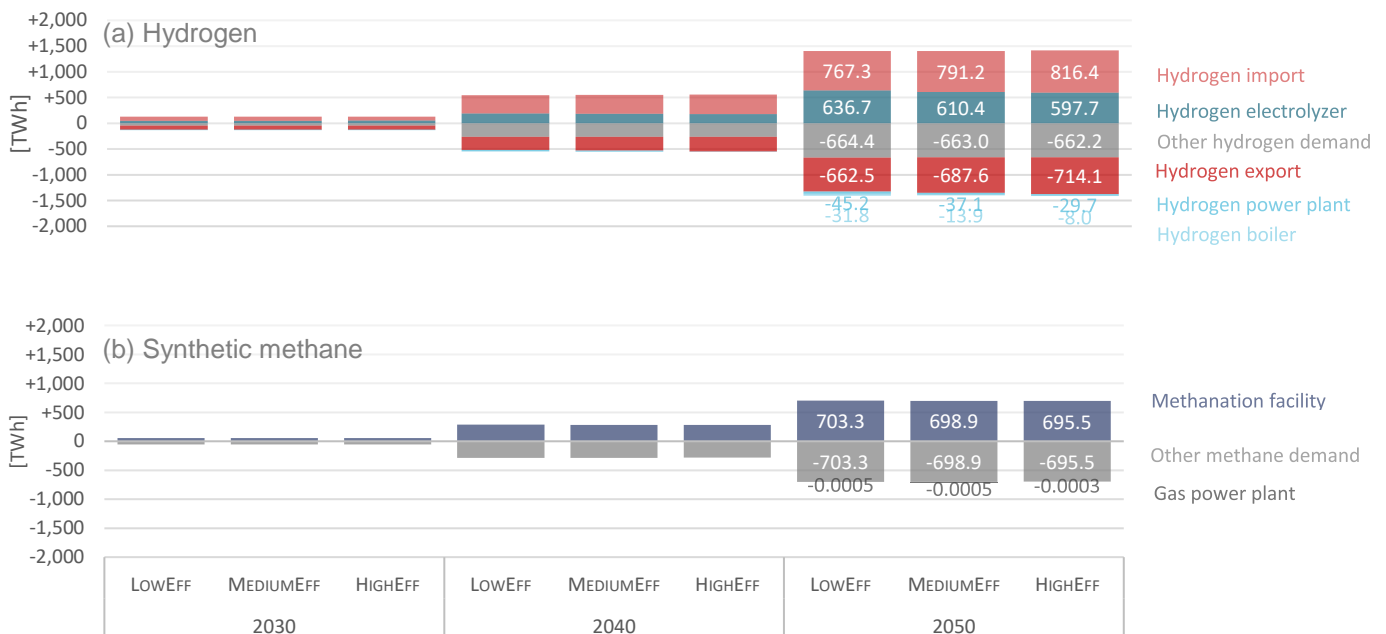


Figure 30. Supply and demand for power-to-gas products in EU-27

Other hydrogen/methane demand comprises direct energy demand in buildings, industry, transportation

Similar trends are visible with respect to **synthetic methane** from methanation facilities in **Figure 30b**. On the demand side, the use of synthetic methane in buildings in 2050 is reduced by -0.6% (MEDIUMEFF) and -1.1% (HIGHEFF) compared to LOWEFF. When compared to the use of hydrogen in electricity and heat supply, the reconversion of synthetic methane in gas power plants is insignificant, reaching levels from 298.4 MWh (HIGHEFF) to 533.7 MWh (LOWEFF) for the entire EU-27. As can be seen from **Figure 31**, there are similar differences in terms of **installed electrical capacity** for hydrogen electrolyzers and methanation facilities. End-use energy efficiency in buildings clearly reduces the need for hydrogen electrolyzers in 2050 by -4.3% (MEDIUMEFF) and -7.1% (HIGHEFF) compared to LOWEFF.

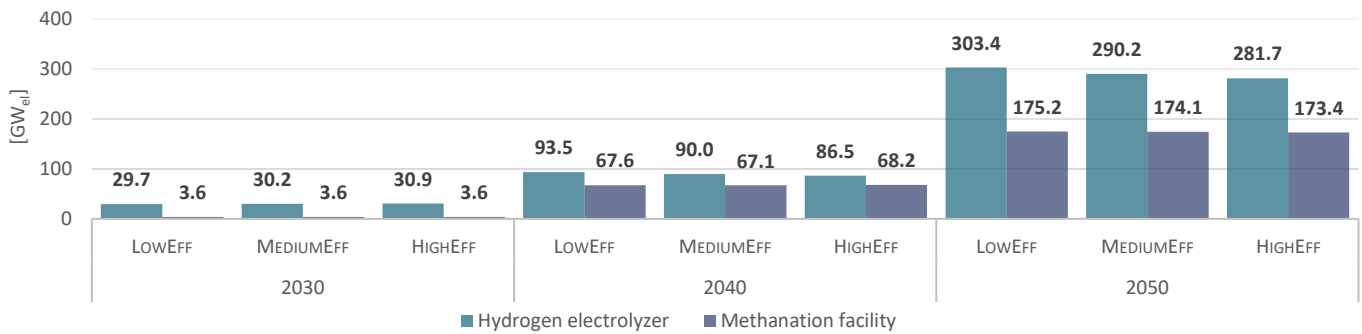


Figure 31. Electrical capacity for power-to-gas facilities in EU-27

The cost balance for hydrogen supply is presented in **Figure 32**. In response to the improvements in end-use energy efficiency in buildings, system cost over the period 2020–2050 is reduced by -1.8% (MEDIUMEFF) and -4.6% (HIGHEFF) compared to LOWEFF. Aside from capital costs, major cost savings arise from reduced import costs for hydrogen as well as fixed and variable operation and maintenance costs. Note that the cost of hydrogen and gas networks was not quantified in this analysis (ENEFIRST 2021a).

(a) LOWEFF vs. MEDIUMEFF

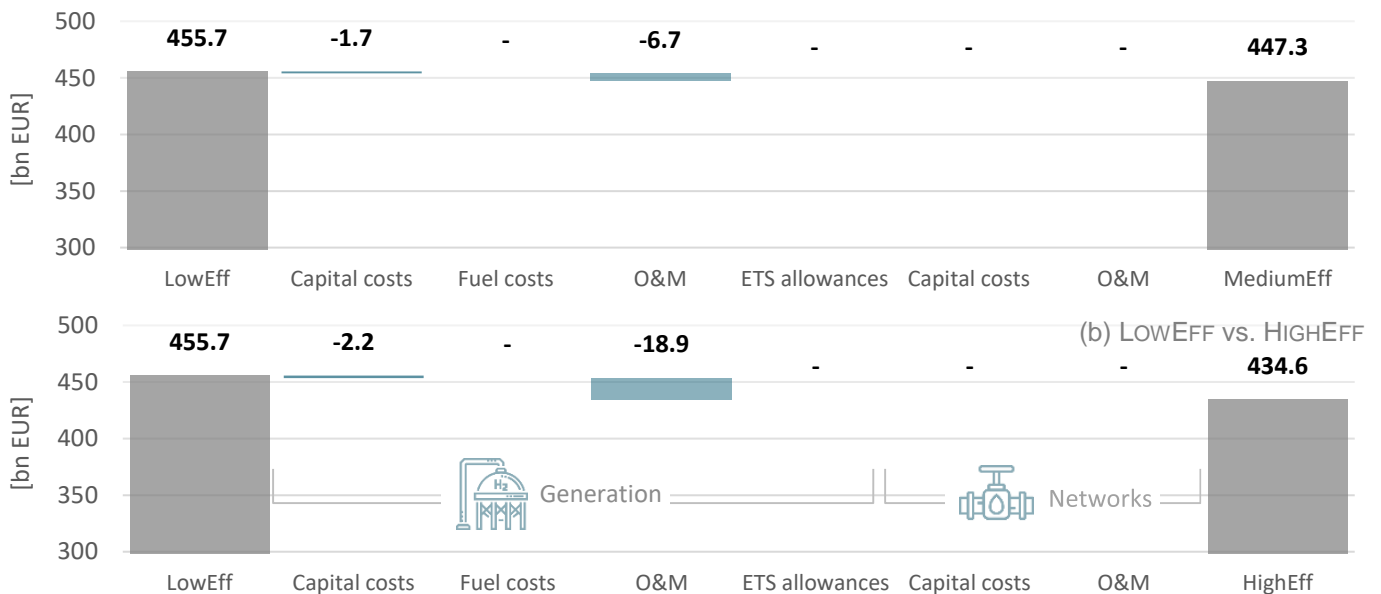


Figure 32. Decomposition of cumulative differential cost in hydrogen supply relative to LOWEFF for EU-27 (2020–2050)

End-use energy efficiency in buildings thus has a clear impact on capacities, generation and the cost of hydrogen-related assets. There is thus clear scope for EE1st in hydrogen supply and demand.

Summary | Chapter 3 | Results

This chapter presented the results from three scenarios that differ considerably regarding their **uptake of end-use energy efficiency measures in the building sector**. The measures considered include comprehensive building retrofits as well as the diffusion of energy-efficient appliances. While these measures require substantial **capital costs**, they significantly reduce the costs for decentralized heating systems, generation and distribution of electricity and district heating, as well as hydrogen supply. However, the investments are not completely **offset by reduced costs for energy supply**.

The HIGHEFF scenario, being the most ambitious one among the three (-35.5% reduction in final energy demand vs. 2020 levels), results in additional energy system cost of +114.7 bn EUR over the period 2020–2050 compared to LOWEFF. The additional cost for end-use energy efficiency amounts to +654.4 bn EUR vs. -539.7 bn EUR in supply cost savings, i.e. a compensation of 82.5%. In the slightly less ambitious MEDIUMEFF scenario (-30.2% reduction in final energy demand), energy system cost over the same period is at +6.0 bn EUR and thus almost equivalent to those of the LOWEFF scenario. Additional cost for end-use energy efficiency is at +267.9 bn EUR vs. -261.8 bn EUR savings in energy supply cost, i.e. a compensation of 97.7%. When comparing *aggregate* rather than differential energy system cost over the period 2020–2050, the three scenarios end up at cost between 15.7 (LOWEFF) and 15.8 trillion EUR (HIGHEFF), i.e. a relative standard deviation of 0.41%. This gives rise to **three main conclusions**:

First, end-use energy efficiency in buildings is a **critical component** of a cost-efficient transition to net-zero emission levels in the EU. Considering the close similarity in energy system cost between LOWEFF and MEDIUMEFF, it can be inferred that ambition levels for energy efficiency *below* LOWEFF are likely to result in *additional* energy system cost that, ultimately, would have to be borne by consumers. The LOWEFF scenario should thus be seen as the lower end of possible ambition levels for end-use energy efficiency in the building sector.

Second, the ongoing around EE1st provides significant added value in that the principle makes explicit the trade-offs between supply- and demand-side resources for reaching the same decision objectives. The numbers presented put into perspective the additional cost for end-use energy efficiency on the demand side and the resulting effects on the supply side, e.g. the reduced need for generation capacities. This underlines the significance of EE1st in that the principle aims for an optimal economic balance between saving and supplying energy.

Finally, **end-use energy efficiency in buildings also has limitations** from an energy system cost perspective. From a neutral viewpoint, as per the indicator of *differential* energy system cost, the scenarios MEDIUMEFF and HIGHEFF are not cost-effective in relation to LOWEFF. At the same time, when looking at the *absolute* cost dimensions in the order of trillions of Euros across the scenarios, these differences appear minor and arguable. Especially in light of the uncertainties and other limitations of this study, this means that there is **not a clear case for prioritizing supply-side investments** either.

As further discussed below, the central indicator of energy system cost is limited to financial metrics and omits the variety of **multiple impacts** associated with energy efficiency. While some commonly discussed impacts are already represented in this study (e.g. avoided supply capacities), others are missing (e.g. health benefits). Moreover, the recent spike in energy prices as of 2021–2022 and its ramifications as a key **uncertainty** is not taken into account in this study. The inclusion of both effects is likely to significantly enhance the cost-effectiveness of the building efficiency measures modelled and thus support a more definitive prioritization of demand-side over supply-side resources in the scope of the E1st principle.

4. DISCUSSION

This chapter discusses the results presented above. **Chapter 4.1** relates the findings to current policy discussions and to similar research. Then, **Chapter 4.2** presents methodological limitations of this study.

4.1 Policy implications

As discussed further below, there are different reasons why these policy implications should be interpreted with caution. In particular, the assumptions on wholesale **energy prices** are based on conservative projections (IEA 2019) that do not factor in the recent spike in energy prices as of 2021–2022. This has a considerable effect on the cost-effectiveness of energy efficiency measures (Eichhammer 2022). In addition, this study's performance indicator of energy system cost does not factor in the **multiple impacts** of energy efficiency, which, again, affects cost-effectiveness, if impacts are monetized (Thema et al. 2019).

To begin with, setting measurable targets on energy efficiency is key to keeping track of policy progress and to guiding policy measures. **Table 5** relates the ambition level of the ENEFIRST scenarios to the **energy efficiency targets** set out in the Energy Efficiency Directive (EED).⁸ The levels of final energy consumption by 2030 in the ENEFIRST scenarios lie roughly between the target set out in the amended directive ('EED-2018', -32.5% compared to PRIMES-2007) and the one in European Commission's proposal for a recast EED ('EED-2021', -37.2%). The ENEFIRST scenarios thus generally support a revision of EED-2018 towards higher ambition levels for final energy of at least -35%, and ensuing primary energy savings.

However, as set out in **Chapter 3.1**, highly ambitious levels of end-use energy efficiency in buildings may lead to additional energy system cost compared to the LOWEFF scenario. This stands in contrast to other studies that call for **an energy efficiency target beyond 40%** – also without taking into account the effect of escalating energy prices as well as of multiple impacts.⁹ In conservative terms, the ambition level of the EED-2021 proposal can thus be seen as a reasonable benchmark. Higher ambition levels can be justified on the grounds of multiple impacts beyond monetary savings as well as higher wholesale energy prices. To illustrate, Eichhammer (2022) assesses the effect of a 30% increase in wholesale energy prices and finds that this would legitimise a higher EU energy efficiency target of -42.3% (final energy) and -45.5% (primary energy) compared to PRIMES-2007.

⁸ In 2018, the EED was amended (European Union 2018a) to deliver on the EU target of at least 32.5% energy efficiency improvements by 2030, defined in terms of energy savings compared to the PRIMES-2007 baseline (Capros et al. 2007). In June 2021, as part of the "Fit for 55" package (European Commission 2021b), the European Commission submitted a proposal for a revision of the EED (European Commission 2021d), with the aim of better aligning the EED to the climate ambition set out in the European Climate Law Regulation (European Union 2021). The proposal includes higher targets for limiting EU final and primary energy consumption by 2030, which corresponds to 37% and 39% savings, respectively.

⁹ For example, Scheuer et al. (2021), based on cost-effective technology potentials calculated in Chan et al. (2021), support a 41.2% reduction target on final energy demand by 2030 compared to the PRIMES-2007 baseline. In terms of technical potentials, final energy demand could be reduced by 45.4% by 2030, according to the study.

Table 5. Possible energy efficiency targets in the Energy Efficiency Directive

^(a) Based on amended Energy Efficiency Directive (European Union 2018a, Art. 3), excluding United Kingdom (European Union 2019) | ^(b) Based on Commission proposal for recast of Energy Efficiency Directive (European Commission 2021d, Art. 4) | ^(c) Projections for residential and tertiary sectors based on ENEFIRST project; industry and transportation sectors based on REG_MAX scenario in Impact Assessment accompanying recast of the Energy Efficiency Directive (European Commission 2021c) | ^(d) EU Reference Scenario 2007 (Capros et al. 2007) | ^(e) EU Reference Scenario 2020 (Capros et al. 2021)

	PRIMES-2007 baseline ^(d)	PRIMES-2020 baseline ^(e)
Targeted/projected level of final energy consumption in year 2030 % difference to baseline		
Energy efficiency target for final energy consumption		
EED-2018 ^(a)	846 Mtoe	1,253 Mtoe -32.5%
EED-2021 ^(b)	787 Mtoe	1,253 Mtoe -37.2%
ENEFIRST scenarios ^(c)		
LOWEFF	800 Mtoe	1,253 Mtoe -34.8%
MEDIUMEFF	792 Mtoe	1,253 Mtoe -35.5%
HIGHEFF	786 Mtoe	1,253 Mtoe -36.0%

The **average renovation rates** in the three scenarios over the period 2020–2050 range from 0.7% in the LOWEFF scenario, to 1.4% in MEDIUMEFF and 1.7% in HIGHEFF (**Chapter 3.2**).¹⁰ Esser et al. (2019) distinguish different levels of renovation measures for assessing the renovation rate in EU-27 for the period 2012-2016, and come to the result of 3.9% renovation rate for light renovations, 1.1% for medium and 0.2% for deep renovation.¹¹ If we consider that the 0.7% renovation rate in the LOWEFF scenario is close to a current policy scenario with the pace of measures from recent years being kept more or less constant, the renovation rate of 0.7% could be interpreted in a sense that it reflects an equivalent renovation intensity between medium and deep renovation according to Esser et al. (2019).

The **definition of renovation rates** varies strongly between different sources and studies, i.e. they can be defined based on number of buildings, number of dwellings, floor area, considering only part-renovation or equivalent full renovations etc. Thus, to our mind a more reasonable approach is to compare the growth of stated renovation rates. The European Commission’s Renovation Wave strategy (2020a) sets the goal to “at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations.” The impact assessment of climate targets (European Commission 2020b) has modelled an increase in the renovation rate from 1% and 0.6% (2016-2020) in the residential and non-residential sector, respectively, to 1.4%–2.4% and 1–1.5% (2026-2030). Taking this into consideration, we can observe that both mentioned sources target at – or result in – at least a doubling of the renovation rate. Since the MEDIUMEFF scenario leads to a **doubling of the renovation rate** compared to the LOWEFF scenario (and considering that the latter one reflects a continuation of current levels of renovation measures) we can observe that this scenario is in line with the lower limit of the target formulated in the renovation wave. The HIGHEFF scenario leads to a stronger increase in the renovation rate resulting in slightly higher energy system cost – under the assumed energy price settings. It remains

¹⁰ The renovation rates in our approach are being defined as the share of conditioned floor area being subject to full renovation of all building envelope components divided through the conditioned floor area of the whole stock of buildings. They are thus understood as “equivalent full renovation rates.” As such, we assume that buildings where e.g. only windows are replaced are not part of the renovation rate, but rather a portion of the whole building envelope.

¹¹ The definition of the renovation intensity levels in this study is being done according to primary energy savings: below 30% for light (and below threshold) renovation, 30-60% for medium and >60% for deep renovation.

a policy decision, whether these slightly higher costs should be considered as investment (similar to an insurance premium) to reduce the risk being hit by energy price and supply shocks as observed in 2021 and 2022.

Besides the energy efficiency target, the present findings also are generally consistent with **other research**. Tsiropoulos et al. (2020) provide a meta-analysis of 16 scenarios for near-zero emissions (emission reduction of at least 90% by 2050 compared to 1990) in the EU. Across these scenarios, the building sector consumes 20% to 55% less energy by 2050 than it does today, with heat pumps and district heating covering the bulk of building energy demand for heating. Likewise, at the global level, the IEA (2021) identifies end-use energy efficiency and electrification through heat pumps as two major drivers of building sector decarbonisation by 2050. These findings largely correspond to the ENEFIRST scenarios, with savings in final energy consumption ranging between -21.1% (LOWEFF) and -35.5% (HIGHEFF) compared to 2020 levels, along with the significance of electrification and district heating.

The present study also confirms the possible **economic limitations of end-use energy efficiency in buildings** with regard to the transition towards climate-neutrality by 2050. For the German building sector, Langenheld et al. (2018) demonstrate that a scenario with a significant but not extreme focus on building retrofits (2.2–2.8% renovation rate) is cost-ineffective compared to one where primarily heat pumps compensate for lower end-use energy efficiency. Likewise – for Italy, Croatia, Romania, and Czech Republic – Hansen et al. (2016) find that building retrofits should not be too ambitious relative to centralised and decentralised heat supply in order to ensure cost-effectiveness. These limitations of energy efficiency in buildings is also apparent when comparing the energy system cost between LOWEFF and especially HIGHEFF in the ENEFIRST scenarios. However, it should be noted that all these studies were made before the strong increase in energy prices observed since 2021.

Overall, the modelling techniques used in this study do not allow for detailed analysis by **policy measure**. What is clear is that the transition to net-zero GHG emissions by 2050 set out in the scenarios of this study requires a highly ambitious and comprehensive package of strategies and policy instruments across sectors. More specifically, with regard to the EE1st principle, establishing a level playing field between demand (end-use energy efficiency) and supply side resources (generation, networks, storage) calls for a suite of targeted planning instruments, market regulations and incentives. Multiple reports in the ENEFIRST project are dedicated to identifying policy areas for EE1st (2021d), barriers and success factors of individual policy approaches (2021c), as well as concluding guidelines on policy design options for implementing EE1st in buildings and its associated energy supply sectors (2021b).

4.2 Methodological limitations

The findings presented above are subject to a number of methodological limitations that raise the question of how robust the outcomes of this study are. In general, the robustness of every model-based scenario analysis is fraught with uncertainties in two respects. On the one hand, parameter uncertainties are a result of the numerical assumptions necessary for the model calculations, resulting in the challenge of establishing specific values for conditions in the far future, e.g. the price of natural gas. On the other hand, model uncertainties result from interaction of the parameters in the modelling as well as the consideration and omission of relevant aspects, e.g. rebound effects (Behn and Byfield 2016; IRGC 2015).

Energy prices and technology costs

As becomes apparent with the spike in energy prices in 2021–2022, there are substantial uncertainties regarding the long-term trends of energy prices until 2050. In turn, as more thoroughly described in ENEFIRST (2021a), the wholesale prices for natural gas, oil, coal and uranium used in this study are

based on the IEA's World Energy Outlook (2019) that assumed relatively stable prices until 2050. While not explicitly investigated, the models applied in the present study are highly sensitive regarding changes in energy prices. Besides energy prices there is uncertainty concerning technology costs and the ensuing magnitude of investments of equipment and efficiency measures like insulation material or related staff costs. On the one hand, learning effects can be expected at least for some measures. On the other hand, short-term shortages or cuts in the supply chains may also lead to price increases. However, due to the fact that in general there are more options to diversify the sources of such equipment and materials, we do not expect similarly high uncertainties and price increases as we are seeing for gas and electricity. Overall, our assumptions regarding technological progress are moderate and are estimated to be rather conservative.

Societal perspective and multiple impacts

This analysis is meant to be carried out from a **societal perspective**. The EE1st principle aims to prioritize those combinations of resource options that provide the greatest benefit to society (see ENEFIRST 2020a). As such, the principle does not imply that all investments in the energy system until 2050 are cost-effective for the respective decision-maker, i.e., a **private or investor perspective** (ENEFIRST 2020b). While a detailed account of gainers and losers is highly relevant, it is so far neither a principal focus of the EE1st principle, nor of this study. Moreover, this quantitative assessment is not evaluated from a **public budget or state perspective** (Chatterjee et al. 2018), i.e., the balance of policy programme costs, tax revenues, subsidy payments and other cost items. Having said that, we are aware that neither all costs nor all benefits which can be relevant for a complete societal perspective are fully considered. In particular, energy efficiency measures may lead to multiple impacts, including health benefits, reduced air pollution, employment gains, and others (Kerr et al. 2017; Fawcett and Killip 2019). Empirical estimates indicate that their monetary impact in the building and industry sectors may be 0.5 to 3.5 higher than the value of energy savings made (Ürge-Vorsatz et al. 2014). To address this issue, the follow-up report ENEFIRST (2022) deals with the quantitative effect of selected multiple impacts on the findings of the present study.

Financial corrections

The quantification of energy system cost from a societal perspective in this study has flaws in accounting terms. For one thing, **transfer payments** such as taxes and subsidies should be excluded from the cost balance as these do not represent real economic costs for society (Konstantin and Konstantin 2018; Atkinson et al. 2018). This can be fairly simple for some technologies, e.g. excluding value-added tax from the cost of an energy-efficient refrigerator. However, a complete elimination of all relevant transfer payments is not possible in this study. For example, the capital expenditures for building retrofit and heating systems include a significant amount of labour costs that, in turn, consist to a large extent of payroll taxes.¹² An elimination of all relevant transfer payments would have required a detailed country- and technology-specific analysis of various cost items that is beyond the scope of this project. For another, an analysis from a societal perspective should ideally be based on **shadow prices**, rather than

¹² To illustrate, the share of labour-related costs of different building retrofitting measures in total renovation costs varies across countries between 20% up to more than 80%, depending on the type of measure and the country (Fernández Boneta 2013). According to OECD (2021), the share of income tax plus employee and employer contributions less cash benefits in EU countries is in the range of 35,3%, with a significant variation among countries and household type. We thus estimate that at least about 18-21% of renovation costs would need to be assigned to income taxes. This shows the significant limitations when it comes to the fiscal corrections of cost data.

market prices, to reflect economic costs.¹³ Again, in the absence of data on individual cost items, neglecting this aspect creates minor inconsistencies in the aggregate cost figures.

Scope of demand-side resources in the context of EE1st principle

With respect to the EE1st principle, the key demand-side resource investigated in this report is **end-use energy efficiency** in the building sector, including thermal efficiency (e.g. thermal retrofit of external walls) and appliance efficiency (e.g. adoption of LED lighting). Additional demand-side resources relevant for the EE1st principle (ENEFIRST 2020b) are **energy sufficiency** (Brischke et al. 2015) and **demand response** (Paterakis et al. 2017). Their role in transitioning to a net-zero economy is not investigated in detail in this study. As for the former, the model ENERTILE (see [Section 2.2](#)) represents load shifting for individual heat pumps in buildings as well as large-scale heat pumps in district heating networks (Bernath et al. 2019). Based on the heating demand, the model determines the practical potential (Gils 2014) for load shifting through heat pumps and their hourly dispatch until 2050. The scenario outputs on energy system cost, hourly dispatch etc. thus involve the effect of such demand response actions. However, the isolated effect of these actions on scenario outputs cannot be determined, which would have required dedicated scenarios that vary only by assumptions on technical feasibility, consumer acceptance, and other relevant inputs, but not by final energy demand in buildings. As for the latter, the impact of **energy service sufficiency** on the scenario outputs is disregarded, given the early scientific debate on the extent to which sufficiency measures can be attached a monetary value so that they can be included in a cost-benefit framework.

Electricity distribution network modelling

While the expansion and costs of electricity transmission networks is an endogenous feature of the Enertile model, the quantification of distribution network cost requires a separate approach. In simplified modelling, future power distribution network costs are frequently assumed to be a function of the level of variable renewable energies in the system, or trends in end-uses that cause increases in peak load (mostly heat pumps and electric vehicles) (Jamasp and Marantes 2011; Horowitz et al. 2018).¹⁴ In this study, distribution network costs were scaled according to total electricity demand [TWh] in annual steps until 2050, based on a detailed account of network costs per Member State for the period 2010–2018 (Gorenstein Dedecca et al. 2020). This simplified approach is likely to overestimate the energy system cost associated with electricity distribution networks in the three scenarios because many of these networks will be deployed regardless of the exact level of final energy demand.

¹³ Market prices (financial costs) are typically used in energy models as data inputs. However, they do not necessarily reflect economic costs to society because of market distortions created by either the government or the private sector. For example, minimum wage legislation in the labour market creates a distortion that would need to be compensated in the costs of building renovations by using shadow prices (Bhattacharyya 2019; Sartori et al. 2015; Belli et al. 1998).

¹⁴ Location-specific distribution network planning is certainly governed by more complex interactions, including the network topology, capacity and constraints, penetration and type of renewable energy sources that inject into the network, end-use demand profiles, interconnections, use of the national network for transit flows (Gorenstein Dedecca et al. 2020).

Economy-wide rebound effects

An important issue in energy demand modelling is the consideration of **economy-wide rebound effects** that counteract energy savings from energy efficiency measures.¹⁵ In this study, direct rebound effects are considered in estimations of energy savings provided by the models INVERT and FORECAST (ENEFIRST 2021a). With particular regard to rebound effects resulting from building retrofits, there are important links to the topic of multiple impacts. While the literature typically interprets direct rebound as a loss of efficiency gains, it has to be acknowledged that these behavioural changes are often associated with an increase in comfort, health and well-being (IEA 2015). To substantiate this point, ENEFIRST (2022) quantifies comfort gains as a result of building retrofits for the three scenarios developed in this study, demonstrating significant comfort gains for countries with poor efficiency of the building stock that should be recognized alongside the mere increases in energy demand as a result of direct rebound effects. In turn, a detailed consideration of both indirect and macroeconomic rebound effects is beyond the scope of this study. Based on the evidence base (e.g. Brockway et al. 2021), the scenarios in this study are likely to overestimate the economy-wide savings potentials of end-use energy efficiency in the building sector.

Summary | Chapter 4 | Discussion

The findings of this study are relevant to current policy discussions in several ways. For one thing, the findings generally support a revision of the EED towards a higher **energy savings target** in final energy terms of at least 35% compared to the PRIMES-2007 reference – without taking into account the effect of escalating wholesale energy prices as well as multiple impacts. The ambition level of the EED-2021 proposal can thus be seen as a reasonable benchmark. As demonstrated in other studies, higher ambition levels beyond 40% can certainly be justified on the grounds of higher wholesale energy prices as well as multiple impacts beyond monetary savings. For another, the findings support a doubling of building **renovation rates** compared with the current pace. This is in line with the Renovation Wave strategy. Again, this represents a lower end of possible ambitions levels in order to achieve a cost-efficient transition to net-zero emissions by 2050. While the modelling techniques used in this study do not allow for detailed analysis by policy measure, it is evident that the transitions set out in the scenarios require a highly ambitious and comprehensive package of strategies and policy instruments across sectors.

These policy implications should be seen as the **lower conservative end of possible ambition levels** for end-use energy efficiency in buildings. Most notably, the recent spike in energy prices highlights how rapidly assumptions made and actual developments can drift apart. While this certainly does not make the scenarios of this study obsolete, it underscores the need for sensitivity analyses to ascertain the impact of individual uncertain parameters on the modelling outcomes. Aside from such classic uncertainties, there are some mechanisms omitted in the modelling calculations. An important issue here is a consistent accounting of costs and benefits from a societal perspective. This assessment is essentially limited to energy system cost as an indicator of capital costs, fuel costs and other financial cost items. To address this limitation, the follow-up report ENEFIRST (2022) deals with the quantitative effect of selected multiple impacts on the findings of the present study.

¹⁵ Direct rebounds mean that energy efficiency improvements reduce the effective price of energy services (e.g. lighting) and hence encourage increased consumption of those services, which in turn partly offsets the energy savings. Indirect rebound effects mean that consumers spend more on other goods and services as a result of saving in energy expenses. Finally, macroeconomic rebounds refer to changes in commodity prices. For example, the widespread adoption of thermal retrofits in buildings may reduce natural gas demand and hence gas prices that will in turn encourage increased consumption of gas and other energy carriers. In practice, these three effects occur simultaneously, with their net effect referred to as the economy-wide rebound effect (Brockway et al. 2021; Blok and Nieuwlaar 2016).

5. CONCLUSION

The **Energy Efficiency First (EE1st) principle** suggests considering and prioritising investments in demand side resources (end-use energy efficiency, demand response, etc.) whenever these cost less or deliver more value than default energy infrastructure (generation, networks, storage, etc.). This study set out to provide a quantitative assessment of the EE1st principle for the European **building sector** and energy supply by investigating the level of end-use energy efficiency measures that would provide the greatest benefit – or least cost – for the EU in achieving net-zero GHG emissions by the year 2050.

A set of three **scenarios** was investigated (LOWEFF, MEDIUMEFF, HIGHEFF). Each of them reaches the 2050 target of **net-zero greenhouse gas emissions** in the EU. However, the scenarios differ regarding the ambition level for end-use energy efficiency in residential and non-residential buildings – including building retrofits, energy-efficient appliances and other measures. These differences, in turn, affect the investments into and operation of energy conversion and network capacities for power, district heating, and hydrogen. **Energy system cost** is the central performance indicator in this assessment, indicating the sum of all capital costs, operation and maintenance costs, and fuel costs for energy use in buildings and related energy supply. In sum, this analysis helps determine the extent to which society is better off – in pure monetary terms – if end-use energy efficiency in buildings on the demand side was prioritized over generators, networks and storage facilities on the supply side, in line with the EE1st principle.

The study has shown that while the modelled energy efficiency measures require substantial capital costs, they also reduce the cost for decentralized heating systems, generation and distribution of electricity and district heating, hydrogen supply, and other **supply side resources**. The HIGHEFF scenario, being the most ambitious one among the three (-35.5% reduction in final energy demand vs. 2020 levels), results in additional energy system cost of +114.7 bn EUR over the period 2020–2050 compared to LOWEFF. The additional cost for end-use energy efficiency amounts to +654.4 bn EUR vs. -539.7 bn EUR in supply cost savings, i.e. a compensation of 82.5%. In the slightly less ambitious MEDIUMEFF scenario (-30.2% reduction in final energy demand), energy system cost over the same period is at +6.0 bn EUR and thus almost equivalent to those of the LOWEFF scenario. Additional cost for end-use energy efficiency is at +267.9 bn EUR vs. -261.8 bn EUR savings in energy supply cost, i.e. a compensation of 97.7%. When comparing *aggregate* rather than differential energy system cost over the period 2020–2050, the three scenarios end up at cost between 15.7 (LOWEFF) and 15.8 trillion EUR (HIGHEFF), i.e. a relative standard deviation of 0.41%. In sum, the results of this study give rise to the following **conclusions**:

- (1) End-use energy efficiency in buildings is a **critical component** of a cost-efficient transition to net-zero emission levels in the EU. Considering the close similarity in energy system cost between LOWEFF and MEDIUMEFF, it can be inferred that ambition levels for energy efficiency *below* LOWEFF are likely to result in *additional* energy system cost that, ultimately, would have to be borne by consumers. The LOWEFF scenario (-21.1% reduction in final energy demand in 2050 vs. 2020 levels) can thus be seen as a conservative lower end of possible ambition levels for energy efficiency in buildings. This ambition level is significantly above the business-as-usual pathway of the EU Reference Scenario (-10.4% reduction in final energy demand in 2050 vs. 2020) (Capros et al. 2021). In this vein, an interesting issue for future research is how a 'NOEFF' scenario with poor energy efficiency in buildings below LOWEFF would perform in terms of energy system cost and what risk this pathway implies with a view to security of supply, expansion of renewables required, and other effects.
- (2) The ongoing debate around EE1st provides significant added value in that the principle makes explicit the **trade-offs between supply- and demand-side resources** for reaching the same decision

objectives. As demonstrated by the scenarios in this study, end-use energy efficiency in buildings clearly reduces the need for electricity, district heating and hydrogen infrastructures on the supply side in transitioning to net-zero GHG emissions. Direct cost savings for energy supply are not the only benefit in this context for society at large. Less generation and network capacity needed on the supply side also has important implications with a view to land-use, improved landscape aesthetics and biodiversity, noise levels and related opposition by residents and local policymakers to proposed developments in their local area. End-use energy efficiency is thus an important enabler for ensuring sufficient and realistic deployment levels of renewable energy capacities with a view to meeting the net-zero target by 2050.

- (3) There is ample reason to **support ambition levels for end-use energy efficiency beyond those set out in the LOWEFF scenario**. From a neutral viewpoint, the scenarios MEDIUMEFF and HIGHEFF are not cost-effective in relation to LOWEFF as per the indicator of energy system cost. At the same time, these differences in energy system cost appear minor and arguable when **put into perspective**. To illustrate, additional cost in HIGHEFF vs. LOWEFF for the entire EU-27 comes down to +3.8 bn EUR per year. For the year 2020, this corresponds to less than 0.03% of the EU's gross domestic product (Eurostat 2022c), 1.4% of the net-import value of fossil fuels (Eurostat 2022b), 2.5% of the EU budget (European Union 2020), or EUR 8.54 per EU citizen and year (Eurostat 2022d).

As regards **policy implications**, the evidence from this study generally supports a revision of the EED towards a higher **energy savings target** in final energy terms of at least 35% compared to the PRIMES-2007 reference. The European Commission's suggestion of a 37% target in the proposal for a recast EED (2021d, Art. 4) can thus be seen as a reasonable benchmark. The findings also support a doubling of building **renovation rates** in line with the Renovation Wave strategy (European Commission 2020a), including an increasing share of deep renovation and ambitious renovation packages. While the modelling techniques used in this study do not allow for detailed analysis by policy measure, it is evident that the transitions set out in the scenarios of this study require a highly ambitious and comprehensive package of strategies, planning and policy instruments across sectors. As set out in another branch of reports of the ENEFIRST project (2021d, 2021c, 2021b), applying the EE1st principle in practice requires a **broad policy response**. This involves measures to ensure that demand-side resources are consistently considered on a fair basis alongside energy supply – including electricity market reforms, performance-based regulation for network companies, carbon pricing and others.

It is critical to emphasize that the policy implications derived from this study are relatively conservative and lie at the **lower end of possible ambition levels** for end-use energy efficiency in buildings. The recent spike in energy prices as of 2021–2022 demonstrates how rapidly assumptions and actual developments can drift apart. This spike was not foreseen at the time of preparing the scenarios, which certainly leads to an **underestimation of cost-efficient levels** of end-use energy efficiency in buildings (Eichhammer 2022). Another issue is a consistent accounting of costs and benefits from a **societal perspective**. This study is limited to energy system cost as an indicator of monetary expenses for energy technologies. This does not factor in the variety of **multiple impacts** associated with energy efficiency, including comfort, employment, air pollution, and others. To address this limitation, the follow-up report ENEFIRST (2022) deals with the quantitative effect of selected multiple impacts on the outcomes of this study.

Aside from enhancing the methodological robustness of model-based assessments in the context of the EE1st principle, further research is needed to investigate the potential benefits from **demand response** and **energy sufficiency** in applying the EE1st principle. Both are important demand-side resources in the narrative of the EE1st principle (ENEFIRST 2020b; Mandel et al. 2022) and their explicit consideration in model-based assessments is likely to provide further support for the EE1st principle.

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ACRONYMS AND ABBREVIATIONS

CHP	Combined heat and power
CSP	Concentrating solar power
EE1st	Energy Efficiency First
EED	Energy Efficiency Directive
EU	European Union
GHG	Greenhouse gas
MI	Multiple impact
PV	Photovoltaics