Concept development for a model-based assessment of the E1st Principle

Project Acronym	Enefirst
Project Name	Enefirst — Making the Energy Efficiency First principle operational
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Project Duration	September 2019 — February 2022
Website	http://enefirst.eu

Deliverable No.	D3.2
Dissemination Level	Public
Work Package	WP3
Lead beneficiary	Fraunhofer ISI
Contributing beneficiary(ies)	TU Wien, IREES
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Date	September 2021
File Name	D3.2 - Concept development for a model-based assessment of the E1st Principle

To quote this reference, please use:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 839509.

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EXECUTIVE SUMMARY

This report aims to develop a **methodological concept** for a **model-based analysis of the E1st principle for the EU-27** that will be carried out and analysed in subsequent reports of the ENEFIRST project. The objective of this energy system analysis is to investigate what level of demand and supply-side resources should be deployed to provide the greatest value to the EU's society in transitioning to net-zero GHG emissions for the building sector by 2050. On the **demand side**, the analysis focuses on the resource option of end-use energy efficiency in buildings, investigating the contributions of thermal retrofits, efficient appliances, and other measures towards the net-zero target. On the **supply side**, the analysis quantifies the possible deployment and costs of various generation, network and storage options for the provision of electricity, district heat and gas products for the building sector.

By determining what resource portfolio should be adopted under given framework conditions to reach the 2050 target, this analysis can help decision-makers identify priorities for policy design and technology investment. The analysis covers a set of **three model-based scenarios**. Each of these scenarios is geared to reach the 2050 target of net-zero emissions in the EU-27. However, the scenarios differ in terms of the contribution of different **resource options** towards target achievement: (1) The **LOWEFF scenario** assumes that energy use in buildings is decarbonized primarily via the use of renewable-based supply-side resources. (2) The **MEDIUMEFF scenario** is characterized by an even deployment of demand- and supply-side resources. (3) In the **HIGHEFF scenario**, end-use energy efficiency measures in buildings are viewed as the most favourable decarbonisation option for the European energy system by 2050, representing a future in which the E1st principle is comprehensively applied in energy system planning and investment.

To capture the interactions between the building sector and the supply side of the EU energy system, this analysis couples four bottom-up energy models: INVERT, FORECAST, ENERTILE and NETHEAT. As such, the analysis 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 both power and district heating systems are explicitly modelled.

To measure the performance of the three scenarios, the outputs of the analysis are analysed in two respects. For one thing, the so-called **techno-economic assessment** focuses on the indicator of energy system costs, indicating the sum of capital expenditures and operating expenses needed to meet the energy service demand in the building sector. Supported by additional indicators, this assessment helps determine the extent to which society is better off – in pure monetary and technical terms – if demand-side resource were prioritized in energy planning and operation. For another, the so-called **socio-environmental assessment** investigates selected multiple impacts of the resource configurations computed in the different scenarios. Where possible, these impacts are quantified and monetized using dedicated methodologies.

In sum, this model-based analysis addresses the four criteria of quantitative assessments for the E1st principle set out in (ENEFIRST 2020e): (1) It features an **integrated model-based appraisal of demand- and supply-side resources** in the building sector and associated supply sectors (electricity, district heat, natural gas and hydrogen). (2) There is a **common planning and policy** objective across all scenarios of reaching net-zero GHG emissions for the EU building sector by the year 2050 while meeting demand for energy services. (3) All costs and benefits are evaluated from a **societal perspective**, rather than a private one. (4) A systematic **appraisal framework** is used to compile all relevant cost and benefit items, including a selection of multiple impacts.

1. INTRODUCTION

« Efficiency First » (E1st) is an organising principle that is to be applied to all policy-making and investment decisions throughout the European Union (EU) energy system. It prioritizes investments in energy efficiency, demand response and other demand side resources whenever these are more cost-effective from a societal perspective in meeting planning objectives than generators, networks and other supply-side resources. Previous reports of the ENEFIRST project have discussed the **theoretical notion of E1st**, addressing its conceptual background (ENEFIRST 2020b), global experiences with similar concepts (ENEFIRST 2020d), the transferability of such concepts to the EU (ENEFIRST 2020a), as well as barriers towards a comprehensive implementation of E1st across the EU (ENEFIRST 2020c).

In **practical energy system planning and policy design**, however, taking explicit account of E1st is a complex planning exercise that is subject to various uncertainties. **Energy systems modelling** plays an indispensable role in making complexities and uncertainties tangible and enabling decision-makers to make informed decisions on policy design, technology investment, and system operation (Connolly et al. 2010). Given the novelty of the concept of E1st in the political and academic debate, there are only few model-based assessments that make explicit reference to the principle (e.g. Langenheld et al. 2018).

To support research and further applications in this field, another previous project report (ENEFIRST 2020e) set out to provide modelling practitioners and policymakers with a comprehensive **guidance on modelling approaches** for assessing demand and supply side resources. It provides a thorough description of existing quantitative approaches associated with the concept of E1st and discusses methodological challenges in modelling the trade-off between demand and supply side resources. Overall, it highlights four implications of E1st for quantitative energy systems modelling:

(i) Quantitative assessments of E1st require an **integrated appraisal** of demand- and supply-side resources in order to determine cost-optimal resource portfolios.
(ii) To systematically compare demand and supply options, a common functional unit is needed in terms of **planning and policy objectives**, e.g., a common greenhouse gas (GHG) reduction target.
(iii) **Cost-benefit analysis (CBA)** provides a fundamental methodological framework for quantitative assessments of E1st, weighting various costs against benefits under consideration of discounting.
(iv) E1st prescribes a **societal perspective** in evaluating costs and benefits, implying a detailed account of monetary and non-monetary impacts under consideration of society's time and risk preferences.

Based on these methodological foundations, a next step in the ENEFIRST project is to provide actual quantitative assessments of the E1st principle for the EU energy system. These assessments are supposed to demonstrate the distinct value of energy efficiency, demand response and other demand-side resources for the EU energy system with a view to economic costs and multiple impacts. More specifically, ENEFIRST carries out such assessments at **two levels of analysis**, as illustrated in Figure 1. At **Level 1**, the project investigates the contribution of energy efficiency in the building sector towards achieving European climate targets at the lowest cost in terms of monetary value and multiple impacts. EU Member States (MS) are modelled individually at national level and conclusions are aggregated for the EU-27 as a whole. At **Level 2**, ENEFIRST examines five local case studies in urban areas within three MS. The spatial scope is deliberately narrower compared with Level 1, providing opportunity for a detailed evaluation of demand- and supply-side resource options in different contexts of building types (residential, non-residential), infrastructures (electricity, district heating, gas) and local conditions (weather, costs, etc.).[1]

Level 1: Energy system analysis for EU-27

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

Level 2: Local case studies for 3 Member States

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

Figure 1. Two levels of quantitative assessments for E1st in the ENEFIRST project
Source: ENEFIRST project

Using the terminology from (ENEFIRST 2020e), both of these levels follow the **normative paradigm** of quantitative assessments for E1st. That is, they investigate what demand- and supply resources *should* be adopted under given framework conditions to reach an anticipated vision of the future – in this case, substantial GHG reductions by the year 2050. Such analyses can help decision-makers identify priorities for policy design and technology investment, along with specific opportunities and risks associated with different pathways. In turn, these analyses do not investigate 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 E1st.

The **objective of this report** is to develop a concept for the energy system analysis at Level 1. Quantitative results of this assessment are presented in subsequent reports, same as the details of the Level 2 analysis. This report is structured as follows. **Chapter 2** provides an outline of the energy system analysis, specifying its objective and describing its scenarios and energy models. **Chapter 3** operationalizes the scenarios for different sectors and presents cross-sectoral input data used. **Chapter 4** provides a detailed account of the calculation of energy system costs as well as the appraisal of multiple impacts. **Chapter 5** critically discusses the limitations of the selected modelling approaches. Finally, **Chapter 6** concludes this report.

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

2. OUTLINE OF ENERGY SYSTEM ANALYSIS FOR EU-27

The energy system analysis carried out in the ENEFIRST project explores the level of demand and supply-side resources that should be deployed to provide the greatest value to the EU's society in transitioning to net-zero GHG emissions for the building sector by 2050. The rationale for this analysis is provided below (**Section 2.1**), followed by a description of the scenarios investigated (**Section 2.2**) and the energy system models used (**Section 2.3**).

2.1 Background and objective

The EU aims to be climate-neutral by 2050, that is, an economy with **net-zero GHG emissions**. In line with the EU's commitment to climate action under the Paris Agreement (United Nations 2015), this objective has been brought up in the Commission's vision for a climate-neutral EU (European Commission 2018a), reaffirmed in the **European Green Deal** (European Commission 2019) and legally established in the **European Climate Law Regulation** (European Union 2021). For the period 2021–2030, the EU and its Member States (MS) are committed to interim goals to prevent that decisions made in the coming years do not lock in emissions levels inconsistent with the 2050 objective of climate-neutrality (**Figure 2**). The Climate Law Regulation sets a 55% GHG reduction target for the year 2030 compared to 1990 levels. With the Fit for 55 communication (European Commission 2021), the Commission adopted a package of actions across all sectors and revisions to key legislations that are currently, as of October 2021, undergoing the legislative process.[2]

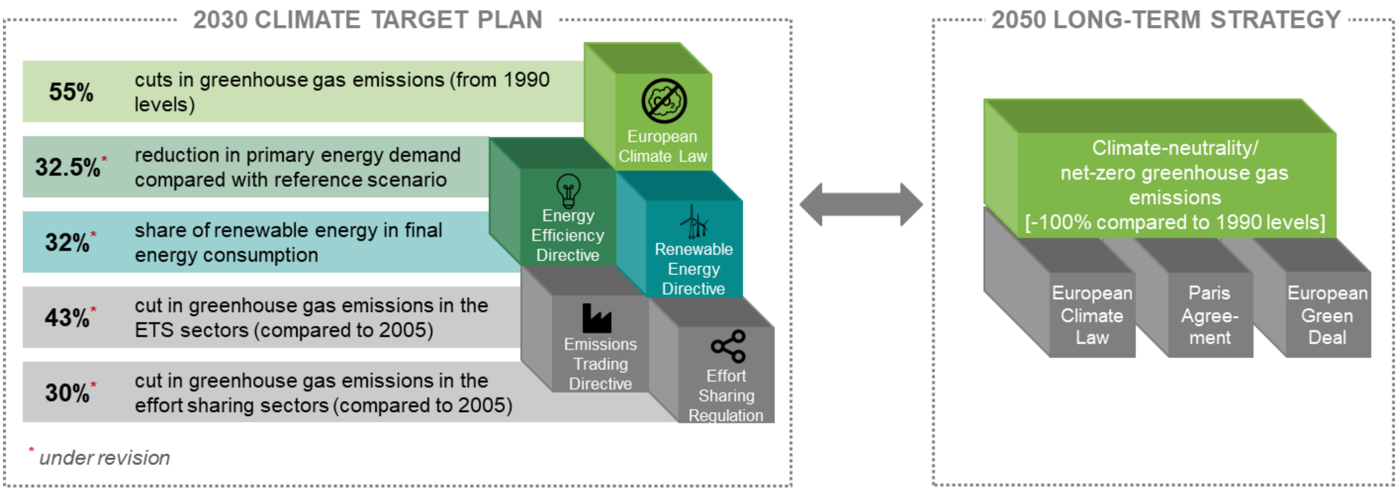

Figure 2. EU energy and climate policy framework for 2030 and 2050

Source: ENEFIRST project

[2] By then, targets are set as follows. The revised Energy Efficiency Directive (EED, (EU) 2018/2002, European Union 2018b) contains a target to achieve an at least 32.5% improvement in energy efficiency at the EU-27 level by 2030, compared with the Commission's 2007 energy baseline scenario. The recast Renewable Energy Directive (RED, (EU) 2018/2001, European Union 2018a) sets a binding target to increase the share of energy from renewable sources in the EU-27 to at least 32.0% of gross final energy consumption by 2030. The Emissions Trading System Directive (ETD, (EU) 2018/410, European Union 2018c), sets a binding emission cap set for sectors covered by the EU Emissions Trading System (ETS). The Effort Sharing Regulation (EFR, (EU) 2018/842, European Union 2018e) contains binding annual minimum targets for reducing GHG emissions from 2021 to 2030 set for MS in sectors that are not covered by the EU ETS.

The **building sector** is of vital importance to meet these targets. Buildings account for 40% of the EU-27's final energy demand in 2019, making them the largest single energy consumer. About two thirds of this energy is used in the households sector, and the remainder in the commercial and public buildings of the services sector (Eurostat 2021). Altogether, buildings are responsible for approximately 36% of GHG emissions in the EU (European Union 2018d). Space heating is the major end-use in the building sector, accounting for 77% of final 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 due to the fact that 75% of the EU's building stock is energy inefficient compared to current regulation on energy performance of buildings (European Union 2018d). This also reflects in a low renovation rate – on average, the total building stock's primary energy consumption reduces by 1% per year through energy renovation (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 E1st (ENEFIRST 2020b). These technologies and actions reduce the quantity or temporal pattern of energy use. Constructional heat insulation measures and heat recovery ventilation reduce the demand for space heating are key 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 comprises decentralised 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 discussed. These range from electrification (heat pumps), to district heating, direct use of biomass, solar thermal and other renewable energy sources (RES), up 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 E1st principle (ENEFIRST 2020e). By determining cost-optimal transitions or 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, there are various model-based assessments investigating the **possible contribution of demand- and supply-side resources towards climate-neutrality by 2050**. 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. D'Aprile et al. (2020) determine one cost-optimal scenario for the EU energy system to achieve net-zero emissions by 2050. This pathway includes substantial improvements in building energy efficiency through insulation as well as a switch to renewable technologies for heating, cooking and other end-uses. 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.

Besides these aggregate projections for the entire EU energy system, only few studies make explicit the **societal trade-off between saving and supplying energy in the building sector** according to the notion of the E1st principle. 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 renovations in the local building stock before deploying new renewable heat supply. At national level, Hansen et al. (2016) investigate the limitations of building energy efficiency measures for four EU MS. The authors suggest that heat savings should not surpass a level of 30-50% of projected heat demands for society to avoid overinvestments in energy efficiency measures. For the German buildings sector, Langenheld et al. (2018) find that climate targets towards 2050 can be achieved at the lowest system cost by enhancing energy efficiency in buildings along with a boosted deployment of heat pumps. All in all, existing studies generally suggest that an **optimal balance of technology options for building sector decarbonisation** involves both demand- and supply-side resources. This, in fact, is in line with the E1st principle, which requires that demand-side resources should be prioritized over supply-side assets only to the extent that they provide greater value for society (Bayer et al. 2016a; ENEFIRST 2020b).

However, existing studies tend to have a number of **limitations** that reduce their value for system planning, technology investment and policy formulation in the context of the E1st principle. First, studies are often limited to the techno-economic costs of resource configurations in terms of capital expenditures and operating expenses. **Multiple impacts** like air pollution and health effects are often disregarded or discussed only in qualitative terms, although their inclusion can significantly alter the outcome of model-based assessments (Ürge-Vorsatz et al. 2016).[3] Second, as for the building sector, studies are typically limited to space heating as an important but not the sole **end-use in buildings**. Electrical appliances, lighting, space cooling and other end-use must not be neglected to provide a comprehensive account of demand-side resources in the building sector (Eurostat 2013). Finally, studies tend to use models with low levels of **temporal, spatial and technical detail**. These may underestimate the need for generation and network capacity in long-term transitions and, conversely, the value of demand response and other demand-side resources (ENEFIRST 2020e).

Against this background, the **objective of this model-based assessment** is to determine the level of demand and supply-side resources that should be deployed to provide the greatest value to the EU's society in transitioning to net-zero GHG emissions for the building sector by 2050. In terms of a **techno-economic assessment**, a set of four bottom-up energy models is applied to ascertain the energy system costs of the building sector and the electricity, district heat and gas sectors. In addition, a **socio-environmental assessment** is carried out to characterise selected multiple impacts of the resource configurations determined. Where possible, these impacts are monetized and added on top of energy system costs to come up with an estimate of societal value associated with different resource options.

Three scenarios are calculated to explore different pathways for the decarbonization of the European building sector by 2050. Each of these scenarios is geared to reach the **2050 target of net-zero emissions**. However, the scenarios differ in terms of the level of end-use energy efficiency measures in buildings and the associated deployment of energy conversion and network capacities for power, district heating, and gas. The scenarios will thus contrast in terms of energy system costs (techno-economic assessment) and multiple impacts (socio-environmental assessment), which can help decision-makers ascertain the value of energy efficiency and identify priorities for policy formulation and technology investment with respect to the E1st principle. The following section describes these scenarios in detail.

[3] Ürge-Vorsatz et al. (2016) provide a screening of 52 monetized case studies on energy efficiency measures. In 63% of these cases, the value of the multiple impacts were equal or greater than the value of monetary energy savings. 30% of these case studies featured multiple impacts valued three times more than the energy savings, and in about 25% of the cases, the multiple impacts were more than four times the energy savings.

2.2 Target scenarios

Three scenarios are defined to investigate different levels of demand- and supply-side resources in the EU building sector to achieve a **climate-neutral economy by the year 2050**. Each of these scenarios is designed to reach the 2050 target of net-zero emissions, however with different strategy elements and technology pathways for buildings and associated sectors (power, district heating, gas). Developments in the **industry and transportation sectors** are kept the same in order to focus on the building sector and to avoid overlapping effects. The geographical coverage of the scenarios is the EU and its 27 Member States. **Figure 3** provides an illustrative outline of the narratives in the three decarbonization scenarios.

	SCENARIOS: Low efficiency in buildings (LOWEFF)	SCENARIOS: Medium efficiency in buildings (MEDIUMEFF)	SCENARIOS: High efficiency in buildings (HIGHEFF)
Planning objective	2030: ≥55% reduction GHG emissions (1990); ≥32% share for renewable energy; ≥32.5% improvement in energy efficiency		2050: Climate neutral economy – net-zero GHG emissions
SCENARIO NARRATIVES: Thermal efficiency	Low component requirements; low renovation rate	Moderate component requirements; moderate renovation rate	Strict component requirements; ambitious renovation rate
Appliance efficiency	Low minimum energy performance standards	Medium minimum energy performance standards	Strict minimum energy performance standards
Building H&C equipment	Large installed capacities; balanced technology deployment	Medium installed capacities; balanced technology deployment	Small installed capacities; balanced technology deployment
Power supply	Large installed capacities; balanced technology deployment	Medium installed capacities; balanced technology deployment	Small installed capacities; balanced technology deployment
District heating supply	Large installed capacities; balanced technology deployment	Medium installed capacities; balanced technology deployment	Small installed capacities; balanced technology deployment
Network expansion	Large installed capacities	Medium installed capacities	Small installed capacities
Hydrogen/ e-fuel use		Limited deployment	

Figure 3. Outline of scenario narratives in energy system analysis

Source: ENEFIRST project

The **Low Efficiency in Buildings** (LOWEFF) **scenario** assumes decarbonization of building energy use primarily via the use of renewable supply-side resources. Consumers and firms widely adopt renewable heating technologies, including solar thermal, biomass and biogas, geothermal, and ambient energy utilized by heat pumps. No heating technology is given particular preference, the scenario thus provides a neutral pathway with respected to installed systems. The transformation sector in LOWEFF undergoes a rapid expansion of renewable capacities. Power is supplied by onshore and offshore wind turbines, photovoltaics, biomass and biogas, geothermal and hydro energy, as well as renewable municipal waste. District heating is an important technology option to deliver renewable energy sources for heating. Conversion of electricity into hydrogen and methane (power-to-gas) and heat (power-to-heat) provides an important flexibility option for the energy system. Overall, the LOWEFF scenario reflects a future in which the **E1st principle is not comprehensively put in practice**. Consumers and firms are assumed to face significant barriers that inhibit them from adopting privately cost-effective energy efficiency measures. Such measures remain an important decarbonisation option, however with lower levels than in the remaining scenarios. To compensate for low levels of end-use efficiency, the deployment of energy conversion and associated network capacities must be very high to achieve net-zero emissions by 2050.

The **Medium Efficiency in Buildings (**MEDIUMEFF**) scenario** is characterized by a balanced deployment of demand-side energy efficiency measures in buildings and supply-side generation and network infrastructures. Compared with LOWEFF, energy demand needed to heat buildings is reduced more ambitiously by improving the insulation of external walls, roofs, floors ceilings, windows and other building components. Both the renovation rate and the renovation depth is raised above the level assumed in LOWEFF. Besides energy use for heating and cooling, MEDIUMEFF also features above-average improvements in the energy efficiency of electrical appliances, lighting, cooking and processes. Just as in LOWEFF, the supply of power and district heating in MEDIUMEFF must undergo a fast-paced transition to renewable energy sources to meet the net-zero emissions target in 2050. However, the generation and network capacities in MEDIUMEFF are expected to be smaller in terms installed power, given the reduced energy demand obtained through demand-side energy efficiency measures. Overall, the MEDIUMEFF scenario reflects a future in which **due regard is given to the E1st principle** in energy system planning and investment, with investment barriers to energy efficiency persisting in the building sector.

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. Heating and cooling demand in buildings is reduced significantly by improving the insulation of building components. The renovation rate and depth for both residential and non-residential is more ambitious than the levels assumed in the other two scenarios. Strict minimum energy performance standards are assumed to boost the adoption of highly-efficient electrical appliances, lighting and cooking equipment, and process technologies. Newly constructed buildings are highly efficient. As in LOWEFF and MEDIUMEFF, no supply-side resource in HIGHEFF is given particular preference. Heating technologies in buildings, power and district heating supply must be based entirely on renewable energy sources by 2050 to achieve net-zero emissions. In sum, HIGHEFF represents a future in which the **E1st principle is comprehensively applied** in energy system planning and investment, that is, demand-side energy efficiency measures are prioritized over supply-side alternatives. Whether this actually presents the best outcome for society in terms of techno-economic and multiple impacts will become apparent in the outputs of the quantitative assessment.

All in all, the scenarios allow to demonstrate the **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. In the context of the **E1st principle**, this analysis thus helps ascertain the difference in terms of monetary costs and multiple impacts 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.

It is worthwhile noting that end-use energy efficiency is not the only important **demand-side resource** subsumed under the header of "Efficiency First" (see ENEFIRST 2020b). Just as present in the debate around E1st is the resource of **demand response**, i.e. automated or reactive changes of load by final consumers from their default consumption patterns in response to market signals (Paterakis et al. 2017). Demand response is designed to shift electrical loads and, if applied consistently over time, can defer power generation and network capacity upgrades on the supply side. **Energy service sufficiency** is another demand-side resource pointed out in the E1st literature. It means measures that reduce final energy demand through a quantitative or qualitative change of utility demanded or energy service delivered (Brischke et al. 2015). For example, the brightness (in lumen) of lighting could be reduced to some extent without adversely impacting the perceived utility for the consumer in terms of illumination.

Although relevant in the context of E1st, the **impact of demand response and energy service sufficiency on the scenario outcomes** is not explicitly considered in this quantitative assessment. As for the former, the model ENERTILE (see **Section 2.3**) is capable of representing load shifting for individual heat pumps in buildings as well as large-scale heat pumps in district heating networks, broadly referred to as power-to-heat (Bernath et al. 2019). Based on the final energy demand for heating in buildings, the model determines the practical potential (Gils 2014) for load shifting through heat pumps and its hourly dispatch until 2050. The scenario outputs on system costs, installed capacities and other indicators thus involve the effect of such demand response activities. However, the isolated effect of these demand response activities on scenario outputs cannot be determined in this analysis. This 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 fully disregarded, given the infancy of the scientific debate and the question to what extent sufficiency measures can be attached a monetary value. The following section describes the **energy system models** used to calculate the individual scenarios as well as the interrelations among the models.

2.3 Energy system models

The objective stated requires a comprehensive modelling approach to capture the mutual effects between the building sector and the supply side of the energy system in terms of generation, network, and storage infrastructures. Four **bottom-up energy models** are soft-coupled in this analysis to ascertain these effects:[4] INVERT, FORECAST, ENERTILE and NETHEAT. Using these models allows to compare the scenarios with regard to costs, GHG emission reductions, energy demand and other indicators. A detailed characterization of the four models is provided in the **Annex: Model factsheets**.

The way these models are coupled to determine the central indicator of energy system costs is given in **Figure 4**. Each of the models provides individual cost items – energy system costs are thus an aggregated indicator that requires scrutiny in terms of aggregating these cost items and avoiding double counting (see **Chapter 4**). Overall, by soft-coupling these bottom-up models, the quantitative 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 both power and district heating systems are explicitly modelled.

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[4] Soft-coupling means that several models are linked in a linear or iterative process, with data being passed back and forth among the models. The counterpart is hard-coupling, meaning that multiple models are integrated in a single development environment. While hard-coupling generally allows for better convergence of key parameters (e.g. prices), it goes at the expense of computational complexity and thus the resources needed for the analysis (IRGC 2015; Pye and Bataille 2016). Note that the soft-coupling approach used here cannot determine equilibrium prices for energy carriers or technologies and other economic feedbacks in the sense of a general or partial equilibrium model (see e.g. Ringkjøb et al. 2018).

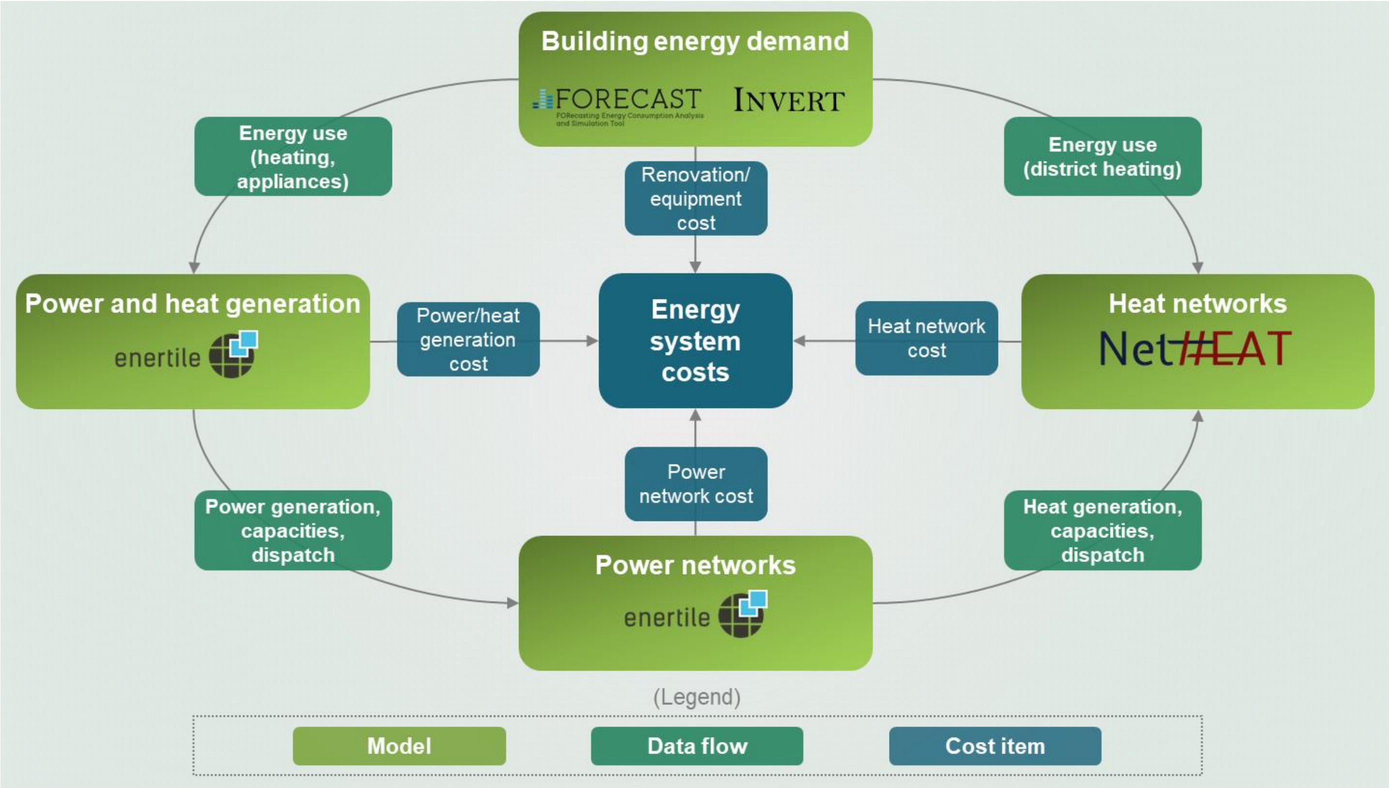

Figure 4. Coupling of models and calculation of energy system costs
Source: ENEFIRST project, illustration based on Langenheld et al. (2018)

The building stock model **INVERT** provides long-term projections on energy related investment decisions in residential and non-residential buildings, focusing on space heating, hot water generation and space cooling. It is based on disaggregated building stocks in the different EU Member States including type of building, age, state of renovation, existing heating systems, user structure as well regional aspects such as availability of energy infrastructure at a sub-country level. It calculates cost-optimal pathways based on a combination of technology options available in different years – both for heat savings (retrofitting measures mainly regarding the building envelope) and heat supply (mainly replacement of heating and hot water supply systems) – and under consideration of diffusion constraints.

FORECAST is a bottom-up simulation model that represents long-term developments in appliance adoption behaviour in residential and non-residential buildings. It covers large electrical appliances (e.g., refrigerators, washing machines, dishwashers), information and communication technologies (ICT) (e.g., laptops, televisions, screens), lighting, as well as small electrical appliances (e.g., coffee machines, vacuum cleaners, microwaves). Besides electrical appliances and lighting, the model also covers cooking equipment (e.g., ovens, exhaust hoods). Given the bottom-up-design, socio-economic drivers (e.g., energy carrier prices), techno-economic characteristics (e.g., operation and standby-power, investments) and user behaviour (e.g., operation hours) can be explicitly modelled. The high level of disaggregation makes it possible to also consider technological trends, such as the enforced phase-out of incandescent bulbs.

ENERTILE is an energy system optimization model focusing on the power sector, but also covering the interdependencies with other sectors, especially heating/cooling and the transport sector. ENERTILE optimizes the investments into all major infrastructures of the power sector, including conventional power generation, heat generation from district heating including combined-heat-and-power (CHP), power-to-heat, renewable power technologies, hydrogen supply, e-fuel supply, cross-border transmission grids, and storage technologies. The model chooses the cost-optimal portfolio of technologies, while determining the utilization of these for all hours of each year. As hourly weather data is applied, seasonal, daily and weekly variations in heat demand as well as in electricity supply are included in the optimization. Likewise, spatial characteristics and interdependencies between different regions and renewable technologies are included.

NETHEAT is a bottom-up spatial energy simulation model that maps renewable heat sources, heat demand, district heating supply infrastructure, and potentials for future infrastructure investments. The model 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 can capture specific local situations with regard to heat demands. By using OpenStreetMap data, the model filters and selects residential and non-residential buildings and calculates the network length between heat sources and heat sinks. The Urban Atlas, CORINE Land Cover and Imperviousness Density datasets provided by the European Copernicus Land Monitoring Service are used to determine the availability of land area, its type, and potential cost of infrastructure investments.

To conclude, the energy system analysis outlined in this chapter is planned to provide a **quantitative assessment of the E1st principle** for the EU energy system, with a particular focus on the building sector. Its objective is to investigate what mix of demand- and supply-side resources should be adopted to reach substantial greenhouse gas (GHG) emission reductions at lowest societal cost for the European economy. **Three scenarios** are planned to analyse different pathways for the decarbonization of the European energy system by the year 2050. Each of these scenarios is designed to reach the 2050 target of net-zero emissions. However, the scenarios differ in terms of the extent of 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 gas. The scenarios will thus contrast in terms of **system costs** (techno-economic assessment) and **multiple impacts** (socio-environmental assessment) and, as such, help decision-makers ascertain the value of energy efficiency and identify priorities for policy formulation and technology investment with respect to E1st. The following chapter provides a detailed appraisal of the planned scenarios.

3. SPECIFICATION OF SCENARIOS

This chapter specifies the scenarios outlined above. **Section 3.1** describes cross-sectoral boundary conditions, i.e., input variables that are used across all scenarios. **Section 3.2** provides specifications for the individual scenarios per sector (buildings, power supply, district heat supply, gas supply).

3.1 Cross-sectoral boundary conditions

A series of exogenous variables are required as boundary conditions across sectors and across scenarios in the model-based analysis. This concerns energy demand in the industry and transportation sectors, fuel prices, socio-economic trends (population, gross domestic product, etc.), as well as climate and weather. This section summarizes relevant framework data.

INVERT uses the growth of **number of buildings** and related floor area in the different building categories as input variable for the growth of the building stock. These are taken from the project SET-Nav and are documented in Table 1 below. Due to the age of buildings and building components, renovation activities as well as demolition of buildings occur. The difference between the total demand of buildings and available buildings after considering demolition result in the endogenously derived new building construction activities. Drivers for the stock of buildings are the development of population and demand of floor area by capita (for residential buildings) and sectoral gross value added as well as number of employees in different service sectors. However, the link between these drivers and the size of the building stock is not exogenously modelled.

The development of **future demand for electricity and hydrogen in the industry and transportation sectors** needs to be assumed exogenously, as ENERTILE optimizes the supply for all sectors and captures inter-sectoral effects and competition for CO_2-neutral energy carriers. As all sectors need to reach a carbon neutral energy supply by 2050, they compete for cheap low-carbon energy supply. While energy needs in buildings will be modelled in detail in INVERT and FORECAST, the energy needs for all other sectors are held constant between those scenarios to ensure comparability and interpretability of differences between the scenarios. Projections for future energy demand in industry and transportation are drawn from the 1.5TECH scenario evaluated under the in-depth analysis (European Commission 2018a) in support of the European Commission's "A Clean Planet for All" communication (European Commission 2018b).

The level of **fossil fuel prices** and their relative relationship to each other influence the model outputs for the period where fossil fuels still hold a significant share in energy consumption. Fossil fuel prices are based on the Sustainable Development scenario of the IEA's World Energy Outlook 2019 (IEA 2019). These fossil fuel prices remain stable or show a slight decrease until 2050. Note that global fossil fuel prices provide an aggregate input to the model-based assessment, with the ENERTILE model computing the wholesale prices of electricity and district heat as derived commodities and INVERT calculating consumer prices for all relevant energy carriers in the building sector.

Table 1. Cross-sectoral boundary conditions for the EU-27

Source: Various sources

	Unit	2020	2030	2040	2050
Socio-economic trends					
Floor area residential buildings	Mio. m²	18,927	19,464	20,001	20,538
Households	Mio.	182	187	191	195
Floor area non-residential buildings	Mio. m²	8,041	8,540	9,039	9,538
Fossil fuel prices (global wholesale)					
Crude oil	EUR_{2018}/MWh	34.6	32.3	30.7	29.2
Natural gas	EUR_{2018}/MWh	21.9	21.7	21.7	21.7
Hard coal	EUR_{2018}/MWh	8.7	6.0	6.2	6.5
Climate and weather data (example countries)					
Mean winter outdoor temperature (DE)	°C	1.5	1.7	2.0	2.1
Mean summer outdoor temperature (DE)	°C	17.7	17.9	18.2	18.3
Mean winter outdoor temperature (ES)	°C	9.4	9.6	9.8	9.9
Mean summer outdoor temperature (ES)	°C	23.1	23.3	23.4	23.6
Mean winter outdoor temperature (FI)	°C	-3.7	-3.4	-3.1	-2.8
Mean summer outdoor temperature (FI)	°C	16.0	16.3	16.6	16.9

Mean winter outdoor temperature is defined as the average over the months December to February.
Mean summer outdoor temperature is defined as the average over the months June to August.
DE = Germany; ES = Spain; FI = Finland

Climate and weather data are important determinants for future energy demand for space heating as well as for generation from variable renewable energies. Concerning heating and cooling degree days (HDD, CDD), long-term average temperature data (1995–2015) is used for the projections of heating and cooling demand in INVERT. Expected climate change in terms of a decrease in HDD and increase in CDD is extrapolated via a linear regression of data at Member State level, assuming an equally weighted average of constant HDDs and CDDs. ENERTILE uses long-term average data for solar radiation, wind speed, and water flow in hydro plants. The following section provides specifications for the individual scenarios per sector (buildings, power supply, district heating supply, gas supply).

3.2 Scenario specifications by sector

The model-based assessment focuses on the building sector but also explicitly models associated supply sectors. The following sub-sections provide specifications for the individual sectors, that is, buildings (**3.2.1**), electricity supply (**3.2.2**), district heat supply (**3.2.3**), and gas and hydrogen supply (**3.2.4**).

3.2.1 Buildings

Energy use in buildings and the contribution of end-use energy efficiency towards meeting the EU's long-term climate and energy targets is a major focus of this work. This section presents the input data and assumptions for the bottom-up models INVERT and FORECAST. While the INVERT model projects energy use for space heating, water heating and space cooling, the FORECAST model represents the end-uses of appliances, lighting, and cooking. The models cover both residential and non-residential buildings.

As stated in **Chapter 2.2**, it is recalled that this quantitative assessment focuses on **end-use energy efficiency** as the principal demand side resource. The effect of **energy service sufficiency** measures is disregarded for reasons of immeasurable costs and to avoid overlapping effects. This means that the level of energy service demand varies over time but is kept equal across all scenarios, with differences between the scenarios arising from the level of end-use energy efficiency and associated final energy demand. With respect to the building sector, the scenarios thus do not differ in terms of sufficiency-related variables, such as living space per person, target indoor room temperature, appliance usage intensity, etc.

Thermal renovation for building envelopes is a major demand side resource for buildings in the EU to substantially reduce their useful energy demand and, eventually, GHG emissions. Measures include improving insulation of external walls, floors, roofs, ceilings, windows, doors. Relevant are also changes in the quality of windows and glass type, affecting the level of both heat transmission losses and solar heat gains. In practice, INVERT models different thermal renovation options which reduce energy needs for space heating. Whether or not a thermal renovation is adopted is determined based on costs and model constraints such as the required CO_2-savings. The HIGHEFF scenario has an ambitious focus on thermal renovations. MEDIUMEFF features moderate component requirements and renovation rates. LOWEFF reflects a future in which E1st is not stringently put in practice, hence including lower component requirements and a lower renovation rate.

The **room temperature** in buildings is an important lever for space heating energy use. Each country or region has a so typical "comfort temperatures" that vary with weather and wealth, as well as with the energy performance level of the building. Current comfort temperatures are found to range from 14°C in central Europe to 25°C in southern Spain, with the average comfort temperature in Europe being at about 20°C (Ballester et al. 2011). As stated above, room temperature reductions as a potential sufficiency measures are disregarded in this model-based assessment. INVERT applies a function between effective indoor temperature and the energy performance of the building as well as the building size derived from (Loga et al. 2003).

Another important variable is the **living space per capita** which determines the energy use intensity of the building. The less floor space is assumed per capita, the less is the energy demand for these applications, all else being equal. This is particularly relevant for space heating and cooling, but also has implications for lighting energy use. As described in Chapter 3.1, living space per capita is an indirect driver of INVERT's building stock growth assumptions. The explicit input variable is the absolute growth of the building stock, which is provided in Table 1.

Buildings in Europe use a variety of different **fuels and technologies for space and water heating**. To achieve a climate-neutral building stock by 2050, all scenarios are bound to replace fossil fuels with alternative renewable technologies. Technology and fuel shares are determined endogenously in INVERT, based on the objective function of minimising total costs and the constraint of the GHG reduction target set. While some fuels or technologies are subject to diffusion constraints in the model (e.g. district heating, gas or solar thermal energy), these constraints do not differ across scenarios to provide a neutral reference with respect to system installed.

Besides heating, another major end-use in buildings are **electrical appliances and lighting**, with a variety of technologies used across the EU. FORECAST projects the diffusion and gradual stock turnover of such equipment for residential and non-residential buildings. Technologies modelled for households include, for example, refrigerators, washing machines, tumble dryers, dishwashers, and computers. Relevant appliances in non-residential buildings are, for example, commercial refrigeration and freezing in the retail sector, laundry and cooking appliances in hotels or the health sector, and office equipment. The three scenarios are set to differ with regard to the level of **appliance efficiency**, i.e., the rate of final energy use for generating the energy service provided by the device. Using more efficient appliances reduces final energy demand and thus is likely to require less supply side infrastructures in the long term. In FORECAST, EU Ecodesign and Energy Labelling are modelled as the major legislations to boost the diffusion of energy efficient appliance technologies in the market. In the HIGHEFF scenario, these provisions are significantly tightened, while MEDIUMEFF assumes more moderate standards. In LOWEFF, standards are only slightly raised above current levels, resulting in the highest final energy demand among the three scenarios.

Final energy consumed for appliances and lighting is not only determined by their efficiency, but also by how the **total number of technologies owned** by households and businesses evolves over time. The FORECAST model projects the stock of various appliances by using sigmoid growth curves that are fitted to empirical stock development. Another important lever is the **appliance use intensity**, i.e., the number of hours an appliance is used. Default values from the FORECAST model database are used for this purpose.

3.2.2 Electricity supply

ENERTILE optimises the expansion and operation of renewable and fossil generators as well as transmission network infrastructures. The capacity expansion of wind and photovoltaics (PV) are among the most important decision variables of the model. The **electricity generation potential** for these renewable technologies is determined in a detailed calculation with a high spatial resolution of about 240,000 tiles of 6.5 km edge length per tile for the continent of Europe. For each tile, the electricity generation potential for wind and solar energy is calculated endogenously. First, land use and terrain data from (Corine Land Cover 2018) is used to determine the available area in each tile. Then, hourly weather time series from several weather years are assigned to the model grid. Finally, for each tile and technology, the installable capacity, full-load hours, possible long-term generation output, and specific generation costs are calculated. This results in cost-potential curves for five different technologies: rooftop PV, field PV, concentrating solar power (CSP), wind onshore, and wind offshore. A detailed description of this approach is available in (SET-Nav 2019).

The capacity expansion and operation of conventional power plants and other technologies are part of the cost optimization with ENERTILE and therefore depend strongly on their **techno-economic characteristics** – such as specific costs, conversion efficiencies, technical lifetimes, and others. This data is essentially based on two sources: the ASSET project (DeVita et al. 2018) and the Danish Energy Agency's technology data for generation of electricity and district heating (Danish Energy Agency 2020). An important concern in power supply is the assumed **role of nuclear power**. Nuclear power generation is driven by political preferences rather than pure economic decision-making. Thus, nuclear generation capacity is not subject to the cost optimisation procedure in ENERTILE but included as an exogenous assumption. The capacity expansion or deconstruction of nuclear plants is set exogenously for each modelled country and is based on the National Champions pathway in (SET-Nav 2019). Similar to nuclear power, EU countries have been active in defining pathways for **coal phase outs**. Various national governments in the EU have announced their intention to phase out coal from their electricity generation (see e.g. Europe Beyond Coal 2021). For the scenarios, phase-out announcements are implemented in two ways. First, the timing of the phase-out is considered in ENERTILE's power plant database to ensure that closure dates are met on plant level. Second, the construction of new coal plants is prohibited in countries with concrete phase-out plans.

Biomass is a critical and scarce renewable energy carrier. In line with previous analyses (SET-Nav 2019), it is assumed that the use of biomass for electricity and district heat supply declines until 2050, as the potentially available biomass is more urgently needed for decarbonization in the industry and transportation sectors. **Carbon capture and storage (CCS)** is assumed to be unavailable for fossil fuel-based electricity generation and instead reserved for negative emissions via biomass usage. This corresponds to the 1.5LIFE scenario in the European Commission's in-depth analysis (European Commission 2018a).

The expansion and costs of power networks are carried out separately for the transmission and distribution levels. As for **power transmission networks**, ENERTILE endogenously models the transmission of electricity between model regions using a model of net transfer capacities. These transfer capacities limit the possible electricity exchange between model regions. In this analysis, Europe including all current 27 member states of the EU plus Norway, Switzerland, and the United Kingdom is covered. Each country thus represents one model region. It is assumed that the reference grid of 2027 from the latest 2018 Ten Year Network Development Plan (TYNDP) (ENTSO-E 2018) is implemented as a minimum status for the transmission grid in 2030. The expansion of these initial cross border interconnector capacities is part of the optimization with ENERTILE, taking into account required investments and occurring grid losses. Besides investments for power transmission networks, ENERTILE also quantifies system service costs, i.e., the costs incurred to ensure the reliable operation of the system, e.g., for balancing or ancillary services.

As for **power distribution networks**, this study cannot rely on dedicated modelling and instead attempts to provide a first-order approximation of network costs for the different scenarios up to the year 2050. The starting point for this approach is a detailed account of network costs per Member State for the period 2010–2018 (Gorenstein Dedecca et al. 2020). These empirical costs are distinguished by country, capital expenditures and operating expenses.[5] In simplified modelling, future power distribution network costs are frequently assumed to be a function of the level of variable renewable energies (VRE) in the system (mostly wind and solar power), or trends in end-uses that cause increases in peak load (mostly heat pumps and electric vehicles) (Jamasb and Marantes 2011; Horowitz et al. 2018).[6] In this study, distribution network

[5] The former here comprises investments for the connection of new network users (network expansion), reinforcements of existing network components, as well as replacement of ageing assets (overhead lines, cables, switchgear, etc.) for safety or reliability reasons. The latter includes various cost components: some are partly fixed (administrative costs), others correlated to physical infrastructure (e.g. maintenance) or correlated to capacity and volumes (e.g. network losses) (Gorenstein Dedecca et al. 2020).

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

costs are thus scaled according to total electricity demand [TWh] in annual steps until 2050. To critically scrutinize this simplified approach, the results will be compared to similar scenario analyses for the EU (see e.g. van Nuffel et al. 2017).

3.2.3 District heat supply

The generation mix and costs of **district heat production and networks** are provided by ENERTILE and NETHEAT, based on heat demand projections from INVERT. ENERTILE models the district heat generation mix with different technology options, for which capacity expansion and hourly operation are optimized. Same as for electricity supply, the available **biomass** is implemented as an upper bound in the optimization in ENERTILE. Below this limit, the actual usage of biomass in district heating is optimised. The use of solar thermal and deep geothermal for district heat supply is associated with comparatively high costs. Nonetheless, their deployment is essential to contribute to net-zero emissions across all three scenarios. **Solar thermal** is assumed to be deployed in all countries until 2050 and to cover 15% of the district heating generation mix by 2050. For **deep geothermal**, it is assumed that countries currently using geothermal energy for heat production will further deploy this energy source, reaching 15 times today's production in 2050. The total share of deep geothermal energy is limited to a maximum of 30% of heat demand. The deployment of **large heat pumps, direct electric heating, and hydrogen** is optimised in ENERTILE and no further restrictions are applied. ENERTILE optimizes the supply for all sectors and captures inter-sectoral effects and competition for CO_2-neutral energy carriers. As all sectors need to reach a carbon neutral energy supply by 2050, they compete for cheap low-carbon energy supply via electricity, hydrogen and e-fuels. Therefore, no additional restrictions are used for hydrogen and e-fuels in district heat supply.

Based on the heat demand outputs from INVERT and their related heat densities, NETHEAT calculates the capital expenditures and operation and maintenance expenses for **district heating networks** at a hectare level. As a suitable district heating region are considered the ones with minimum heat density of 20 GWh/km². This threshold is constant for each scenario. By calculating the road length usage based on the building connection rate, the potential district heating pipe length is calculated. The investment costs are classified in three categories depending on the area sealing density. 100% sealing density implies that the area is fully covered with buildings and roads. The model assumes that the higher the sealing density, the higher are the specific construction costs for building a DH network in that area. Construction cost constant C_1 (€/m) and construction costs coefficient C_2 (€/m²) are calculated for each construction area type by using Eurostat labour and material costs coefficients. For areas with a continuous urban fabric and a sealing density of more than 80% the highest costs coefficients are considered, whereas for the areas with the medium to low urban fabric of sealing density below 50% the lowest specific costs area considered.

3.2.4 Natural gas and hydrogen supply

To achieve net-zero GHG emissions in the building sector, natural gas consumption must decrease substantially in all three scenarios. However, **synthetic methane** and **hydrogen** produced from renewable electricity as well as **biomethane** are possible alternatives to natural gas with limited potentials in the building sector. While synthetic methane and biomethane can be fed into the gas distribution network without any additional modifications (Oberle et al. 2020), hydrogen would require dedicated infrastructure unless its volumetric share in natural gas remains under given thresholds (Guelpa et al. 2019).

ENERTILE endogenously determines the deployment of **hydrogen electrolyzers and methanation facilities** (Lux and Pfluger 2020). Hydrogen and synthetic methane can either be produced with renewable electricity within the EU or be imported from countries with very good potentials for renewable electricity generation outside the EU – typically the MENA region. In all scenarios, import of hydrogen and synthetic methane is generally allowed but at high prices to prioritise production in the EU. The demand for these fuels in the building sector is derived from INVERT as part of the total gas demand using assumptions on shares for the addition of hydrogen or synthetic methane in the gas network. The key assumption is that in 2050, hydrogen and synthetic methane each cover **10% of building energy demand for gas**. Electrolyzer and methanation facilities are deployed accordingly in the ENERTILE model, along with their costs.

As for the associated **network costs of** natural gas and hydrogen supply, this analysis relies on a first order approximation. Generally, the assumed share of 10% hydrogen in overall gas demand for the building sector by 2050 is likely to remain below common technical limitations of gas networks (Götz et al. 2016). Partial conversion of gas networks to hydrogen can thus be disregarded in this analysis.[7] This leaves the question how the existing gas network and its system costs evolve until 2050. In general, renovation works, as well as security of supply and market integration-driven projects imply some capital expenditures until 2050. This number essentially depends on the gas demand and thus the duration that existing network assets will continue to be used until 2050. For simplification purposes, this analysis assumes that in none of the scenarios additional investments are made in gas infrastructures.[8] In turn, following the simplified approach in (Langenheld et al. 2018), maintenance and service costs (e.g. costs for transport, administration, data management) are extrapolated as a function of the number of connected buildings. Using gas network operating costs from 2018 (Gorenstein Dedecca et al. 2020), operating expenses are proportionally calculated until 2050, based on the number of connected buildings calculated by INVERT.[9]

[7] Pure hydrogen networks can be thought to exist in the scenarios for industry and transportation. However, as explained about the Cross-sectoral boundary conditions, these sectors are beyond the scope of this analysis, with their final energy demand being the same across all three scenarios. The differential costs for any hydrogen infrastructure thus cancel each other out – given that the analysis only quantifies incremental costs in relation to the LOWEFF scenario.

[8] Ongoing capital costs of existing gas networks thus cancel each other out in the final figures.

[9] These costs are available by Member State, and distinguished by gas transmission and distribution levels (Gorenstein Dedecca et al. 2020). Extrapolating this data from the year 2018 implies the assumption that the length of networks evolves in parallel to the likely drop in gas demand, thus resulting in constant specific operating costs (Oberle et al. 2020).

This chapter provided specifications on the scenarios. For one thing, the assessment uses a set of **boundary conditions** on socio-economic trends, fossil fuel prices, and climate and weather data, applied across all scenarios and sectors. For another, the scenarios are specified for the individual sectors investigated (buildings, electricity supply, district heat supply, natural gas and hydrogen supply). For **buildings**, the INVERT model projects energy use for space heating, water heating and space cooling. FORECAST represents the end-uses of appliances, lighting, and cooking. The models cover both residential and non-residential buildings. According to the scenarios, the models use different input assumptions with respect to the thermal efficiency of buildings and the efficiency of appliance use. As for **electricity supply**, ENERTILE determines the expansion, operation and associated costs of generators as well as transmission network infrastructures. The costs of power distribution networks are estimated based on a first-order approximation. Concerning **district heat supply**, ENERTILE models the district heat generation mix with different technology options. In parallel, NETHEAT calculates the capital expenditures and operation and maintenance expenses for district heating networks, based on scenario-specific heat densities provided by INVERT. Finally, concerning **natural gas and hydrogen supply**, ENERTILE endogenously determines the deployment of hydrogen electrolysers and methanation facilities. The demand for these fuels in the building sector is derived from INVERT as part of the total gas demand, using assumptions on shares for the addition of hydrogen or synthetic methane in the gas network. In terms of gas network costs, the study assumes no additional investments for gas infrastructures. In turn, maintenance and service costs are extrapolated as a function of the number of connected buildings. The following chapter describes in what respects the outputs of the model-based assessment will be evaluated.

4. OUTPUT EVALUATION OF ENERGY SYSTEM ANALYSIS

The model-based assessment described in this report will be evaluated in two respects. First, a **techno-economic assessment** is carried out (**Chapter 4.1**) to ascertain costs, energy demand and other system variables. Second, a **socio-environmental assessment** (**Chapter 4.2**) investigates and, where possible, quantifies the multiple impacts of the resource configurations calculated in the analysis.[10]

4.1 Techno-economic assessment

A first cornerstone of the analysis is a techno-economic assessment of the three scenarios. This assessment covers the following set of indicators:

- **Energy system costs** | Costs for resource options per sector, distinguished by capital expenditures and operating expenses.
- **Energy demand** | Primary and final energy demand used by sector, energy carrier, and end-use.
- **GHG emissions** | Direct GHG emissions. Note that all scenarios are set to achieve net-zero GHG emissions in 2050. However, the transition until 2050 will differ and thus the total carbon budget.

[10] Note that these evaluation perspectives bear some resemblance to cost-effectiveness tests developed and used by energy utilities and regulators in the United States since the late 1980s to determine the value of energy efficiency measures and other system resources (CPUC 2001; U.S. EPA 2008). The techno-economic and socio-environmental assessments in this report together essentially correspond to the Societal Cost Test, determining costs and benefits that accrue to society altogether. The techno-economic assessment in itself comes closest to the Total Resource Cost Test, with the difference that the former excludes taxes, subsidies and other transfer payments while the latter does include such cost items.

- **Market development** | Ramp-up of key technologies (e.g., heat pumps or insulation material) in terms of unit sales and/or market shares.
- **Power and district heating system operation** | Seasonal and daily variations in load and generation.

Energy system costs indicate the total monetary costs to meet the energy service demand of households and firms in the building sector. They are the central indicator in the model-based assessment to evaluate the performance of each of the three decarbonization scenarios towards achieving a climate-neutral economy in 2050 by indicating the most cost-effective resource configurations of demand and supply side resources. As such, the indicator helps ascertain the value of energy efficiency concerning its mutual effects with the supply sector, highlighting the extent to which society is better off – in pure monetary terms – if efficiency was prioritized in energy planning and operation. Note that this study only quantifies **incremental costs** in relation to the LOWEFF scenario. In doing so, estimates of the ongoing capital costs of assets that were deployed before the evaluation period 2020–2050 can be avoided, as well as any costs in the industry or transport sectors, which are not in the scope of this study.

In essence, energy system costs comprise **capital expenditures** (CAPEX) for various building efficiency measures and equipment as well as for various supply side assets (generation, networks, storage). In addition, they comprise **operating expenses** (OPEX) for fuels, maintenance, personnel, and other cost items on both the demand and the supply sides. **Table 2** displays the major cost items considered for the calculation of energy system costs. To neglect the effect of **inflation** and thus to ensure that values are comparable from year to year (Atkinson et al. 2018), all costs are reported in **real terms** instead of nominal money terms in relation to 2018 (EUR_{2018}). Consumer price and producer price indices are used to refer cost data to the price level of the reference year 2018.

To account for the fact that investments that are made before the time period under consideration ends (year 2050), all CAPEX are reported as **annual capital costs** and thus only partially considered in the calculations. This is done by transforming upfront investments (EUR) into equal annual instalments ("annuities") (EUR/a) of capital expenditures over the investment's lifetime or depreciation period, using the equivalent annuity cost method (Blok and Nieuwlaar 2016; Konstantin and Konstantin 2018). As described further below, this requires the selection of a **discount rate**.

In calculating an aggregate indicator of energy system costs it is important to account for **double counting of cost items**. To illustrate, consumers incur certain costs for purchasing electricity, with the price per kilowatt-hour consisting of an energy component, transmission and distribution fees, RES charges, value added tax and miscellaneous price components. Most of these cost items are a function of the future evolution of energy supply, with generators, network operators and suppliers incurring and passing on costs to the consumers. Ultimately, accounting of electricity and district heating costs must be based on either demand or supply estimates. Given the detailed model framework on the supply side provided by ENERTILE and NETHEAT, and to avoid having to estimate consumer prices, this study reports **costs for electricity and district heating provision based on the supply side modelling**. Note, however, that wholesale and supply costs for biomass and oil as final energy carriers in the building sector are based on input assumptions as this analysis does not endogenously model their respective future development.

Table 2. Cost items for calculation of energy system costs by sector

Source: ENEFIRST project, based on Capros et al. (2016)

Sector	Cost items		
	CAPEX	*OPEX*	*Comment*
Buildings	• Building renovation • Heating equipment • Electrical appliances and lighting equipment	• Operation and maintenance of heating equipment and appliances • Biomass/oil wholesale costs	Purchasing of electricity and district heat incurred for *supply* costs
Electricity supply	• Generation plants • Power networks • Electricity storage facilities	• Fuel costs • Operation and maintenance of electricity supply assets	Payments to acquire ETS allowances not included
District heat supply	• Generation plants • Heat networks • Heat storage facilities	• Fuel costs • Operation and maintenance of district heat supply assets	Generation plants only heat boilers; CHP included under *Electricity supply*
Gas supply	-	• Gas wholesale costs • Operation and maintenance of gas network assets	Assumption: no additional gas network investment in all scenarios

Costs within the system boundary of **buildings** are calculated using the models INVERT and FORECAST. A major cost item is the CAPEX for renovation measures, i.e., improvements in the thermal insulation performance of external walls, floors, roofs, ceilings, windows, doors. INVERT calculates the capital costs for renovation measures based on fixed fractions and fractions varying by insulation thickness. Another cost item are the expenditures for heating equipment as well as for electrical appliances and lighting. The former are calculated by INVERT by nominal power (kW), taking into account that specific costs per kW are higher with smaller facilities than with larger ones. The latter are computed by FORECAST on a per-item basis (e.g., EUR/refrigerator of given type and efficiency class). All renovation measures, heating equipment and appliances are assigned learning curves to take into account economies of scale. On the OPEX side, the models calculate operation and maintenance (O&M) costs for heating equipment and appliances as well as fuel costs for fuel oil and biomass.

In terms of **electricity supply**, ENERTILE determines the CAPEX and OPEX of various supply assets, covering generation (e.g., gas turbine), storage (e.g., battery storage) and transmission networks. The costs of distribution network are estimated based on a simplified approach (see **Chapter 3.2.2**). As explained above, any O&M and fuel costs for electricity supply that are eventually incurred by consumers are reported under power supply to avoid double counting. Concerning **district heating supply**, NETHEAT computes the CAPEX for network expansions. These expenditures only include the heat distribution networks including branch lines to buildings. Expenditures for heat exchange stations are considered as heating equipment under the buildings category. ENERTILE calculates the capital costs for various district heating generation plants, including various combined heat and power (CHP) plants, heat-only boilers, large-scale heat pumps, and more. CHP plants are reported under electricity supply and the remaining heat-only technologies (e.g., large-scale heat pump) under district heating supply. Similar to electricity, consumer purchases of district heating are not accounted for but instead the supply-side OPEX. As for **gas supply**, this study takes a simplified approach to estimate its future costs (see **Chapter 3.2.4**).

In accordance with the notion of E1st, energy system costs are evaluated from a **societal perspective**. As discussed in **Chapter 1** and (ENEFIRST 2020e), this has a number of implications:

- **Discount rate:** In line with similar studies in the field (e.g. Langenheld et al. 2018) and existing guidelines (Sartori et al. 2015; European Commission 2017), a social discount rate (SDR) of 2.0% is selected to calculate annual capital costs.[11] Note that the payment date itself is not discounted, i.e., costs incurred in 2050 are attached the same weight as those in 2020.
- **Fiscal corrections:** Taxes and subsidies are omitted from a societal perspective as they reflect transfer payments. Such payments are disbursements of money that do not receive any good or service in return and that do not contribute to an increase or decrease of the real value of a product (Konstantin and Konstantin 2018; Sartori et al. 2015). The analysis thus, to the extent possible, excludes payroll taxes and non-wage labour costs in wage costs; energy costs exclude flat-rate surcharges and taxes.[12] Moreover, subsidies are not included as they are transfers between agents that do not affect economic welfare as a whole.
- **Multiple impacts:** Quantitative assessments from a societal perspective should take explicit account of the multiple impacts of different resource options in order to represent their net social welfare effects.

The following section presents the framework to evaluate the multiple impacts of demand and supply side resources in what is referred to as the socio-environmental assessment of this study.

4.2 Socio-environmental assessment

Acknowledging and measuring the **multiple impacts**[13] (MIs) of energy efficiency in policy formulation and project-related investment appraisals is a subject continuously raised in the ENEFIRST project (ENEFIRST 2020b) and preceding literature on the E1st principle (e.g. Bayer et al. 2016b). The key proposition is that, as the E1st principle seeks to address the trade-off between demand- and supply-side resources from a **societal perspective**, costs and benefits of these resource options need to reflect society's interest. As more thoroughly explained in (ENEFIRST 2020e), it follows that quantitative assessments of E1st must not be limited to the techno-economic costs of resource options, but also have to take into account the societal value of these technologies in terms of air pollution, energy-poverty related health and other MIs.

It is critical to note that **MIs do not only accrue to end-use energy efficiency** and other demand-side resources. While the bulk of the recent literature tends to focus on this perspective (IEA 2015; Reuter et al. 2020), MIs have also been associated with renewable energy sources (RES) on the supply side (Edenhofer et al. 2013; U.S. EPA 2018). Climate change mitigation, energy security, green jobs, reduced environmental damages and poverty reduction are but a few examples of MIs that can be related to both

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[11] As pointed out in ENEFIRST (2020e), SDRs can be estimated for individual countries using a variety of approaches. For the sake of transparency, this study refrains from such estimates and applies a uniform SDR across all Member States.

[12] Despite the general rule to omit transfer payments from the societal perspective, there are cases where indirect taxes or allowances are intended as a correction for externalities (e.g. carbon tax in some MS). In this case, it is justified to include these charges in the cost balance, provided that they adequately reflect the underlying willingness-to-pay. Either way, the appraisal must avoid double counting, i.e., including both energy taxes and estimates of external environmental costs (Sartori et al. 2015). To ensure consistency, this study completely omits such charges and instead quantifies external environmental costs in the form of air pollution and GHG emissions (see Chapter 4.2).

[13] The term 'multiple impacts' has been used almost interchangeably with the terms 'co-benefits', 'multiple benefits', 'ancillary benefits', 'indirect costs', and 'adverse side-effects'. See Thema et al. (2019) and Ürge-Vorsatz et al. (2014) for a discussion of the subtle differences between these terms. Following the definition by Ürge-Vorsatz et al. (2016), MIs are here understood as "all benefits and costs related to the implementation of low-carbon energy measures which are not direct private benefits or costs involving a financial transaction and accruing to those participating in this transaction."

demand- and supply-side resources. As E1st aims for a **level playing field** between demand- and supply-side resources, the MIs of both sides need to be considered. An exclusive focus on the MIs of end-use energy efficiency and other demand-side resources would result in a positive bias that can create misleading conclusions, up to overinvestment in demand-side measures above socially optimal levels.

The **objective of this socio-environmental assessment** is to investigate and quantify selected MIs of the resource configurations calculated in the model-based system analysis. In terms of sequence, the analysis of MIs in the socio-environmental assessment is conducted **subsequent to the model-based techno-economic assessment**.[14] The assessment thus provides the missing piece of an actual societal perspective. In addition, the assessment provides a dedicated perspective on how the inclusion of MIs changes the outcome of conventional techno-economic energy system analysis.

The methodology applied for the socio-environmental assessment will be presented in an upcoming report of the ENEFIRST project. In short, the following steps are followed to include selected MIs in the analysis (Thema et al. 2019): (1) Identification and characterisation of relevant MIs; (2) identification of causal effects and overlaps among MIs; (3) quantification of selected MIs in physical units; (4) monetization of physical values; (5) aggregation of impacts; (6) integration of monetized MIs with energy system costs.

[14] In theory, an integrated energy system model could determine socially cost-optimal resource levels across all sectors considered and including all relevant MIs. However, the practical complexity of both techno-economic systems modelling and socio-environmental quantification of MIs so far has not yet allowed for such an integrated approach to quantitative assessments of E1st.

5. LIMITATIONS OF MODELLING APPROACH

The energy system analysis for the EU-27 carried out in this project is subject to a number of limitations:

Societal perspective

In terms of perspective, it is recalled that this analysis is carried out from a **societal viewpoint**. The E1st principle aims to prioritize those portfolios of demand- and supply-side resources that provide the greatest benefit to society (see ENEFIRST 2020b). 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 2020e). The conflict between societal and private perspective is obvious, for example, with regard to premature decommissioning of fossil-based power plants to comply with the societal objective of net-zero emissions. While a detailed account of gainers and losers is highly relevant in this transition process, it is neither a principal focus of the E1st 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.

Financial corrections

The quantification of energy system costs from a societal perspective in this study has flaws in accounting terms. For one thing, as pointed out in **Chapter 4.1**, **transfer payments** such as taxes and subsidies should be excluded from the cost balance as these do not represent real economic costs for society (e.g., Konstantin and Konstantin 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 thorough elimination of all relevant transfer payments is not possible in this study. For example, the capital expenditures for building renovation and heating systems include a significant amount of labour costs that, in turn, consist to a large extent of payroll taxes.[15] 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 market prices, to reflect economic costs.[16] 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 E1st principle

With respect to the E1st principle, the key demand-side resource investigated in this quantitative assessment is **end-use energy efficiency** in the building sector. This does not only cover the thermal efficiency (e.g., thermal retrofit of external walls), but also various forms of appliance efficiency (e.g., adoption of efficient LED lighting). However, as discussed in **Chapter 2.2**, other demand-side resources

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[15] 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.

[16] Market prices (financial costs) are used in energy models in terms of 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 (Belli et al. 1998; Sartori et al. 2015). 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; Belli et al. 1998).

relevant for the E1st principle are **energy service sufficiency** (Brischke et al. 2015) and **demand response** (Paterakis et al. 2017). The role of these resource options for transitioning to an economy with net-zero emissions in the EU is not investigated in detail in this quantitative assessment. The implications of energy service sufficiency for the concept of E1st are not yet firmly embedded in the literature and essentially would require novel modelling approaches to attach a monetary value to individual sufficiency measures. Likewise, demand response requires dedicated modelling to determine its potentials and operation in various power various power markets, both of which are not possible in the scope of this study. As such, the analysis provides only a partial image of the E1st principle, albeit a very comprehensive one for the resource of end-use energy efficiency.

Gas and power network modelling

To quantify the networks **costs of natural gas and hydrogen supply**, this study relies on a first order approximation (**Chapter 3.2.4**). Network maintenance and service costs are extrapolated as a function of the number of connected buildings. Additional capital expenditures for gas networks until 2050 are assumed to cancel out one another. This simplified approach is likely to underestimate the system costs associated with gas and hydrogen infrastructures. In the absence of dedicated modelling tools available, a similar quantification approach is selected for **power distribution networks** (**Chapter 3.2.2**). Future distribution network costs are calculated as a function of final energy demand for electricity that, in turn, depends on the diffusion of heat pumps and other technologies in the scenarios. Note, however, that the expansion and costs of power transmission networks are explicitly modelled through the ENERTILE model.

Market equilibrium and economy-wide rebound effects

As pointed out in **Chapter 2.3**, the four bottom-up energy models used in this quantitative assessment use a **soft-coupling approach**: data is manually transferred among the models in a unidirectional data flow from energy demand to energy supply models. This has minor implications for the prices of electricity and district heat determined and used across the models. Ideally, to determine a partial **market equilibrium** for these prices, the chain of coupled models would need to be iterated multiple times to reach convergence in terms of equilibrium prices that balance the amount of energy supplied and the amount demanded. While the long computation times of some of the models used are prohibitive to such iterations, the actual effect on market prices determined can be considered negligible (see e.g. Helgesen and Tomasgard 2018). An associated issue is the cursory consideration of **economy-wide rebound effects**.[17] Direct rebound effects are partially included in estimations of energy savings provided by the models INVERT and FORECAST (see **Annex: Model factsheets**). However, a detailed account of both indirect and macroeconomic rebound effects is beyond the scope of this study. Based on the recent evidence base (e.g. Brockway et al. 2021), the scenarios in this study are likely to overestimate the potential for energy efficiency measures.

[17] 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).

6. CONCLUSION

The **E1st principle** states that demand-side resources should be prioritized whenever these provide greater value to society than alternative supply-side resources in meeting policy and planning objectives. In practice, taking explicit account of the principle in energy system planning and policy formulation is a complex planning exercise. **Energy systems modelling** can help making these complexities tangible and thus enable decision-makers to make informed decisions on policy design, technology investment and system operation. However, as E1st only recently entered the political and academic debate, there are only few model-based assessments that make explicit reference to the principle by systematically investigating the implications of various demand- and supply-side resources for the EU energy system.

Against this background, this report set out to develop a methodological concept for a **model-based analysis of the E1st principle** for the EU-27 that will be carried out and analysed in subsequent reports of the ENEFIRST project. The **objective** of this energy system analysis is to investigate what level of demand and supply-side resources should be deployed to provide the greatest value to the EU's society in transitioning to net-zero GHG emissions for the building sector by 2050. On the **demand side**, the analysis focuses on the resource option of end-use energy efficiency in buildings, investigating the contributions of thermal retrofits, efficient appliances, and other measures towards the net-zero target. On the **supply side**, the analysis quantifies the possible deployment and costs of various generation, network and storage options for the provision of electricity, district heat and gas products for the building sector. By determining what resource portfolio should be adopted under given framework conditions to reach the 2050 target, this analysis can **help decision-makers identify priorities for policy design and technology investment**, along with opportunities and risks associated with different pathways.

In terms of pathways investigated, this analysis covers a **set of three model-based scenarios**. Each of these scenarios is geared to reach the 2050 target of **net-zero emissions** in the EU-27. However, the scenarios differ in terms of the contribution of different **resource options** towards target achievement:

- The **LowEff scenario** assumes that energy use in buildings is decarbonized primarily via the use of renewable-based supply-side resources – ranging from heat pumps to non-fossil district heating systems, up to utilization of hydrogen and synthetic methane. This reflects a future in which the E1st principle is not comprehensively put in practice. End-use energy efficiency measures are an important decarbonisation option, but with lower levels than in the remaining scenarios. To compensate for low levels of end-use energy efficiency, the deployment of supply-side generation, network and storage capacities must be comparably high to achieve net-zero emissions by 2050.
- The **MediumEff scenario** is characterized by a slightly increased deployment of demand-side energy efficiency measures in buildings and supply-side generation and network infrastructures. In contrast to LowEff, the levels of thermal efficiency and appliance efficiency in buildings are raised, leading to a reduction in final energy demand. This, in turn, implies smaller capacities for various generation, network and storage assets. The scenario thus exhibits a future in which due regard is given to the E1st principle in energy system planning and investment. However, economic potentials for end-use energy efficiency measures are not fully exploited due to persisting investment barriers and lack of dedicated policies.
- In the **HighEff scenario**, end-use energy efficiency measures in buildings are viewed as the most favourable decarbonisation option for the European energy system by 2050. While heating, appliances and other end-uses in buildings will continue to require some level of renewable-based energy supply, the overall energy use is way below the levels in LowEff and MediumEff. As such, HighEff

represents a future in which the E1st principle is comprehensively applied in energy system planning and investment.

To capture the systemic effects between the building sector and the supply side of the EU energy system in terms of generation, network, and storage infrastructures, this analysis couples four bottom-up energy models: INVERT, FORECAST, ENERTILE and NETHEAT. By using these models, the analysis 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 both power and district heating systems are explicitly modelled, supported by approximations for the deployment and costs and natural gas supply in the individual scenarios.

To measure the performance of the three scenarios and thus to determine the extent to which demand-side resources should be prioritized over their supply-side counterparts, the outputs of the analysis are analysed in two respects. For one thing, the so-called **techno-economic assessment** focuses on the indicator of energy system costs, indicating the sum of capital expenditures and operating expenses needed to meet the energy service demand in the building sector. Supported by additional indicators (e.g., ramp-up of specific technologies), this assessment helps determine the extent to which society is better off – in pure monetary and technical terms – if demand-side resource were prioritized in energy planning and operation. For another, the so-called **socio-environmental assessment** investigates the multiple impacts of the resource configurations computed in the different scenarios. Impacts to be investigated may include air pollution, energy-poverty related health, and workforce productivity. Where possible, these impacts are quantified and monetized using dedicated methodologies. The socio-environmental assessment thus provides the missing element to a dedicated societal perspective targeted by the E1st principle.

In sum, this model-based analysis addresses the four criteria of quantitative assessments for the E1st principle set out in (ENEFIRST 2020e): (1) It features an **integrated model-based appraisal of demand- and supply-side resources** in the building sector and associated supply sectors (electricity, district heat, natural gas and hydrogen). (2) There is a **common planning and policy** objective across all scenarios of reaching net-zero GHG emissions for the EU building sector by the year 2050 while meeting demand for energy services. (3) All costs and benefits are evaluated from a **societal perspective**, rather than a private one. (4) A systematic **appraisal framework** is selected to compile all relevant cost and benefit items, including a selection of multiple impacts.

It should, nevertheless, be noted that this energy system analysis is subject to a number of **limitations** in terms of the modelling approaches selected. First, following the E1st principle, this analysis is carried out from a **societal perspective**. Given the multitude of decision-makers in the energy system, a supplementary private or investor-based evaluation perspective of costs and benefits is beyond the scope of this analysis. Second, the techno-economic assessment focuses on **end-use energy efficiency** as a key demand-side resource in the building sector. While energy service sufficiency and demand response are also relevant demand-side resources, their possible contribution to the 2050 target of net-zero emissions is not evaluated in detail. Third, the socio-environmental assessment only integrates a **subset of all existing multiple impacts** into the framework, given the complexity of dedicated methodologies needed to quantify and monetize relevant impacts. Fourth, this analysis relies on simplified approaches for the quantification of the future deployment **gas infrastructures as well as power distribution networks**. This implies possible over- or underestimation of costs in the techno-economic assessment. Finally, the soft-coupling approach used to integrate the four individual energy system models can neither determine **market equilibria**, nor take comprehensive account of **economy-wide rebound effects**. This may result in overestimated potentials for energy efficiency measures.

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ACRONYMS AND ABBREVIATIONS

CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CDD	Cooling degree days
CHP	Combined heat and power
CSP	Concentrating solar power
E1st	Efficiency first
EED	Energy Efficiency Directive
EFR	Effort Sharing Regulation
ETD	Emissions Trading System Directive
ETS	Emissions Trading System
EU	European Union
HDD	Heating degree days
ICT	Information and communications technology
MI	Multiple impact
MS	Member State
O&M	Operation and maintenance
OPEX	Operating expenses
PV	Photovoltaics
RED	Renewable Energy Directive
RES	Renewable energy sources

ANNEX: MODEL FACTSHEETS

This annex characterizes the energy system models applied in this quantitative assessment in more detail (see **Section 2.3**). **One-page factsheets** are used to help identify key characteristics of the four individual models INVERT, FORECAST, ENERTILE, and NETHEAT. References to scientific articles, as well as sample projects in which the models were previously applied, are indicated to support the factsheet information. The information provided in the factsheets is understood as follows:

General model logic: **Top-down** modelling covers input-output models, econometric techniques, computable general equilibriums and others approaches to provide an aggregated economy-wide view and incorporates energy technologies with less detail through aggregated functions within a large macroeconomic system. **Bottom-up** models feature a technology-rich and detailed representation of the energy system. They usually do not include interactions between the energy system and the broader economic system. **Hybrid** models attempt to integrate the detailed energy technology representation of bottom-up models into top-down macroeconomic modelling (Crespo del Granado et al. 2018). **Optimisation** models apply mathematical optimisation to find a preferred mix of technologies given certain constraints. **Simulation** models depict the behaviour of producers and consumers in response to prices and other signals. **Accounting** models are simple and transparent frameworks that rely on comprehensive inputs from the user as they do not model market behaviour or optimal choices (Hall and Buckley 2016).

Coverage & resolution: **Temporal coverage** means the typical horizon of the analysis, e.g. distinguishing models limited to short-term planning (near-term years) to long-term planning (2050 and beyond). **Temporal resolution** refers to the level of detail with which the system is represented, e.g. accounting for the short-term variability of VRE via an hourly resolution. **Geographical coverage** is understood as the system boundaries, e g. to discern isolated from integrated systems. **Geographical resolution** means how detailed VRE generation, demand patterns and other variables are represented (IRENA 2017).

Demand scope: Indicates what demand **sectors** are covered by the model in this assessment. Note that the ENEFIRST project focuses on the building sector (i.e., households, and commercial and public services) and that some of the models are also capable to represent the industry and transport sectors. The **building end-uses** covered by the individual models are listed below this field. Technology heterogeneity means the degree of technological detail, e.g. distinguishing air- and ground-source heat pumps in buildings. **Decision heterogeneity** means the extent to which different types of investors are discerned, e.g. tenants versus house-owners. **Investment rationale** describes how purchase decisions for energy efficiency measures, heating technologies and other building technologies are modelled.

Supply scope: Describes if, and how, the model models the supply of electricity, heat, and other **energy vectors** (Guelpa et al. 2019). **Supply assets** indicates the coverage of supply-side resources in the E1st-sense, covering generation, storage, transmission and distribution networks, as well as energy vector conversion through power-to-gas, power-to-heat, and power-to-liquid – subsumed under power-to-X (P2X). **'Markets'** indicates how the power and associated markets are treated, including balancing supply and demand under perfect market conditions without explicit market modelling, spot market (merit-order modelling), the reserve market, up to balancing markets (Ringkjøb et al. 2018).

Inputs and outputs: Models operate upon input data and assumptions, so called **exogenous variables**. Based on these variables, target values are calculated through the model, referred to as **endogenous variables** (Hall and Buckley 2016). Technically, **output variables** are also endogenous variables. The term is used here to discern key outputs from intermediate outputs.

INVERT/EE-Lab	INVERT

Basic information			
Model name	INVERT/OPT[18]	Model environment	Python
Institution	TU Wien & e-think	Auxiliary software	SQLite, Excel, VBA
Contact	Lukas Kranzl (lukas.kranzl@tuwien.ac.at)	Model availability	Commercial
Website	https://INVERT.at/		
Sample projects	SET-Nav, BRISKEE, CHEETAH, Hotmaps,		
Key references	Müller (2015), Kranzl et al. (2019), Hummel et al. (2020)		

General model logic	
Methodology	**Simulation** | **Optimization** | Accounting | Equilibrium | Other
Approach	**Bottom-up** | Top-down | Hybrid
Notes	-

Coverage & resolution	
Temporal coverage	2015–2050
Temporal resolution	**Multi-yearly** | **Yearly** | Hourly | Sub-hourly
Geographical coverage	European Union (EU-27) + UK, CH, IS, NO
Geographical resolution	Supra-national | **National** | Regional | Local | Other
Notes	Part of the results can be broken down on hectare level and to hourly resolution

Demand scope	
Demand sectors	**Households** | **Services** | Industry | Transport
Building end-uses	**Space heating** | **Water heating** | Appliances & lighting | Cooking | **Space cooling** | Process heating | Process cooling | Other
Technology heterogeneity	About 15 decentral and central space heating and hot water technologies combined with the relevant set of 10 energy carriers.
Decision heterogeneity	Invert/Opt carries out an optimisation over the full set of renovation and heat supply measures
Investment rationale	Minimisation of total system costs under certain carbon emission constraints

Supply scope	
Supply vectors	Electricity | Heat | Gas | Hydrogen | Synthetic fuels
Supply assets	Fossil generation | RES generation | Transmission | Distribution | Storage | P2X
Markets	Supply/demand | Spot market | Balancing market | Other
Investment rationale	-

Inputs and outputs	
Exogenous variables	Building stock characteristics | growth of building stock by building category | energy prices | technology data | etc.
Endogenous variables	Renovation activities | heating system replacement | future characteristics of building stock | market shares | etc.
Output variables	Final energy demand by energy carrier and building type| Costs (CAPEX, OPEX) | GHG-emissions | etc.

[18] The information in this fact sheet is provided for the model branch Invert/Opt. For Invert/EE-Lab and Invert/accounting slightly different characteristics apply.

FORECAST

FORECAST – FORecasting Energy Consumption Analysis and Simulation Tool

Basic information

Model name	FORECAST	Model environment	VB.Net
Institution	Fraunhofer ISI	Auxiliary software	SQLite, Excel
Contact	Tim Mandel (tim.mandel@isi.fraunhofer.de)	Model availability	Commercial
Website	https://www.FORECAST-model.eu/		
Sample projects	Heat Roadmap Europe, HotMaps, REFLEX, SET-Nav		
Key references	Elsland (2016), Mandel et al. (2019), Fleiter et al. (2018)		

General model logic

Methodology	**Simulation**	Optimization	Accounting	Equilibrium	Other
Approach	**Bottom-up**	Top-down	Hybrid		
Notes	Bottom-up vintage stock model with endogenous representation of decision-makers' technology adoption to project energy demand by demand sector (residential, industry, commercial and public services)				

Coverage & resolution

Temporal coverage	2015–2050				
Temporal resolution	Multi-yearly	**Yearly**	Hourly	Sub-hourly	
Geographical coverage	European Union (EU-27) + UK, CH, IS, NO				
Geographical resolution	Supra-national	**National**	Regional	Local	Other
Notes	Sub-module FORECAST-Regional can disaggregate national electricity demand by districts/municipalities, based on cross-sectoral and sector-specific drivers (e.g. GDP, GVA).				

Demand scope

Demand sectors	**Households**	**Services**	Industry	Transport
Building end-uses	Space heating	Water heating	**Appliances & lighting**	**Cooking**
	Space cooling	**Process heating**	**Process cooling**	Other
Technology heterogeneity	Ca. 30 explicitly modelled appliances and lighting technologies with multiple efficiency classes each			
Decision heterogeneity	Decision-makers in households distinguished by income levels, household size, environmental awareness			
Investment rationale	Total cost of ownership as function of technology cost, operating expenses, other costs, discount rate, lifetime			

Supply scope

Supply vectors	Electricity	Heat	Gas	Hydrogen	Synthetic fuels	
Supply assets	Fossil generation	RES generation	Transmission	Distribution	Storage	P2X
Markets	Supply/demand	Spot market	Balancing market	Other		
Investment rationale	-					

Inputs and outputs

Exogenous variables	Population | GDP | disposable income | energy consumer prices | technology costs in base year | etc.
Endogenous variables	Technology ownership | market shares (sales) | technology stock | technology costs (technological learning)
Output variables	Final energy demand by standard/technology/end-use | Costs (CAPEX, OPEX) | Direct emissions

Enertile

Basic information

Model name	Enertile	Model environment	Java
Institution	Fraunhofer ISI	Auxiliary software	CPLEX solver
Contact	Frank Sensfuß (frank.sensfuss@isi.fraunhofer.de)	Model availability	Commercial
Website	https://www.Enertile.eu/		
Sample projects	MUSTEC, SET-Nav, Langfristszenarien III		
Key references	Bernath et al. (2021), Lux and Pfluger (2020), Held et al. (2018)		

General model logic

Methodology	Simulation	**Optimization**	Accounting	Equilibrium	Other
Approach	**Bottom-up**	Top-down	Hybrid		

Notes: Optimization model for the power and heating sectors with high temporal and technical resolution to develop long-term scenario studies with high shares of renewable energies. Based on exogenous demand for electricity, heat, and hydrogen, the model simultaneously optimizes capacity expansion and hourly dispatch of all system components. Objective function is cost minimization of all modeled technologies and infrastructures.

Coverage & resolution

Temporal coverage	2015–2050				
Temporal resolution	**Multi-yearly**	Yearly	**Hourly**	Sub-hourly	
Geographical coverage	European Union (EU-27) + UK, CH, IS, NO; MENA region				
Geographical resolution	Supra-national	**National**	**Regional**	**Local**	Other

Notes: Model covers Europe, North Africa and the Middle East. Power flows represented by one node per country. RES generation potentials based on ~240,000 tiles with 6.5 edge length, subject to weather and land data. Model features hourly resolution for dispatch; development paths for capacity expansion modelled in 10-year intervals.

Demand scope

Demand sectors	Households	Services	Industry	Transport
Building end-uses	Space heating	Water heating	Appliances & lighting	Cooking
	Space cooling	Process heating	Process cooling	Other
Technology heterogeneity	-			
Decision heterogeneity	-			
Investment rationale	-			

Supply scope

Supply vectors	**Electricity**	**Heat**	Gas	**Hydrogen**	**Synthetic fuels**	
Supply assets	**Fossil generation**	**RES generation**	**Transmission**	Distribution	**Storage**	**P2X**
Markets	**Supply/demand**	Spot market	Balancing market	Other		

Investment rationale: Model selects the cost-optimal portfolio of technologies while determining their hourly operation. Electricity networks cover only transmission. Heat infrastructures cover only generation and storage, no networks. Decentralized heat pumps in buildings modelled as flexibility option. Hydrogen and synthetic fuels include costs of electrolyzers and storage units.

Inputs and outputs

Exogenous variables	Final energy demand | fuel prices | existing capacities | spec. investments (€/kW) | conversion efficiencies | technology availability | learning rates | etc.
Endogenous variables	RES generation potential | power flows | dispatch of various generators and flexibility options
Output variables	Primary energy demand for electricity and heat | Installed capacities | system costs | CO_2 emissions

NETHEAT	NetHEAT

Basic information			
Model name	NetHEAT	Model environment	Python
Institution	IREES GmbH	Auxiliary software	QGIS, Excel, GitHub
Contact	Eftim Popovski (e.popovski@irees.de)	Model availability	Commercial
Website	https://irees.de/en/NetHEAT-en/		
Sample projects	AIRE), Comprehensive Assessment Heating and Cooling, DACH – Energieeffiziente Stadt		
Key references	IREES et al. (2020)		

General model logic					
Methodology	**Simulation**	Optimization	Accounting	Equilibrium	Other
Approach	**Bottom-up**	Top-down	Hybrid		
Notes	Bottom-up spatial energy simulation model developed with the purpose of analysing heating and cooling demand and the expansion of heat supply infrastructure It allows a detailed assessment of heat distribution costs by considering specific conditions of existing infrastructures, streets, and buildings.				

Coverage & resolution					
Temporal coverage	2015 - 2050				
Temporal resolution	**Multi-yearly**	**Yearly**	Hourly	Sub-hourly	
Geographical coverage	European Union (EU-27) + UK + CH				
Geographical resolution	Supra-national	**National**	**Regional**	**Local**	Other
Notes	The model uses 100 x 100 – meter scale grid and can be applied on any local (municipality), regional, or national level.				

Demand scope				
Demand sectors	Households	Services	Industry	Transport
Building end-uses	Space heating	Water heating	Appliances & lighting	Cooking
	Space cooling	Process heating	Process cooling	Other
Technology heterogeneity	-			
Decision heterogeneity	-			
Investment rationale	-			

Supply scope						
Supply vectors	Electricity	Heat	Gas	Hydrogen	Synthetic fuels	
Supply assets	Fossil generation	RES generation	**Transmission**	**Distribution**	Storage	P2X
Markets	**Supply/demand**	Spot market	Balancing market	Other		
Investment rationale	Specific investment costs as a function of heat density, road length, building stock, and imperviousness density					

Inputs and outputs	
Exogenous variables	Useful Energy Demand | Fuel and Electricity Prices | Imperviousness Density | Road length | Building stock
Endogenous variables	Specific capital distribution cost (€/MWh) | Specific operation cost (€/MWh) | Linear heat density (MWh/m) | Specific installation costs (€/m) | Connected buildings
Output variables	Total DH network length (km) | Total investment (M€) | Annual capital and operation cost (M€/a)