



Investigating pathways to a net-zero emissions building sector in the European Union: what role for the energy efficiency first principle?

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Received: 23 September 2022 / Accepted: 2 March 2023
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Abstract European Union (EU) legislation is increasingly embracing the energy efficiency first (EE1st) principle. This principle seeks to prioritise energy efficiency measures whenever these involve lower costs to society than generators, networks and other energy supply options while achieving the same outcomes. This study contributes to the quantitative evidence on the relevance of EE1st by modelling the impact of moderate to ambitious end-use energy efficiency measures on energy supply and the associated system cost under a net-zero greenhouse gas

emissions constraint by 2050. These measures focus on the EU building sector and include both building retrofits (e.g. wall insulation) and efficient products (e.g. lighting). The results indicate that implementing more ambitious energy saving measures reduces the total electricity, heat and hydrogen capacities needed to achieve the net-zero target. Reducing energy use in buildings by at least 21% between 2020 and 2050 is essential to avoid excessive energy supply costs. This requires actions that go well beyond business-as-usual trends. Reductions of around 30% could be justified on the grounds of (i) high fossil fuel prices and (ii) multiple impacts (e.g. health benefits). Overall, the outcomes provide reasonable justification for the EE1st principle. To put the principle into practice, policy actions such as doubling building renovation rates and setting higher energy efficiency targets are key.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12053-023-10100-0>.

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Keywords Energy efficiency first · Building renovation · Energy systems modelling · Demand-side resources · Multiple impacts · Cost–benefit analysis

Introduction

The energy efficiency first (EE1st) principle has lately gained traction as a guiding principle for energy-related planning, investment and policy-making in the European Union (EU). Following its formal recognition in the EU

Governance Regulation (European Union 2018b) and dedicated guidelines (European Union 2021a), the European Commission recently included a dedicated Article 3 on EE1st in its proposal for a recast of the Energy Efficiency Directive (2021c).

The concept of EE1st essentially rests on two premises (Mandel et al., 2022c). First, a kilowatt-hour of energy saved is equivalent to a kilowatt-hour produced when it comes to meeting consumers' energy service needs and achieving societal objectives such as decarbonisation. Second, there appears to be an imbalance between the level of energy efficiency that makes economic sense and the level observed, a phenomenon referred to as the energy efficiency gap (Brown & Wang, 2017; Gillingham et al., 2018). Hence, the EE1st principle suggests that so-called demand-side resources (end-use energy efficiency, demand response, etc.) should be prioritised whenever these cost less or deliver more value to society than supply-side resources (generators, networks, etc.), while still meeting stated objectives.

As such, it is argued that the EE1st principle can help avoid lock-in situations with long-lived and capital-intensive energy supply infrastructures, ensure that energy service needs are met using the least-cost alternatives available and thus contribute to cost-efficient decarbonisation of the economy (Mandel et al., 2022c; Rosenow & Cowart, 2019). The latter is particularly relevant in light of the EU's commitment to become an economy with net-zero greenhouse gas (GHG) emissions by the year 2050, as set out in the European Climate Law (European Union 2021b, Art. 2).

Implementing the EE1st principle requires actions across sectors. The building sector is of central concern as it accounted for 40% of final energy consumption (Eurostat, 2022b) and 35% of energy-related GHG emissions in the EU-27 in 2019 (EEA, 2021, 2022). The sector features a variety of demand-side resources that can potentially reduce the quantity or temporal pattern of energy use. These include retrofitting existing buildings (Pacheco et al., 2012), new construction of net-zero-energy buildings (Ürge-Vorsatz et al., 2020), low-energy-consumption lifestyle changes (Brugger et al., 2021), efficient products (Michel et al., 2015) and demand response (Paterakis et al., 2017; Wohlfarth et al., 2020).

In the transition towards a net-zero emissions energy system (Davis et al., 2018), these options

compete with supply-side resources in the form of utility-scale and distributed generation, network infrastructures, storage facilities and others (Mandel et al., 2022c). With regard to heating buildings, renewable energy supply options range from the direct use of renewables (e.g. solar thermal), electrification via heat pumps, district heating systems, up to hydrogen and derived synthetic fuels (Korberg et al., 2022; Kranzl et al., 2021). Ultimately, both demand-side and supply-side resources have costs and benefits, which raises the question about the extent to which one or the other should be given priority in strategic planning and policy-making in terms of the EE1st principle.

Energy systems modelling is a significant tool in the context of EE1st as it can assist decision-makers in making informed decisions about policy design and technology investment (Boll et al., 2021). In a meta-analysis of 16 scenarios for near-zero emissions ($\geq 90\%$ reduction by 2050 vs. 1990), Tsiropoulos et al. (2020) show that the EU building sector in 2050 could consume 20 to 55% less energy than today, with heat pumps and district heating covering the bulk of heat demand. Substantial improvements in buildings' energy performance, electrification and stronger sector coupling are also evident in dedicated scenarios for net-zero GHG emissions by 2050 (Camarasa et al., 2022; D'Aprile et al., 2020; IEA, 2021).

However, the techno-economic trade-off between demand-side and supply-side resources in the transition towards net-zero emissions for the EU building sector has not been dealt with in depth. Zeyen et al. (2021) demonstrate that comprehensive building retrofitting could reduce the costs for transitioning to net-zero emissions in the EU by 14% (104 bn EUR/a) compared to a scenario without any retrofitting activities. For the case of Germany and an 87.5% GHG reduction target, Langenheld et al. (2018) highlight that a moderate focus on building retrofits can reduce costs by between 2.2 and 8.3 bn EUR/a compared to scenarios with greater emission reductions from renewables and hydrogen.

The majority of studies focus on the trade-off between building retrofits versus district heating and decentralised heating at municipal level (Ben Amer-Allam et al., 2017; Büchele et al., 2019; Delmastro & Gargiulo, 2020; Harrestrup & Svendsen, 2014; Milic et al., 2020; Romanchenko et al., 2020). These studies generally conclude that heat energy savings can

be cheaper than the deployment of new heat supply options up to a certain extent. While some studies do feature a national scope (Drysdale et al., 2019; Hansen et al., 2016), they are likewise limited to thermal loads while disregarding the interactions with electricity and hydrogen supply. As a result, they need to rely on exogenous prices, which ignores that energy supply is price elastic and can adapt to new demand profiles (Zeyen et al., 2021).

Moreover, existing studies tend not to take a consistent societal perspective, which is a key feature of the concept of EE1st (European Union 2021a; Mandel et al., 2022c). Studies typically operationalise a societal perspective by adding up financial costs and by applying a low social discount rate (e.g. Ben Amer-Allam et al., 2017). The true societal value of energy efficiency, however, is also defined by welfare gains to individuals (thermal comfort, poverty alleviation, etc.) and to society as a whole (avoided air pollution, energy security etc.). Including these multiple impacts (Ürge-Vorsatz et al., 2016) or multiple benefits (Reuter et al., 2020) has been demonstrated to significantly alter the outcomes of cost–benefit calculations in energy systems modelling (Thema et al., 2019; Ürge-Vorsatz et al., 2016).

This study aims to provide quantitative evidence for the relevance of the EE1st principle by modelling the effect of moderate to ambitious end-use energy efficiency measures on an energy supply system that is transitioning towards net-zero GHG emissions. The central research questions are:

- How do energy savings in the building sector affect the deployment and operation of supply-side resources for electricity, heat and hydrogen?
- To what extent should end-use energy efficiency measures be prioritised over supply-side resources in the EU's transition towards a net-zero emissions energy system?

Answering these questions can lead to a better understanding of an economically viable balance of demand-side and supply-side resources within the scope of EE1st. The central contribution of this study is the analysis of three model-based scenarios, each set to achieve the normative target of net-zero GHG emissions, but with different ambition levels for end-use energy efficiency in buildings. The study also contributes a systematic accounting of energy system costs, comprising all monetary costs in buildings and

energy supply, plus damage costs due to air pollution, as one of many relevant multiple impacts.¹

In the following, “**Methodology**” describes the scenarios, modelling approaches and the central performance indicator of energy system cost. “**Results**” presents the results. “**Discussion**” contains policy implications as well as a critical appraisal. “**Conclusion**” concludes the study and provides an outlook to further research.

Methodology

This analysis applied four interlinked modelling tools under the constraint to reach net-zero GHG emissions by 2050. Three scenarios were investigated, which differ by their ambition level for end-use energy efficiency in the building sector.² The indicator of energy system cost was used to assess each scenario's performance.

Outline of scenarios

The three scenarios approach the net-zero target with different levels of ambition for building retrofits and efficient products. This involves differences in the supply mix, capacities installed and overall energy system costs. Table 1 provides a qualitative outline of the scenarios. Detailed scenario parametrisations are presented under ‘**Modelling approaches**’.

Altogether, the scenarios demonstrate the value of end-use energy efficiency in the building sector as the central demand-side resource within the scope of the EE1st principle. Note that end-use energy efficiency is one of many relevant demand-side resources under the EE1st principle, as further considered in the ‘**Discussion**’.

Definition of energy system cost

Energy system cost (*ESC*) is the central performance indicator in this analysis. It indicates the total

¹ Air pollution is considered the second biggest environmental concern for the EU after climate change (González Ortiz et al., 2020). In a net-zero future with the absence of fossil fuels, air pollution emissions from bioenergy carriers remain relevant, e.g. particulate matter from solid biomass combustion in households (Vicente and Alves 2018).

² Throughout this study, the term ‘building sector’ is used to refer to the total final energy consumption in the sectors households and commercial and public services (European Commission 2019), excluding the industry sector.

Table 1 Qualitative outline of scenarios

Scenario	Description
Low energy efficiency in buildings (LOWEFF)	The EU primarily relies on renewable energy sources to decarbonise energy use in buildings. Ambitions for thermal retrofitting remain below the goal of doubling renovation rates set in the European Commission's Renovation Wave strategy (2020a). Energy performance standards under the EU Ecodesign Directive (European Union 2009) are not tightened. As a consequence, comparatively high investments in generation, networks and storage capacities are needed to help achieve net-zero GHG emission levels. LOWEFF should not be interpreted as a business-as-usual scenario, given (i) the net-zero outcome by 2050 and (ii) reductions in final energy consumption that go well beyond the EU Reference Scenario (Capros et al., 2021)
Medium energy efficiency in buildings (MEDIUMEFF)	Due regard is given to the EE1st principle. Building renovation rates are doubled compared to LOWEFF, along with greater renovation depth. Energy performance requirements for appliances are increased. In response to energy savings in buildings, the required investments in energy supply systems to achieve the 2050 net-zero target are lower than in LOWEFF
High energy efficiency in buildings (HIGHEFF)	The EE1st principle is well established. Renovation rates and depths are further increased for both residential and non-residential buildings. Strict performance requirements drive the adoption of highly efficient appliances. This is reflected in reduced investments in electricity, heat and hydrogen supply compared with the other two scenarios. HIGHEFF can also be framed as a future with significant barriers to renewable energy supply (Eleftheriadis & Anagnostopoulou, 2015) (e.g. delays in the issuing of construction permits), as a result of which energy efficiency measures need to make a greater contribution to minimising GHG emissions

monetary costs incurred to meet the energy service needs of the building sector. It thus helps determine the extent to which the EU would be better off if end-use energy efficiency measures in buildings were systematically prioritised over supply-side resources when transitioning to a net-zero energy system.

ESC is defined according to Eq. (1) as the total discounted average costs (*C*) over each EU-27 country (*k*), each yearly time step (*t*), each cost type (*i*) and cost item (*j*) for the period 2020–2050 (*n* = 31), where δ represents the discount rate. Note that for the sake of interpretability, *ESC* is given in annual equivalent amounts (*EUR/a*). This is done by multiplying the summarised present value of all costs by the capital recovery factor or annuity factor α (Konstantin & Konstantin, 2018):

$$ESC = \sum_{k=1}^{27} \sum_{t=1}^{31} \sum_{i=1}^4 \sum_{j=1}^{10} \left[\frac{C_{k,t,i,j}}{(1+\delta)^t} \right] \cdot \alpha \quad [EUR/a] \quad (1)$$

where

$$\alpha = \frac{\delta}{1 - (1 + \delta)^{-n}} \quad [1/a]$$

The range of cost types *i* and cost items *j* is listed in Fig. 1. Cost types involve capital costs for various

demand-side resources (e.g. building renovation) and supply-side resources (e.g. wind turbines). In addition, the *ESC* includes operating expenses in the form of fuel and operation and maintenance (O&M) costs. Finally, other costs include the costs of CO₂ emission certificates in the scope of the EU Emissions Trading System (ETS), as well as monetised damage costs due to air pollution.³

The *ESC* distinguishes ten cost items. To rule out any double-counting in this cross-sectoral analysis, the generation and network costs for electricity, district heating and synthetic combustibles (hydrogen, gaseous and liquid hydrocarbons) were calculated endogenously in bottom-up terms on the supply side. In turn, for the cost item of 'Fuel costs in buildings', the wholesale costs for fossil fuels (natural gas, fuel oil, coal) and bioenergy carriers (solid biomass, biomethane, bio-oil) were calculated based on estimated demand and specific costs in *EUR/kWh*, as described in the 'Energy demand' section.

³ CO₂ emission certificates are here regarded as a correction for the externality of climate damage, even though these charges may not reflect actual damage costs to society (Smith et al., 2020). In turn, for air pollution, cost rates are applied, rather than the value of environmental taxes and other corrective measures.

		COST TYPES i			
COST ITEMS j		① Capital costs	② Fuel costs	③ O&M costs	④ Other costs
	① Building renovation	Renovation measures on walls, roofs, windows, ventilation; etc.	-	-	-
	② Electrical appliances	Refrigerators, washing machines, lighting, etc.	-	Fixed O&M	-
	③ Heating systems	Decentralised boilers, ovens, heat pumps, solar thermal, etc.	-	Fixed O&M	-
	④ Fuel costs in buildings	-	Gaseous/liquid fuels, bioenergy, minus hydrogen generation	-	-
	⑤ District heating generation	Centralised boilers, CHP, heat pumps, solar, storage, etc.	Wholesale costs for fossil fuels and bioenergy carriers	Fixed & variable O&M	CO ₂ emission certificates
	⑥ District heating networks	Heat distribution networks	-	Fixed & variable O&M	-
	⑦ Electricity generation	Fossil, nuclear, renewable plants, battery storage, etc.	Wholesale costs for fossil, nuclear, bio energy carriers	Import/export cost, fixed & variable O&M	CO ₂ emission certificates
	⑧ Electricity networks	Cross-border transmission networks, distribution networks	-	Fixed & variable O&M, system service costs	-
	⑨ Hydrogen generation	Electrolysers, hydrogen storage, methanation reactors	-	Import/export cost, fixed & variable O&M	-
	⑩ Negative externalities	-	-	-	Air pollution damage cost

Fig. 1 Definition of cost items and cost types in energy system cost. CHP combined heat and power, O&M operation and maintenance

To neglect the effect of inflation, all costs in the *ESC* are reported in real money terms (EUR_{2018}). Note that in the ‘Results’ section, *ESC* is expressed as a differential cost relative to the *LOWEFF* scenario. This helps to isolate the specific impact of building sector efficiency measures and dismisses any costs accruing in both the industry and transport sectors, as these costs cancel each other out across scenarios.

As described above, the most relevant evaluation perspective within the scope of the EE1st principle is the societal perspective (Mandel et al., 2022c). This has two major implications with respect to *ESC*:

1. In line with existing guidance (Sartori et al., 2015) and related studies (e.g. Langenheld et al., 2018), a social discount rate of 2.0% in real terms was selected to discount yearly costs.⁴

⁴ There are various approaches to empirically estimating social discount rates for a given country (Atkinson et al., 2018; Sartori et al., 2015). One common approach is to use the rates of government bonds as proxies for the social rate of time preference. For the sake of simplicity, this work applied a uniform social discount rate across countries.

2. To the extent possible, direct and indirect taxes were omitted from all costs as they are considered to be transfer payments between members of society (Khatib, 2014; Konstantin & Konstantin, 2018). In the *ESC*, this particularly concerns the exclusion of value added tax and other flat-rate surcharges from fuel costs in buildings. However, it was not possible to completely eliminate all relevant transfer payments in this study. To illustrate, building renovations include a significant share of labour costs that, in turn, largely consist of payroll taxes.⁵ A thorough elimination of all relevant transfer payments would require dedicated country- and technology-specific analyses.

⁵ The share of labour-related costs in the overall costs of retrofitting measures ranges across EU countries from 20 to more than 80% (Fernández Boneta 2013). According to OECD (2021), the share of income tax in EU countries is in the range of 35%, again with significant variation across countries. Thus, a rough estimate is that at least about 18–21% of refurbishment costs could be counted as income taxes, and thus transfer payments.

Table 2 Key features of modelling tools applied

	INVERT/OPT	FORECAST	ENERTILE	NETHEAT
Cost items ^a	• Building renovation • Heating systems	• Electrical appliances^b	• District heating generation • Electricity generation • Electricity networks^c • Hydrogen generation	• District heating networks
Approach	Optimisation	Simulation	Optimisation	Simulation
Temporal resolution	Yearly	Yearly	Hourly (system operation), 10-yearly (capacity expansion)	Yearly
Spatial resolution	National	National	Local (RES potentials at 6.5 × 6.5 km grid), national (power flows)	Local (0.1 × 0.1 km grid)
Main input variables	Building stock data, technology properties and costs, consumer energy prices	Technology costs, consumer energy prices, learning rates	Final energy demand, technology costs, fuel prices, existing capacities	Useful energy demand, fuel and electricity prices, building stock, road lengths
Main output variables	Final energy demand by energy carrier and building type, costs, direct CO ₂ emissions	Final energy demand by technology and efficiency class, market shares, costs	Generation mix, primary energy consumption, installed capacities, costs, direct CO ₂ emissions, prices	Network length, costs, linear heat densities, buildings connected
Model environment Aux. software	Python SQLite, Excel	VB.Net SQLite	Java MySQL	Python QGIS, Excel
Licence	Commercial	Commercial	Commercial	Commercial
Website	TU Wien (2020)	Fraunhofer ISI (2022b)	Fraunhofer ISI (2022a)	IREES (2022)
Key applications	Hummel et al. (2023)	Mandel et al. (2019), Elsland (2016)	Bernath et al. (2021), Lux and Pfluger (2020)	Popovski et al. (2023), Steinbach et al. (2020)

^aSee Fig. 1^bResidential buildings only^cCross-border transmission networks only

In sum, energy system cost (*ESC*) as defined here can be seen as a simplified measure of societal welfare.⁶ As such, *ESC* resembles the *societal cost test*, one of the five cost-effectiveness tests used by energy utilities and regulators in the USA to determine the value of energy efficiency measures and other system resources (Yushchenko & Patel, 2017; U.S. EPA, 2008). The following section describes how the *ESC* was calculated for the three defined scenarios using sectoral modelling tools.

⁶ Paltsev and Capros (2013) discuss other cost metrics for the evaluation of energy and climate policy. They conclude that the more abstract, but also more difficult to measure, concepts of changes in gross domestic product (GDP) or welfare would be a more appropriate indicator of socially beneficial outcomes than energy system cost.

Modelling approaches

Four bottom-up modelling tools were applied. The tools were soft-coupled (Pye & Bataille, 2016), i.e. interlinked in an iterative process, with data transferred across the models. Table 2 presents their key features. Note that the differences in resolution across the models involved some aggregation of data. For example, ENERTILE computes hourly electricity prices, which were aggregated into annual values to make them usable for the other three models.

Energy demand

The soft-coupled model setup requires estimates of final energy consumption for all energy demand sectors. Energy needs in both residential and

non-residential buildings are explicitly modelled by applying the models INVERT/OPT and FORECAST. Developments in the industry and transport sectors are kept constant across the three scenarios so that scenario differences result exclusively from the different ambition levels for end-use energy efficiency in buildings.⁷

The optimisation model INVERT/OPT (Hummel et al., 2023) covers the end-uses of space heating, water heating, space cooling and ventilation in both residential and non-residential buildings, excluding industry. The model is based on detailed representation of existing building stocks at EU Member State level. It projects future heating and cooling demand by combining building archetypes, the calculation procedure of ISO 13790:2008 and various options for renovation and conversion equipment. Building occupants' behaviour is taken into consideration when determining energy needs. For instance, Mandel et al. (2022a) present the approach used in INVERT/OPT to endogenously determine indoor temperature changes in response to building retrofits, i.e. a form of direct rebound effects.

INVERT/OPT uses a mixed-integer linear programming algorithm to determine combinations of renovation and heat supply options that minimise technical system costs from the existing state to the target year, i.e. the sum of annual capital costs plus fuel and O&M costs. Based on this cost optimisation logic, the model endogenously determines the share of buildings in each archetype undergoing renovation along with the market shares of heating and cooling systems. The optimisation problem is subjected to two major constraints (Hummel et al., 2023): (i) CO₂ emissions associated with heating and cooling must be reduced by at least 95% between 2017 and 2050; (ii) energy carrier use must be below the energy carrier potentials. These potentials are reported in Hummel et al. (2023). In essence, they comprise technical restrictions (e.g. gas network availability) and socio-economic restrictions (e.g. acceptance of biomass combustion).

INVERT/OPT features three major input databases (Hummel et al., 2023):

- Existing building stocks | Building stocks are distinguished by construction period, geometry, physical properties of building shell (e.g. U-values), type of use and status of last renovation. Data are compiled from Loga et al. (2016), ZEBRA2020 (2015), ENTRANZE (2014) and other sources.
- Supply technologies | Data on conversion efficiencies, technical lifetimes, specific investments and O&M costs are distinguished by country, taking into account technological learning and different system sizes. Data are primarily based on DEA (2021b), complemented by country-specific sources.
- Renovation options | For each building archetype, multiple renovation packages consisting of single measures (e.g. triple glazing of windows) are defined, along with their specific costs and resulting U-values. Costs are based on a dedicated method detailed in Hummel et al. (2020).

The three scenarios LOWEFF, MEDIUMEFF and HIGHEFF were operationalised in INVERT/OPT using three settings related to renovation activities (Hummel et al., 2023)⁸: the permitted share of refurbishments in (i) the entire building stock, (ii) in individual building segments and (iii) the average length of renovation cycles (Table 3).⁹ In essence, LOWEFF is characterised by a high minimum share of refurbishment in renovation activities, while HIGHEFF involves relatively short renovation cycles.

The simulation model FORECAST (Fraunhofer ISI 2022b) was used to project the energy use of electrical appliances, lighting and cooking equipment in

⁷ Projections on final energy consumption for electricity, heat and synthetic combustibles in industry and transport are based on the 1.5TECH scenario evaluated by the in-depth analysis (European Commission 2018a) in support of the European Commission's 'A Clean Planet for All' communication (European Commission 2018b).

⁸ In line with Mazzarella (2015) and Esser et al. (2019), the following terminology is used. 'Retrofits' refer to the process of improving the energy performance of an existing building, e.g. by adding insulation. 'Refurbishments' refer to maintaining or improving a building's aesthetics, functionality and safety, without explicitly addressing energy performance. Finally, 'renovation' encompasses both retrofits and refurbishments.

⁹ Practically speaking, the maintenance settings generally represent the renovation depth, i.e. the extent to which a building undergoes deep to shallow thermal retrofits that improve its thermal performance. The renovation cycle setting can be interpreted as the renovation rate in terms of the overall stock turnover of building components.

Table 3 Definition of scenarios for energy demand

Variable	Scenario		
	LOWEFF	MEDIUMEFF	HIGHEFF
Refurbishment share in total renovations (entire stock)	65–90%	20–50%	10–90%
Refurbishment share in total renovations (building segments)	25–100%	10–90%	0–100%
Modification of renovation cycles of building shell elements	1	1	1/1.4
Ecodesign requirements for appliances	Existing provisions as of Dec 2020	• 2020–2030: best four available classes • 2031–2050: best three available classes	• 2020–2030: best three available classes • 2031–2050: best two available classes
Energy demand in transport and industry	Final energy consumption for electricity, heat, and synthetic combustibles based on the 1.5TECH scenario (European Commission 2018a)		

See Footnote 8 for definition of retrofits, refurbishments and renovations

residential buildings.¹⁰ It is designed as a bottom-up vintage stock model, with technologies reaching the end of their lifetime being scrapped and new appliances gradually entering the market. The market shares of new technologies are endogenously determined based on a combination of utility functions and a logit approach able to represent observed technology purchase behaviour in households (Elsland, 2016; Mandel et al., 2019).

The model consists of the following product groups with different technologies that, in turn, are disaggregated by their efficiency class (e.g. A label):

- White goods (refrigerators, freezers, washing machines, dryers, dishwashers, stoves)
- Information and communications technology (laptops, tablets, televisions, etc.)
- Lighting (light emitting diodes, compact fluorescent lamps, halogen lamps)
- Other energy use: aggregate of small electrical appliances that are not explicitly modelled (e.g. coffee machines), plus emerging appliances which could potentially diffuse in the market until 2050

Technology adoption and the related stock turnover in FORECAST are largely based on techno-economic drivers (unit price, power per unit, etc.) and assumed user behaviour (e.g. number of washing machine cycles per year). These data are primarily based on the technology-specific preparatory studies (e.g. VHK/ARMINES 2016) under the EU Ecodesign Directive (European Union 2009) and the complementary Energy Labelling Regulation (European Union 2017). Unit prices are collected for the EU as a whole and transformed into country-specific values using price level indices (Eurostat 2022m). Consumer price indices (Eurostat, 2022i) are used to refer all prices to EUR_{2018} levels.

To operationalise the three scenarios in FORECAST, the energy performance standards that new appliances must meet were modified (Table 3). More energy-efficient appliances thus gradually replace relatively inefficient ones, resulting in a decrease in energy demand. In LOWEFF, it is assumed that the existing Ecodesign requirements as of December 2020 are not modified, whereas these provisions are gradually increased in MEDIUMEFF and HIGHEFF.

Energy supply

Energy supply and the associated energy system costs for electricity, district heating and synthetic combustibles were determined endogenously using the modelling tools ENERTILE and NETHEAT. The

¹⁰ To specify, the module ‘Residential appliances’ (Elsland 2016; Mandel et al., 2019) within the modelling platform FORECAST (Fraunhofer ISI 2022b) is applied. This module does not cover non-residential buildings. Projections for these end-uses are taken from the ‘Centralized’ scenario of the ‘REflex’ project (REflex 2019).

Table 4 Definition of scenarios for energy supply

Variable	Scenario		
	LOWEff	MEDIUMEff	HIGHEff
Fossil fuel prices	Wholesale prices for crude oil, natural gas, hard coal, uranium based on Sustainable Development Scenario in IEA (2019)		
Biomass	Available biomass for electricity and district heating generation in 2050 at maximum of 50% of consumption level in 2020 (Eurostat, 2022c)		
Coal	Phase-outs/new construction ban based on Europe Beyond Coal (2021)		
Carbon capture and storage	Unavailable for electricity generation, based on 1.5LIFE scenario in European Commission (2018a)		
Cross-border electricity transmission	Minimum status for transmission grid in 2030 according to 2018 Ten Year Network Development Plan (ENTSO-E, 2018)		
Nuclear power	Capacity expansion/deconstruction of nuclear power plants based on National Champions Pathway in Sensfuss et al. (2019)		

techno-economic optimisation model ENERTILE (Fraunhofer ISI 2022a) optimises both the capacity expansion and unit dispatch of renewable energies, conventional power plants, electricity transmission, heat and hydrogen generation technologies, energy storage facilities and demand-side flexibility.

The model is characterised by its high temporal resolution, which considers seasonal, weekly, daily and hourly variations in demand and supply. Likewise, a high spatial resolution is used to calculate the generation potential of wind and solar technologies. ENERTILE endogenously determines their installable capacity, possible generation output and specific generation costs using a GIS-based model at a resolution of about 240,000 tiles with 6.5-km edge length per tile for the continent of Europe. This approach is detailed in Sensfuss et al. (2019). It results in cost-potential curves for five technologies: rooftop photovoltaics (PV), field PV, concentrated solar power (CSP), wind onshore and wind offshore.

The capacity expansion and operation of supply technologies in ENERTILE are based on a linear cost minimisation problem with perfect foresight. The objective function is to minimise the system costs for the provision of electricity, heat and hydrogen over all model regions in all 8760 h per year. These costs comprise annuitised fixed and variable costs for all employed technologies of the three energy vectors. Central constraints of the minimization problem require that (Lux & Pfluger, 2020): (i) hourly outputs of a generation unit do not exceed installed capacity; (ii) hourly electricity transfers between regions to not exceed transmission capacities; (iii) storage units only

operate within the limits of their technical parameterization and (iv), in this study, a decarbonisation level of 100% in 2050.

Given its cost optimisation logic, techno-economic data represent a key input to ENERTILE, such as specific capital expenditures (CAPEX), conversion efficiencies and technical lifetimes. These data were essentially based on (a) ASSET project (DeVita et al., 2018) and the Danish Energy Agency's technology data (DEA, 2021a). For many technologies, capacity expansion is driven by political preferences rather than purely economic decision-making. For this reason, technology-specific assumptions were applied (Table 4), which are not modified across the three scenarios.

Fuel prices are a central variable in ENERTILE, especially during the period when fossil fuel use is still significant. Wholesale prices for crude oil, natural gas, hard coal and uranium are based on the Sustainable Development scenario of the IEA's World Energy Outlook (2019), with prices remaining largely stable until 2050. Note that global fuel prices are an aggregated input to the model setup, with ENERTILE computing supply prices for electricity, district heating and hydrogen as derived commodities and INVERT/OPT again deriving consumer prices for all energy carriers in the building sector.

Electricity networks are addressed separately for the transmission and distribution levels:

- For transmission, ENERTILE endogenously models the transmission of electricity between model regions using a model of net transfer capacities

(Lux & Pfluger, 2020). In this analysis, each European country is represented by one node without grid restrictions within countries, known as a copper plate approach (Lunz et al., 2016). Capacity expansion is determined endogenously, taking into account CAPEX, grid losses and system service costs, e.g. for balancing or ancillary services.

- For distribution, a linear extrapolation of future network costs is applied, based on a detailed account of network charges per Member State (Eurostat, 2022d, 2022e, 2022o). While in reality, location-specific distribution network planning is governed by complex system interactions (Jamash & Marantes, 2011), this study extrapolates distribution network charges (*EUR/kWh*) based on electricity demand (*TWh*) up to 2050.

Capacity expansion and operation of district heating generators are determined in ENERTILE, based on the heat demand projections from INVERT/OPT. Generation potentials for renewable energy sources (e.g. solar thermal) are restricted, as set out in Sensfuss et al. (2019). Below these restrictions, their actual expansion and usage are optimised in ENERTILE. The deployment of large heat pumps, direct electric heating and hydrogen is based purely on the cost optimisation logic in ENERTILE, without applying any exogenous capacity restrictions.

The bottom-up spatial energy simulation model NETHEAT (IREES, 2022) is used to determine the expansion and operation of district heating networks, based on the heat demand projections from INVERT/OPT and the district heating generation mix from ENERTILE. NETHEAT applies a hectare-level resolution across all EU countries, thus capturing local specifics. The locations of residential and non-residential buildings are identified based on OpenStreetMap (2021b) and custom filters. The length of streets where a district heating pipeline can be built is determined based on the urban atlas dataset (Copernicus Land Monitoring Service, 2018b) and additional OpenStreetMap data (2021a).

As detailed in Popovski et al. (2023), CAPEX and O&M costs for networks are determined at hectare level as a function of the heat density, the potential road length and the surface sealing density. The latter is based on an imperviousness dataset (Copernicus Land Monitoring Service, 2018a), indicating the extent to which surfaces are covered with buildings and roads. Depending on the final energy demand for district heating resulting from

INVERT/OPT, a heat density threshold between 7 and 20 GWh/(km² · a) is set across the scenarios and countries. Cost data are taken from Persson et al. (2019), applying cost indices for labour (Eurostat, 2022j) and material (Eurostat 2022i).

As regards hydrogen, ENERTILE endogenously determines the deployment of electrolyser technologies and hydrogen storage facilities, as reported in Lux and Pfluger (2020). In the model, the hydrogen produced can either be used directly (e.g. reconversion to electricity in hydrogen turbines) or synthesised into methane (power-to-methane) or liquid hydrocarbons (power-to-liquid). Hydrogen and derived fuels can either be produced within the EU or imported from abroad.

Demand for synthetic fuels is derived from INVERT/OPT as part of the total demand for gaseous and liquid fuels in the building sector, applying assumptions on fuel composition and prices (Table 5). The assumed fuel compositions are based on the technical limitations for hydrogen in existing gas networks (Götz et al., 2016), estimated EU-wide potentials for bio-energy carriers (Peters et al., 2020; van Nuffel et al., 2020) and the target of net-zero GHG emissions by 2050 (Hummel et al., 2023). Prices are either endogenously determined in ENERTILE (hydrogen, synthetic methane), based on dedicated projections (natural gas, crude oil, bio-methane) or on reasonable assumptions (bio-oil, synthetic liquid fuels).

Gas network costs up to 2050 are estimated based on a linear extrapolation of specific network charges (Eurostat, 2022f, 2022g). Generally, a drop in gas demand is a key feature across net-zero emission scenarios (Tsiropoulos et al., 2020). In response, contrary to electricity infrastructures, gas networks are subject to decommissioning. Assuming that the rate of the decrease in gas demand is higher than the parallel decommissioning rate of gas networks implies increasing specific costs for the remaining network assets (Oberle et al., 2020). Hence, following, see e.g. Hummel et al. (2023), it is assumed that (i) one-third of the specific network costs scales inversely proportional with the decrease rate in gas demand and (ii) a 5% mark-up is added to the specific cost to account for the construction of parallel infrastructures for methane and hydrogen. This specific cost multiplied by the final energy demand for gas then yields the total network cost, which is counted under ‘fuel costs in buildings’ in Table 2.

Table 5 Assumptions concerning fuel composition and prices for liquid and gaseous fuels in the building sector

Fuel composition	Gaseous fuels	Liquid fuels	Wholesale price trend
Bio-methane	77%		van Nuffel et al. (2020)
Hydrogen	10%		Endogenously determined in ENERTILE
Synthetic methane	10%		Endogenously determined in ENERTILE
Natural gas	3%		IEA (2019): Sustainable Development scenario
Bio-oil		85%	Assumption: price bio-methane + 25% mark-up
Synthetic liquid hydrocarbons		10%	Assumption: price synthetic methane + 10% mark-up
Fossil heating oil		5%	IEA (2019): Sustainable Development scenario

Hummel et al. (2023) | Values for EU-27 in year 2050

Air pollution impacts

This study estimated the impacts of air pollution on four receptors (González Ortiz et al., 2020): human health (mortality and morbidity), biodiversity (eutrophication and acidification), crop damage (agricultural

yields) and material damage (building structure deterioration). The methodology is based on direct monetization using cost rates per air pollutant and receptor (Table 6). This involves the following steps:

Table 6 Cost rates by emission source, type and receptor ($EUR_{2018}/t_{emission}$)

Emission type	Receptor	Emission source	
		Energy supply ^a	Buildings ^b
SO ₂	Health damage	5898–28,287	6826–32,742
	Biodiversity losses	1010–1072	1010–1072
	Crop damage	–214 to –202	–214 to –202
	Material damage	279–1336	279 to 1336
NO _x	Health damage	5155–24,724	7337–35,192
	Biodiversity losses	2626–2787	2626–2787
	Crop damage	808–858	808–858
	Material damage	46–223	46–223
PM	Health damage	10,263–49,224	20,200–96,889
NMVOC	Health damage	557–2,673	557–2673
	Crop damage	1010–1072	1010–1072

Matthey and Bünger (2019). Ranges indicate differences among EU countries

SO₂ sulphur dioxide, NO_x nitrogen oxide, PM particulate matter, NMVOC volatile organic compounds without methane

^aFuel combustion in electricity and district heating supply

^bFuel combustion in building sector

1. Summary of energy consumption by energy carrier [kWh_{th}] | The four modelling tools yield data on energy consumption by energy carrier (e.g. natural gas), emission source (e.g. power plant), EU Member State and scenario for the period 2020–2050.
2. Compilation of air pollution emission factors [$t_{emission}/kWh_{th}$] | Based on data from the European and German Environmental Agencies (EEA, 2019; Lauf et al., 2021), each energy carrier is assigned an emission factor, differentiated by pollutant (e.g. sulphur dioxide, SO₂).¹¹
3. Estimation of total emissions [$t_{emission}$] | Energy consumption by energy carrier multiplied by the respective emission factor yields the total emissions by pollutant.
4. Compilation of cost rates [$EUR_{2018}/t_{emission}$] | Cost rates by pollutant, emission source and receptor are available from Matthey and Bünger (2019) for Germany. For the health damage receptor, the cost rates are corrected for differences in gross domestic product per capita (Eurostat 2022n), reflecting that the willingness to pay for avoiding health damage increases with income.
5. Estimation of total damage costs [EUR_{2018}] | Multiplication of total emissions by cost rates

¹¹ The focus here is on direct emissions. Upstream or indirect emissions, e.g. from the production of PV modules, are beyond the scope of this analysis.

Table 7 Overview of selected scenario outputs for EU-27

Domain	Indicator	Unit	Scenario		
			LOWEFF	MEDIUMEFF	HIGHEFF
Cost and emissions	Energy system cost 2020–2050 ^a	<i>EUR</i> ₂₀₁₈ / <i>a</i>	530.59	530.73	534.29
	GHG emissions reduction in 2050 vs. 2020 ^b	–	–98.2%	–98.8%	–99.3%
	Cumulative GHG emissions 2020–2050 ^b	<i>MtCO₂eq</i>	12,540	12,172	11,741
Building sector ^c	Final energy consumption in 2050	<i>TWh</i>	3488	3060	2812
	Annual building renovation rate (2050–2020) ^d	–	0.7%	1.4%	1.7%
Energy supply	Electrical generation capacities in 2050	<i>GW_{el}</i>	2712	2613	2535
	Thermal generation capacities in 2050	<i>GW_{th}</i>	294	208	173
	Hydrogen electrolyser capacities in 2050	<i>GW_{el}</i>	303	290	282

^aAs defined in Eq. (1)

^bSum of emission categories: main activity electricity and heat production (1A1a), commercial/institutional (1A4a), residential (1A4b), according to IPCC (2019)

^cSum of sectors: commercial and public services (FC_OTH_CP_E), households (FC_OTH_HH_E), according to European Commission (2019)

^dDefined as equivalent full renovation rates, i.e. the share of conditioned floor area subject to full renovation of all building envelope components, divided by the conditioned floor area of the whole building stock

yields the total damage costs by country, pollutant and receptor.

Overall, the advantage of the cost rates used in this study is that they can be readily integrated into the energy system cost indicator. More sophisticated air pollution modelling requires dedicated approaches for specific sectors, recipients and types of emissions (e.g. TREMOVE), as well as whole-economy models (e.g. GAINS) to estimate their monetary impacts (Thema et al., 2019).

Results

The following sections present the results of the analysis, starting with energy system cost and then turning to sectoral features for buildings, energy supply and air pollution.

To summarise the overall performance of the three scenarios, Table 7 provides selected outputs for the EU-27. Note that the scenarios achieve GHG emissions reductions greater than 98% in 2050 compared to 2020. Assuming a balance of GHG sources and sinks according to the 1.5TECH scenario (European Commission 2018a) (see footnote 7 above), the three scenarios are all compatible

with net-zero GHG emission levels in 2050. Cumulative GHG emissions have a small relative standard deviation of 3.3% due to the optimisation constraints in the INVERT/OPT and ENERTILE models being based on the 2050 GHG emission level, rather than the 2020–2050 carbon budget (see ‘Modelling approaches’).

Energy system cost and investment needs

Figure 2 shows the performance of the three scenarios in terms of ESC. It indicates that the higher ambition levels for building sector energy efficiency in MEDIUM-EFF and HIGHEFF are not necessarily cost-effective compared to the more moderate ambition level of LOWEFF. Additional costs amount to +0.14 bn EUR/a (MEDIUM-EFF) and +3.71 bn EUR/a. (HIGHEFF). These two scenarios thus incur additional costs in order to achieve the common objective of net-zero GHG emissions by 2050.

Figure 3 illustrates the trade-off between saving energy and supplying energy when achieving net-zero GHG emissions in more detail. Improving energy efficiency in buildings lowers costs for decentralised heating systems as well as centralised energy supply (electricity, district heating, hydrogen). Moreover, there are some savings in air pollution damage costs (negative externalities). Overall, additional costs in MEDIUM-EFF

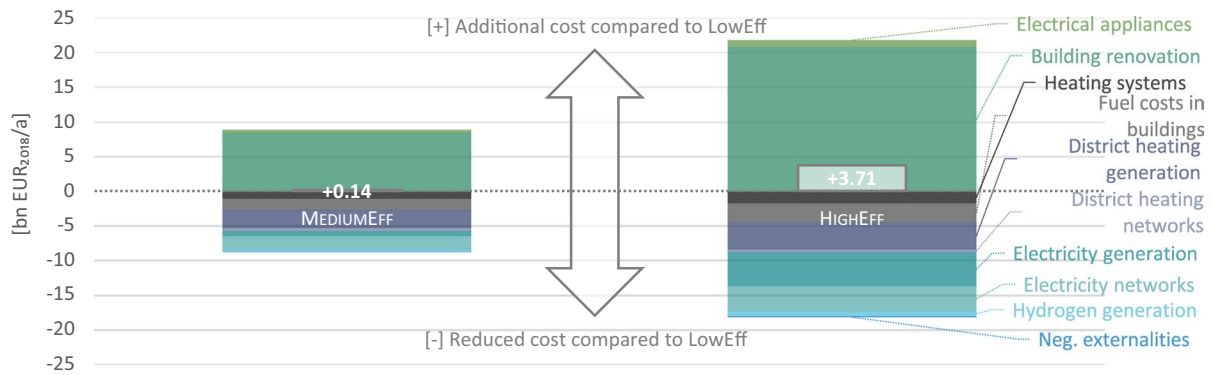


Fig. 2 Energy system cost relative to LowEFF scenario for EU-27 by cost item (2020–2050). See Fig. 1 for definition of cost items

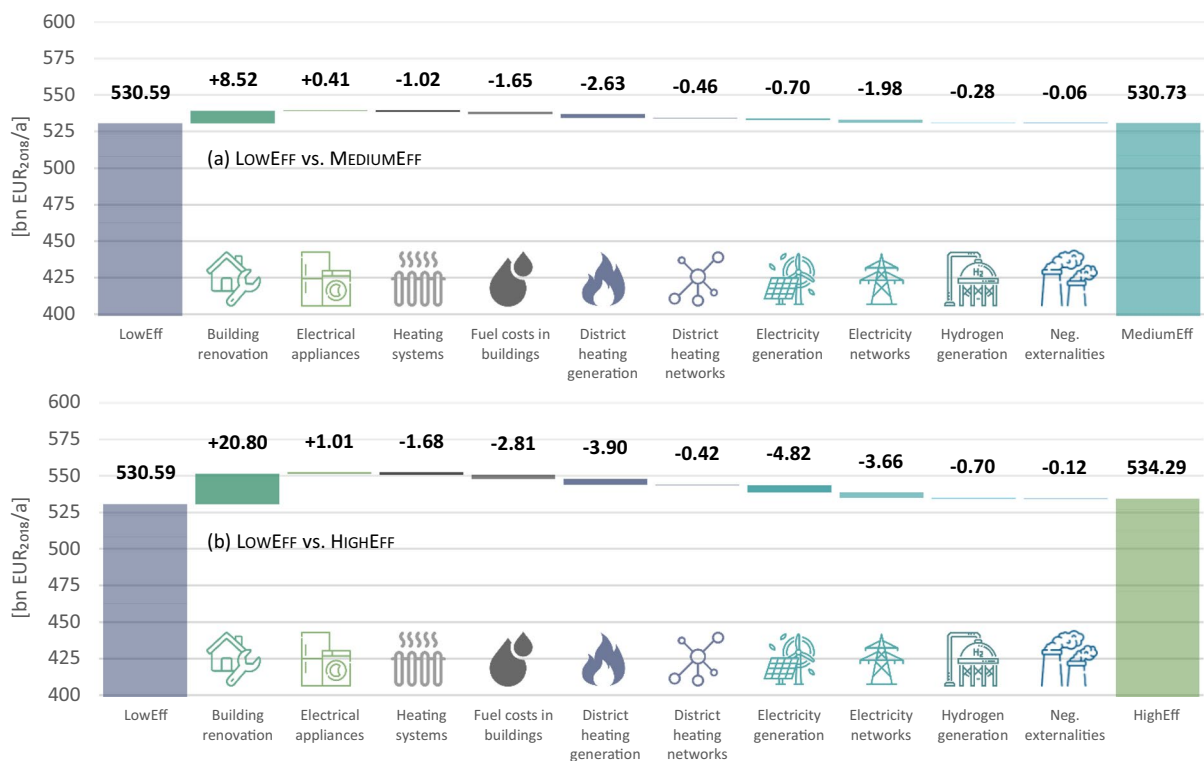


Fig. 3 Decomposition of energy system costs in EU-27 by cost item (2020–2050). See Fig. 1 for definition of cost items

compared to LowEFF amount to 8.9 bn EUR/a and are almost entirely offset by savings in energy supply of 8.8 bn EUR/a (98.4%). HighEFF incurs incremental costs of 21.8 bn EUR/a and savings of 18.1 bn EUR/a (83.0%).

Overall, the aggregated cost volumes in Fig. 3 are similar. Despite the significant differences in

ambition levels for building sector efficiency, the scenarios all have average annual costs between 530.6 (LowEFF) and 534.3 bn EUR/a (HighEFF) over the period 2020–2050, i.e. a relative standard deviation of 0.4%. This demonstrates that energy system costs will be substantial until 2050, regardless of whether

Table 8 Investment needs in EU-27 by cost item (2020–2050) [bn EUR₂₀₁₈]

Cost item ^a	Scenario		
	LowEFF	MEDIUMEFF	HIGHEFF
Building renovation	228	248	276
Electrical appliances ^b	36	38	41
Heating systems	204	200	198
District heating generation	202	190	166
District heating networks	98	79	76
Electricity generation	5212	5167	5023
Electricity networks ^c	219	207	204
Hydrogen generation	553	546	535
Total investment (2020–2050)	6751	6675	6520

^aSee Fig. 1^bResidential buildings only^cCross-border transmission networks only

building sector efficiency is given absolute priority over supply-side resources or not.¹²

Table 8 shows the cumulative investment needs for the EU-27 in all scenarios over the period 2020–2050. This indicator differs from the *ESC* in that it only represents the initial capital expenditures of the technology options. The energy-saving measures, in particular building renovation, involve significant investments, but effectively reduce the investments in new energy supply. Again, differences in total investments across scenarios are moderate, with a relative standard deviation of 1.8%.

Unlike the trend for *ESC* (Fig. 3), *HIGHEFF* involves the lowest total investments across the EU-27 and therefore appears to be more favourable than the other scenarios. These total investments should not be over-interpreted, as they exclude any operating expenses, do not apply discounting and include investments whose lifetime extends beyond the period 2020–2050. Therefore, *ESC* remains the central performance indicator in this analysis.

Buildings

The *INVERT/OPT* and *FORECAST* models were used to project the energy required for residential and

non-residential buildings. Figure 4a provides the breakdown of final energy consumption for heating and cooling by technology group. The aggregated difference between *LowEFF* and *HIGHEFF* in 2050 is 633 TWh. Across the three scenarios, heat pumps cover 42–43% of total heating demand in 2050, with nominal capacities reaching 719 GW_{th} (*HIGHEFF*) to 834 GW_{th} (*LowEFF*) (data not shown here).

Figure 4b displays the final energy consumption for appliances and processes. In response to the tightened energy performance requirements (Table 3), *HIGHEFF* achieves savings of 43 TWh in 2050 compared to *LowEFF*. As described in ‘Modelling approaches’, only technologies in households were explicitly modelled, while those in non-residential buildings were based on exogenous trends. As a result, these figures are relatively conservative (see e.g. European Commission 2021a).

The sum of all end-uses in the building sector is shown in Fig. 4c. In comparison to 2020 levels, final energy consumption in 2050 is reduced by 21% (*LowEFF*), 30% (*MEDIUMEFF*) and 35% (*HIGHEFF*).¹³ The levels of ambition for energy efficiency in all three scenarios are thus significantly above the business-as-usual pathways of the EU Reference Scenario, which projects a 10% decrease for the EU-27 building sector between 2020 and 2050 (Capros et al., 2021).

Electricity supply

The *ENERTILE* model was used to quantify electricity generation as well as its transmission. Figure 5 illustrates electricity demand in the form of a load duration curve (IEA, 2014) for the EU-27 in 2050. This represents the entire power system, i.e. not only demand in the building sector, but also in transportation, industry and other loads. Given the different end-use energy efficiency levels in buildings, peak load is reduced by 4% (*MEDIUMEFF*) and 7% (*HIGHEFF*) compared to *LowEFF*.

Likewise, as shown in Fig. 6a, the more ambitious the level of energy savings, the less wind and solar power generation is needed. Installed capacities for variable renewables can be reduced by 171 GW_{el} or 7%

¹² Note that these are total figures that do not reflect the additional costs for reaching net-zero greenhouse gas emission levels compared to any scenario following a business-as-usual pathway.

¹³ For the base year 2020, total final energy consumption in the models is 4,420 TWh (households plus tertiary sector), compared to 4,295 TWh (+3%) in Eurostat’s (2022b) energy balance for the EU-27 in the same year.

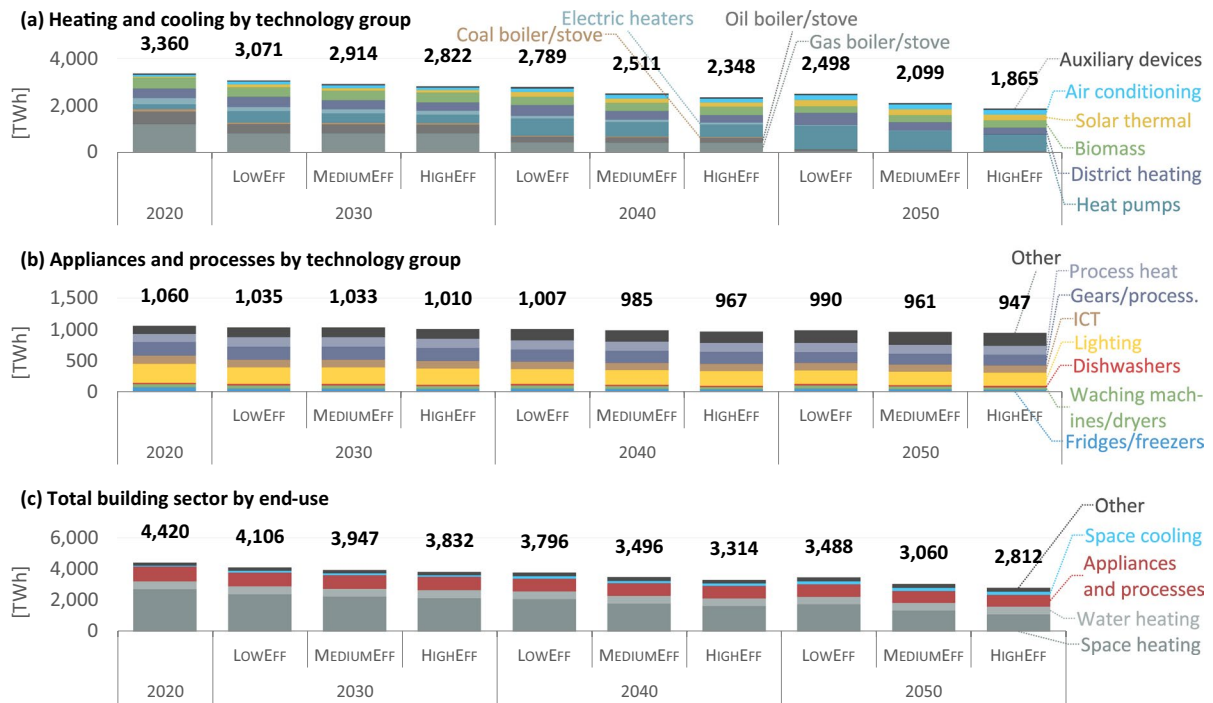


Fig. 4 Final energy consumption in the building sector. Heat pumps incl. electricity and ambient heat | ICT information and communications technologies

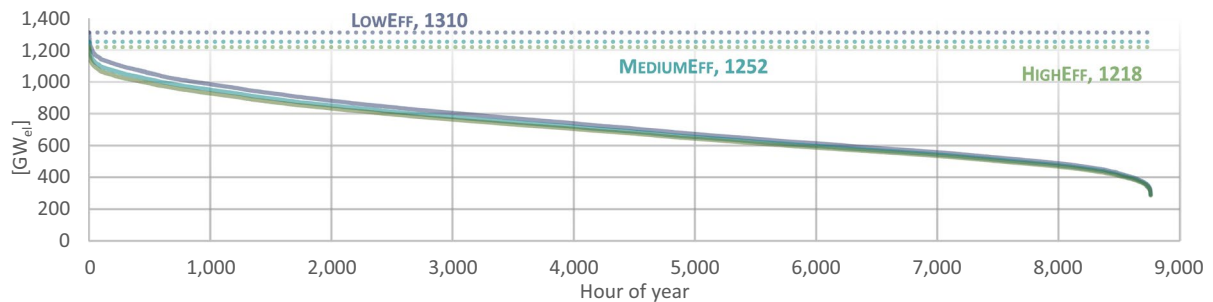


Fig. 5 Electrical load duration curve in EU-27 in 2050. Electrical load for entire EU power system, including buildings, transportation, industry and other loads (e.g. electrolyzers)

in 2050 in HIGH EFF compared to LOW EFF. With regard to dispatchable generators in Fig. 6b, especially the need for back-up hydrogen generators is reduced by 29 GW_{el} or 24% in HIGH EFF compared to LOW EFF. Also, as displayed in Fig. 6c, cross-border transmission capacities can be reduced by 47 GW_{el} or 7% in HIGH EFF compared to LOW EFF.

As Fig. 7 shows, electricity generation increases significantly by 2050. Across all scenarios, variable renewable generators are the backbone of the power system, supplying around 90% 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.

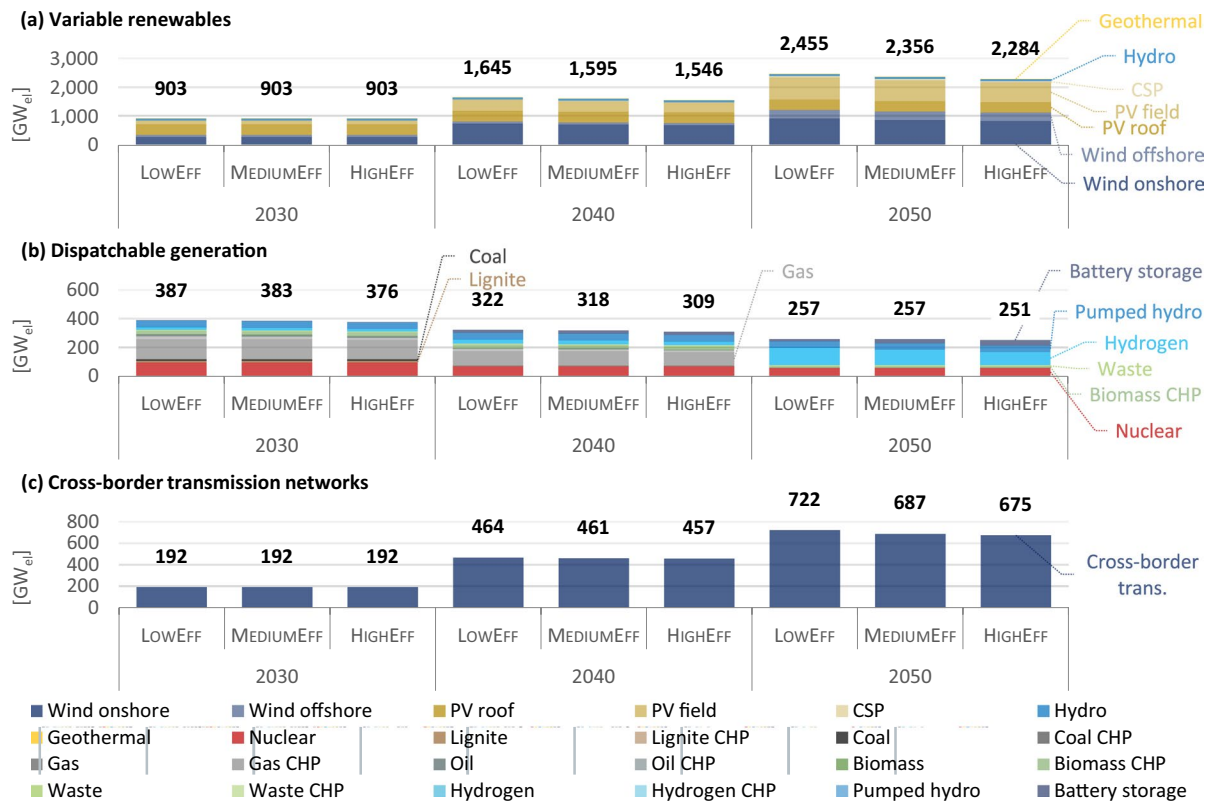


Fig. 6 Electrical generation and transmission capacities by technology in EU-27. CHP combined heat and power, CSP concentrated solar power, PV photovoltaics

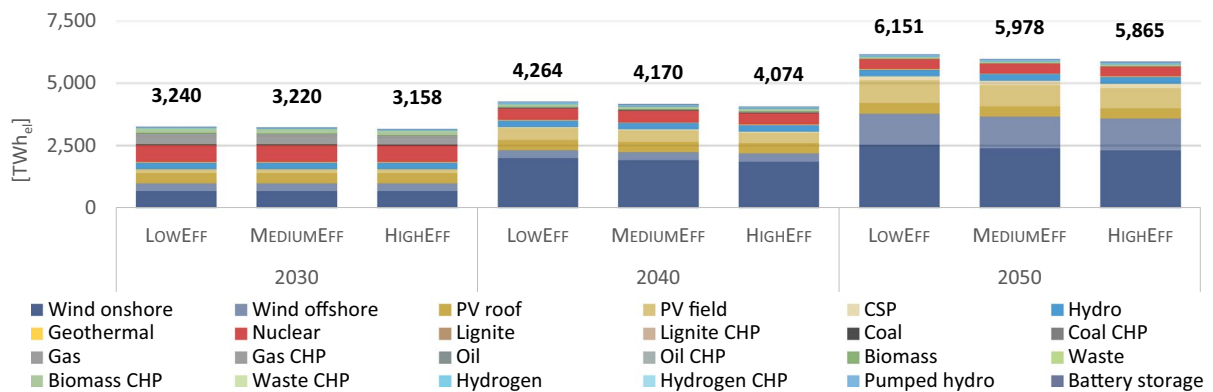


Fig. 7 Electricity generation by technology in EU-27. CHP combined heat and power; CSP concentrated solar power; PV photovoltaics

In accordance with the scenario storylines (Table 4), nuclear power remains significant until 2050. In sum, overall generation in 2050 is lower by 3% (MEDIUMEFF) and 5% (HIGH EFF) compared to LOWEFF.

As shown in Fig. 8, energy savings in buildings also lead to a moderate reduction in long-term marginal electricity generation prices. For the entire EU, average prices in the year 2050 are reduced by 3% in HIGH EFF

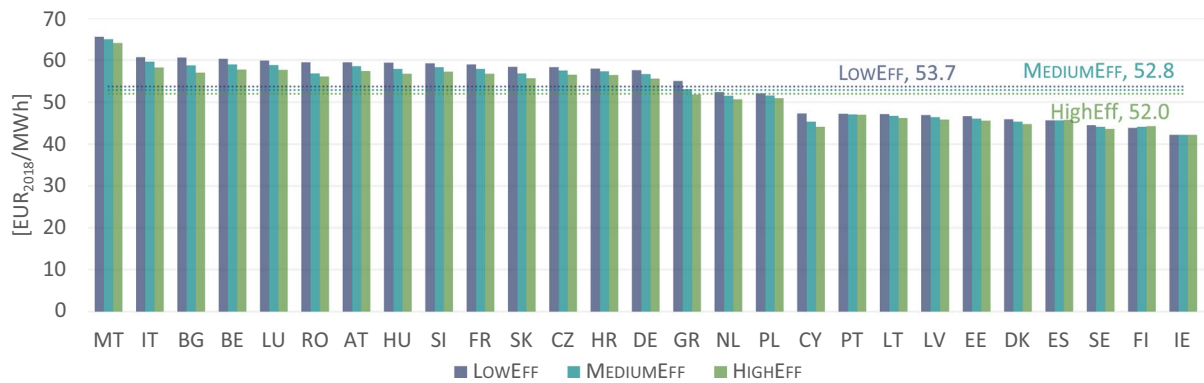


Fig. 8 Long-run marginal prices for electricity generation in year 2050 by country. Horizontal lines: EU-27 average, weighted by electricity generation | Country codes according to European Union (2022)

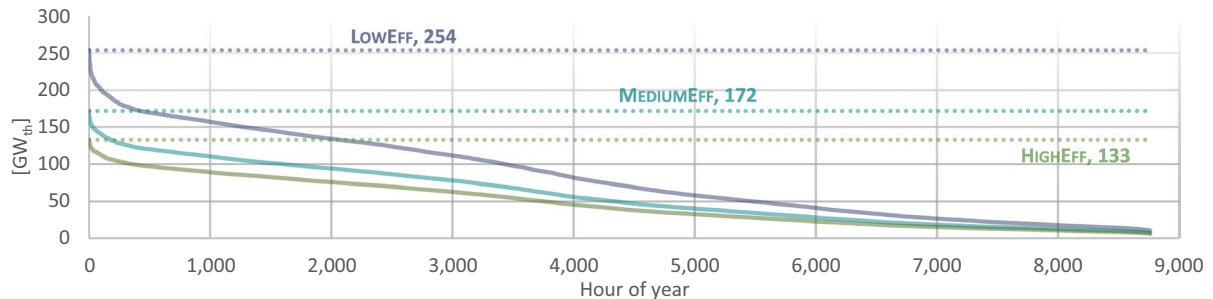


Fig. 9 Thermal load duration curve for district heating in EU-27 in 2050. Heat load for entire EU, including buildings and industry

compared to LOWEFF. This is because energy efficiency reduces the installed capacities and thus the fixed cost components in total production costs. The marginal generator at a point in time thus operates at slightly lower marginal costs, resulting in lower clearing prices.

District heating supply

Based on its optimisation logic, the ENERTILE model determines the district heating supply mix and related costs for each EU Member State. The NETHEAT model calculates the expansion and associated costs of district heating networks. Figure 9 provides the aggregated heat load duration curve for the EU-27 in 2050, covering buildings and industry applications. The enhanced thermal performance of buildings results in a clear reduction in peak load by 32% (MEDIUMEFF) and 48% (HIGHEFF) compared to LOWEFF. Minimum load is between 6 GW_{th} (HIGHEFF) and 11 GW_{th} (LOWEFF).

Reduced thermal load implies smaller capacities for heat supply, as shown in Fig. 10a. The bulk of district heating capacity is provided by large-scale heat pumps, with installed capacities reaching 82 GW_{th} (HIGHEFF) to 155 GW_{th} (LOWEFF) in 2050. Hydrogen-fuelled boilers account for 20% (HIGHEFF) to 27% (LOWEFF) of total capacity in 2050. When linked to Fig. 10b, it becomes clear that these boilers primarily operate at peak load, with full capacity equivalent hours between 246 h/a. (HIGHEFF) and 411 h/a. (LOWEFF). Total heat output in 2050 is lower by 30% (MEDIUMEFF) and 42% (HIGHEFF) compared to LOWEFF. Biomass contributes between 11% (LOWEFF) and 19% (HIGHEFF) of heat output in 2050.

Figure 11 displays the projected district heating network length along with the number of connected buildings. In 2050, total network length in HIGHEFF is 1.7 million km (13%) lower than in LOWEFF. Likewise, in HIGHEFF, there are 40,000 fewer

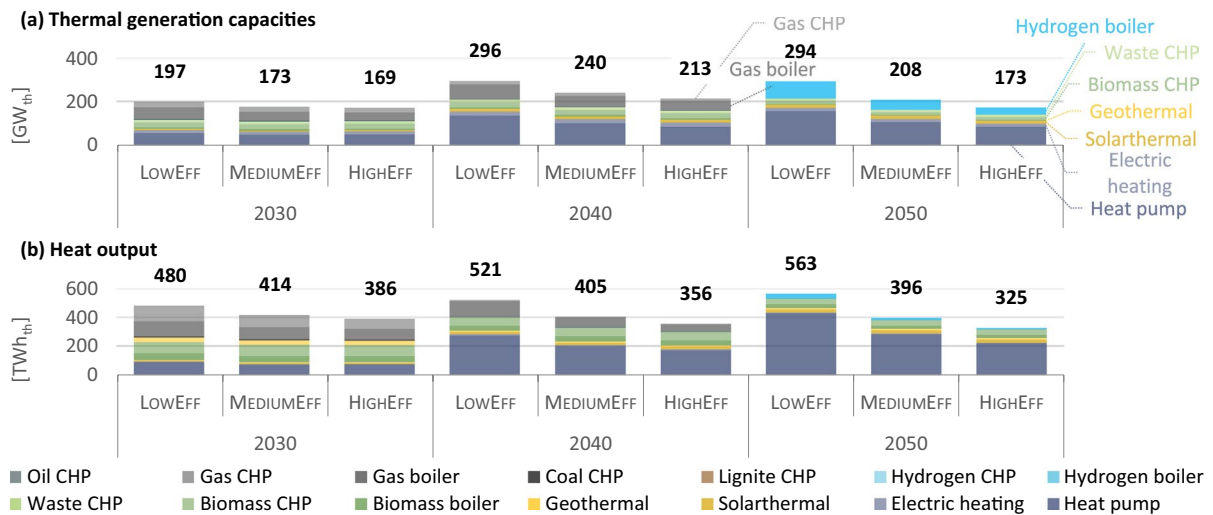


Fig. 10 Thermal generation capacities and heat output for district heating by technology in EU-27. CHP combined heat and power

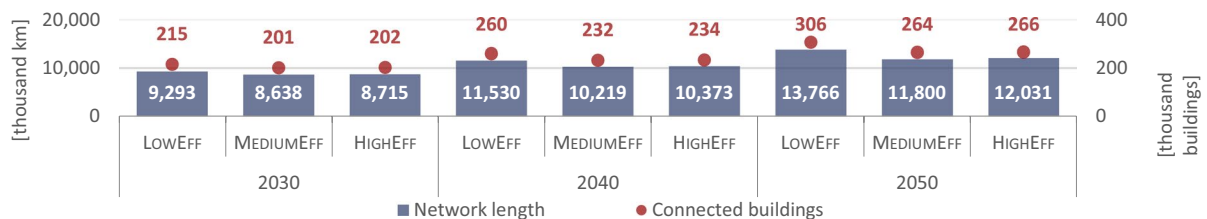


Fig. 11 District heating network length and number of connected buildings in EU-27

buildings connected to district heating networks than in LOWEff in 2050. Combining these numbers with heat output (Fig. 10b) yields the heat density for district heating networks. These densities range from 41 (LOWEff) to 27 (HIGHEff) MWh per year and network kilometre in 2050. In response to the building retrofits, the average utilisation of district heating networks in 2050 is thus 34% lower in HIGHEff compared to LOWEff.

Hydrogen supply

The ENERTILE model endogenously determines the capacity expansion and operation of hydrogen (H₂) supply. H₂ produced can either be reconverted in power plants and boilers or synthesised into methane (CH₄). As shown in Fig. 12a, more ambitious energy savings in buildings imply lower capacities for electrolyzers and methanation reactors. H₂ capacity is

reduced between 4% (MEDIUMEff) and 7% (HIGHEff) compared to LOWEff in 2050. Figure 12b and c show the demand–supply balances for H₂ and CH₄, respectively. In both cases, slightly less energy is needed for heating purposes in boilers, fuel cells etc. when comparing HIGHEff and LOWEff. Likewise, power plants and centralised boilers reconvert slightly lower volumes of both H₂ and CH₄ into electricity and heat.

Air pollution impacts

All three scenarios end up with net-zero GHG emissions levels by 2050. However, as presented in Table 9, the scenarios differ in terms of the air pollution emissions accumulating over the period 2020–2050, resulting from decentralised (buildings) and centralised (energy supply) combustion of energy carriers, particularly biomass. More energy savings on the demand side generally involve less air

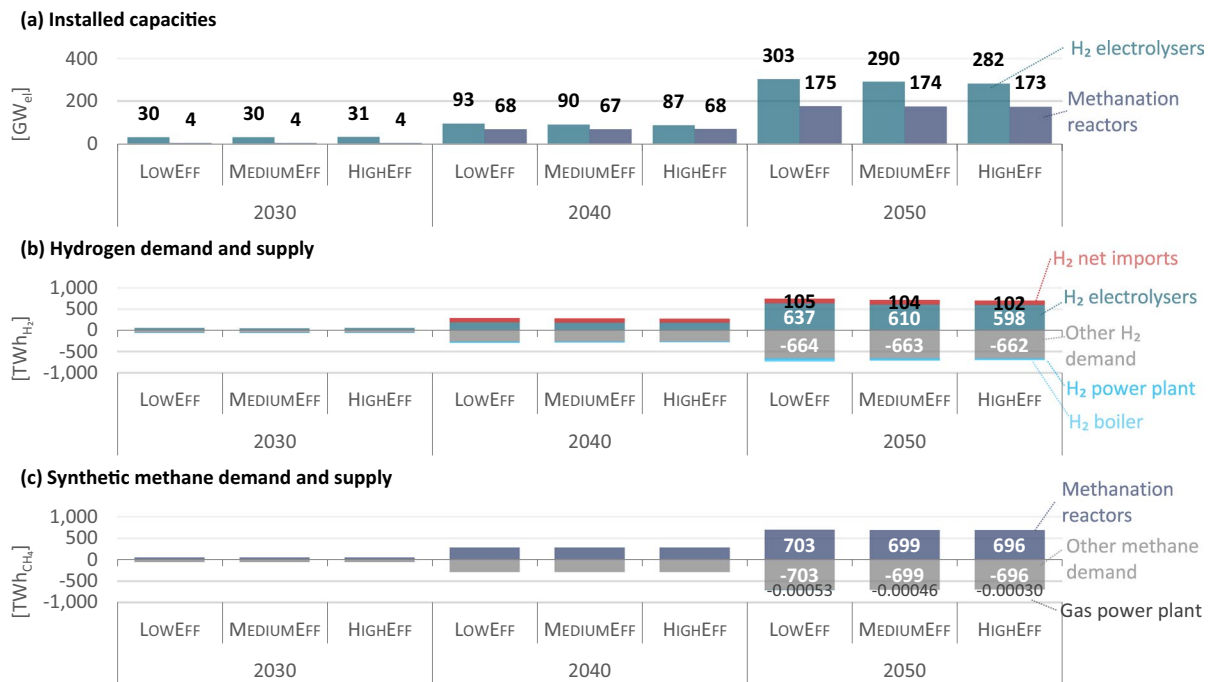


Fig. 12 Installed capacities and demand–supply balance for hydrogen and synthetic methane. Other hydrogen/methane demand comprises direct energy demand in buildings, industry, transportation

Table 9 Cumulative air pollution emissions for EU-27 (2020–2050) [t_{emission}]

SO₂ sulphur dioxide, NO_x nitrogen oxide, PM particulate matter, NMVOC volatile organic compounds without methane

Scenario	Emission source	Emission type			
		NMVOC	NO _x	PM	SO ₂
LOWEFF	Buildings	573,046	6,897,457	932,037	2,702,254
	Energy supply	132,274	4,839,720	68,849	1,163,315
MEDIUMEFF	Buildings	571,072	6,855,804	941,435	2,701,009
	Energy supply	127,892	4,697,482	67,727	1,161,958
HIGHEFF	Buildings	570,133	6,859,144	957,270	2,701,942
	Energy supply	121,624	4,494,603	66,048	1,156,071

pollution, since combustion in thermal power plants, cogeneration plants, boilers and ovens is reduced.

This is reflected in different levels of damage costs from air pollution, as shown in Table 10. Across the scenarios, health damage is the most significant in monetary terms (82%), followed by biodiversity losses (13–14%), crop damage (4%) and material damage (1%). Differences in total damage costs are marginal, with MEDIUMEFF and HIGHEFF saving 0.06 bn EUR/a and 0.12 bn EUR/a, respectively, compared to LOWEFF. As shown in the analysis of ‘Energy system cost’, including or omitting monetised estimates

of air pollution impacts in scenarios transitioning to net-zero GHG emissions does not significantly affect the overall cost-effectiveness of energy efficiency measures.

Discussion

This paper investigated the effect that moderate to ambitious levels of end-use energy efficiency in the EU building sector have on energy system cost and energy supply configurations. The general results

Table 10 Air pollution damage cost for EU-27 (2020–2050) [*bn EUR*₂₀₁₈/*a*]

Scenario	Emission source	Receptor				
		Biodiversity losses	Crop damage	Health damage	Material damage	Total
LOWEFF	Buildings	0.570	0.153	4.206	0.049	7.317
	Energy supply	0.422	0.115	1.772	0.030	
MEDIUMEFF	Buildings	0.567	0.152	4.201	0.049	7.259
	Energy supply	0.412	0.112	1.736	0.030	
HIGHEFF	Buildings	0.568	0.152	4.216	0.049	7.199
	Energy supply	0.398	0.107	1.681	0.029	

indicate that implementing more ambitious energy-saving measures in buildings reduces the total electricity, heat and hydrogen capacities needed to achieve the transition to net-zero GHG emissions. However, according to the indicator of energy system cost (*ESC*), the ambitious energy savings portrayed in the MEDIUMEFF and HIGHEFF scenarios are not necessarily cost-effective compared to the more moderate ambition levels of LOWEFF. This chapter gives an overview of methodological limitations and discusses policy implications.

Critical appraisal

Adopting a societal perspective when assessing demand-side and supply-side resources is a key feature of the EE1st principle as this represents the public interest (Mandel et al., 2022c). In this study, the performance indicator of *ESC* was used as a simplified measure of welfare. The key limitation concerning *ESC* is that this does not consider all the costs or all the benefits relevant to society. The notion of multiple impacts (MIs) — also termed multiple benefits, co-benefits, non-energy benefits, among others (Ürge-Vorsatz et al., 2016) — has become a key argument for supporters of higher ambition levels of energy efficiency. When categorised by recipient, MIs come in two forms:

Internal MIs accrue to individual decision-makers, e.g. a building occupant. To illustrate, building retrofits in combination with advanced ventilation systems affect thermal comfort, which can have significant benefits in the form of improved health and labour productivity (Chatterjee & Ürge-Vorsatz, 2021). There are also internal MIs that occur as costs. Transaction costs or the ‘time and hassle’ borne by building owners and developers during the planning and

implementation phases of retrofits can be as high as 20% of the initial investment (Kiss, 2016).

There are also external MIs borne by society as a whole, i.e. externalities. As described above, negative externalities from air pollution are relatively insignificant under a net-zero GHG emissions constraint, as renewable energy sources gradually replace fossil fuels while the utilisation of bioenergy carriers is similar across the scenarios.¹⁴ However, there are also external costs related to renewable energy supply, including changes to land use, aesthetic issues, disruption of ecosystems, water use and others (Sovacool et al., 2021).¹⁵ Ideally, to ensure a fair comparison of resource options, all negative externalities related to the processing of materials and manufacturing would need to be taken into account by a life cycle assessment, including those related to building insulation materials (Rodrigues & Freire, 2021). In turn, there may also be significant positive externalities from energy efficiency, e.g. energy security in the sense of a reduced risk related to imported energy sources (Gillingham et al., 2009).

¹⁴ Projected biomass consumption in the EU-27 — including buildings, electricity supply and district heating supply — is between 48 Mtoe (LOWEFF) and 50 Mtoe (HIGHEFF) in 2050. When also including the assumed sectoral trends for transport and industry of the 1.5TECH scenario (European Commission 2018a) (see Footnote 7), total biomass consumption amounts to 120–122 Mtoe, which is well below the sustainable potential for bioenergy for the EU-27 of 196–335 Mtoe estimated by Panoutsou and Maniatis (2021).

¹⁵ In a meta-analysis of 139 studies, Sovacool et al. (2021) arrive at mean external costs for electricity supply ranging from 2.9 €/kWh for wind power, through 5.3 €/kWh for PV, up to 14.5 €/kWh for coal — values that closely match their respective levelized cost of electricity (LCOE) (Lazard 2021).

The magnitude of multiple impacts can be significant in cost–benefit analysis indicators such as the *ESC*. According to a screening of studies in Ürge-Vorsatz et al. (2016), the monetary impact of MIs in the building sector can be 0.2 to 3.2 times the value of the energy savings made. When applying the conservative end of this range to the *ESC* (see ‘Energy system cost’), the *MEDIUMEFF* scenario would clearly be cost-effective (1.54 bn EUR/a reduced costs compared to *LOWEFF*) while *HIGHEFF* would remain cost-ineffective (+0.23 bn EUR/a additional costs compared to *LOWEFF*). Hence, it is likely that the societal value of building efficiency measures is significantly undervalued in this study.

It is critical to take into account the limitations of integrating relevant MIs in cost–benefit indicators like the *ESC*. These range from insufficiently grounded methods and associated uncertainty (Fawcett & Killip, 2019) over ethical concerns relating to monetization (Thema et al., 2019) to the issue of overlaps and double-counting of MIs (Ürge-Vorsatz et al., 2016). This raises the question about the extent to which quantitative analyses should be substantiated by alternative frameworks within the scope of EE1st, such as multi-criteria analysis, in order to approximate welfare-optimal systems (Mandel et al., 2022a).

Apart from the general issue of valuing energy efficiency, the findings of this study are naturally subject to various uncertainties. Most notably, the Russian invasion of Ukraine along with other effects has triggered an unforeseen and sharp increase in the wholesale prices for coal (+69%), oil (+29%) and natural gas (+27%) as of 01 June 2022 compared to the January 2022 average (OECD, 2022). The fossil fuel price assumptions in this study are based on the considerably more conservative projections of the 2019 World Energy Outlook (IEA, 2019) with relatively stable commodity prices until 2050.

Eichhammer (2022) demonstrates that high energy prices have a significant effect on the cost-effectiveness of energy savings. To illustrate, using the values in ‘Energy system cost’, the prices for coal, oil and gas would need to be +5% (*MEDIUMEFF*) and +68% (*HIGHEFF*) higher over the period 2020–2050 than in the default trends (see ‘Energy supply’) to make these scenarios cost-effective compared to *LOWEFF*, all else equal. Beyond short-term shocks, the long-term price trend for fossil fuels until 2050 may not necessarily go upward. In the sense of a macroeconomic rebound effect (Brockway et al., 2021), the wholesale prices for oil, gas and oil could decrease

in response to significant global reductions in energy demand and large-scale deployment of renewable energies. Hence, long-term fossil fuel price trends could either improve or reduce the cost-effectiveness of energy efficiency measures.

Another limitation of this study is its restricted scope of relevant demand-side resources in the building sector that could contribute to both cost and emission savings (Mandel et al., 2022c). Apart from end-use energy efficiency, these also encompass energy sufficiency, i.e. strategies for reducing consumers’ energy service needs while keeping utility constant (Sorrell et al., 2020; Thomas & Brischke, 2015).¹⁶ Another example is demand response. While this study did include price-based flexibility provision from both centralised and decentralised heat pumps as part of the *ENERTILE* model (Bernath et al., 2019), the scenario design does not allow the isolated effect of these actions to be determined for *ESC* and other outputs. The reported economic benefits of demand response generally involve lower, stable electricity prices (Paterakis et al., 2017) and related reductions in consumer bills (Brown & Chapman, 2021).

Finally, it should be noted that the modelling tools in this study cannot be validated, as this would require waiting until 2050 in order to compare the model results with actual outcomes, thus negating their purpose as planning tools (DeCarolis et al., 2012). The modelling tools are calibrated to historical and base years, and the quality of numerical input data is scrutinised. The results are not to be interpreted as forecasts, but rather as consistent and coherent descriptions of hypothetical futures (Pérez-Soba & Maas, 2015).

Policy implications

Setting measurable targets for energy efficiency is key to keeping track of policy progress and guiding policy measures. Table 11 refers the ambition level of the three scenarios for the building sector to the energy efficiency target for final energy consumption set in the Energy Efficiency Directive (EED). For this purpose, projections for the transport and industry sectors were adopted from the *REG_MAX* scenario in the impact

¹⁶ One example of a sufficiency measure in the *TECH* scenario within the *EUCalc* model (EUCalc 2022; Pestiaux et al., 2019) is that encouraging a reduction in living space per person from an average of 49.5 to 43.4 m² across the EU could decrease final energy demand in the building sector in 2050 by 3.9%.

Table 11 Energy efficiency targets for 2030 in the Energy Efficiency Directive

		PRIMES-2007 baseline ^d	PRIMES-2020 baseline ^e
Energy efficiency target for final energy consumption in 2030 % difference to baseline			
EED-2018 ^a	846 Mtoe	1,253 Mtoe − 32.5%	864 Mtoe − 2.1%
EED-2021 ^b	787 Mtoe	1,253 Mtoe − 37.2%	864 Mtoe − 9.0%
Scenario projections for 2030 ^c % difference to baseline			
LOWEFF	800 Mtoe	1,253 Mtoe − 34.8%	864 Mtoe − 5.5%
MEDIUMEFF	792 Mtoe	1,253 Mtoe − 35.5%	864 Mtoe − 6.5%
HIGH EFF	786 Mtoe	1,253 Mtoe − 36.0%	864 Mtoe − 7.2%

^aBased on amended EED (European Union 2018a, Art. 3), excluding United Kingdom (European Union, 2019)

^bBased on Commission proposal for EED recast (European Commission 2021c, Art. 4)

^cProjections for industry and transport sectors based on REG_MAX scenario in Impact Assessment accompanying EED recast (European Commission 2021b)

^dEU Reference Scenario 2007 (Capros et al., 2007)

^eEU Reference Scenario 2020 (Capros et al., 2021)

assessment accompanying the European Commission's proposal for a recast of the EED (2021b). Final energy consumption levels by 2030 in the scenarios lie roughly between the target set in the amended directive ('EED-2018') (European Union 2018a, Art. 3) and the one in the proposal for a recast EED ('EED-2021') (European Commission 2021c, Art. 4). The scenarios thus generally support a revision of the EED-2018 towards higher ambition levels of at least 35% in final energy terms.

However, as described above, very ambitious levels of energy efficiency in buildings may lead to additional costs compared to the LOWEFF scenario. This is in contrast to studies that call for an energy efficiency target beyond 40% without considering the effects of escalating energy prices and multiple impacts.¹⁷ In conservative terms, therefore, the ambition level of the EED-2021 proposal can be seen as a reasonable benchmark. Higher ambition levels could be reasonably justified on the grounds of multiple impacts beyond financial savings as well as on the grounds of higher wholesale energy prices.¹⁸

The findings of this study are also congruent with the goal in the European Commission's Renovation Wave strategy (2020a) to 'at least double the annual energy renovation rate of residential and non-residential buildings

by 2030'. According to the INVERT/OPT model, average renovation rates for the EU-27 over the period 2020–2050 range from 0.7% in the LOWEFF scenario, through 1.4% in MEDIUMEFF to 1.7% in HIGH EFF (Table 7). The renovation rate in LOWEFF can be interpreted as a continuation of current trends (European Commission 2020b; Esser et al., 2019). Hence, the renovation rate in MEDIUMEFF corresponds to the current political ambition, with HIGH EFF going beyond that ambition.

Note that this techno-economic analysis cannot directly suggest how to achieve the three normative scenario pathways by means of policy measures. This issue is addressed in the following chapter.

Conclusion

This study set out to provide quantitative evidence for the relevance of the energy efficiency first (EE1st) principle in the EU by modelling the effect of moderate to ambitious end-use energy efficiency measures on an energy supply system that is transitioning towards net-zero GHG emissions.¹⁹ Two major conclusions can be drawn from this work.

¹⁷ For example, based on cost-effective technology potentials calculated in Chan et al. (2021), Scheuer et al. (2021) support a 41.2% reduction target for 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 authors.

¹⁸ 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) compared to PRIMES-2007.

¹⁹ Although the findings of the study are mainly applicable to the EU, they may be relevant for other industrialised countries and regions with net-zero GHG targets in place. For instance, the EE1st principle has also been a matter of interest in New Zealand (EECA 2019). In the USA, there are long-established experiences with integrated resource planning, non-wire solutions and other concepts related to EE1st (Mandel et al., 2022c).

First, energy efficiency in buildings is crucial for a cost-efficient transition to a net-zero emissions energy system. Given the close similarity in energy system cost (*ESC*) between *LOWEFF* and *MEDIUMEFF*, it can be inferred that ambition levels for energy efficiency *below* *LOWEFF* are likely to result in *additional* costs. The *LOWEFF* scenario (21% reduction in final energy consumption for buildings in 2050 vs. 2020 levels) can thus be seen as the 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% reduction for buildings in 2050 vs. 2020) (Capros et al., 2021). A relevant issue for future research is how a ‘*NoEFF*’ scenario with energy efficiency in buildings below *LOWEFF* would perform in terms of energy system cost and what risks this pathway involves with a view to the security of supply and the required expansion of renewables, among others.

Second, there is ample reason to support the ambition levels for end-use energy efficiency in the *MEDIUMEFF* and *HIGHEFF* scenarios, even though these may not be cost-effective relative to *LOWEFF* if only the measure of energy system cost is applied. For one thing, the cost differences across the scenarios are minor when put into perspective. Additional costs in *HIGHEFF* vs. *LOWEFF* amount to +3.8 bn EUR/a, corresponding to 0.03% of the EU’s gross domestic product (Eurostat, 2022h), 1.4% of the net-import value of fossil fuels (Eurostat, 2022a) or 8.54 EUR per EU citizen and year (Eurostat 2022k). For another, this work omitted two effects that are likely to significantly increase the cost-effectiveness of energy efficiency: high fossil fuel prices as well as multiple impacts (MIs). An on-going issue for future research is how to rigorously quantify, monetise and aggregate individual MIs so that they can be included in cost-benefit analyses to support decision-making within the scope of *EE1st*.

In terms of policy implications, the findings of this work support a higher energy savings target in the *EED* of at least 35% in final energy terms compared to the *PRIMES-2007* reference, as well as a doubling of building renovation rates. While the modelling techniques applied do not allow a detailed analysis of policy measures, it is evident that each scenario pathway requires a combined approach of saving energy and decarbonising energy supply. As addressed in dedicated research (Mandel et al., 2022b; Pató & Mandel, 2022), properly applying the *EE1st* principle

requires electricity market reforms, incentive regulation for network companies, carbon pricing, financing schemes and other actions.

To conclude, the *EE1st* principle can be considered a timely and critical initiative to help achieve a robust, resilient and affordable net-zero emissions energy system in the EU. Further research is needed to investigate the potential system-wide benefits of demand response and energy sufficiency. Both are important demand-side resources in the narrative of *EE1st*, and their explicit consideration in model-based assessments is likely to provide further support for the principle.

Acknowledgements The authors would like to thank all the *ENEFIRST* partners and two anonymous reviewers for their valuable comments. Additional thanks go to Anna Billerbeck, Benjamin Lux and Sebastian Forthuber for their help in interpreting model data from *Enertile* and *Invert/Opt*.

Author contribution All the authors contributed to the study conception and design. TM, LK, EP, FS and AM performed the model-based simulations. TM analysed and visualised the data. TM reviewed the literature and wrote the original manuscript. All the authors discussed the results and contributed to the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was funded by the European Union’s Horizon 2020 Research and Innovation programme through their support for the *ENEFIRST* project (Grant no. 839509).

Data Availability The input data used in this study is available in the supplementary material accompanying this article. The result data supporting the findings of this study is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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