The energy efficiency first principle in European energy and climate policy

Bridging the gap between conceptual foundations and practical policy implementation

Tim Dominik Mandel

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Het energie-efficiëntie-eerstbeginsel in het Europese energie- en klimaatbeleid.
Het overbruggen van de kloof tussen conceptuele grondslagen en praktische beleidsuitvoering

(met een samenvatting in het Nederlands)

Das Energy Efficiency First-Prinzip in der europäischen Energie- und Klimapolitik.
Überwindung der Lücke zwischen konzeptionellen Grundlagen und praktischer Politikumsetzung

(mit einer Zusammenfassung in deutscher Sprache)

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Background

Energy efficiency refers to the ratio of useful outputs to physical energy inputs. On the demand side of the energy system, improving energy efficiency involves reducing the amount of energy required through practices such as designing energy-efficient buildings that maintain indoor comfort while minimising energy use, or using heat pumps as a more efficient alternative to traditional heating systems. On the supply side, it involves generating and transmitting final energy with less primary or secondary energy input, such as using efficient district heating and cooling systems, or reducing line losses in transmission and distribution. It also includes demand-side flexibility to adjust energy use in response to supply conditions, thereby enhancing overall system efficiency.

Improving energy efficiency across the energy value chain is widely recognised as a key strategy for reducing energy system costs and tackling climate change. It is also increasingly acknowledged for reducing dependence on energy imports, creating jobs, improving air quality, and delivering other so-called multiple impacts or co-benefits. In response, the European Union (EU) has long focused its energy and climate policy on increasing energy efficiency. The European Commission's Green Deal strategy, introduced in 2019, reaffirms the need for energy efficiency to achieve the EU's long-term objective of net-zero greenhouse gas (GHG) emissions by 2050, as set out in the European Climate Law Regulation. Established policies and measures in the EU and its Member States include regulations mandating energy efficiency improvements, incentives for energy-efficient technologies, and programmes to encourage behavioural changes in energy use.

However, empirical data and academic discussions around the so-called energy efficiency gap indicate that the EU is not investing enough in energy efficiency compared to new generation, network, and storage infrastructure. To address this imbalance, the energy efficiency first (EE1st) principle has recently entered the EU policy debate. This principle is based on the idea that energy efficiency is often the most sustainable and cost-effective means of meeting consumers' energy service needs (e.g. thermal comfort), and wider societal objectives (e.g. decarbonisation). Where this is the case, the principle suggests that energy efficiency solutions should be systematically prioritised over the development of relatively inefficient energy supply infrastructure. As such, the EE1st principle could facilitate an effective and affordable decarbonisation of the EU energy system.

In a remarkably short time, the EE1st principle has become a key element of EU energy and climate policy. Starting in the mid-2010s with brochures from non-governmental organisations, it has gradually been integrated into EU strategies and legislation. A potential milestone was the adoption of the recast Energy Efficiency Directive in late 2023, which requires the assessment of energy efficiency solutions in planning, policy, and investment decisions, as well as monitoring and reporting on the application of the EE1st principle.

Research questions

Despite its rapid rise in the EU political debate, the EE1st principle has not yet been extensively grounded and supported by academic research. Based on a thorough investigation of the existing literature, Chapter 1 of this work identifies three major research gaps.

First, the EE1st principle lacks conceptual clarity. The concept is largely drawn from grey literature and legislative texts, yet sparsely represented in peer-reviewed academic literature. This leads to ambiguity and inconsistency in its terminology and understanding. There is also a tendency to equate EE1st with similar regulatory practices in the United States (U.S.), such as integrated resource planning. As a result, there is a risk that the EE1st concept will be misunderstood or reduced to a slogan, potentially limiting its practical impact. This motivates the first research question (RQ):

RQ 1: How can the energy efficiency first principle be systematically conceptualised to clarify its meaning and distinguish it from related concepts?

Second, there is a lack of quantitative evidence on the potential impacts of the EE1st principle in the EU's transition towards net-zero emissions. An important area to consider is the interaction between (a) the building sector – including residential, commercial, and public buildings, with energy efficiency solutions such as building retrofits – and (b) the corresponding energy supply infrastructure, including generation, network, and storage facilities for electricity, heat, gas, hydrogen and other energy carriers. Ultimately, both energy efficiency solutions and energy supply infrastructure involve economic costs and benefits, leading to the second research question:

RQ 2: To what extent does prioritising energy efficiency in the building sector impact energy supply infrastructure requirements and energy system costs for a net-zero emissions transition in the EU?

Finally, there is a lack of practical guidance on the possible application of the EE1st principle by Member States and sub-national decision-makers. While some recommendations were made by the European Commission in 2021, the Energy Efficiency Directive calls for more definitive and scientifically robust guidance, in particular regarding the design of specific policy instruments for EE1st and its integration into strategic energy planning. This prompts the third research question:

RQ 3: How can the energy efficiency first principle be effectively applied in the European Union and its Member States through policy instruments and strategic energy planning?

As summarised below, these research questions are addressed in six dedicated chapters (2-7), each representing a separate study that explores the intricate aspects of the EE1st principle. In doing so, this research makes three main contributions.

Contribution 1: Improving conceptual clarity and unravelling the scope of the energy efficiency first principle

Chapter 2 addresses the question of what the EE1st principle means and how it compares to other related concepts by critically reviewing and reflecting on the multidisciplinary literature on energy efficiency and policy. This study provides a clearer distinction between energy efficiency solutions and energy supply infrastructure. Energy efficiency solutions are further categorised into demand-side resources – including end-use energy efficiency, demand-side flexibility and energy sufficiency – and supply-side energy efficiency, such as efficient district heating and cooling.

This conceptual work underlines that the scope of EE1st extends beyond end-use energy efficiency, particularly in the electricity system where demand-side flexibility is argued to be more significant than permanent load reduction, a point discussed in detail in Chapter 6. Moreover, while EE1st may have relevance in the private domain, for example for a firm seeking to identify energy efficiency opportunities, it is fundamentally a matter of public policy, aimed at delivering those solutions, whether particularly energy efficient or not, that provide the highest net benefit to society.

Given this, Chapter 2 suggests that the focus of EE1st should not be on establishing strict hierarchies of solutions based on their standalone energy efficiency. Instead, EE1st is best conceived as an optimisation problem: the objective function is to minimise societal costs or maximise net benefits, taking into account the investments and operation of all available technological and behavioural options, subject to meeting consumers' energy service needs and broader societal objectives. This reconceptualisation leads to a refined definition of EE1st as a decision-making principle for energy-related planning, investment and policymaking within given system boundaries, which prioritises energy efficiency solutions whenever they are more cost-efficient than energy supply infrastructure in meeting both individual and collective needs.

Chapter 2 also systematically compares EE1st with related concepts from the U.S., including least-cost planning, integrated resource planning, and non-wires solutions. Three key differences emerge. Unlike much of the U.S., energy markets in the EU are unbundled and liberalised, which means that regulators have limited direct leverage to apply EE1st, except for network companies due to their natural monopoly status. This points to the need for an appropriate policy and planning framework for power plants, storage facilities, and other competitive market activities to apply the principle. In addition, the scope of EE1st in the EU is broader, covering not only electricity but also heat, gas, hydrogen and even water infrastructures. Finally, EE1st in the EU has a distinct societal focus, aiming at solutions that are optimal for society as a whole, not just for utility customers.

In summary, this research improves the understanding of the EE1st principle by providing a clearer and more nuanced account of its terminology and scope. This foundation is central to both the quantitative analyses in Chapters 3 and 4 and the practical guidance on EE1st in Chapters 5 to 7.

Contribution 2: Examining the quantitative impacts of the energy efficiency first principle on buildings and energy supply

Chapters 3 and 4 address the question of how a systematic prioritisation of energy efficiency solutions in the building sector affects energy supply infrastructure requirements and energy system costs for a net-zero emissions transition in the EU. Through temporally and spatially resolved bottom-up energy system modelling, these studies provide robust quantitative evidence on EE1st.

In particular, Chapter 3 examines scenarios with different levels of ambition for building retrofits and efficient products, assessing their impact on electricity, heat, and hydrogen supply under a net-zero GHG emissions constraint for 2050. The study models each of the 27 EU Member States, taking into account mutual energy imports and exports. Energy system costs are the key performance indicator, encompassing traditional financial costs and external costs such as those caused by air pollution. Chapter 4 follows a similar analytical logic, but focuses on the local level, examining a mixed-use urban district. This study assesses the trade-offs between building retrofits and heat supply options, both building-integrated and district heating, across different Member States, with a dedicated sensitivity analysis to test the robustness and generalisability of the findings.

Taken together, Chapters 3 and 4 show that energy efficiency in the building sector can substantially reduce the need for energy supply infrastructure in the net-zero system transition, including wind turbines, electrolysers, district heating and associated networks. From a cost perspective, Chapter 3 indicates that a 30% reduction in final energy use in the building sector by 2050, relative to 2020 levels, could be justified by net cost savings, a pathway that is considerably more ambitious than current business-as-usual energy savings trends. Chapter 4 adds nuance to these findings by showing that the cost-optimal balance between heat savings and supply depends on a variety of exogenous factors, including labour and material costs, climatic conditions, energy prices, and the magnitude of external costs. Under favourable conditions, building retrofits can lead to significant cost savings, whereas in other contexts, it may be more economically viable to install low-carbon heating systems, such as heat pumps, without prior retrofitting. Rather than contradicting the EE1st principle, this insight underlines its essence: not just promoting energy efficiency for its own sake, but seeking an optimal mix of all available options that maximises net benefits.

These studies also identify technical synergies, in particular between reduced flow temperatures in buildings after retrofits and the energetic performance of low-temperature heating systems. Heat pumps and solar thermal systems emerge as central to low-cost heat supply, whether in decentralised building-integrated systems or centralised fourth generation district heating. The studies also point to a moderate uptake of hydrogen and synthetic hydrocarbons, primarily as a storage solution to manage the variable nature of renewable energies in electricity supply.

Therefore, this research makes several contributions. It provides a systematic consideration of the societal perspective, addressing discount rates, transfer payments, and external costs such as air pollution emissions. The latter addresses the underrepresentation of multiple impacts, although further research is needed to incorporate more of these into such cost-benefit analyses. In addition, by applying systematic comparative analyses, this research provides generalisable evidence on EE1st, taking into account the EU target of net-zero GHG emissions by 2050 and the associated modelling challenges in terms of representing flexibility and sector coupling needs. This underscores the significance of the EE1st principle in the EU, calling for a sensible balance between energy savings and the expansion of renewable energy supply in order to facilitate a sustainable, robust and cost-efficient transition to a net-zero emissions energy system.

Contribution 3: Providing guidance on the practical application of the energy efficiency first principle in strategic energy planning and policymaking

Chapters 5 to 7 address the question of how EE1st could be effectively applied in the EU and its Member States. These studies examine two main mechanisms for applying EE1st. The first one is strategic energy planning, which aims to identify an optimal mix of energy efficiency solutions and energy supply infrastructure, supported by stakeholder engagement and quantitative analysis. While traditionally the domain of network operators and utilities, energy planning has increasingly become a responsibility of public authorities, including municipalities, for example in the development of national energy and climate plans under the EU Governance Regulation.

As detailed in Chapter 7, strategic energy planning under the EE1st principle requires an integrated assessment of both energy supply infrastructure and energy efficiency solutions, recognising that both can meet consumers' energy service needs and broader societal objectives. It also requires a fair assessment that takes into account all relevant costs and benefits, including multiple social, environmental and economic impacts. In recognition of the practical complexity of strategic energy planning, Chapter 7 introduces a novel decision tree framework. This framework provides a structured approach to navigating intricate planning decisions by providing a visual representation of decision paths and possible outcomes. As such, this framework can serve as a tool in a broader toolkit of decision support techniques for both public and private planners. Its practical applicability is demonstrated through common planning situations such as electricity network planning.

However, a key challenge in strategic energy planning is that the various demand and supply-side assets in the energy system are typically owned by different entities, who inherently pursue private rather than collective societal interests. Aligning these divergent interests and stakeholders towards a collectively optimal outcome requires not only planning, but also dedicated policy instruments.

Therefore, the second mechanism examined is policy instruments, understood as formal measures adopted by government bodies or regulatory authorities to create a level playing field for energy efficiency solutions and energy supply infrastructure in line with the EE1st principle. In response to the lack of academic literature on EE1st, Chapter 5 develops a comprehensive theoretical framework for its application through policy instruments, integrating insights from neoclassical, institutional, regulatory and behavioural economics. Central to this framework is the concept of well-functioning markets that, in line with the conceptual foundation in Chapter 2, serves as a normative benchmark for EE1st. This concept suggests a policy intervention logic that addresses market failures when the societal benefits of public intervention outweigh the costs of policy implementation.

Based on this logic, Chapter 5 provides a novel classification and characterisation of over twenty-five policy instruments that address the EE1st principle. These range from regulatory interventions and market design to emissions pricing and aggregation business models, each targeting specific market failures. Complementing this, Chapter 6 focuses on policy instruments in the electricity system, which is crucial given the increasing role of electrification and demand-side flexibility. For example, it proposes innovative incentive mechanisms, such as performance-based regulation, for network companies to consider demand-side alternatives to traditional network expansion.

These studies thus make several contributions. They move beyond the prevailing concept of barriers to energy efficiency, providing a more theoretically nuanced framework for the comprehensive application of EE1st. This includes integrating not only end-use energy efficiency, but also demand-side flexibility and efficient energy conversion as key energy efficiency solutions under the EE1st concept. In addition, these studies clarify the scope of EE1st policy, highlighting that its application requires a broad policy response that goes beyond the traditional portfolio of energy efficiency policies by incorporating what might be mistaken for supply-side policies, such as electricity market design or the regulation of network companies. In this way, this research adds scrutiny and theoretical substance to existing guidance. This groundwork can help Member States and sub-national decision-makers to effectively apply EE1st, moving from principle to practice.

Outlook

The recast Energy Efficiency Directive has introduced new provisions for Member States, including the assessment of energy efficiency solutions, the promotion of cost-benefit analysis methods and regular monitoring of the EE1st principle. This increased focus is likely to significantly raise awareness of the EE1st principle among Member States. However, several research needs remain.

With regard to the foundations of EE1st, this research provides a coherent theoretical framework from which a comprehensive set of practical policy instruments can be derived. However, reliance on this framework alone may overlook real-world complexities. Other theories, such as socio-technical systems and the multi-level perspective framework, could provide a more nuanced understanding of EE1st by explaining how energy supply structures resist change and how niche innovations in energy efficiency, such as demand-side flexibility, struggle for broader acceptance.

In terms of quantitative evidence on EE1st, this research focuses primarily on end-use energy efficiency. However, the EE1st concept also includes demand-side flexibility and energy sufficiency, which warrant further research. In addition, while this research focuses on the building sector's interaction with energy supply, there is a need for more evidence on the potential for EE1st in the industrial sector as part of the EU's transition to net-zero emissions. Furthermore, the cost-benefit analyses carried out in this research use energy system costs, including selected external costs such as air pollution, as a key performance indicator. Future research should aim to include a wider range of multiple impacts, such as labour productivity and energy security effects, requiring empirical data for monetisation and frameworks to avoid double counting of impacts. Finally, to complement the economic analyses from a societal perspective in this research, there is a need for dedicated financial analyses that examine the distributional impacts across different demographic groups.

Regarding the practical application of the EE1st principle, this research provides actionable guidance on policy instruments and strategic energy planning. This application will require robust ex-post evaluations of the measures taken, which in turn calls for comprehensive monitoring and reporting processes. There is also a need for a better understanding of policy mixes, taking into account the collective impact and compatibility of different policy instruments.

In conclusion, the EE1st principle has the potential to facilitate an economically viable, robust and equitable transition to a net-zero emissions energy system in the EU by 2050. The current political momentum creates an opportunity for implementing effective actions. However, it remains to be seen how Member States will interpret, implement and report on the application of the EE1st principle. The effectiveness of these implementations will be crucial to achieving the EU's ambitious energy and climate objectives.

1

Introduction

1.1 Background

1.1.1 Energy efficiency in European energy and climate policy

Energy efficiency generally refers to the ratio of useful output to physical energy input (Saunders et al. 2021; Schlomann et al. 2015). Improving energy efficiency is a widely recognised strategy for achieving greenhouse gas (GHG) emission reductions in line with the Paris Agreement ambition of limiting global temperature increase to 1.5°C (United Nations 2015). According to a Paris Agreement-compatible scenario developed by the International Energy Agency (IEA) (2021a), around 23% of global GHG emission reductions by the year 2050 would need to come from energy efficient end-use technologies and behaviours. In addition to emission reductions, energy efficiency is associated with a wide range of multiple impacts or co-benefits. These include improved air quality and associated health effects, energy security, economic growth, energy poverty alleviation, reduced land requirements, and others (IEA 2014a; Fawcett and Killip 2019; Ürge-Vorsatz et al. 2016; Reuter et al. 2020; Karlsson et al. 2020; Kerr et al. 2017; Ürge-Vorsatz et al. 2014).

The European Union (EU) has long recognised the need to improve energy efficiency as part of its energy and climate policy. As early as the 1990s, the European Commission's White Paper on Energy Policy (1995a) identified energy efficiency as a solution to improve the EU's economic and environmental performance. More recently, the European Green Deal strategy (European Commission 2019b) has argued that energy efficiency is crucial to achieving the EU's objective of net-zero GHG emissions by 2050, as set out in the European Climate Law (European Union 2021b).

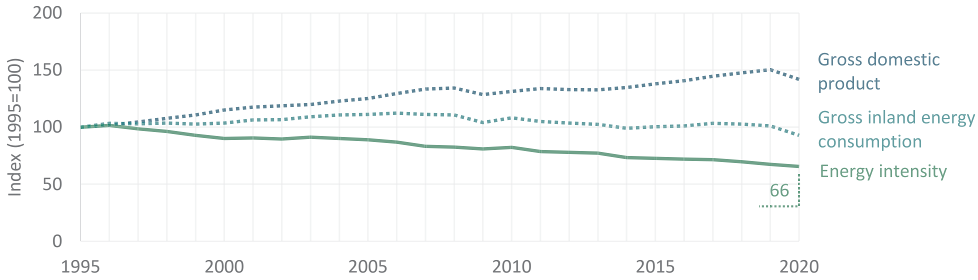
To promote energy efficiency throughout the energy system, the EU policy framework includes a number of established directives and regulations (IEA 2020b). In particular, these include the Energy Efficiency Directive (EED) (European Union 2023a), which sets out a framework for Member States to adopt measures to increase energy efficiency in their economies, the Energy Performance of Buildings Directive (EPBD) (European Union 2010, 2018c), the Ecodesign Directive (European Union 2009a), and the related Energy Labelling Regulation (European Union 2017).

In response, the EU has made significant progress in improving its energy efficiency. Figure 1 shows the EU's monetary energy intensity, a widely used indicator of economy-wide progress in the amount of primary energy used to produce a given level of economic output (Saunders et al. 2021; Bhattacharyya 2019).[1] Between 1995 and 2020, energy intensity in the EU fell by 34%. In this context,

1 Note that monetary energy intensity is a proxy measure for technical energy efficiency, as it involves variables that distort the ratio of energy use and economic output, including structural shifts from energy-intensive industries, climate conditions, and changes in demand for energy services (Saunders et al. 2021; Blok and Nieuwlaar 2021). Decomposition analysis is a common method for unravelling these underlying drivers of economy-wide energy use (Reuter et al. 2019; Smit et al. 2014).

the EU also managed to meet its 2020 target of a 20% reduction in energy consumption compared to projections of the expected energy use, albeit partly due to the economic downturn caused by the COVID-19 crisis (European Commission 2022a).

Figure 1: Trends in energy intensity, gross domestic product and gross inland energy consumption in the European Union



Energy intensity in EU-27 Member States, expressed as the ratio of gross inland energy consumption to gross domestic product, excluding the United Kingdom. Source: Eurostat (2022j), Eurostat (2022c), Eurostat (2022m)

Beyond 2020, however, a major challenge for the EU is to achieve the long-term objective of climate neutrality by 2050, together with the interim target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels (European Union 2021b). In light of these targets, it is widely argued that more effort is needed to improve the current uptake and ambition of energy efficiency improvements. Much of this debate revolves around the EU's 2030 headline energy efficiency target (Scheuer et al. 2021; Eichhammer 2022), which was recently revised in the recast EED (European Union 2023a) to reduce energy consumption by 11.7% compared to the EU Reference Scenario projections for 2030 (Capros et al. 2021).

Beyond target setting, a notion that has received increasing attention is that energy demand and energy supply are interdependent. Most fundamentally, it is widely accepted that consumers do not demand electricity and other energy carriers per se, but the energy services they provide (Sorrell 2015; Yatchew 2014). Under this premise, a kilowatt-hour of energy produced can be said to be equivalent to a kilowatt-hour saved (Eckman 2011). To illustrate, the energy service of warm indoor spaces could be provided either by installing energy-efficient building envelopes, or by installing gas boilers, which in turn require large gas network and storage infrastructures. The more energy is saved, the less energy needs to be generated and transported to meet both energy service needs and wider societal objectives such as decarbonisation.

In this context, observers increasingly argue that the EU is not investing enough in energy savings compared to the development of energy supply infrastructure. In practice, the IEA (2023) reports that total investment in power generation, networks and fuel supply reached USD 259 billion in

2020, more than double the USD 104 billion invested in end-use energy efficiency measures. In theory, there has been a long-standing academic debate about the existence and magnitude of the so-called energy efficiency gap (Brown and Wang 2017), which refers to a deviation between the level of energy efficiency that appears to make economic sense and the level actually observed (Gillingham et al. 2018). To address this apparent imbalance between energy savings and energy supply, the principle of 'energy efficiency first' has recently entered the EU policy debate.

1.1.2 Energy efficiency first principle

The fundamental idea behind the energy efficiency first (EE1st) principle is that increasing energy efficiency is often the most economical and readily available means of delivering energy services, and that, where this is the case, it should be prioritised over the development of new energy generation, network and storage infrastructure (Rosenow and Cowart 2019; Pató et al. 2019b).

This idea is not fundamentally new and dates back to the U.S., where regulators and electric utilities have been active since the 1970s in promoting reductions or temporal shifts in consumer energy use as a possible alternative to energy supply expansion (Gellings 2017; York and Narum 1996; IEA-DSM 1996; Vine 2008). Initially referred to as least-cost planning (LCP) and later as integrated resource planning (IRP), these regulatory approaches aim to require the utility company to identify a mix of so-called resources that will provide energy services at least cost. Resources in this context refer to any asset or measure that meets the energy service needs of consumers. This includes both supply-side resources (generation, networks, storage) and demand-side resources (e.g. energy efficient household appliances) (Pató et al. 2020a).[2]

In the early 1990s, the concept of IRP also made a brief appearance in European jurisdictions, including Denmark (Sandholt and Nielsen 1995), Germany (Leprich and Schulte Janson 1995), Poland (Wolcott et al. 1993), and the Netherlands (van den Berg and Welling 1993). During this period, the European Commission (1995b) also put forward a dedicated proposal for a directive to promote IRP in the European electricity and gas sectors. Ultimately, however, IRP did not gain the same prominence as in the U.S., as it coincided with the simultaneous process of unbundling and liberalisation, formally launched with the First Energy Package in 1995 (Faure-Schuyer et al. 2017).

IRP is largely incompatible with this market structure for two main reasons (Guertler 2011; Didden and D'haeseleer 2003; IEA-DSM 1996). First, unbundling means that the market activities

2 The notion of energy efficiency as a resource dates back to 1980 U.S. federal legislation, which states that regional power system planning shall *"give priority to resources which the Council determines to be cost-effective. Priority shall be given: first, to conservation; second, to renewable resources; third, to generating resources utilizing waste heat or generating resources of high fuel conversion efficiency; and fourth, to all other resources"* (United States Congress 1980, p. 2705).

of generation, transmission, distribution, and retail/supply are owned and operated by separate entities (Batlle and Ocaña 2016). This introduces organisational complexity and information asymmetries along the value chain, making it impractical to devise a collectively beneficial resource plan. Second, liberalisation exposes generation and retail to competition without direct regulatory oversight. In this environment, selling kilowatt-hours increases an actor's revenues and profits, while retaining kilowatt-hours through demand-side energy savings reduces profits.

As a result, instead of integrating resource options in a holistic framework such as IRP, the EU gradually moved towards separate policy frameworks for energy demand and supply objectives (Pató et al. 2020a; Guertler 2011). The Energy Services Directive (ESD) (European Union 2006), later followed by the EED (European Union 2012b, 2018b, 2023a), was instrumental in promoting energy efficiency at the end-use level by setting targets and addressing barriers to the uptake of energy efficiency measures. Some aspects of IRP were still considered relevant in this context (Thomas et al. 2003). For example, the ESD introduced energy efficiency obligation schemes as government-mandated programmes requiring energy suppliers to help their customers reduce energy consumption (Fawcett et al. 2019; Rosenow and Bayer 2017).

In terms of energy supply, the EU has introduced measures to increase the use of renewable energy, reduce its dependence on fossil fuels, and promote market integration:

- The Renewable Energy Directive (European Union 2018a), first adopted in 2009, sets targets for the share of renewable energy and establishes rules for support schemes and grid access.
- The Emissions Trading Directive (European Union 2023b), first adopted in 2003, establishes a cap-and-trade system on GHG emissions from power plants, industry, transport and buildings.
- The internal energy market is governed by the Electricity Market Directive (European Union 2019d) and Regulation (European Union 2019e), as well as the Gas Market Directive (European Union 2009b, 2019c), which set the framework for its liberalisation and regulation.

Overall, as argued by Guertler (2011), these policy efforts for energy supply have been largely indifferent to the integration of energy efficiency solutions. However, since the early 2010s, there has been a renewed interest in integrating energy demand and supply objectives in EU energy and climate policy. In its Energy Efficiency Market Report, the IEA (2013) reinvigorated the idea that end-use energy efficiency and its avoided energy use can directly substitute, and thus be equated with, supply-side assets. The report referred to energy efficiency as the 'first fuel' because its induced savings in many industrialised countries were greater than the supply of gas, electricity and other energy carriers in final energy consumption. The idea of energy efficiency as a resource has also resurfaced, for example in the European Commission's 2015 Energy Union package:

"It is […] necessary to fundamentally rethink energy efficiency and treat it as an energy source in its own right, representing the value of energy saved" (2015, p. 12).

Around this time, the EE1st principle first began to appear in policy briefs, brochures and other documents mainly produced by non-profit organisations, think tanks, and consultancies. To the author's knowledge, Cowart (2014) was the first to use the term 'efficiency first' in the EU context. This was followed by various documents by recurring authors using either the term 'efficiency first' or 'energy efficiency first' (Bayer 2015a; Coalition for Energy Savings 2015; Bayer et al. 2016b; Bayer et al. 2016a; Petroula et al. 2016; Rosenow et al. 2016; Bayer 2018).[3] As discussed in Section 1.2, this literature addresses three aspects: defining the EE1st principle, gathering and quantitative evidence on its potential effects, and outlining actions to move from principle to practice.

While EE1st is a relatively new concept in the literature, it has quickly found its way into the strategic documents of the European Commission as the executive branch of the EU. Table 1 shows relevant Commission strategies from recent years and how they refer to the EE1st principle. Starting with the aforementioned Energy Union package, a recurring theme is that energy efficiency measures can cost-effectively reduce investment needs and costs associated with energy production, infrastructure and use. Therefore, it should be 'put first' (European Commission 2016b) or 'prioritised' (European Commission 2019b) throughout the energy system.

In legal terms, the EE1st principle has been enshrined in the 2018 Governance Regulation (European Union 2018d). In particular, the regulation provides a formal definition of the EE1st principle:

"'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions" (2018, Art. 2(18)).

As shown in Table 2, following the adoption of the Governance Regulation, the EE1st principle has been gradually embedded in various EU directives and regulations in the form of specific legal provisions. For example, the Renewable Energy Directive requires national rules on the authorisation of power plants and transmission and distribution networks to contribute to the implementation of the EE1st principle (European Union 2018a).

3 Pató et al. (2020a) argue that 'efficiency first' should be preferred, arguing that 'energy efficiency first' has a connotation of end-use energy efficiency that excludes other energy efficiency solutions (e.g. demand response). However, the latter term has now become more established in EU legislation and supporting literature and is therefore adopted throughout this research.

Table 1: Energy efficiency first principle and related themes in the European Commission's energy and climate policy strategies

Strategy	Mention of energy efficiency first principle
Energy Union COM(2015) 80 final (European Commission 2015)	Energy efficiency should be treated as an 'energy source', representing the value of energy saved. It should be ensured that energy efficiency and demand response can compete on an equal footing with generation capacity.
Clean Energy for All Europeans COM(2016) 860 final (European Commission 2016b)	Energy efficiency is the cheapest and cleanest source of energy and should therefore be 'put first' across the energy system to accelerate both the clean energy transition and growth and job creation.
European Green Deal COM(2019) 640 final (European Commission 2019b)	Promoting energy efficiency as one of the initiatives that should be 'prioritised' to make the EU climate-neutral by 2050. In particular, the rate of renovation of buildings needs to be accelerated.
Renovation Wave COM/2020/662 final (European Commission 2020a)	'Energy Efficiency First' as a guiding principle for increasing renovation rates in private and public buildings to help ensure affordability, decarbonisation and circularity and health in Europe's energy transition.
Strategy for Energy System Integration COM(2020) 299 final (European Commission 2020d)	Applying the 'energy-efficiency-first principle' reduces the investment needs and costs associated with energy production, infrastructure and use. Energy efficiency is therefore at the core of energy system integration.
2030 Climate Target Plan COM/2020/562 final (European Commission 2020e)	In order to achieve the 55% greenhouse gas emissions reduction target by 2030 (compared to 1990 levels), the application of the 'energy efficiency first principle' is a priority to drive change in buildings and power generation.
Fit for 55 package COM/2021/550 final (European Commission 2021b)	Reducing energy consumption will bring down emissions and energy costs for consumers and industry. Planned revision of the Energy Efficiency Directive with an energy efficiency target of 9%.*
REPowerEU Plan COM/2022/230 final (European Commission 2022d)	Energy savings as a strategy to make EU independent of Russian fossil fuels before 2030, in the light of Russia's invasion of Ukraine. Proposal to increase the binding energy efficiency target in the Energy Efficiency Directive to 13%.*
EU 'Save Energy' COM(2022) 240 final (European Commission 2022b)	Voluntary reduction of unnecessary energy consumption and acceleration of energy efficiency can reduce gas and oil shortages in case of disruption of flows from Russia, thus supporting the REPowerEU Plan.

* Comparison of percentage changes in primary and final energy consumption with baseline projections from the EU Reference Scenario for 2030 (Capros et al. 2021)

More recently, the recast EED (European Union 2023a), adopted in summer 2023, represents a potential milestone in the application of the EE1st principle. The Directive includes a dedicated Article 3 "*Energy efficiency first principle*", which requires the assessment of energy efficiency solutions in planning, policy and investment decisions, the monitoring of the application of the principle, the promotion of cost-benefit methodologies that allow a proper assessment of the multiple benefits of energy efficiency, and the reporting on EE1st in the national energy climate progress reports under the Governance Regulation (European Union 2018d).

Table 2: Status of the Energy efficiency first principle in EU legal acts

Legal act	Section	Legal provision
Governance Regulation (EU) 2018/1999 (European Union 2018d)	Art. 2(18)	Definition of the EE1st principle
	Art. 3(3)	Member States to take into account EE1st principle in their national energy and climate plans
Renewable Energy Directive (EU) 2018/2001 (European Union 2018a)	Art. 15(1)	National rules concerning authorisation for plants and transmission and distribution networks to contribute to implementation of the EE1st principle
European Climate Law Regulation (EU) 2021/1119 (European Union 2021b)	Art. 4(5)	European Commission to consider the EE1st principle when proposing a 2040 climate target
TEN-E Regulation [a] (EU) 2022/869 (European Union 2022b)	Art. 12(1)	ACER [b] to develop assessment guidelines for cross-border network projects in line with EE1st principle
Energy Efficiency Directive (EU) 2023/1791 (European Union 2023a)	Art. 3(1)	Member States to ensure that energy efficiency solutions are assessed in planning, policy and major investment decisions [c], concerning both energy systems and non-energy sectors
	Art. 3(2)	European Commission to revise monetary thresholds for major investment decisions within four years
	Art. 3(3)	Member States encouraged to take into account Commission recommendation on EE1st (European Union 2021a)
	Art. 3(4)	Member States to ensure that competent authorities monitor the application of the EE1st principle
	Art. 3(5)	Member States to (a) promote cost-benefit methodologies that allow proper assessment of wider benefits of energy efficiency; (b) address the impact on energy poverty; (c) identify a monitoring entity for the application of EE1st principle; (d) report to Commission on the consideration of the EE1st principle in integrated national energy and climate progress reports
	Art. 3(6)	European Commission to adopt guidelines for monitoring and reporting on EE1st principle
	Art. 7(1)	Member States to ensure that public authorities apply EE1st principle in public contracts and concessions
	Art. 25(3)	Member States to carry out heating and cooling assessment taking into account EE1st principle
	Art. 25(6)	Member States to ensure that regional and local authorities prepare local heating and cooling plans that should be compliant with EE1st principle
	Art. 27(1)	National regulatory authorities to apply EE1st principle in carrying out regulatory tasks regarding their decisions on the operation of the gas and electricity infrastructure, including network tariffs
	Art. 27(2)	Member States to ensure that transmission and distribution system operators apply the EE1st principle

Legal status as of Oct 2023 | [a] Trans-European Networks for Energy (TEN-E) | [b] European Union Agency for the Cooperation of Energy Regulators (ACER) | [c] Investments exceeding EUR 100 million each or EUR 175 million for transport infrastructure projects

Overall, there is a clear ambition in EU energy policy to consider and implement energy efficiency measures whenever they offer greater value than alternative supply-side solutions. It is widely argued that the application of the EE1st principle across the EU would help to avoid lock-in situations with long-lived and capital-intensive energy supply infrastructures, ensure that energy service needs are met using the least-cost alternatives available, and thus contribute to an effective and affordable decarbonisation of the EU economy (Bayer 2015a; Rosenow and Cowart 2017).

1.2 State of research and research gaps

Although the EE1st principle has attracted considerable attention in the EU policy debate, it has yet to be substantiated and supported by academic research. Based on a thorough examination of the existing literature, three research gaps can be identified: (i) a lack of conceptual clarity, (ii) a lack of quantitative evidence on the potential impacts of EE1st, and (iii) a lack of practical guidance.

1.2.1 Lack of conceptual clarity in the energy efficiency first principle

Existing material on the EE1st principle comes mainly from a body of policy briefs, brochures and other so-called grey literature (Adams et al. 2017), which tends to be oriented to practitioners (Bayer 2015a; Coalition for Energy Savings 2015; Bayer et al. 2016b; Bayer et al. 2016a; Petroula et al. 2016; Rosenow et al. 2016; Bayer 2018). Apart from a few conference proceedings (Rosenow and Cowart 2019; Pató et al. 2019b; Bayer 2015b) and, at the start of this research, a single journal article (Rosenow et al. 2017a), there is little peer-reviewed literature dedicated to the EE1st principle.

As a result, the idea of EE1st lacks conceptual clarity. One problem is the lack of a clear and comprehensive definition of the EE1st principle embedded in the multidisciplinary literature on energy efficiency, energy supply, and policy. As listed in in Table A1, many of the above references have proposed definitions of the principle. Perhaps the most politically legitimised definition of EE1st is that found in the EU Governance Regulation (European Union 2018d, Art. 2(18)), cited in Section 1.1.2 above. Altogether, these existing definitions lack a concise and accurate description and integration of key terms such as 'energy efficiency measures', 'cost-efficient' and 'objectives'.

Another issue is how EE1st relates to other relevant concepts. For example, Cowart (2014) associates EE1st with 'least-cost investment requirements' and 'non-wires solutions' in the U.S. context. This reference to the U.S. is a recurring theme in the literature on EE1st (Rosenow et al. 2016; Bayer et al. 2016a). In order to avoid confusion with these practices from abroad and to highlight its unique characteristics, the concept of EE1st should be systematically compared. As outlined in Section 1.1, an important criterion for comparison is the required market structure, i.e. the extent to which market activities are unbundled and conducted on a competitive basis (Batlle and Ocaña 2016).

Overall, as has been repeatedly argued (Teffer 2018; Coalition for Energy Savings 2015), without a sound conceptual basis, the EE1st principle may become a short-lived slogan with limited impact on the energy system and related policymaking. Therefore, improving the theoretical understanding of the EE1st principle by reviewing and critically reflecting on existing work in the energy efficiency literature would provide an important foundation for further research.

1.2.2 Lack of quantitative evidence on the impacts of the energy efficiency first principle in buildings and energy supply

The EE1st principle suggests that both energy efficiency (end-use energy efficiency, demand-side flexibility, etc.) and energy supply (generation, networks, storage, etc.) can be means to meet energy service needs as well as broader societal objectives such as decarbonisation. The building sector is an important focus for the EE1st principle, accounting for 40% of EU final energy consumption (Eurostat 2022b) and 35% of 2019's energy-related GHG emissions (EEA 2021, 2022).[4]

In the building sector, there are various resource options to meet the demand for energy services such as heating, cooling, and lighting. Demand-side solutions encompass building retrofitting, construction of net-zero energy buildings, lifestyle changes towards energy sufficiency, efficient products, and demand response (Bertoldi et al. 2022; Pató et al. 2020a). Building-related supply-side strategies involve various utility-scale and distributed generation options, including network and storage infrastructures for electricity, heat, and gas (Clarke et al. 2022; Guelpa et al. 2019).

Ultimately, both demand-side and supply-side resources involve costs and benefits. This raises the question of the extent to which one or the other should be given priority in strategic planning and policymaking under the EE1st principle. Bottom-up energy systems modelling offers a valuable tool for addressing this issue and guiding decision-makers in policy design, technology investment, and system operation (Pfenninger et al. 2014; Hall and Buckley 2016; Ringkjøb et al. 2018).

Previous research (Saunders et al. 2021; Brown and Wang 2017) has highlighted seemingly cost-effective energy efficiency potentials. However, apart from methodological issues[5], it frequently overlooks the fact that energy supply is price-elastic can adapt to changing demand profiles (Zeyen et al. 2021). Addressing this issue requires *integrated* analyses of demand-side and supply-side resources. Such studies suggest substantial cost reductions in achieving net-zero emissions with

4 Throughout this research, the term 'building sector' is understood as total final energy consumption in the sectors 'households' and 'commercial & public services' (European Commission 2019a), excluding the industrial sector.

5 It is widely argued that traditional model-based analyses tend to overstate potentials for cost-effective energy efficiency measures because the underlying calculations do not take into account hidden costs, uncertainty, consumer heterogeneity, rebound effects and other confounding factors (Saunders et al. 2021; Brown and Wang 2017; Gillingham and Palmer 2014)

large-scale building retrofitting (Zeyen et al. 2021), and that energy-saving strategies can be less expensive than increasing electricity, heat, and hydrogen supply alone (Langenheld et al. 2018).

Similar results have been observed at the municipal level, for example in Romania and Denmark (Büchele et al. 2019; Harrestrup and Svendsen 2014). This suggests that investing in building retrofits and other energy efficiency solutions could lead to lower overall costs than developing new heat supply, either building-integrated or centralised in district heating systems.

Taken together, existing work suggests that energy savings in the building sector can be less costly than deploying and operating energy supply infrastructures to achieve equivalent outcomes in terms of energy services and broader objectives. The literature also highlights technical synergies. For example, retrofitting buildings typically allows the flow temperatures of heating systems to be reduced. This improves the energetic performance of low-temperature heating options such as heat pumps, resulting in a more economical overall system configuration (IRENA 2021). These aspects generally support the relevance of integrated energy planning in line with the EE1st principle.

However, several research gaps remain. First, much of the current research assesses energy efficiency potentials from the private financial perspective of building owners, utilities, or undefined groups of actors (Büchele et al. 2019; D'Agostino and Parker 2018; Delmastro and Gargiulo 2020). While financial analysis is important for assessing the ex-ante impact of existing policy frameworks, the EE1st principle emphasises a societal, or macroeconomic, perspective to enable a level playing field between energy savings and supply (European Union 2021a; Pató et al. 2020a). In cost-benefit analysis, this involves examining broader societal impacts, including socio-environmental externalities such as air pollution, as well as secondary market effects such as job creation.

Second, existing studies often neglect the multiple impacts of energy efficiency (Ürge-Vorsatz et al. 2016), also referred to as wider benefits (European Union 2023a), multiple benefits (IEA 2014a) or co-benefits (Karlsson et al. 2020). These are social, environmental, and economic effects that do not involve a financial transaction, but are relevant from both a private/financial and a societal/macroeconomic perspective. For example, improved indoor comfort after building retrofits affects private utility, while job creation affects broader societal welfare. Progress has been made in quantifying these impacts in physical units (e.g. full-time job equivalents) (Reuter et al. 2020). However, challenges such as their monetisation and avoiding potential overlaps to prevent double counting (Suerkemper et al. 2022; Ürge-Vorsatz et al. 2016) need to be addressed to affirm the extent to which energy efficiency outweighs energy supply benefits.

Third, another limitation of current research is its frequent focus on specific EU Member States (Langenheld et al. 2018) or municipalities (Büchele et al. 2019). Such a narrow scope may not adequately represent the diverse conditions within the EU, from varying climates and technology potentials to different price levels and building stock characteristics. Systematic comparative analyses that take this diversity into account are needed to provide more generalisable evidence.

Finally, many studies evaluating energy savings and supply either lack a GHG emissions target (Milic et al. 2020; Hansen et al. 2016; Büchele et al. 2019) or represent politically outdated GHG targets (Langenheld et al. 2018). The EU's commitment to net-zero emissions by 2050 (European Union 2021b) adds complexity to energy systems modelling, requiring detailed consideration of energy storage, grid expansion, power-to-heat, hydrogen supply, and other flexibility and sector coupling options (Oberle et al. 2020). This commitment can potentially be represented by GHG optimisation constraints or by considering the external costs associated with GHGs.

In short, understanding the economic trade-offs and technical synergies between energy savings in the EU building sector and energy supply is crucial to determine sustainable, robust, and cost-efficient system configurations in line with the EE1st principle. More quantitative evidence is needed to fully assess the relevance of the principle, especially in the context of net-zero emission futures.

1.2.3 Lack of practical guidance on the application of the energy efficiency first principle in policymaking and energy planning

As outlined in above, the conceptual understanding of the EE1st principle is a major research gap. Closely related is the challenge for policymakers and system planners to ensure that the principle is applied in practice by the various decision-makers who own and operate demand-side and supply-side assets, in order to deliver cost-efficient and sustainable energy systems.

In legal terms, the EU Governance Regulation (European Union 2018d, Art. 3(3)) mandates Member States to consider the EE1st principle in their National Energy and Climate Plans (NECPs). However, according to an European Commission assessment (2020b), most NECPs only set out limited details on EE1st due to lack of details on how to implement the principle. To address this, the Commission developed a specific recommendations on EE1st (European Union 2021a), proposing potential policy areas (e.g. electricity markets) and decision-making guidelines (e.g. on cost-benefit analysis).

Existing literature considers different aspects of EE1st application (Fabbri 2022; Boll et al. 2021; Pató et al. 2021; Bayer et al. 2016b; Bayer 2015a; Coalition for Energy Savings 2015). For example, Rosenow and Cowart (2019) identify four key areas for applying the principle:

- *Planning* (e.g. recognising the value of energy efficiency in policy impact assessments);
- *Energy efficiency programmes* (e.g. setting minimum energy performance requirements);
- *Infrastructure decision rules* (e.g. introducing energy efficiency performance incentives in the regulation of network companies);
- *Compliance and review* (e.g. establishing EE1st monitoring and verification bodies).

However, three research gaps remain. First, it is unclear how EE1st policy differs from traditional energy efficiency policy. Established instruments to promote energy efficiency, such as minimum energy performance standards, public financing, and labels, have proven to be effective in terms of energy savings and seemingly cost-effective (Bertoldi 2020; Del Solà et al. 2021; Trotta et al. 2018; Boza-Kiss et al. 2013; Shen et al. 2016). This raises the question of what distinguishes EE1st policy, and thus what added value the principle could bring to EU energy and climate policy.

Second, relatedly, the theoretical foundation for EE1st policy lacks clarity, leading to an ambiguous scope for action. The often-cited concept of barriers to energy efficiency (Sorrell et al. 2000b; Brown 2001; Cattaneo 2019) is occasionally mentioned as a rationale for EE1st policy (Rosenow and Cowart 2019; Pató et al. 2020a). However, this concept focuses primarily on end-use energy efficiency and tends to separate demand-side flexibility and other relevant energy efficiency solutions (e.g. Cardoso et al. 2020), limiting the comprehensive application of EE1st. Moreover, the barriers concept has been criticised for its analytical inaccuracies (Jaffe and Stavins 1994; Golove and Eto 1996; Sanstad and Howarth 1994). Frequently cited barriers, such as high upfront costs or perceived risk (e.g. Sorrell et al. 2000b) are often normal market characteristics and, in themselves, may not justify policy interventions (Brown and Wang 2017). There is therefore a need for a coherent theoretical framework that not only clarifies the rationale for EE1st policy, but also provides a practical intervention logic for the application of appropriate policy instruments. [6]

Third, there is a need to integrate the EE1st principle into strategic energy planning, as mandated by Article 3 of the EED (European Union 2023a). Strategic energy planning, traditionally the domain of network operators and energy utilities, has increasingly become a key responsibility for public authorities, including municipalities. EU provisions include, for instance, local heating and cooling planning under Article 25(6) of the EED (European Union 2023a), long-term building renovation strategies as per Article 2a of the EPBD (European Union 2018c), and the NECPs under Article 3 of the Governance Regulation (European Union 2018d). The challenge is to not only to identify which energy efficiency solutions should be assessed but also to determine adequate performance metrics. This ties into to the conceptual and quantitative gaps identified above. A comprehensive yet specific framework would be valuable in providing structured guidance for aligning energy planning processes with the EE1st principle, ensuring their compliance and effectiveness.

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6 According to Rogge and Reichardt (2016), the term 'instruments' is often used interchangeably with 'implementing measures', 'programmes', or 'policies'. Throughout this research, the terms 'policy instruments' or simply 'policies' will be used. However, in line with Schlomann (2014), the term 'measure' is deliberately avoided because, in the energy efficiency literature, this usually refers to a specific technical or behavioural action to improve energy efficiency, such as installing energy-efficient lighting.

Altogether, there is a need for comprehensive and coherent guidance on the practical application of the EE1st principle. Such guidance should not only clarify the distinct nature of EE1st policy, but also provide concrete orientations for its integration into strategic energy planning.

1.3 Research questions and outline

To address the identified research gaps, the overarching question posed is:

How can the energy efficiency first principle be conceptualised, quantified, and integrated within the energy and climate policy framework of the European Union?

To break down this overarching question, it is divided into three distinct but interrelated research questions (RQs). These research questions are explored in depth in six dedicated chapters (2-7), each representing a separate study that explores the intricate aspects of the respective question. At the time of writing, five studies have been published as peer-reviewed papers in academic journals, and one is under review. Table 3 presents a detailed overview of each research question, the corresponding chapters, and the specific methodologies used in each chapter.

The first research question focuses on conceptual clarity, which is important to provide a solid foundation for further research and understanding of the principle within the EU context:

RQ 1: How can the energy efficiency first principle be systematically conceptualised to clarify its meaning and distinguish it from related concepts?

Based on an exploratory review of the multidisciplinary literature on energy efficiency, **Chapter 2** makes three main contributions. First, it develops a conceptual framework that characterises EE1st as an economic principle that prioritises energy efficiency solutions over energy supply infrastructure when they provide greater value to society. Second, it contrasts EE1st with related concepts such as integrated resource planning, highlighting its unique features. Third, it clarifies the economic rationale and outlines a practical scope for the principle. In doing so, it demonstrates that EE1st has a sound theoretical foundation that can facilitate its practical application.

The second research question explores the quantitative implications of the principle. It focuses on the interaction between the building sector, which includes residential, commercial, and public buildings, and the corresponding energy supply infrastructure, including generation, network, and storage facilities for electricity, heat, gas, hydrogen, and other energy sources:

RQ 2: To what extent does prioritising energy efficiency in the building sector impact energy supply infrastructure requirements and energy system costs for a net-zero emissions transition in the EU?

Chapter 3 uses sectoral bottom-up energy system models to analyse three scenarios for a net-zero emissions energy system in the EU, each with different levels of ambition for thermal retrofits and efficient products in the building sector. The study models each of the 27 EU Member States, taking into account mutual energy imports and exports. Energy system cost is the key performance indicator, which includes financial costs as well as external costs, e.g. those caused by air pollution. The study underlines the significance of end-use energy efficiency measures in buildings for a sustainable and cost-optimal transformation of the energy system in line with the EE1st principle.

Chapter 4 follows a similar analytical logic, but applies more spatially resolved modelling techniques at the local level, examining a mixed-use urban district from the 1970–1989 construction period. The study focuses on the economic trade-offs and technical synergies between building retrofits and heat supply options, both building-integrated and district heating. For generalisability, the generic urban district is analysed for three European countries, each with different price levels, climatic conditions, and building stock characteristics. A dedicated sensitivity analysis is carried out to test the robustness of the results. The findings confirm the importance of integrated energy planning to balance end-use energy efficiency measures and energy supply development.

The third and final research question aims to provide guidance to policymakers and other decision-makers in the application of the EE1st principle:

RQ 3: How can the energy efficiency first principle be effectively applied in the European Union and its Member States through policy instruments and strategic energy planning?

Chapter 5 aims to bridge the gap between the theoretical foundations of EE1st and its practical implementation through policy instruments. Using market failure theory, the study identifies an inherent bias in the EU energy system in favour of energy infrastructure. By highlighting the correction of market failures through targeted policy instruments, it presents a theoretical policy intervention logic for EE1st. Based on this, it offers a set of twenty-nine policy instruments linked to specific market failures, thus providing a systematic roadmap for the application of EE1st. The study finds that the application of EE1st requires a broad policy response that extends beyond traditional energy efficiency policy by including instruments such as electricity market design, incentive regulation for network companies, aggregation business models, and emissions pricing.

Chapter 6 focuses on the application of the EE1st principle in electricity systems, given the increasing role of electrification and demand-side flexibility. This study uses semi-structured interviews with regulators, energy companies and researchers, combined with a literature review, to discuss policy instruments enabling consumers to provide flexibility and distribution system operators (DSOs) to integrate it into network planning and operation. In particular, it highlights innovative incentive mechanisms, such as performance-based regulation, for DSOs to consider energy efficiency solutions, including demand-side flexibility, as alternatives to network expansion.

Chapter 7 focuses on the application of EE1st through strategic energy planning. The study methodically develops a decision tree framework based on management literature and the EE1st concept. This framework provides a structured approach to considering energy efficiency solutions alongside energy supply infrastructure by providing a visual representation of decision paths and possible outcomes. As such, this framework can serve as a tool in a broader toolkit of decision support techniques for public authorities and utilities. Its practical applicability is demonstrated through two examples, including electricity network planning and district heating system planning.

Finally, **Chapter 8** summarises the findings from all six studies and draws overall conclusions.

Table 3: Overview of thematic chapters

Research question	Chapter	Title	Methods
RQ 1: How can the energy efficiency first principle be systematically conceptualised to clarify its meaning and distinguish it from related concepts?	2	Conceptualising the energy efficiency first principle: insights from theory and practice	Literature review; conceptual and theoretical analysis
RQ 2: To what extent does prioritising energy efficiency in the building sector impact energy supply infrastructure requirements and energy system costs for a net-zero emissions transition in the EU?	3	Investigating pathways to a net-zero emissions building sector in the European Union: what role for the energy efficiency first principle?	Bottom-up energy system modelling (EU level); cost-benefit analysis
	4	Balancing heat saving and supply in local energy planning: insights from 1970–1989 buildings in three European countries	Bottom-up energy system modelling (local level); cost-benefit analysis
RQ 3: How can the energy efficiency first principle be effectively applied in the European Union and its Member States through policy instruments and strategic energy planning?	5	Towards effective implementation of the energy efficiency first principle: a theory-based classification and analysis of policy instruments	Literature review; conceptual and theoretical analysis
	6	Energy efficiency first in the power sector: incentivising consumers and network	Semi-structured interviews; literature review
	7	Applying the energy efficiency first principle based on a decision-tree framework	Decision tree framework development; literature review

2

Conceptualising the energy efficiency first principle: insights from theory and practice

Mandel, Tim; Pató, Zsuzsanna; Broc, Jean-Sébastien; Eichhammer, Wolfgang (2022): Conceptualising the energy efficiency first principle: insights from theory and practice. In *Energy Efficiency* 15 (6), pp. 1–24. DOI: 10.1007/s12053-022-10053-w.

2.1 Introduction

Energy efficiency is widely recognised as a key resource for achieving various societal objectives related to environment and climate protection, competitiveness, and energy security. Its principal merit lies in the potential it holds to lower both the economic cost and negative environmental side-effects of transitions to low-carbon energy systems. To illustrate, Langenheld et al. (2018) find that focusing on thermal building renovations could reduce the cost for reaching long-term greenhouse gas (GHG) reduction targets in the German building sector by 2.5 to 8.2 billion euros per year. Moreover, energy efficiency has been associated with a variety of multiple impacts for consumers and for society at large, including improved air quality and associated health effects, energy security, and others (Reuter et al. 2020; IEA 2014a). Empirical estimates indicate that their monetary impact in the buildings and industry sectors may be 0.5 to 3.5 times higher than the value of energy savings made (Ürge-Vorsatz et al. 2014).

In response, the European Union (EU) has introduced energy and climate policy strategies and measures intended to increase energy efficiency in various sectors. The European Green Deal strategy (European Commission 2019b) recognises that energy efficiency is needed to achieve the EU's long-term objective of net-zero GHG emissions by 2050, as defined in the European Climate Law (European Union 2021b). Established policy measures in the EU to improve energy efficiency in households, firms and transportation include minimum energy performance standards, labelling, financial incentives and others (IEA 2020b). Additional measures focus on efficiency improvements in energy supply, e.g. by reducing losses in electricity networks (Bompard et al. 2020).

Despite this, observers note that the EU is not investing enough in energy efficiency and demand reduction measures relative to the expansion and use of energy supply infrastructures (Rosenow et al. 2017a; Bayer 2015a). In empirical terms, the IEA (2021b) reports that capital expenditures for power generation, network assets and other fossil fuel supply in Europe amounted to USD 178.8 billion for the year 2020, which is almost double the investment in end-use energy efficiency measures of USD 101.4 billion. In theoretical terms, there has been a long-standing academic debate around the existence and magnitude of the so-called energy efficiency gap (Brown and Wang 2017), i.e. the deviation between the levels of energy efficiency that appear to make economic sense and the levels actually observed in practice (Gillingham et al. 2018).

To address this apparent imbalance between energy efficiency and supply-side investments, the principle of energy efficiency first (EE1st) has recently entered the political debate in the EU. EE1st is generally understood as a guiding principle for energy-related policymaking, planning and investment. In essence, it is meant to consider and prioritise investments in both demand-side resources (end-use energy efficiency, demand response, etc.) and supply-side energy efficiency whenever these cost less or deliver more value than default energy infrastructure (generation, networks, storage, etc.) (Rosenow and Cowart 2019; Pató et al. 2019b). Its advocates argue that EE1st can help to avoid lock-in situations with more expensive infrastructures, ensure that energy needs are met using the least-cost alternatives available, and thus ensure a cost-effective decarbonisation of the economy (Bayer 2015a; Rosenow and Cowart 2017). The EE1st principle was formally introduced into EU legislation in the Governance Regulation (European Union 2018d), which includes a formal definition and requires Member States to report on the implementation of EE1st in their National Energy and Climate Plans (NECPs).

However, while EE1st has gained traction in the political debate, it is not yet consciously grounded and supported by academic research. Existing material essentially stems from a body of grey literature which tends to be oriented to practitioners (e.g. Bayer et al. 2016a). There is hardly any peer-reviewed, academic literature on the principle (Rosenow et al. 2017a; Pató et al. 2019b). As such, the notion of EE1st lacks conceptual clarity. For instance, it is unclear how the decision between saving and supplying energy should be evaluated in terms of costs and benefits. Moreover, while a variety of policy measures have been proposed to support EE1st (Zondag et al. 2020; Rosenow and Cowart 2019), these seem to lack a consistent framework that is substantiated by the interdisciplinary literature on energy efficiency and policy (Saunders et al. 2021; Gillingham et al. 2009; Dunlop 2019).

This lack of conceptual clarity carries the risk that the EE1st principle could become a short-lived slogan that does not make a tangible difference to the status quo of energy-related investment and policymaking in the EU (Coalition for Energy Savings 2015; Teffer 2018). In fact, EU Member States do appear to struggle with moving from principle to practice.[7] While the European Union recently issued dedicated guidelines on the implementation of EE1st (2021), there remains a need for critical scrutiny of the principle to broaden its support base and ensure that it will yield robust policy outcomes.

Against this background, the objective of this article is to improve the theoretical understanding of EE1st and thus to contribute to changes in policymaking practices in line with this principle. This article's contribution is fourfold: First, it discusses existing notions of EE1st and provides a conceptual framework. Second, it highlights the unique aspects of EE1st by systematically comparing the principle with associated concepts, such as integrated resource planning. Third, it provides theoretical justification for EE1st by describing the economic rationale behind the principle. Fourth, it outlines policy considerations for its practical implementation. The paper concludes with a general summary of the principle and an outlook to further research.

7 A recent assessment of NECPs (European Commission 2020b) found that these include few references to the EE1st principle and lack dedicated instruments. Likewise, in a survey of practitioners in the energy field (Schmatzberger and Boll 2020), respondents stressed a lack of expertise, awareness and understanding of the principle.

Given the novelty of this subject in academic research, this article is based on an exploratory investigation of the literature, corresponding to a 'narrative review' according to the review types suggested by Sovacool et al. (2018). In addition, the examples in this article refer primarily to energy efficiency in buildings and industry and do not address transportation in detail, even though the EE1st principle could be applied to all energy-using sectors (European Union 2021a).

2.2 Definition of energy efficiency first

Prior to its formal appearance in EU legislation, grey literature featured multiple definitions of EE1st, with early mentions in Cowart (2014) and Coalition for Energy Savings (2015). Pató et al. (2020a) compare these definitions. In short, EE1st is understood as a decision principle that takes into account the available options for technology adoption and behaviour change, evaluates them against a set of objectives, and implements those that best meet these objectives.[8]

Perhaps the most politically legitimised definition of EE1st is the one in the EU Governance Regulation (European Union 2018d, Art. 2.18): "*'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions*". To enhance the conceptual clarity of EE1st, three particular aspects in this definition are discussed in the following: decision objectives, the scope of so-called resource options, and the actual decision rule. A substantiated definition of EE1st is then presented as a result.

2.2.1 Decision objectives

EE1st is not merely about comparing technology options, but about doing so with respect to decision objectives. Conceptually, these can be broken down into energy service and policy objectives (Mandel et al. 2020). Providing energy services can be viewed as the fundamental purpose of energy systems (Droste-Franke et al. 2015), as they are the means for consumers to obtain utility or other beneficial end states (Kalt et al. 2019; Fell 2017; Swisher et al. 1997).[9] For example, the energy service of space heating is to obtain the end state of thermal comfort (Fell 2017). Accordingly, energy is frequently referred to as a derived demand, as consumers do not demand electricity and other energy carriers

8 Note that there is no universal definition of energy efficiency per se, and the appropriate definition depends on the problem considered and the academic discipline (Saunders et al. 2021). Generally, a typical definition of energy efficiency is some form of useful output divided by energy input (Schlomann et al. 2015).
9 Similar to energy efficiency, the term 'energy services' is subject to ambiguities (Fell 2017; Kalt et al. 2019). Fell (2017, p. 137) reviews 27 definitions and proposes the following definition: *"energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states."*

per se, but the services and eventual utility they provide (Sorrell 2015; Yatchew 2014). This demand for energy services drives profit-oriented firms to invest in technologies and to supply energy to consumers. It also leads consumers to opt between conversion devices (e.g. heat pumps) and passive systems (e.g. building envelopes) to obtain their desired end states (Kalt et al. 2019).

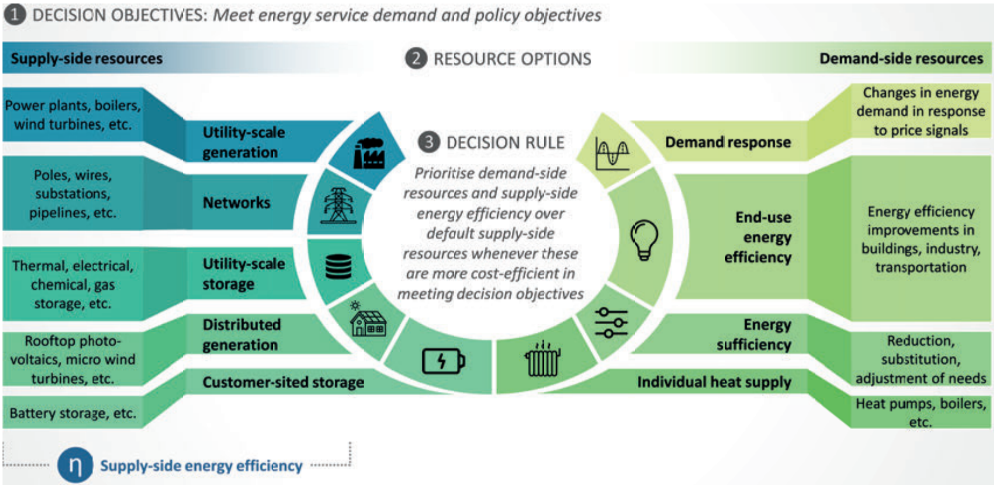
The energy system is likewise driven by various policy objectives. For example, energy security, energy efficiency, market integration, decarbonisation, and innovation are key elements of EU policy, as per the Energy Union framework (European Commission 2015). A more generic set of policy objectives is the 'magical triangle' of security of supply, economic competitiveness, and environmental protection (Zweifel et al. 2017; Yatchew 2014). From an economic perspective, the principal objective of any public policy is to bring about economic efficiency – typically operationalised as maximising the total surplus received by all members of society (Mankiw 2017; Harris and Roach 2018) or a weighting of particular policy objectives (e.g. distributive justice) by means of social welfare function (Weimer and Vining 2017; Mulder 2021).[10] Overall, energy service and policy objectives can be conceptualised as the functional units (Hauschild et al. 2018) for any decision related to the EE1st principle, i.e. the qualitative or quantitative aspects for which the trade-off between supplying and saving energy is to be solved.

2.2.2 Resource options

It is fundamental to EE1st that energy decision objectives can be addressed by either supplying or saving energy. For example, the expansion of wind power capacity may cover new or existing demand for energy service and enable GHG savings. However, the same could apply to measures that save energy, such as energy-efficient building envelopes that reduce the electricity demand for heat pumps and thus the need for additional generation. In Europe, these options are increasingly referred to as 'resources' in the context of EE1st (Pató et al. 2020a; Rosenow and Cowart 2017). The principle thus acknowledges that there are a multitude of resources to achieve decision objectives, epitomised in the statement that 'a kilowatt-hour generated is equivalent to a kilowatt-hour saved' (Eckman 2011). Figure 2 presents a conceptual framework for EE1st and distinguishes between demand-side and supply-side resources.

10 Economic efficiency should not be equated with energy efficiency, as pointed out by various economists (Zweifel et al. 2017; Sutherland 1994). The key proposition made is that energy efficiency does not imply that fewer total inputs (capital, labour, research etc.) are used to meet energy service demand. Instead, inputs are substituted for one another. Thus, policies intended to improve energy efficiency per se are not considered a legitimate objective for public policy per se, unless they contribute to economic efficiency (Golove and Eto 1996; Jaffe and Stavins 1994)

Figure 2: Conceptual framework of the energy efficiency first principle



Source: Mandel et al. (2020), own adjustments

Supply-side resources here refer to physical assets of renewable and non-renewable energy conversion, networks, and storage facilities. For a comprehensive review of supply-side resources in electricity, heat and gas supply, see Guelpa et al. (2019). Note that the framework indicates that supply-side energy efficiency is an overarching supply-side resource. For example, electricity and gas networks hold significant potentials for reductions in losses and leakages (Bompard et al. 2020; European Commission 2016c). Another example of supply-side energy efficiency is the utilisation of waste heat from industrial processes in district heating networks (Papapetrou et al. 2018). Also note the centred position of customer-sited energy storage and individual heat supply in the framework. The former work at the interface of demand and supply. The latter, in energy accounting terms, belong to the demand side as they convert final into useful energy. As discussed in the following chapter, the EE1st principle is relevant to different system boundaries, which leads to different trade-offs between resource options.

Demand-side resources are referred to here as technologies and consumer actions that reduce the quantity and/or temporal pattern of energy use for the same level of utility. These include the following resource options (Rosenow and Cowart 2017; Pató et al. 2020a):

- End-use energy efficiency means technologies that increase the ratio of energy service output to final energy input while holding the output constant (European Union 2012b). For example, light-emitting diodes (LEDs) require significantly less energy per unit of output (light emitted in lumen) than incandescent lamps. In essence, energy-efficient technologies trade off higher initial capital expenditures and lower operating expenses compared to an otherwise equivalent technology that provides the same energy services but uses more energy (Gillingham et al. 2009).

- Demand response means automated or reactive changes of load by consumers from their default consumption patterns in response to market signals (European Union 2019d).[11] It primarily addresses load shifting, not necessarily energy demand reduction (Paterakis et al. 2017) and is also referred to as system efficiency in the context of EE1st (Bayer et al. 2016a).
- Energy sufficiency can be conceptualised as quantitative or qualitative changes of utility demanded or energy service delivered that lead to a reduction in final energy demand (Brischke et al. 2015; Sorrell et al. 2020). According to Brischke et al. (2015), this may come in the form of reduction (e.g. smaller appliances), substitution (e.g. using a clothesline instead of a tumble dryer), or adjustment of needs (e.g. raising the cooling temperature of refrigerators). Energy sufficiency is distinct from end-use energy efficiency in that it changes the output level in terms of energy service needs, rather than improving the ratio of output to energy input (Brischke et al. 2015).

The decision rule at the centre of Figure 2 anticipates the following element of the EE1st definition: how to address the trade-off between supply-side and demand-side resources.

2.2.3 Decision rule

A final key property of the EE1st definition is the decision rule about taking the 'utmost account' of 'cost-efficient' demand-side measures (see above). These formulations are ambiguous. With regard to the former, we argue that a clear decision rule would require dedicated legal conditions defining when efforts to consider demand-side resources in investment and policymaking are considered adequate to comply with the principle. Alternative definitions of EE1st are more explicit in this regard by referring to a 'prioritisation' of demand-side resources whenever these provide greater value than supply-side resources (European Parliament 2018; Bayer et al. 2016a; Pató et al. 2020a).

With regard to the latter, it is unclear from which perspective cost-efficiency – i.e. a given output metric over net costs – should be evaluated.[12] In general, there is a common distinction between a private and a societal perspective of investment appraisal (Ürge-Vorsatz et al. 2016; Konstantin and

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11 More precisely, demand response programs based on time-of-use tariffs are referred to as implicit demand response. In turn, trading committed and dispatchable flexibility in power markets by single large-scale consumers or through aggregators is referred to as explicit demand response (IRENA 2019b; SEDC 2016).

12 Some definitions of EE1st suggest the term 'cost-effectiveness' instead of 'cost-efficiency' (e.g. Coalition for Energy Savings 2015). In line with the Governance Regulation (European Union 2018d, Art. 2), we argue in favour of the latter, understanding it as a given output metric over the difference between costs and benefits, i.e. a unit of energy service or utility delivered per euro. This understanding of cost-efficiency is best illustrated by conservation supply curves (e.g. EECA 2019) that enable a ranking of demand- and supply-side resources in terms of specific cost.

Konstantin 2018a). The private perspective, also referred to as the financial appraisal, is concerned with the profitability of an investment for its owners and investors. In terms of costs, it takes into account the actual cash flows incurred, e.g. the capital costs for a building retrofit. In terms of benefits, it values only private utility gains, e.g. reduced energy bills. Aside from actual financial transactions, this can also include a variety of multiple impacts (IEA 2014a; Thema et al. 2019)[13] that accrue to the decision-maker alone, e.g. improved indoor comfort. Time preferences and risk are taken into account through a financial discount rate. Transfer payments – that is, direct and indirect taxes as well as subsidies (Konstantin and Konstantin 2018a) – are included as actual cash flows.

In contrast, the societal perspective, also referred to as the economic appraisal, ideally considers all the costs and benefits to society. In addition to multiple impacts that affect private utility alone, this also includes uncompensated costs and benefits that individuals impose on one another, e.g. negative externalities from fossil fuel combustion (Krugman and Wells 2015). Policy implementation costs are also critical to take into account, e.g. expenses to design, administer, and evaluate policy measures (Ürge-Vorsatz et al. 2016). Costs and benefits are evaluated through a social discount rate, reflecting time preferences and risk from the point of view of society.[14] Transfer payments are usually omitted as they do not affect the real value of a domestic product (Khatib 2014).

It is widely acknowledged that the trade-off between resource options in terms of cost-efficiency should be primarily addressed from a societal, rather than a private perspective. This is evident in both official documents on EE1st (European Union 2021a) as well as in the academic literature (Pató et al. 2020a). The reason for this primacy of the societal perspective is that EE1st is clearly a public policy issue in accordance with EU legislation and overarching policy objectives. There is also scope for EE1st from a dedicated private perspective.[15] Yet from an economic perspective, as will be explained further below, cost-minimising or utility-maximising behaviour by households and firms is only a necessary but not a sufficient condition for social optimality, hence again the primacy of a societal perspective.

13 The term 'multiple impacts' is used almost interchangeably with the terms 'co-benefits', 'multiple benefits', 'ancillary benefits', 'indirect costs', and 'adverse side-effects' (Ürge-Vorsatz et al. 2014; Thema et al. 2019). Following Ürge-Vorsatz et al. (2016), they are understood here 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.

14 Mandel et al. (2020) discuss the role of financial and social discount rates in quantitative assessments associated with the EE1st principle, highlighting their respective areas of applications and methods to determine them.

15 For example, a recurring theme in the EE1st literature is the trade-off between installing a large-capacity heat pump versus improving the building's energy efficiency through thermal renovation (Boll et al. 2021).

In order to accommodate both the societal and the private perspective in the definition of EE1st, we suggest an emphasis on the more flexible concept of system boundaries (Mai et al. 2013). With narrow system boundaries, the principle could, for instance, address the trade-off between end-use energy efficiency and individual heat supply from the private perspective of a building owner. In turn, with extensive system boundaries (e.g. entire EU economy), the trade-off involves a greater range of resource options and decision-makers involved. What perspective is taken depends on the context. For example, policymakers are inclined to adopt a societal perspective for impact assessments while network companies pursuing demand-side actions are driven by a private business rationale. As further discussed in 'Economic rationale for energy efficiency first', bridging the gap between private and societal optimality provides an essential rationale for public policy in the scope of EE1st (Boll et al. 2021).

To conclude, the definition of EE1st in the EU Governance Regulation leaves ample scope for interpretation. Based on the critical appraisal in this section, we suggest a slightly modified definition: 'energy efficiency first' is a decision principle for energy-related planning, investment and policymaking within given system boundaries. It prioritises demand-side resources and supply-side efficiency whenever these are more cost-efficient in meeting decision objectives than default supply-side resources.' To further characterise the notion of EE1st, the following chapter compares the principle with related concepts.

2.3 Relation of energy efficiency first to similar concepts

The idea of considering demand-side alternatives to supply-side resources is not unique to EE1st. In fact, similar concepts have been practiced across the U.S. in the form of least-cost planning, integrated resource planning, and non-wires solutions. To point out the unique features of EE1st, this chapter compares these concepts in terms of the market structure required[16], the scope of energy vectors, and the scope of costs and benefits considered when assessing resource options.

2.3.1 Least-cost planning

Least-Cost planning (LCP) emerged in the U.S. during the oil supply shortages and environmental concerns of the 1970s and 1980s (York and Narum 1996; IEA-DSM 1996). The concept was designed for a market structure of vertically-integrated monopolies in the power sector, i.e. a single company responsible for all the market activities of generation, networks, and retail. Only few early cases have been reported for LCP at gas utilities (Goldman and Hopkins 1992). The fundamental idea of

16 Market structure here means the extent to which market activities in energy supply (generation, transmission, distribution, retail) are unbundled from others and which activities are conducted on a competitive basis or constitute monopoly businesses (Batlle and Ocaña 2016).

LCP was that utility companies can, to some extent, bring about reductions or shifts in consumer energy use by means of energy audits, information provision, and subsidies for energy efficient equipment – generally referred to as demand-side management (DSM) (Gellings 2017). LCP thus marked a shift from the presumption of steady demand growth and corresponding capacity expansion to a balanced appraisal of both supply-side and demand-side options, with the objective for the utility company to determine a so-called resource plan that provides energy services at least cost (York and Narum 1996). Costs in this context were essentially the monetary expenses incurred by the customers and the utility company for capital, operation and DSM programmes – measured by what is known as the total resource cost test.[17]

2.3.2 Integrated resource planning

In the 1980s and 1990s, the practice of LCP gradually incorporated environmental and social concerns in its selection of resource plans, henceforth referred to as integrated resource planning (IRP) (Swisher et al. 1997). With this expanded scope, the principal criterion to rank alternative resource plans shifted to the so-called societal cost test. In theory, this test is more comprehensive than the total resource cost test in LCP, as it also takes into account the external costs of air pollution and other selected impacts that have an effect beyond the service area of the utility company (Bhattacharyya 2019; Woolf et al. 2012). Today, IRP is applied by utility companies in about 30 U.S. states (Wilson and Biewald 2013). U.S. State requirements for IRP vary in terms of planning horizons, the frequency with which plans must be updated, the resources to be considered, stakeholder involvement, and the extent to which regulators are involved in selecting resource plans (Wilson and Biewald 2013). States also differ with respect to the principal cost test used for ranking resource plans, thus blurring the lines between LCP and IRP.[18]

The concept of IRP also reached Europe in the 1990s, but did not gain the same relevance as in the U.S. (Pató et al. 2020a). This was related to the concurrent process of unbundling and liberalisation of power and gas markets in Europe in the 1990s, which formally began with the First Energy Package in 1995 (Thomas et al. 1999). Under this market structure, only the market activities of network planning and operation remained monopoly businesses that are subject to regulatory

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17 Regulators in the U.S. have been active since the late 1980s in defining five cost-effectiveness tests to weigh up the costs and benefits of demand-side measures against alternative supply-side options from different perspectives (U.S. EPA 2008; Woolf et al. 2012; CPUC 2001). The total resource cost test is a comparison of DSM implementation and installation costs against the utility's avoided energy- and capacity-related costs. Ideally, this includes direct multiple impacts to customers (e.g. improved comfort levels). In practice, however, these non-monetary aspects are not systematically accounted for by utilities and regulators (Yushchenko and Patel 2017).

18 Although, in theory, the societal cost test is the preferred decision criterion for IRP, about 71% of U.S. states rely on the less comprehensive total resource cost test, thus neglecting external costs and benefits accruing to society as a whole (Woolf et al. 2012).

oversight. Generation and retail were gradually liberalised, i.e. became market- and competition-based activities (Faure-Schuyer et al. 2017). IRP is largely incompatible with this market structure as the concept becomes protracted and complex the more utilities are unbundled and the more market activities are subject to competition rather than regulatory oversight (Pató et al. 2020a; York and Narum 1996). However, IRP can be directly relevant for the regulated monopoly activities of transmission and distribution, a practice referred to as non-wires solutions (NWS) in the U.S. (Dyson et al. 2018; Chew et al. 2018).[19]

2.3.3 Non-wires solutions

NWS are electric utility investments and operating practices that can defer or replace the need for specific transmission or distribution network projects by consistently reducing the network load in specific grid areas (Stanton 2015). Similar to LCP and IRP, the practice of NWS is meant to consider all the resources available for providing energy services, including demand response, end-use energy efficiency, storage, and distributed generation. In the U.S., driven by state-level regulation and public-private partnerships, there are an increasing number of NWS projects that cost-effectively defer or displace the need for higher-cost network infrastructure investments (Chew et al. 2018). In terms of the costs and benefits considered, NWS practices resemble the total resource cost test originating from LCP. Concerning market structure, NWS works for both vertically-integrated utilities and unbundled monopolies with competitive markets as networks remain regulated monopolies in both settings. However, the greater the degree of vertical integration, the greater NWS can leverage demand-side resources to replace or defer supply-side infrastructures, leading back to the original concept of LCP.

2.3.4 Energy efficiency first

Historically, EE1st emerged in the early 2010s in EU debates related to energy efficiency (Pató et al. 2020a) and is a key element of EU energy policy since 2018.[20] Table 4 indicates the characteristics of EE1st compared to the other concepts. In terms of market structure, EE1st is embedded in the EU's unbundled and liberalised energy markets. LCP, IRP and NWS can be viewed as one-sided concepts, since regulated utilities initiate the deployment of demand-side resources for specific planning projects. EE1st, on the other hand, can be seen as a multi-sided concept, as it seeks to address all the investment decisions made in the energy system (European Union 2021a), whether initiated by regulated network companies, liberalised generation companies, or individual households and businesses. Hence, in terms of energy vectors, EE1st is inherently holistic. Possible applications have been discussed not only for electricity, but also for heat, gas,

19 The term NWS is used interchangeably with non-wires alternatives (NWA) (Chew et al. 2018) and non-transmission alternatives (NTA) (Stanton 2015)

20 EE1st has also been a matter of debate in New Zealand (EECA 2019) and in the province of Ontario in Canada under the label 'Conservation First' (Ministry of Energy 2013).

Table 4: Comparison of energy efficiency first with related concepts

Concept	Time period	Geographical scope	Market structure	Energy vectors	Costs and benefits
Least-cost planning (LCP)	1980s – 1990s	U.S.	Vertically-integrated monopolies	Electricity, gas	Monetary costs and benefits
Integrated resource planning (IRP)	1990s – ongoing	U.S.	Vertically-integrated monopolies	Electricity	Monetary costs and benefits + external costs
Non-wires solutions (NWS)	2000s – ongoing	U.S.	Regulated network companies	Electricity	Monetary costs and benefits
Energy efficiency first (EE1st)	2010s – ongoing	European Union	Unbundled monopolies / competitive markets	All energy vectors	All costs and benefits to society

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hydrogen and others (Zondag et al. 2020). With regard to costs and benefits, as described above, EE1st includes all costs and benefits to society, i.e. the monetary costs incurred by corporate and private actors, but also multiple impacts.

To conclude, what makes EE1st unique is its wider scope in terms of market activities, energy vectors and costs and benefits concerned. The other concepts can be considered as predecessors to EE1st. For example, the idea of NWS – which, in turn, is largely based upon LCP and IRP – is taken up again in the scope of EE1st in the form of planning guidelines and incentives for regulated network companies. However, it is clear that EE1st goes substantially beyond these existing concepts by attempting to integrate energy saving options in all energy-related planning, investment and policy decisions.

2.4 Economic rationale for energy efficiency first

While EE1st is broadly acknowledged as a guiding principle for policymaking and energy-related investment in the EU, its exact rationale is not well established in the existing literature.[21] This chapter takes a techno-economic perspective to explain why end-use energy efficiency and other demand-side resources require dedicated policy by referring to aspects of neoclassical, behavioural,

21 Bayer et al. (2016a) broadly refer to a *"persistent bias towards increasing supply over managing demand."* Rosenow et al. (2017a) argue that demand-side investments are impeded by *"numerous barriers to individual action"*, while supply-side investments are favoured by *"industry traditions, business models and regulatory practices."*

and regulatory economics.[22] This perspective is warranted for two reasons. First, market failures are widely acknowledged to be conditions that necessitate state interventions with a view to improving social welfare (Gillingham and Palmer 2014). Second, the analysis of specific market failures provides an understanding of adequate policies to resolve them (Linares and Labandeira 2010). We begin with describing the theoretical concept of well-functioning markets. Then, we discuss a range of market failures that provide the principal rationale for state intervention in the scope of EE1st.

2.4.1 Theoretical benchmark of well-functioning markets

The theoretical notion of well-functioning markets provides a benchmark for analysing the performance of real markets (Mulder 2021). It thus helps determine the extent to which the EE1st principle is applied in the EU energy system. In economic theory, there are a variety of institutional arrangements that can potentially yield socially optimal levels of demand-side and supply-side resources. These range from dictatorship to central planning and markets. Under ideal circumstances, any of these arrangements may achieve the highest possible social welfare (Perman et al. 2011; Ventosa et al. 2016).

In practice, the EU energy system is a market economy, i.e., production and consumption are the result of decentralised decisions by corporate and private actors (Krugman and Wells 2015). According to economic notions of well-functioning markets, these decisions of actors who act in their own self-interest can lead to outcomes that are collectively beneficial. This state is referred to as economic efficiency, indicating an allocation of capital, labour, energy and other inputs that maximises social welfare or total surplus (Mankiw 2017; Harris and Roach 2018; Zweifel et al. 2017).

In this ideal state, decentralised decisions would yield a mix of resource options that corresponded to society's best interest in line with the EE1st principle. More specifically, individuals and firms would maximise their utility by selecting the least-cost means of obtaining energy services. As such, they would adopt end-use energy efficiency measures and other demand-side resources whenever the incremental capital expenditures and hidden costs are lower than the discounted savings in operating expenses (Allcott and Greenstone 2012). In turn, energy companies would maximise their profit by reducing their costs of production, using all resource options at their disposal (Mulder 2021).

However, perfect markets and thus a state of economic efficiency require a strict set of conditions to be satisfied (Brown and Wang 2017; Mulder 2021; Gunn 1997):

22 In general, an interdisciplinary theoretical approach to EE1st should prove valuable (Saunders et al. 2021). In this vein, Edomah et al. (2017) and Wilson and Dowlatabadi (2007) present a range of theoretical frameworks that explain the adoption of demand-side resources by broader institutional and cultural factors.

- market actors are fully informed about the characteristics of goods and services (perfect information);
- market exchanges are instantaneous and cost-free (no transaction costs);
- consumers maximise their utility and producers maximise their profit (rationality);
- no individual producer or consumer can individually influence any market price (competition);
- any negative or positive externalities are internalised into the marginal social costs (internalisation).

Undoubtedly, the EU and other market economies deviate in many ways from these ideal circumstances (Brown and Wang 2017; Mulder 2021) and, as such, do not produce economically efficient resource allocations in line with the EE1st principle.[23] Deviations from this ideal state are broadly referred to as market failures (Mankiw 2017; Perman et al. 2011; Convery 2011).

Before reviewing a set of persistent market failures in the EU, it is critical to emphasise the difference between the concepts of market failures and barriers to energy efficiency (Brown and Wang 2017; Jaffe and Stavins 1994). Market failures are a general economic concept (e.g. Krugman and Wells 2015) that indicate deviations from the benchmark of well-functioning markets. Their presence leads to a misallocation of resource options overall, not just of end-use energy efficiency. In turn, barriers to energy efficiency are a concept from the energy literature (Brown 2001; Sorrell et al. 2000a) that impede the adoption of energy-efficient technologies per se. Barriers may or may not be market failures in the traditional economic sense.[24] As we will argue in 'Policy considerations for energy efficiency first', this distinction has important implications with a view to applying EE1st in practice.

2.4.2 Market failures

A comprehensive review of all relevant energy-related market failures in the EU economy is beyond the scope of this paper. In the following, we provide examples relevant to understanding how individual market failures distort a level playing field between demand- and supply-side resources. As further discussed in 'Policy considerations for energy efficiency first', these market failures

23 If and to what extent energy efficiency is below optimal deployment levels has been disputed for several decades under the term 'energy efficiency gap' (Hirst and Brown 1990; Jaffe and Stavins 1994). In the context of EE1st, the energy efficiency gap can be defined as the difference between welfare-optimal deployment levels of demand-side resources and the actual deployment levels. A dedicated discussion of the energy efficiency gap is beyond the scope of this paper. Useful discussions on the existence and magnitude of the gap and ways to address it are provided in (Brown and Wang 2017; Gerarden et al. 2017; Gillingham and Palmer 2014).

24 For example, low energy prices, high technology costs and uncertainty can be seen as barriers that act against the adoption of energy-efficient technologies. However, in itself, they are characteristics of the normal functioning of markets which does not qualify them as genuine market failures (Linares and Labandeira 2010; Ordonez et al. 2017).

provide an essential rationale for government intervention in the scope of the EE1st principle. Our review focuses on the categories of energy market failures, regulatory failures and behavioural failures. Other categories – including information, innovation and capital market failures – are thoroughly discussed elsewhere (Saunders et al. 2021; Gillingham et al. 2018; Brown and Wang 2017).

Energy market failures

Energy market failures are fundamental imperfections in how markets allocate levels of resource options (Brown and Wang 2017; Gillingham et al. 2009). Note that this is not merely about the internal energy markets for electricity and gas but, more globally, about the 'market for energy services' (Golove and Eto 1996) as a collection of overlapping markets between the production and ultimate use of energy.[25] Although well known, energy market failures are not necessarily well addressed in the EU. Below we give three particular examples.

Externalities are uncompensated costs or benefits that an individual or firm imposes on others (Krugman and Wells 2015). By definition, externalities are not reflected in the market price of goods and services and lead to an economically inefficient outcome (Laloux and Rivier 2016; Mankiw 2017). Most energy conversion processes generate significant negative externalities, i.e. have an external cost for society. In particular, fossil fuel combustion leads to emissions of carbon dioxide and air pollutants, which have adverse impacts on the climate, human health and ecosystems (González Ortiz et al. 2020). Negative externalities can also be created by renewable supply-side resources in the form of direct land use, water use, reduced aesthetics, noise, etc. (Sovacool et al. 2021). As the cost-effectiveness of demand-side resources depends on the price of energy, externalities create a systematic bias to their adoption. To correct this market failure and thus contribute to the implementation of EE1st, externalities must be internalised, i.e., added to the market price. This creates an incentive for consumers to save energy and penalises producers for adverse impacts (Allcott and Greenstone 2012). Pollution permits and Pigouvian taxes are established mechanisms to internalise the externality of emissions and other negative externalities (Mankiw 2017). However, Smith et al. (2020) estimate that only around 40% of the external costs associated with power and heat production in the EU are internalised through the emissions trading system, carbon taxes, and other corrective measures.

Although EU electricity markets are seen as liberalised in the sense of competitive generators, there remains the market failure of imperfect competition between supply- and demand-side resources.

25 More specifically, on the supply side, profit-oriented firms deliver energy in form of electricity and other vectors. Some of these firms are rate-regulated while others set prices in response to competitive pressures of the market. On the demand side, consumers purchase energy carriers, adopt technologies for their conversion into useful energy, and make decisions between using and saving energy. In between these two ends lies a spectrum of manufacturers, vendors and retailers that influence these transactions (Golove and Eto 1996)

Applying EE1st in this context means acknowledging that demand response and other demand-side resources in various markets (wholesale, balancing, capacity, etc.) can reduce the amount of energy and capacity procured and, in the long term, help to avoid supply-side investments. This may also benefit consumers by lowering clearing prices (Rosenow et al. 2017a). For demand-side resources to contribute to perfect competition in various power markets, market rules are needed in terms of free entry and exit (Krugman and Wells 2015).[26] In other words, there should be no obstacles in the form of governmental regulations or additional costs associated with leaving the market that prevent individuals and aggregators from entering the market and providing their services. However, market access is still restricted for demand-side resources and its aggregators in various EU power markets and value streams (smartEn 2020; Pató et al. 2019b). Aside from electricity markets, imperfect competition is also present in district heating systems. Market access for third-party waste heat providers in district heating systems could improve supply-side efficiency but is likewise impeded by market access restrictions (Holzleitner et al. 2020; Bacquet et al. 2021).

Average-cost pricing is another pervasive energy market failure (Gillingham et al. 2009; Brown 2001). From an economic viewpoint, price signals are efficient if they reflect the marginal cost of supply, i.e., the costs of generating and transmitting an additional unit of energy. Common consumer prices, however, average these marginal costs over a period of months, thus concealing short-term dynamics. This leads to underuse or overuse of energy relative to the economic optimum: if average prices are lower than the marginal cost at a certain point in time, consumers are encouraged to overuse energy with respect to the economic optimum, and vice versa. (Gillingham et al. 2009). As a result, generation and network capacities may be used more than is socially optimal. Time-of-use (TOU) pricing can address this market failure by bringing marginal costs in line with consumers' willingness to pay. This makes them an important enabler of implicit demand response in line with the EE1st principle. By shifting their demand to off-peak or lower-price time intervals, consumers can reduce their energy expenses and investments in generation or network infrastructures can be deferred (IRENA 2019b).[27] In practice, TOU tariffs are increasingly being adopted for electricity supply in most EU countries. However, obstacles to their widespread adoption remain (ACER/CEER 2021; Eid et al. 2016).

Regulatory failures

In the unbundled EU power and gas markets, transmission and distribution (T&D) constitute monopoly businesses, which is why they are subject to regulation by regulatory authorities

26 To be precise, according to economic theory, free entry and exit is not strictly a necessary condition for perfect competition, but a common feature of most perfectly competitive industries (Krugman and Wells 2015).

27 To illustrate, the French Tempo tariff, a form of TOU pricing launched in the 1990s, has been found to have reduced the national peak load by about 4%, with households shifting about 6 GW of load daily (Rosenow et al. 2016).

(Batlle and Ocaña 2016). To comply with the EE1st principle, it is widely argued that regulated utilities should take systematic account of demand-side resources in their system planning and operation, similar to the concept of NWS described above (Bayer 2015b; Pató et al. 2019b). There is comprehensive evidence from the U.S. that demand-side resources implemented through utility-managed DSM programmes can be cost-effective alternatives to traditional T&D network infrastructure investment (Neme and Grevatt 2015; Chew et al. 2018). However, in the EU, network infrastructure investment tends to be carried out without systematic consideration of lower-cost demand-side alternatives (Rosenow and Cowart 2019).

This lack of consideration can be classified as regulatory failure. Regulatory authorities are said to fail when they do not produce the outcomes stipulated in their mandates (Baldwin et al. 2012). Regulators of T&D companies in the EU are instructed to minimise the cost of providing energy services while ensuring a satisfactory quality of supply and system reliability (Laloux and Rivier 2016). To steer regulated utilities towards systematically considering demand-side resources, regulatory authorities can use extrinsic and intrinsic mechanisms in the form of planning guidelines and incentive structures, respectively (Thomas et al. 1999; Pató et al. 2019b). Guidelines can range from legal provisions to force systematic consideration of demand-side resources in an integrated cost-benefit analysis to procedures that utilities can adopt voluntarily. Such requirements can prevent the overestimation of energy demand, and hence superfluous investments in energy infrastructure (Petroula et al. 2016).

Besides guidelines, regulated utilities need to be intrinsically motivated to consider demand-side resources in their planning practices. As noted by Thomas et al. (1999), the strongest incentive for regulated utilities to implement DSM actions is the possibility of increased profit. If the financial benefit of avoided network use is greater than DSM implementation costs and lost revenue due to reduced sales, such measures are likely to be carried out. The ways in which demand-side actions influence a utility's profit depend largely on the remuneration schemes or price control regimes prescribed by regulators. The remuneration schemes traditionally imposed on power and gas network utilities have been associated with adverse effects on the cost of energy supply and thus regulatory failure.

Cost-of-service remuneration, also known as rate-of-return regulation or cost-plus regulation, is widely seen to result in the regulatory failure of moral hazard (Mulder 2021; Joskow 2014).[28] In this remuneration scheme, T&D companies have no incentive to relieve network investments through DSM actions because all actual costs are reimbursed through the tariffs charged to consumers. In other words, demand-side actions do not pay off as they cannot increase profits for the T&D

28 In economic theory, moral hazard means the distortion of incentives for effort to lower costs when someone else bears the costs of the lack of care or effort (Krugman and Wells 2015).

company. Rate-of-return regulation may also give the company an incentive to overinvest in supply infrastructure if the allowed rate of return exceeds the actual costs of capital in the capital market. This so-called gold plating (Mulder 2021; Gómez 2016) is formally referred to as the *Averch-Johnson effect* (Averch and Johnson 1962).

These well-known problems with cost-of-service regulation have lead regulators in the EU to rely on revenue cap regulation for T&D companies (CEER 2023). It largely solves the regulatory failure of moral hazard as the regulator sets a maximum allowed revenue ('revenue cap') that the T&D company can charge over a regulatory period. This creates an incentive for the company to reduce costs below the cap as it will retain as profit any difference between the cap and its actual costs. Cost savings are gradually passed on to consumers with the periodical review of the cap (Rious and Rosetto 2018b; Mulder 2021). While a T&D company under cost-of-service remuneration is incentivised to use capital-intensive solutions to solve network congestions, a company under revenue cap regulation may work towards reducing line losses in terms of supply-side energy efficiency (Mulder 2021).

However, it is increasingly recognised that classic revenue cap regulation alone does not sufficiently incentivise T&D companies to make use of demand-side resources in system operation and planning. This regulatory failure can be broadly described as X-inefficiency, i.e. the notion that that regulated companies do not achieve the minimum costs that are technically feasible (Weimer and Vining 2017). Pató et al. (2019a) suggest that, in the definition of the revenue cap for the regulatory period, T&D companies should receive a rate of return on their avoided capital expenditures in order to make the financial incentives for demand-side resources comparable to investment in traditional network assets. Referred to as TOTEX allowances ('total expenditures') (Rious and Rosetto 2018b), companies still have the incentive from the revenue cap to reduce their overall costs, but have a stronger incentive to also consider demand-side resources (Pató et al. 2021).

Rious and Rosetto (2018a) further point out that T&D companies may view demand-side resources as immature and risky, raising the need for innovation funding to trigger such activities. Finally, the deployment of demand-side resources could be included as an output in so-called performance-based regulation (Pató et al. 2019a; Rious and Rosetto 2018b), making T&D companies subject to a reward-penalty scheme associated with the outputs delivered. In sum, more research is needed to determine effective remuneration schemes for T&D companies that deliver demand-side resources in line with the EE1st principle, and to discuss the limitations of these regulatory approaches in terms of the technical expertise and financial means required as well as unintended side-effects.

Behavioural failures

Besides energy market and regulatory failures, recent literature from the discipline of behavioural economics indicates behavioural failures as another significant market failure that leads to an economic imbalance between demand- and supply-side resources (Gillingham and Palmer 2014;

Häckel et al. 2017; Saunders et al. 2021). As noted above, one condition for markets to reach economic efficiency is that decision-makers act rationally. Producers maximise profit while consumers maximise utility, i.e., the value they attach to goods and services (Mankiw 2017).

On the supply side, the assumption of rational producers may hold, for example, in the case of electricity wholesale markets where the only option for producers to maximise their profits is to choose an optimal mix of capital, labour, and other inputs (Mulder 2021). On the other hand, there is growing evidence that consumers do not make consistent and systematic choices in the sense of rationality.[29] Even if provided with perfect information, they exhibit biases, heuristics and other irrational tendencies in their energy-related decisions (Madrian 2014; Frederiks et al. 2015). Behavioural failures have been generally defined as deviations in an actor's behaviour from rational choice theory (Shogren and Taylor 2008). More systematically, Gillingham et al. (2018) define them as *"any feature of decision-making that leads the consumer to exhibit a deviation between the utility at the time of the decision – known as decision utility – and the utility at the time when the consequences of the decision occur [known as expected utility]."*

In practice, well over twenty-five behavioural failures have been identified as relevant to economic decision-making (Shogren and Taylor 2008).[30] To illustrate, it is widely acknowledged that consumers exhibit bounded rationality, meaning limited cognitive abilities to process and evaluate all information available to make rational choices (Shogren and Taylor 2008; Madrian 2014). As a result, they rely on a sub-set of choice alternatives and follow simple rules-of-thumb heuristics to accelerate the decision-making process (Bhattacharyya 2019). Simplification strategies may help reduce cognitive overload and facilitate more effective energy-related decision-making (Frederiks et al. 2015). For example, positive experiences have been made with so-called logbooks provided to building owners as a comprehensible digital repository of possibly cost-effective thermal renovation measures (Pató et al. 2020b).

Another example of behavioural failure is loss aversion, i.e., the notion that consumers value the impact of losses more than that of gains (Gillingham and Palmer 2014; Häckel et al. 2017). Investing in end-use energy efficiency measures is a risky decision for consumers due to the uncertainty

29 Implicit discount rates (IDRs) are an established metric to make these irrationalities and other market imperfections visible (Schleich et al. 2016). However, as various authors contend (Stadelmann 2017; Allcott and Greenstone 2012), IDRs typically do not correctly factor in rational decision variables that are part of the individual's utility function and thus reflect a privately optimal decision. Such decision variables include specific preferences (e.g. high rates of time preference, subjective risk and uncertainty considerations) and confounding variables that influence purchase decisions (e.g. hidden costs for finding and installing a more energy-efficient product).

30 The reason why behavioural failures occur at all is being investigated in neuroeconomics, attempting to understand the neural pathways that control how consumers make decisions (Gillingham and Palmer 2014; Fehr and Rangel 2011). Other authors associate them with lifestyles, social practices and other structures that individuals act in (Thomas et al. 2019).

surrounding market prices, policies, and the long-term financial payoffs (Frederiks et al. 2015; Hirst and Brown 1990). When loss aversion is present, consumers may refrain from engaging in otherwise cost-effective investments because they attach too much weight to the losses associated with them – whether from possible negative payoffs or the loss of the initial capital expenditure itself (Schleich et al. 2016). To address loss aversion, energy savings insurances or guarantees could be promoted to reduce the likelihood of negative payoffs, while presenting novel business cases for insurance companies (Häckel et al. 2017).

Overall, behavioural failures create a systematic bias in the adoption of supply- and demand-side resources. While producers consistently invest in power plants, storage facilities and other assets whenever there is a robust chance of profit, consumers are impeded from investing in otherwise cost-effective energy efficiency measures because of their bounded rationality and other behavioural failures. Fostering the EE1st principle would mean systematically addressing these imperfections in order to move closer to the theoretical benchmark of well-functioning markets. Government intervention is generally considered legitimate to address behavioural failures, given that they are systematic and pervasive biases to decision-making (Häckel et al. 2017; Gillingham et al. 2018). Allcott and Mullainathan (2010) hold that some behaviourally informed policies can be just as effective as price-based policies. However, which behavioural anomalies qualify as genuine behavioural failures and therefore warrant government intervention has not gone unchallenged (Gillingham et al. 2018). Moreover, most work focuses on the residential sector, with much less attention given to possible behavioural failures in the commercial and industrial sectors (Gerarden et al. 2017).

2.5 Policy considerations for energy efficiency first

In recent years, a growing body of literature has outlined how EE1st as a general principle could be put into practice. Rosenow and Cowart (2019) present four steps for applying EE1st. These include *planning* (e.g. recognising the value of multiple impacts in EU impact assessments); *targeted energy efficiency policies* (e.g. building codes); *infrastructure decision rules* (e.g. performance-based regulation); and *compliance and review* (e.g. periodic reviews of targets). Bayer et al. (2016a) refer to similar steps, stressing also the aspect of *finance* (e.g. EE1st as a guiding principle for allocation of EU funds). Perhaps most prominently, the European Commission's guidelines on EE1st (European Union 2021a), based on the principle's definition in the Governance Regulation (European Union 2018d), refer to *planning*, *policy* and *investment* decisions to be addressed in the scope of EE1st, without clearly delineating these terms.

It is evident that there are various aspects to EE1st and that its implementation currently lacks a theoretically substantiated and widely acknowledged framework for Member States to act upon.

In this chapter, we first focus on the aspect of 'targeted energy efficiency policies' (Rosenow and Cowart 2019), also referred to as 'delivering' (Bayer et al. 2016a) or 'incentivising EE1st' (European Union 2021a). In other words, what policy instruments could be selected for consumers and producers to invest in and operate their assets in line with the EE1st principle. Based on the theoretical background presented above, we first propose a conceptual distinction between wider policies based on the energy efficiency first principle (EE1st policies) and energy efficiency policies (EE policies). Our key proposition is that EE1st policies differ from traditional EE policies (e.g. standards) in that the former address the interplay between resource options and corresponding market failures, rather than promoting end-use energy efficiency per se. Second, we focus on the relevance of the EE1st principle in overarching policy formulation, i.e. the process by which policies are designed within government, through both strategic planning and technical analysis (Birkland 2020).

2.5.1 Policy instruments

The EU and its Member States have a well-established package of policy instruments dedicated to improving energy efficiency in various sectors (IEA 2020b). Numerous review articles (Del Solà et al. 2021; Bertoldi 2020; Trotta et al. 2018; Shen et al. 2016; Markandya et al. 2015) and databases (ODYSSEE-MURE 2022; IEA 2015) provide different classifications of these instruments. For example, Markandya et al. (2015) distinguish between (i) command and control approaches (e.g. building codes), (ii) price instruments (e.g. grants), and (iii) information instruments (e.g. labels). More comprehensively, Bertoldi (2020) classify energy efficiency policies as (i) regulatory (e.g. standards), (ii) financial and fiscal (e.g. soft loans), (iii) information and awareness (e.g. information campaigns), (iv) qualification and training (e.g. capacity building), (v) market-based (e.g. energy efficiency obligation schemes), (vi) voluntary action (e.g. voluntary certification), and (vii) infrastructure investment (e.g. smart meter roll-out).

What is notable about these policy instruments is that they are justified predominantly on the grounds of barriers to energy efficiency (Bertoldi 2020; Cattaneo 2019; Markandya et al. 2015), not all of which are market failures. As proposed in the 'Economic rationale for energy efficiency first', there is a critical difference between the two concepts. The former impede the adoption of end-use energy efficiency as one particular resource option, while the latter affect the competition or level playing field between demand- and supply-side resources overall. To illustrate, a common justification for grants and tax incentives as financial instruments are high upfront costs, scarcity of private capital, and perceived risk (Bertoldi et al. 2021). None of these barriers constitute genuine market failures (Linares and Labandeira 2010). Likewise, minimum energy performance standards and building codes are not directed towards a specific market failure, but a market outcome (Sutherland 1996). We suggest that instruments targeting barriers should be referred to as energy efficiency policies (EE policies) because they are aimed at reducing energy demand, rather than explicitly addressing the interplay between resource options.

In turn, based on the definition developed in 'Definition of energy efficiency first', we believe there is a justification for framing policies for energy efficiency first (EE1st policies) on the grounds of market failure. If each market failure were addressed by one or several policy instruments, energy system investments and operation would correspond to the theoretical benchmark of well-functioning markets and thus, according to economic theory, maximise welfare in line with the EE1st principle. For instance, the market failure of imperfect competition calls for market rules that treat demand-side resources on an equal competitive footing with supply. Negative externalities can be addressed by Pigouvian taxes or cap-and-trade instruments, thus incentivising end-use energy efficiency while dis-incentivising adverse energy supply. The regulatory failure of X-inefficiency requires intricate design changes to regulatory price control regimes, including TOTEX allowances and performance-based incentives. Table 5 compares EE1st and EE policies. Note that this distinction is more conceptual than practical, given the frequent overlap between the concepts of market failures and barriers.[31]

Table 5: Difference between energy efficiency first and energy efficiency policies

	Energy efficiency first (EE1st) policies	**Energy efficiency (EE) policies**
Rationale	Market failures | Establish a level playing field between demand- and supply-side resources by addressing fundamental market imperfections	Barriers to energy efficiency | Contribute to welfare-optimal and equitable levels of energy efficiency by addressing barriers that are not necessarily market failures
Scope	Multilateral | Policies to address the economic imbalance between demand and supply where energy efficiency is one possible market outcome	Unilateral | Policies to enhance energy efficiency and to reduce energy demand per se
Example	Market access rules for demand response in power markets to address the energy market failure of imperfect competition	Grants for energy-efficient building renovations to address the barrier of high upfront costs
Limitations	Political and jurisdictional constraints, distributional concerns	Transaction and policy enforcement cost, rebound effects, free-rider effects, consumer heterogeneity

Hence, as expressed by Pató et al. (2019b), EE1st policies are *more* and *less* than traditional EE policies at the same time. They are 'more' than EE policies in that the logic of addressing market failures involves areas of energy policy that are not themselves primarily aimed at reducing energy use (e.g. market access rules).[32] They are 'less' than EE policies in that they aim to establish a level playing field between demand- and supply-side resources, rather than

31 For example, information instruments like labels and audits could be interpreted as both EE1st and EE policies because the underlying issue of imperfect information constitutes both a common barrier to energy efficiency (Cattaneo 2019) as well as a general market failure as per economic theory (Brown and Wang 2017).
32 With few exceptions (e.g. Warren 2019), such policy instruments do not yet seem to be consciously addressed in the research literature on energy efficiency policy, but typically associated with supply-side or renewable energy policy (e.g. Edenhofer et al. 2013)

commanding the adoption of energy-efficient technologies or behaviour as a market outcome (European Union 2021a).

In designing a sound package of policy instruments (Kern et al. 2017; Rosenow et al. 2017b), EE1st policies and traditional EE policies should not be seen as mutually exclusive, but as complementary in nature. Standards, subsidies and other established EE policies are generally found to be effective in bringing about energy savings (ODYSSEE-MURE 2022), while contributing to an equitable distribution of wealth and income (Ordonez et al. 2017). In return, they are frequently associated with rebound and free-rider effects, relatively high policy implementation costs, and the issue of heterogeneous consumer properties (Gillingham et al. 2018). This has led to some scepticism among economists about their cost-effectiveness from a societal viewpoint (Allcott and Greenstone 2012; Sutherland 1996).[33]

A broad consideration of EE1st policies in the policy mix could fill important gaps in the scope of energy efficiency policy and contribute to welfare-optimal levels of resource options. At the same time, it has to be taken into account that, in practice, addressing each market failure through one or several EE1st policies is limited by political economy constraints. These include jurisdictional limitations, political inertia, incomplete scientific evidence, and other issues (Fischer et al. 2021; Jenkins 2014). For instance, a rigorous implementation of carbon pricing across the EU's building and transportation sectors would have a disproportionate effect on low-income households and thus raise distributional concerns that are likely to result in significant political opposition (Thomas et al. 2021).

In sum, based on the theoretical background presented in 'Definition of energy efficiency first' and 'Economic rationale for energy efficiency first', we consider the defining feature of policies for Energy Efficiency First to be the removal of market failures that are not just barriers to energy efficiency. Considering such EE1st policies would be an important complement to the existing scope of energy efficiency policies. In addition to dedicated policy instruments, the debate around EE1st has been accompanied by a renewed interest in the process of policy formulation.

2.5.2 Policy formulation

The process of policy formulation establishes the wider context in which policy instruments are designed and implemented (Birkland 2020; Turnpenny et al. 2015). In this section, we touch upon three aspects particularly relevant to implementing the EE1st principle. First, there is the need to integrate long-term policy strategies. Strategies such as the NECPs are critical to an effective

33 In a recent meta-analysis, Gillingham et al. (2018) found that the cost-effectiveness of EE policies ranges from 1.1 cent for information programmes to 47.9 US cents and higher per kilowatt-hour for energy savings subsidies. Some of these policies are thus not cost-effective or welfare-enhancing relative to the marginal cost of energy.

economic transformation in line with GHG reductions, security of supply and other policy objectives. Acknowledging the EE1st principle in this context means providing, wherever possible, integrated strategies concerning all technically feasible resource options. In practice, however, the landscape of strategies set out in EU legislation tends to be fragmented into 'silos of policymaking' (Boll et al. 2021). This carries the risk that strategies are not internally coherent and thus fail to deliver the most cost-efficient resources to meeting energy service needs.

To illustrate, the Energy Efficiency Directive (European Union 2012b, 2018b, Art. 14) requires Member States to carry out 'comprehensive assessments' of the potential for efficient district heating and cooling. With respect to EE1st, these assessments fall short in terms of integrating end-use energy efficiency and other demand-side resources among the options to be considered (Pató et al. 2021). In parallel, the 'long-term renovation strategies' required under the Energy Performance of Buildings Directive (European Union 2018c, Art. 2a) are intended to promote the renovation of residential and non-residential buildings, but do not explicitly factor in the range of possible supply-side resources. Boll et al. (2021) suggest the joint preparation of these two strategies to ensure coherent quantitative projections and an integrated appraisal of resource options, and thus to achieve robust policy outcomes.

Second, EE1st needs to be consciously considered in computerised models, cost-benefit analysis, and other tools of policy formulation (Turnpenny et al. 2015). At the EU level, before introducing a new legislative proposal, the European Commission estimates the potential economic, social and environmental impacts of alternative policy options in a model-based impact assessment. Acknowledging EE1st in this process means evaluating costs and benefits primarily from a societal rather than a private perspective in order to enable a fair comparison of resources (Bayer et al. 2016b).

As set out in the 'Definition of energy efficiency first', besides revisiting the discount rates used for demand- vs. supply-side resources (Hermelink and Jager 2015), adopting a societal perspective also requires determining the wide range of multiple impacts that go beyond private utility gains (Fawcett and Killip 2019). In practice, for example, Shnapp et al. (2020) argue that cost-optimal levels of building energy performance requirements under the Energy Performance of Buildings Directive (European Union 2018c) should properly factor in multiple impacts to both individuals (e.g. comfort gains) *and* society at large (e.g. air pollution reductions) in order to capture the true value of end-use energy efficiency, and thus to legitimise more ambitious building codes.[34]

34 Policymakers and other practitioners at the EU level seem to lack expertise, inter alia, on how to incorporate multiple impacts in policy formulation and related impact assessments (Schmatzberger and Boll 2020). This is also reflected at the national level where the European Commission (2020b) criticised a lack of systematic consideration of 'co-benefits' in Member States' NECPs. At the local level, a similar indifference to

Finally, another aspect relevant to policy formulation in line with EE1st is to review the causal model underlying policy instruments, i.e. the cause-impact relationship to both desired and undesired outcomes (Birkland 2020). A frequently cited case (Pató et al. 2021; Boll et al. 2021) is the provision of public funding for new or upgraded renewable heating installations that does not take into account the energy performance of the building envelope as an eligibility criterion. This may result in an unintended outcome in the sense that the systems installed are over-dimensioned in terms of their rated capacity, resulting in higher heating costs than if the building had also undergone an upgrade of the thermal envelope. Proponents of EE1st have been arguing that public funding for heating, air conditioning and other technical building systems should be contingent on the building having high levels of energy performance. This so-called 'fabric first' idea has been practised, for instance, in Ireland, where the government provides grants for heat pump systems only if the building complies with a minimum level of energy performance (Pató et al. 2020b).

Note that it is simplistic to assume that policy formulation can proceed in a fully logical, comprehensive and purposive manner. In practice, governments will continue to be faced with incomplete information, uncertainty, pressure from interest groups and other constraints (Weimer and Vining 2017; Hill and Varone 2021). These phenomena influencing policy formulation can be conceptualised as government failure (Weimer and Vining 2017), similar to the idea of regulatory failure associated with regulatory authorities described above. In summary, policy design for EE1st should be informed not only by an understanding of market failure, but of government failure as well.

2.6 Conclusion

The EE1st principle has recently been gaining momentum in EU energy and climate policy. However, some of its key aspects and implications for policymaking remain unclear, with the associated risk that EE1st remains merely a slogan without tangible impact on energy-related investment, planning, and policymaking. This article set out to address four aspects within the current debate around EE1st.

First, we proposed a conceptual framework for the EE1st principle, emphasising the role of decision objectives, resource options, and the overall decision rule therein. EE1st is thus theorised as a decision principle that prioritises demand-side resources and supply-side energy efficiency over default supply-side resources whenever they provide greater value to society in meeting decision

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multiple impacts has been observed in regional development plans (Oikonomou and Eichhammer 2021). In response, there have been efforts to formulate guidance on the proper comparison of resource options in the scope of EE1st (Mandel et al. 2020).

objectives. An important line of inquiry is how the notion of multiple impacts can be integrated into established economic concepts of private utility and societal welfare and, subsequently, how these can be operationalised for quantitative and model-based assessments.

Second, we addressed the question of how EE1st differs from related planning concepts that consider end-use energy efficiency and other demand-side resources alongside supply infrastructure expansion and operation. EE1st is found to be a unique concept in this regard. As it is embedded in the EU's unbundled and liberalised energy markets, it relies on a multitude of decision-makers and addresses not only electricity, but all energy vectors. An associated feature is its focus on the societal perspective, making it a principle of public policy rather than only regulated utility business.

Third, we demonstrated that EE1st can be justified as a guiding principle on the grounds of economic efficiency and the theoretical benchmark of well-functioning markets. Relevant market failures were presented that help explain why the EU market economy does not yield welfare-optimal levels of demand-side resources in line with the EE1st principle. While energy market failures are a well-established feature of the energy literature, regulatory failures have so far received little attention with a view to exploring how to incorporate demand-side resources in the system planning and operation of regulated network companies. Likewise, as is the case for behavioural failures, more research is warranted to match specific policy approaches to the individual failures. In addition to the existing literature on barriers to energy efficiency, the concept of EE1st would benefit from an exhaustive account of genuine market failures as per economic theory. Such investigations are logically prior to questions of how particular policies should be designed (Sanstad and Howarth 1994).

Fourth, we outlined possibilities for how EE1st as a theoretical decision principle could be practically implemented in the EU. Our key proposition is that EE1st policies (e.g. market access rules) differ from traditional energy efficiency policies (e.g. minimum energy performance standards) in that the former aim to level the playing field between resource options, rather than promoting energy-saving measures per se. As such, applying the EE1st principle calls for a broader policy response that goes beyond the portfolio of established energy efficiency policies – including performance-based regulation for network companies, dynamic pricing, behaviourally informed policies, and other instruments. At the same time, given the range of practical constraints, traditional energy efficiency policies like standards and subsidies must remain a critical element of the policy framework at EU and Member State levels.

Apart from dedicated instruments, we also highlighted the need for thorough consideration of the EE1st principle in the policy formulation process. Strategic planning within government is a key issue. Combining sector-specific strategies into integrated holistic ones that address all the technically feasible resource options could help achieve robust policy outcomes. Another important aspect of policy formulation is the adoption of a genuinely societal perspective in ex-ante impact assessments and related energy system models. This involves the rigorous assessment of multiple impacts as well as the proper use of discount rates. EE1st also needs to be a guiding principle in the causal logic underlying policy instruments, e.g. when designing grants, loans and other forms of public funding.

To conclude, the EE1st principle is found to have a compelling theoretical background. This knowledge can help guide policymakers and regulators in supporting and enabling the application of the principle in practice. Long-term strategies and policymaking in the EU and its Member States will show how thoroughly the principle is taken into account.

3

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

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3.1 Introduction

The energy efficiency first (EE1st) principle has lately gained traction as a guiding principle for energy-related planning, investment and policy-making in the European Union (EU). Following its formal recognition in the EU Governance Regulation (European Union 2018d) and dedicated guidelines (European Union 2021a), the European Commission recently included a dedicated Article 3 on EE1st in its proposal for a recast of the Energy Efficiency Directive (2021e).

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

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

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

In the transition towards a net-zero emissions energy system (Davis et al. 2018), these options compete with supply-side resources in the form of utility-scale and distributed generation, network infrastructures, storage facilities, and others (Mandel et al. 2022c). With regard to heating buildings, renewable energy supply options range from the direct use of renewables (e.g. solar thermal), electrification via heat pumps, district heating systems, up to hydrogen and derived synthetic fuels

(Kranzl et al. 2021; Korberg et al. 2022). Ultimately, both demand-side and supply-side resources have costs and benefits, which raises the question about the extent to which one or the other should be given priority in strategic planning and policy-making in terms of the EE1st principle.

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

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

The majority of studies focus on the trade-off between building retrofits versus district heating and decentralised heating at municipal level (Delmastro and Gargiulo 2020; Milic et al. 2020; Romanchenko et al. 2020; Büchele et al. 2019; Ben Amer-Allam et al. 2017; Harrestrup and Svendsen 2014). These studies generally conclude that heat energy savings can be cheaper than the deployment of new heat supply options up to a certain extent. While some studies do feature a national scope (Drysdale et al. 2019; Hansen et al. 2016), they are likewise limited to thermal loads while disregarding the interactions with electricity and hydrogen supply. As a result, they need to rely on exogenous prices, which ignores that energy supply is price elastic and can adapt to new demand profiles (Zeyen et al. 2021).

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

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

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

Answering these questions can lead to a better understanding of an economically viable balance of demand-side and supply-side resources within the scope of EE1st. The central contribution of this study is the analysis of three model-based scenarios, each set to achieve the normative target of net-zero GHG emissions, but with different ambition levels for end-use energy efficiency in buildings. The study also contributes a systematic accounting of energy system costs, comprising all monetary costs in buildings and energy supply, plus damage costs due to air pollution, as one of many relevant multiple impacts.[35]

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

3.2 Methodology

This analysis applied four interlinked modelling tools under the constraint to reach net-zero GHG emissions by 2050. Three scenarios were investigated, which differ by their ambition level for end-use energy efficiency in the building sector.[36] The indicator of energy system cost was used to assess each scenario's performance.

35 Air pollution is considered the second biggest environmental concern for the EU after climate change (González Ortiz et al. 2020). In a net-zero future with the absence of fossil fuels, air pollution emissions from bioenergy carriers remain relevant, e.g. particulate matter from solid biomass combustion in households (Vicente and Alves 2018).
36 Throughout this study, the term 'building sector' is used to refer to the total final energy consumption in the sectors households and commercial & public services (European Commission 2019a), excluding the industry sector.

Table 6: Qualitative outline of scenarios

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

3.2.1 Outline of scenarios

The three scenarios approach the net-zero target with different levels of ambition for building retrofits and efficient products. This involves differences in the supply mix, capacities installed, and overall energy system costs. Table 6 provides a qualitative outline of the scenarios. Detailed scenario parametrisations are presented under 'Modelling approaches'.

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

3.2.2 Definition of energy system cost

Energy system cost (*ESC*) is the central performance indicator in this analysis. It indicates the total monetary costs incurred to meet the energy service needs of the building sector. It thus helps determine the extent to which the EU would be better off if end-use energy efficiency measures in buildings were systematically prioritised over supply-side resources when transitioning to a net-zero energy system.

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

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

where Equation 1

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

The range of cost types *i* and cost items *j* is listed in Figure 3. Cost types involve capital costs for various demand-side resources (e.g. building renovation) and supply-side resources (e.g. wind turbines). In addition, the *ECS* includes operating expenses in the form of fuel and operation & maintenance (O&M) costs. Finally, other costs include the costs of CO_2 emission certificates in the scope of the EU Emissions Trading System (ETS), as well as monetised damage costs due to air pollution.[37]

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

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

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

Figure 3: Definition of cost items and cost types in energy system cost

COST ITEMS /	① Capital costs	② Fuel costs	③ O&M costs	④ Other costs
① Building renovation	Renovation measures on walls, roofs, windows, ventilation; etc.	-	-	-
② Electrical appliances	Refrigerators, washing machines, lighting, etc.	-	Fixed O&M	-
③ Heating systems	Decentralised boilers, ovens, heat pumps, solar thermal, etc.	-	Fixed O&M	-
④ Fuel costs in buildings	-	Gaseous/liquid fuels, bioenergy, minus hydrogen generation	-	-
⑤ District heating generation	Centralised boilers, CHP, heat pumps, solar, storage, etc.	Wholesale costs for fossil fuels and bioenergy carriers	Fixed & variable O&M	CO_2 emission certificates
⑥ District heating networks	Heat distribution networks	-	Fixed & variable O&M	-
⑦ Electricity generation	Fossil, nuclear, renewable plants, battery storage, etc.	Wholesale costs for fossil, nuclear, bio energy carriers	Import/export cost, fixed & variable O&M	CO_2 emission certificates
⑧ Electricity networks	Cross-border transmission networks, distribution networks	-	Fixed & variable O&M, system service costs	-
⑨ Hydrogen generation	Electrolysers, hydrogen storage, methanation reactors	-	Import/export cost, fixed & variable O&M	-
⑩ Negative externalities	-	-	-	Air pollution damage cost

CHP = combined heat and power, O&M = operation & maintenance

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

1) In line with existing guidance (Sartori et al. 2015) and related studies (e.g. Langenheld et al. 2018), a social discount rate of 2.0% in real terms was selected to discount yearly costs.[38]
2) To the extent possible, direct and indirect taxes were omitted from all costs as they are considered to be transfer payments between members of society (Konstantin and Konstantin 2018a; Khatib 2014). In the *ECS*, this particularly concerns the exclusion of value added tax and other flat-rate surcharges from fuel costs in buildings. However, it was not possible to completely eliminate all relevant transfer payments in this study. To illustrate, building renovations include a significant share of labour costs that, in turn, largely consist of payroll taxes.[39] A thorough elimination of all relevant transfer payments would require dedicated country- and technology-specific analyses.

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

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

In sum, energy system cost (*ECS*) as defined here can be seen as a simplified measure of societal welfare.[40] As such, *ECS* resembles the *societal cost test,* one of the five cost-effectiveness tests used by energy utilities and regulators in the U.S. to determine the value of energy efficiency measures and other system resources (Yushchenko and Patel 2017; U.S. EPA 2008). The following section describes how the *ECS* was calculated for the three defined scenarios using sectoral modelling tools.

3.2.3 Modelling approaches

Four bottom-up modelling tools were applied. The tools were soft-coupled (Pye and Bataille 2016), i.e. interlinked in an iterative process, with data transferred across the models. Table 7 presents their key features. Note that the differences in resolution across the models involved some aggregation of data. For example, Enertile computes hourly electricity prices, which were aggregated into annual values to make them usable for the other three models.

Energy demand

The soft-coupled model setup requires estimates of final energy consumption for all energy demand sectors. Energy needs in both residential and non-residential buildings are explicitly modelled by applying the models Invert/Opt and Forecast. Developments in the industry and transport sectors are kept constant across the three scenarios so that scenario differences result exclusively from the different ambition levels for end-use energy efficiency in buildings.[41]

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

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

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

Table 7: Key features of modelling tools applied

	INVERT/OPT	FORECAST	ENERTILE	NetHEAT
Cost items [a]	Building renovation Heating systems	Electrical appliances[b]	District heating generation Electricity generation Electricity networks [c] Hydrogen generation	District heating networks
Approach	Optimisation	Simulation	Optimisation	Simulation
Temporal resolution	Yearly	Yearly	Hourly (system operation), 10-yearly (capacity expansion)	Yearly
Spatial resolution	National	National	Local (RES potentials at 6.5 x 6.5 km grid), national (power flows)	Local (0.1 x 0.1 km grid)
Main input variables	Building stock data, technology properties and costs, consumer energy prices	Technology costs, consumer energy prices, learning rates	Final energy demand, technology costs, fuel prices, existing capacities	Useful energy demand, fuel and electricity prices, building stock, road lengths
Main output variables	Final energy demand by energy carrier and building type, costs, direct CO2 emissions	Final energy demand by technology and efficiency class, market shares, costs	Generation mix, primary energy consumption, installed capacities, costs, direct CO2 emissions, prices	Network length, costs, linear heat densities, buildings connected
Model environment | Aux. software	Python | SQLite, Excel,	VB.Net | SQLite	Java | MySQL	Python | QGIS, Excel
Licence	Commercial	Commercial	Commercial	Commercial
Website	TU Wien (2020)	Fraunhofer ISI (2022b)	Fraunhofer ISI (2022a)	IREES (2022)
Key applications	Hummel et al. (2023)	Mandel et al. (2019), Elsland (2016)	Bernath et al. (2021), Lux and Pfluger (2020)	Popovski et al. (2023), Steinbach et al. (2020)

[a] See Figure 3 | [b] Residential buildings only | [c] Cross-border transmission networks only

Invert/Opt uses a mixed-integer linear programming algorithm to determine combinations of renovation and heat supply options that minimise technical system costs from the existing state to the target year, i.e. the sum of annual capital costs plus fuel and O&M costs. Based on this cost optimisation logic, the model endogenously determines the share of buildings in each archetype undergoing renovation along with the market shares of heating and cooling systems. The optimisation problem is subjected to two major constraints (Hummel et al. 2023): (i) CO_2 emissions associated with heating and cooling must be reduced by at least 95% between 2017 and 2050; (ii) energy carrier use must be below the energy carrier potentials. These potentials are reported in Hummel et al. (2023). In essence, they comprise technical restrictions (e.g. gas network availability), and socio-economic restrictions (e.g. acceptance of biomass combustion).

Invert/Opt features three major input databases (Hummel et al. 2023):

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

The three scenarios LowEff, MediumEff and HighEff were operationalised in Invert/Opt using three settings related to renovation activities (Hummel et al. 2023):[42] the permitted share of refurbishments in (i) the entire building stock, (ii) in individual building segments, and (iii) the average length of renovation cycles (Table 8).[43] In essence, LowEff is characterised by a high

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

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

Table 8: Definition of scenarios for energy demand

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

See Footnote 42 for definition of retrofits, refurbishments, and renovations.

minimum share of refurbishment in renovation activities, while HighEff involves relatively short renovation cycles.

The simulation model Forecast (Fraunhofer ISI 2022b) was used to project the energy use of electrical appliances, lighting and cooking equipment in residential buildings.[44] It is designed as a bottom-up vintage stock model, with technologies reaching the end of their lifetime being scrapped and new appliances gradually entering the market. The market shares of new technologies are endogenously determined based on a combination of utility functions and a logit approach able to represent observed technology purchase behaviour in households (Mandel et al. 2019; Elsland 2016).

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

- White goods (refrigerators, freezers, washing machines, dryers, dishwashers, stoves);
- Information and communications technology (laptops, tablets, televisions, etc.);
- Lighting (light emitting diodes, compact fluorescent lamps, halogen lamps);
- Other energy use: aggregate of small electrical appliances that are not explicitly modelled (e.g.

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

coffee machines), plus emerging appliances which could potentially diffuse in the market until 2050.

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

To operationalise the three scenarios in Forecast, the energy performance standards that new appliances must meet were modified (Table 8). More energy-efficient appliances thus gradually replace relatively inefficient ones, resulting in a decrease in energy demand. In LowEff, it is assumed that the existing Ecodesign requirements as of December 2020 are not modified, whereas these provisions are gradually increased in MediumEff and HighEff.

Energy supply

Energy supply and the associated energy system costs for electricity, district heating and synthetic combustibles were determined endogenously using the modelling tools Enertile and NetHEAT. The techno-economic optimisation model Enertile (Fraunhofer ISI 2022a) optimises both the capacity expansion and unit dispatch of renewable energies, conventional power plants, electricity transmission, heat and hydrogen generation technologies, energy storage facilities, and demand-side flexibility.

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

The capacity expansion and operation of supply technologies in Enertile are based on a linear cost minimisation problem with perfect foresight. The objective function is to minimise the system costs for the provision of electricity, heat and hydrogen over all model regions in all 8,760 hours per year. These costs comprise annuitised fixed and variable costs for all employed technologies of the three energy vectors. Central constraints of the minimisation problem require that (Lux and Pfluger

2020): (i) hourly outputs of a generation unit do not exceed installed capacity; (ii) hourly electricity transfers between regions to not exceed transmission capacities; (iii) storage units only operate within the limits of their technical parameterisation; and (iv), in this study, a decarbonisation level of 100% in 2050.

Given its cost optimisation logic, techno-economic data represent a key input to Enertile, such as specific capital expenditures (CAPEX), conversion efficiencies, technical lifetimes, etc. These data were essentially based on (a) ASSET project (DeVita et al. 2018) and the Danish Energy Agency's technology data (DEA 2021b). For many technologies, capacity expansion is driven by political preferences rather than purely economic decision-making. For this reason, technology-specific assumptions were applied (Table 9), which are not modified across the three scenarios.

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

Table 9: Definition of scenarios for energy supply

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

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

- For transmission, Enertile endogenously models the transmission of electricity between model regions using a model of net transfer capacities (Lux and Pfluger 2020). In this analysis, each European country is represented by one node without grid restrictions within countries, known as a copper plate approach (Lunz et al. 2016). Capacity expansion is determined endogenously, taking into account CAPEX, grid losses and system service costs, e.g. for balancing or ancillary services.

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

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

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

As detailed in Popovski et al. (2023), CAPEX and O&M costs for networks are determined at hectare level as a function of the heat density, the potential road length, and the surface sealing density. The latter is based on an imperviousness dataset (Copernicus Land Monitoring Service 2018a), indicating the extent to which surfaces are covered with buildings and roads. Depending on the final energy demand for district heating resulting from Invert/Opt, a heat density threshold between 7 and 20 $GWh/(km^2 \cdot a)$ is set across the scenarios and countries. Cost data are taken from Persson et al. (2019), applying cost indices for labour (Eurostat 2022q) and material (Eurostat 2022s).

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

Table 10: Assumptions concerning fuel composition and prices for liquid and gaseous fuels in the building sector

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

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

Demand for synthetic fuels is derived from INVERT/OPT as part of the total demand for fuels in the building sector, applying assumptions on fuel composition and prices (Table 10). The assumed fuel compositions are based on the technical limitations for hydrogen in existing gas networks (Götz et al. 2016), estimated EU-wide potentials for bioenergy (van Nuffel et al. 2020; Peters et al. 2020), and the target of net-zero GHG emissions by 2050 (Hummel et al. 2023). Prices are either endogenously determined in ENERTILE (hydrogen, synthetic methane), based on dedicated projections (natural gas, crude oil, bio-methane) or on reasonable assumptions (bio-oil, synthetic liquid fuels).

Gas network costs up to 2050 are estimated based on a linear extrapolation of specific network charges (Eurostat 2022k, 2022l). Generally, a drop in gas demand is a key feature across net-zero emission scenarios (Tsiropoulos et al. 2020). In response, contrary to electricity infrastructures, gas networks are subject to decommissioning. Assuming that the rate of the decrease in gas demand is higher than the parallel decommissioning rate of gas networks implies increasing specific costs for the remaining network assets (Oberle et al. 2020). Hence, following see e.g. Hummel et al. (2023), it is assumed that (i) one third of the specific network costs scales inversely proportional with the decrease rate in gas demand and (ii) a 5% mark-up is added to the specific cost to account for the construction of parallel infrastructures for methane and hydrogen. This specific cost multiplied by the final energy demand for gas then yields the total network cost, which is counted under 'fuel costs in buildings' in Figure 3.

Air pollution impacts

This study estimated the impacts of air pollution on four receptors (González Ortiz et al. 2020): human health (mortality and morbidity); biodiversity (eutrophication and acidification); crop damage (agricultural yields); and material damage (building structure deterioration). The methodology is based on direct monetisation using cost rates per air pollutant and receptor. This involves the following steps:

1) Summary of energy consumption by energy carrier [kWh_{th}] | The four modelling tools yield data on energy consumption by energy carrier (e.g. natural gas), emission source (e.g. power plant), EU Member State, and scenario for the period 2020–2050.
2) Compilation of air pollution emission factors [$t_{emission}/kWh_{th}$] | Based on data from the European and German Environmental Agencies (EEA 2019; Lauf et al. 2023), each energy carrier is assigned an emission factor, differentiated by pollutant (e.g. sulphur dioxide, SO_2).[45]
3) Estimation of total emissions [$t_{emission}$] | Energy consumption by energy carrier multiplied by the respective emission factor yields the total emissions by pollutant.
4) Compilation of cost rates [$EUR_{2018}/t_{emission}$] | Cost rates by pollutant, emission source and receptor are available from Matthey and Bünger (2020) for Germany. For the health damage receptor, the cost rates are corrected for differences in gross domestic product per capita (Eurostat 2022w), reflecting that the willingness to pay for avoiding health damage increases with income.
5) Estimation of total damage costs [EUR_{2018}] | Multiplication of total emissions by cost rates yields the total damage costs by country, pollutant, and receptor.

Table 11: Cost rates by emission source, type and receptor [$EUR_{2018}/t_{emission}$]

		Emission source	
Emission type	**Receptor**	**Energy supply** [a]	**Buildings** [b]
SO_2	Health damage	5,898 – 28,287	6,826 – 32,742
	Biodiversity losses	1,010 – 1,072	1,010 – 1,072
	Crop damage	-214 – -202	-214 – -202
	Material damage	279 – 1,336	279 – 1,336
NO_X	Health damage	5,155 – 24,724	7,337 – 35,192
	Biodiversity losses	2,626 – 2,787	2,626 – 2,787
	Crop damage	808 – 858	808 – 858
	Material damage	46 – 223	46 – 223
PM	Health damage	10,263 – 49,224	20,200 – 96,889
NMVOC	Health damage	557 – 2,673	557 – 2,673
	Crop damage	1,010 – 1,072	1,010 – 1,072

Source: Matthey and Bünger (2020) | [a] Fuel combustion in electricity and district heating supply, [b] Fuel combustion in building sector | Ranges indicating differences among EU countries | SO_2 = sulphur dioxide, NO_X = nitrogen oxide, PM = particulate matter, NMVOC = volatile organic compounds without methane

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

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

3.3 Results

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

To summarise the overall performance of the three scenarios, Table 12 provides selected outputs for the EU-27. Note that the scenarios achieve GHG emissions reductions greater than 98% in 2050 compared to 2020. Assuming a balance of GHG sources and sinks according to the 1.5TECH scenario (European Commission 2018a) (see footnote 41), the three scenarios are all compatible with net-zero GHG emission levels in 2050. Cumulative GHG emissions have a small relative standard deviation of 3.3% due to the optimisation constraints in the INVERT/OPT and ENERTILE models being based on the 2050 GHG emission level, rather than the 2020–2050 carbon budget (see above).

3.3.1 Energy system cost and investment needs

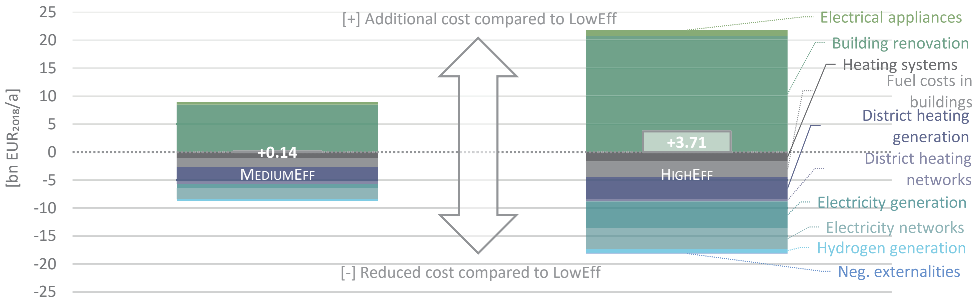
Figure 4 shows the performance of the three scenarios in terms of *ESC*. It indicates that the higher ambition levels for building sector energy efficiency in MEDIUMEFF and HIGHEFF are not necessarily cost-effective compared to the more moderate ambition level of LOWEFF. Additional costs amount to +0.14 bn EUR/a (MEDIUMEFF) and +3.71 bn EUR/a. (HIGHEFF). These two scenarios thus incur additional costs in order to achieve the common objective of net-zero GHG emissions by 2050.

Table 12: Overview of selected scenario outputs for EU-27

			Scenario		
Domain	**Indicator**	**Unit**	**LOWEFF**	**MEDIUMEFF**	**HIGHEFF**
Cost and emissions	Energy system cost 2020–2050 [a]	EUR_{2018}/a	530.59	530.73	534.29
	GHG emissions reduction in 2050 vs. 2020 [b]	-	-98.2%	-98.8%	-99.3%
	Cumulative GHG emissions 2020–2050 [b]	$MtCO_2eq$	12,540	12,172	11,741
Building sector [c]	Final energy consumption in 2050	*TWh*	3,488	3,060	2,812
	Annual building renovation rate (2050-2020) [d]	-	0.7%	1.4%	1.7%
Energy supply	Electrical generation capacities in 2050	GW_{el}	2,712	2,613	2,535
	Thermal generation capacities in 2050	GW_{th}	294	208	173
	Hydrogen electrolyser capacities in 2050	GW_{el}	303	290	282

[a] As defined in Equation 1 | [b] Sum of emission categories: Main activity electricity and heat production (1A1a), commercial/institutional (1A4a), residential (1A4b), according to IPCC (2019) | [c] Sum of sectors: commercial & public services (FC_OTH_CP_E), households (FC_OTH_HH_E), according to European Commission (2019a) | [d] Defined as equivalent full renovation rates, i.e. the share of conditioned floor area subject to full renovation of all building envelope components, divided by the conditioned floor area of the whole building stock

Figure 4: Energy system cost relative to LowEff scenario for EU-27 by cost item (2020–2050)



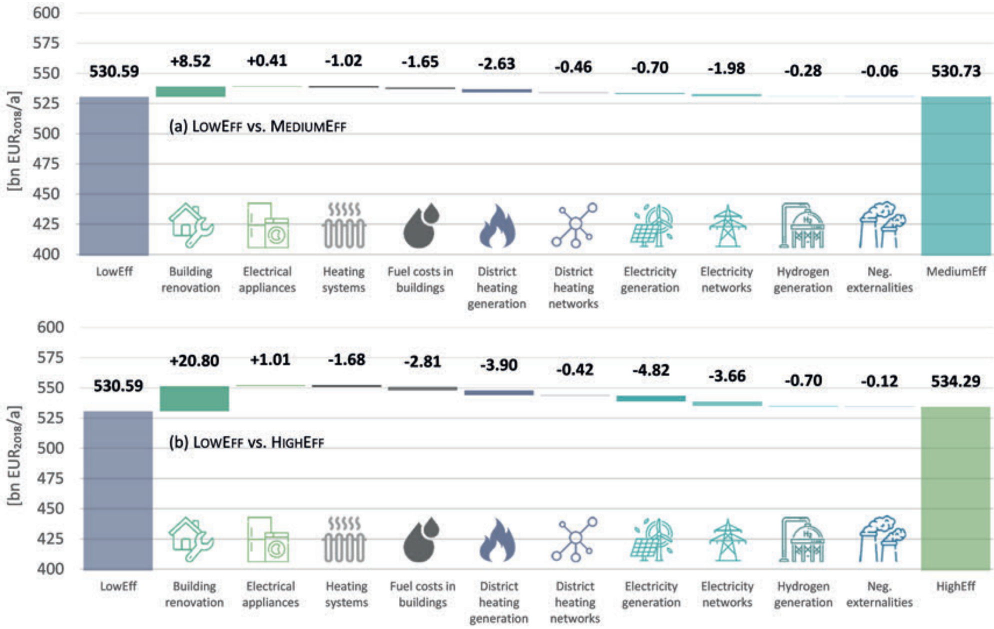
See Figure 3 for definition of cost items

Figure 5 illustrates the trade-off between saving energy and supplying energy when achieving net-zero GHG emissions in more detail. Improving energy efficiency in buildings lowers costs for decentralised heating systems as well as centralised energy supply (electricity, district heating, hydrogen). Moreover, there are some savings in air pollution damage costs (negative externalities). Overall, additional costs in MediumEff compared to LowEff amount to 8.9 bn EUR/a and are almost entirely offset by savings in energy supply of 8.8 bn EUR/a (98.4%). HighEff incurs incremental costs of 21.8 bn EUR/a and savings of 18.1 bn EUR/a (83.0%).

Overall, the aggregated cost volumes in Figure 5 are similar. Despite the significant differences in ambition levels for building sector efficiency, the scenarios all have average annual costs between 530.6 (LowEff) and 534.3 bn EUR/a (HighEff) over the period 2020–2050, i.e. a relative standard deviation of 0.4%. This demonstrates that energy system costs will be substantial until 2050, regardless of whether building sector efficiency is given absolute priority over supply-side resources or not.[46]

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

Figure 5: Decomposition of energy system costs in EU-27 by cost item (2020–2050)



See Figure 3 for definition of cost items

Table 13 shows the cumulative investment needs for the EU-27 in all scenarios over the period 2020–2050. This indicator differs from the *ECS* in that it only represents the initial capital expenditures of the technology options. The energy-saving measures, in particular building renovation, involve significant investments, but effectively reduce the investments in new energy supply. Again, differences in total investments across scenarios are moderate, with a relative standard deviation of 1.8%.

Unlike the trend for *ECS* (Figure 4, Figure 5), HighEff involves the lowest total investments across the EU-27 and therefore appears to be more favourable than the other scenarios. These total investments should not be over-interpreted, as they exclude any operating expenses, do not apply discounting, and include investments whose lifetime extends beyond the period 2020–2050. Therefore, *ECS* remains the central performance indicator in this analysis.

Table 13: **Investment needs in EU-27 by cost item (2020–2050) [bn EUR_{2018}]**

	Scenario		
Cost item [a]	**LowEff**	**MediumEff**	**HighEff**
Building renovation	228	248	276
Electrical appliances [b]	36	38	41
Heating systems	204	200	198
District heating generation	202	190	166
District heating networks	98	79	76
Electricity generation	5,212	5,167	5,023
Electricity networks [c]	219	207	204
Hydrogen generation	553	546	535
Total investment (2020–2050)	6,751	6,675	6,520

[a] See Figure 3 | [b] Residential buildings only | [c] Cross-border transmission networks only

3.3.2 Buildings

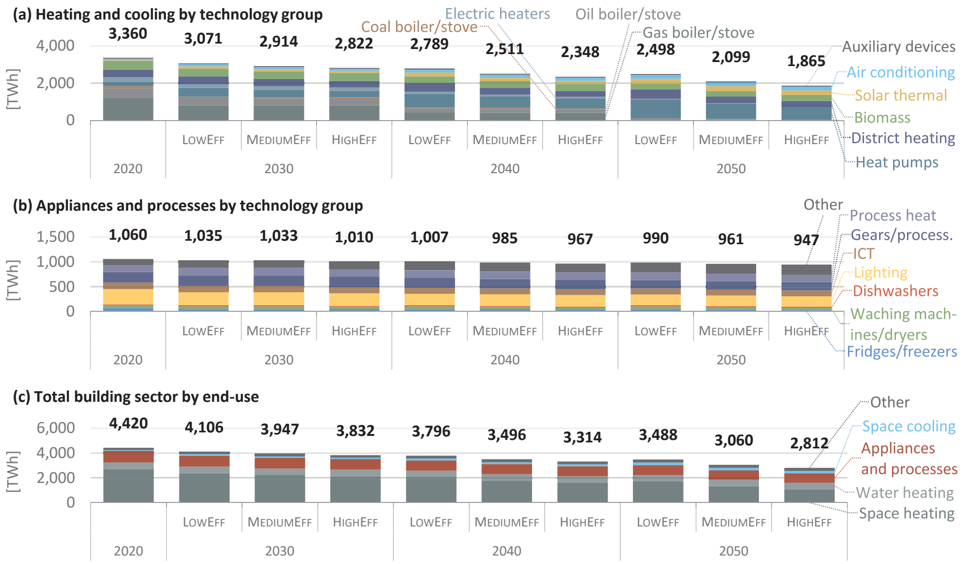
The Invert/Opt and Forecast models were used to project the energy required for residential and non-residential buildings. Figure 6a provides the breakdown of final energy consumption for heating and cooling by technology group. The aggregated difference between LowEff and HighEff in 2050 is 633 TWh. Across the three scenarios, heat pumps cover 42%–43% of total heating demand in 2050, with nominal capacities reaching 719 GW_{th} (HighEff) to 834 GW_{th} (LowEff) (data not shown here).

Figure 6b displays the final energy consumption for appliances and processes. In response to the tightened energy performance requirements (Table 8), HighEff achieves savings of 43 TWh in 2050 compared to LowEff. As described above, only technologies in households were explicitly modelled, while those in non-residential buildings were based on exogenous trends. As a result, these figures are relatively conservative (see e.g. European Commission 2021a).

The sum of all end-uses in the building sector is shown in Figure 6c. In comparison to 2020 levels, final energy consumption in 2050 is reduced by 21% (LowEff), 30% (MediumEff) and 35% (HighEff).[47] The levels of ambition for energy efficiency in all three scenarios are thus significantly above the business-as-usual pathways of the EU Reference Scenario, which projects a 10% decrease for the EU-27 building sector between 2020 and 2050 (Capros et al. 2021).

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

Figure 6: Final energy consumption in the building sector

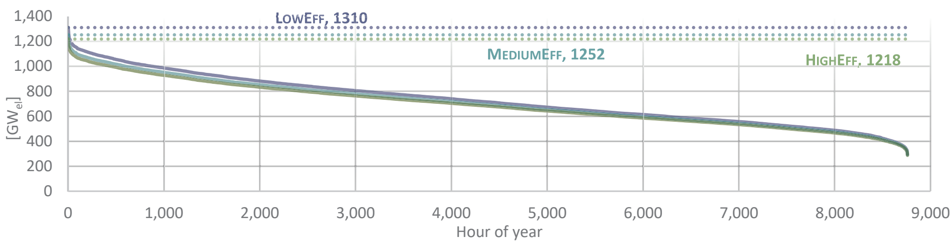


Heat pumps incl. electricity and ambient heat | ICT = information and communications technologies

3.3.3 Electricity supply

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

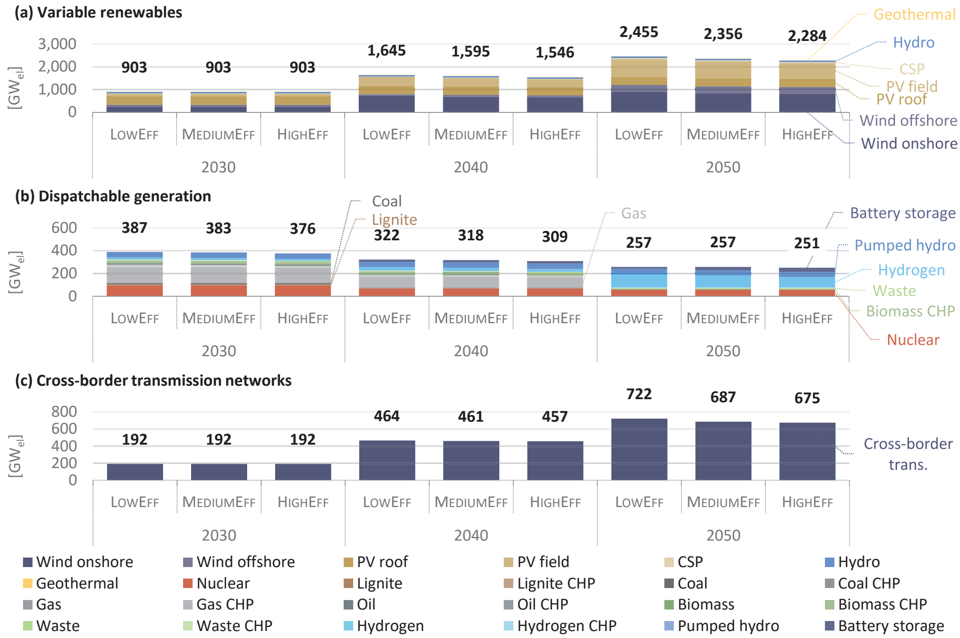
Figure 7: Electrical load duration curve in EU-27 in 2050



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

Likewise, as shown in Figure 8a, the more ambitious the level of energy savings, the less wind and solar power generation is needed. Installed capacities for variable renewables can be reduced by 171 GW_{el} or 7% in 2050 in HIGHEFF compared to LOWEFF. With regard to dispatchable generators in Figure 8b, especially the need for back-up hydrogen generators is reduced by 29 GW_{el} or 24% in HIGHEFF compared to LOWEFF. Also, as displayed in Figure 8c, cross-border transmission capacities can be reduced by 47 GW_{el} or 7% in HIGHEFF compared to LOWEFF.

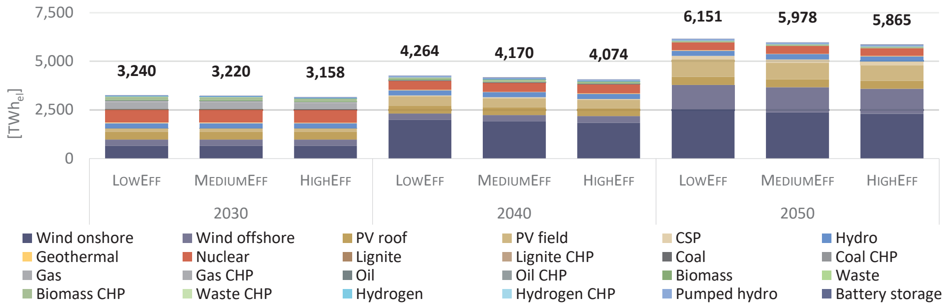
Figure 8: Electrical generation and transmission capacities by technology in EU-27



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

As Figure 9 shows, electricity generation increases significantly by 2050. Across all scenarios, variable renewable generators are the backbone of the power system, supplying around 90% of generation. Fossil generators are completely phased out by 2050, with dispatchable generation provided by biomass- and hydrogen-fired power plants as well as energy storage. In accordance with the scenario storylines (Table 9), nuclear power remains significant until 2050. In sum, overall generation in 2050 is lower by 3% (MEDIUMEFF) and 5% (HIGHEFF) compared to LOWEFF.

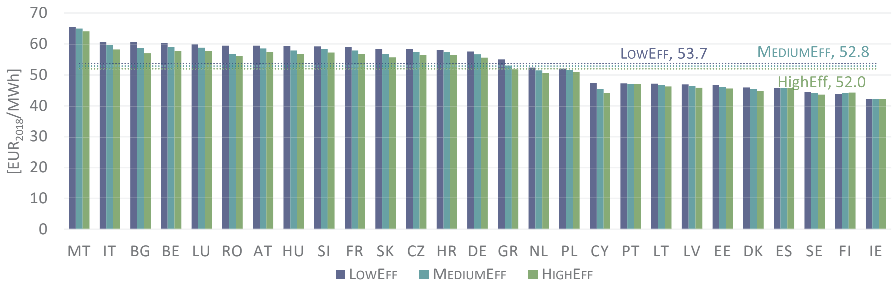
Figure 9: Electricity generation by technology in EU-27



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

As shown in Figure 10, energy savings in buildings also lead to a moderate reduction in long-term marginal electricity generation prices. For the entire EU, average prices in the year 2050 are reduced by 3% in HIGHEFF compared to LOWEFF. This is because energy efficiency reduces the installed capacities and thus the fixed cost components in total production costs. The marginal generator at a point in time thus operate at slightly lower marginal costs, resulting in lower clearing prices.

Figure 10: Long-run marginal prices for electricity generation in year 2050 by country

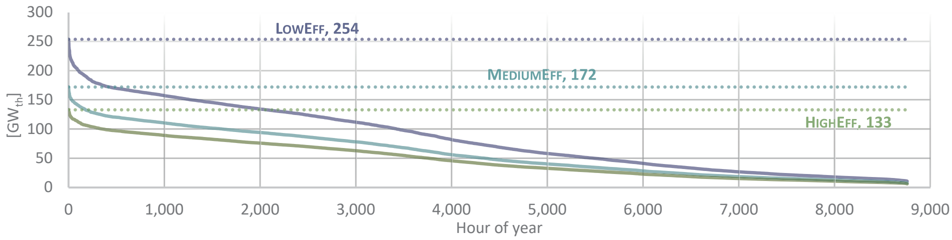


Horizontal lines: EU-27 average, weighted by electricity generation | Country codes according to European Union (2022a)

3.3.4 District heating supply

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

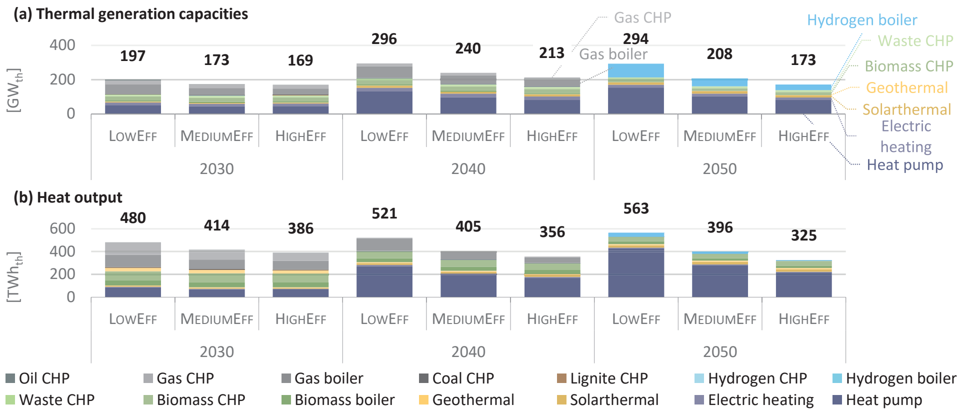
Figure 11: Thermal load duration curve for district heating in EU-27 in 2050



Heat load for entire EU, including buildings and industry

Reduced thermal load implies smaller capacities for heat supply, as shown in Figure 12a. The bulk of district heating capacity is provided by large-scale heat pumps, with installed capacities reaching 82 GW_{th} (HighEff) to 155 GW_{th} (LowEff) in 2050. Hydrogen-fuelled boilers account for 20% (HighEff) to 27% (LowEff) of total capacity in 2050. When linked to Figure 12b, it becomes clear that these boilers primarily operate at peak load, with full capacity equivalent hours between 246 h/a. (HighEff) and 411 h/a. (LowEff). Total heat output in 2050 is lower by 30% (MediumEff) and 42% (HighEff) compared to LowEff. Biomass contributes between 11% (LowEff) and 19% (HighEff) of heat output in 2050.

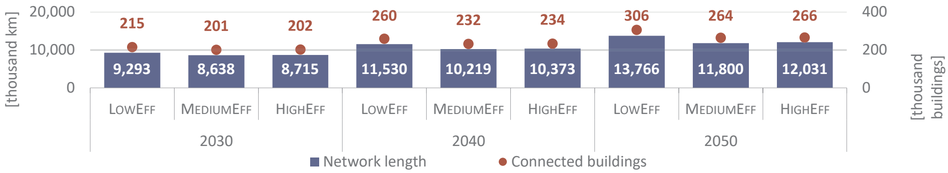
Figure 12: Thermal generation capacities and heat output for district heating by technology in EU-27



CHP = combined heat and power

Figure 13 displays the projected district heating network length along with the number of connected buildings. In 2050, total network length in HighEff is 1.7 million kilometres (13%) lower than in LowEff. Likewise, in HighEff, there are 40 thousand fewer buildings connected to district heating networks than in LowEff in 2050. Combining these numbers with heat output (Figure 12b) yields the heat density for district heating networks. These densities range from 41 (LowEff) to 27 (HighEff) MWh per year and network kilometre in 2050. In response to the building retrofits, the average utilisation of district heating networks in 2050 is thus 34% lower in HighEff compared to LowEff.

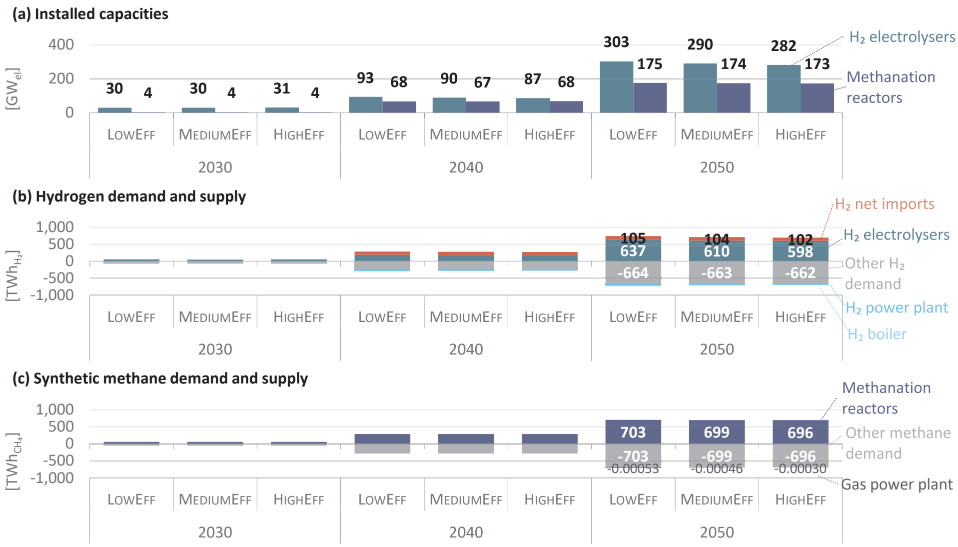
Figure 13: District heating network length and number of connected buildings in EU-27



3.3.5 Hydrogen supply

The Enertile model endogenously determines the capacity expansion and operation of hydrogen (H_2) supply. H_2 produced can either be reconverted in power plants and boilers, or synthesised into methane (CH_4). As shown in Figure 14a, more ambitious energy savings in buildings imply lower capacities for electrolysers and methanation reactors. H_2 capacity is reduced between 4% (MediumEff) and 7% (HighEff) compared to LowEff in 2050. Figure 14b and Figure 14c show the demand-supply balances for H_2 and CH_4, respectively. In both cases, slightly less energy is needed for heating purposes in boilers, fuel cells etc. when comparing HighEff and LowEff. Likewise, power plants and centralised boilers reconvert slightly lower volumes of both H_2 and CH_4 into electricity and heat.

Figure 14: Installed capacities and demand-supply balance for hydrogen and synthetic methane



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

3.3.6 Air pollution impacts

All three scenarios end up with net-zero GHG emissions levels by 2050. However, as presented in Table 14, the scenarios differ in terms of the air pollution emissions accumulating over the period 2020–2050, resulting from decentralised (buildings) and centralised (energy supply) combustion of energy carriers, particularly biomass. More energy savings on the demand side generally involve less air pollution, since combustion in thermal power plants, cogeneration plants, boilers and ovens is reduced.

3

This is reflected in different levels of damage costs from air pollution, as shown in Table 15. Across the scenarios, health damage is the most significant in monetary terms (82%), followed by biodiversity losses (13%–14%), crop damage (4%) and material damage (1%). Differences in total damage costs are marginal, with MEDIUMEFF and HIGHEFF saving 0.06 bn EUR/a and 0.12 bn EUR/a, respectively, compared to LOWEFF. As shown in the analysis of 'Energy system cost and investment needs', including or omitting monetised estimates of air pollution impacts in scenarios transitioning to net-zero GHG emissions does not significantly affect the overall cost-effectiveness of energy efficiency measures.

Table 14: Cumulative air pollution emissions for EU-27 (2020–2050) [$t_{emission}$]

		Emission type			
Scenario	**Emission source**	**NMVOC**	**NO_X**	**PM**	**SO_2**
LOWEFF	Buildings	573,046	6,897,457	932,037	2,702,254
	Energy supply	132,274	4,839,720	68,849	1,163,315
MEDIUMEFF	Buildings	571,072	6,855,804	941,435	2,701,009
	Energy supply	127,892	4,697,482	67,727	1,161,958
HIGHEFF	Buildings	570,133	6,859,144	957,270	2,701,942
	Energy supply	121,624	4,494,603	66,048	1,156,071

SO_2 = sulphur dioxide, NO_X = nitrogen oxide, PM = particulate matter, NMVOC = volatile organic compounds without methane

Table 15: Air pollution damage cost for EU-27 (2020–2050) [bn EUR_{2018}/a]

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

3.4 Discussion

This paper investigated the effect that moderate to ambitious levels of end-use energy efficiency in the EU building sector have on energy system cost and energy supply configurations. The general results indicate that implementing more ambitious energy-saving measures in buildings reduces the total electricity, heat and hydrogen capacities needed to achieve the transition to net-zero GHG emissions. However, according to the indicator of energy system cost (*ECS*), the ambitious energy savings portrayed in the MediumEff and HighEff scenarios are not necessarily cost-effective compared to the more moderate ambition levels of LowEff. This chapter gives an overview of methodological limitations and discusses policy implications.

3.4.1 Critical appraisal

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

Internal MIs accrue to individual decision-makers, e.g. a building occupant. To illustrate, building retrofits in combination with advanced ventilation systems affect thermal comfort, which can have significant benefits in the form of improved health and labour productivity (Chatterjee and Ürge-Vorsatz 2021). There are also internal MIs that occur as costs. Transaction costs or the 'time and hassle' borne by building owners and developers during the planning and implementation phases of retrofits can be as high as 20% of the initial investment (Kiss 2016).

There are also external MIs borne by society as a whole, i.e. externalities. As described above, negative externalities from air pollution are relatively insignificant under a net-zero GHG emissions constraint, as renewable energy sources gradually replace fossil fuels while the utilisation of bioenergy carriers is similar across the scenarios.[48] However, there are also external costs related to renewable energy supply, including changes to land use, aesthetic issues, disruption of ecosystems, water use, and others (Sovacool et al. 2021).[49] Ideally, to ensure a fair comparison of resource options,

48 Projected biomass consumption in the EU-27 – including buildings, electricity supply and district heating supply – is between 48 Mtoe (LowEff) and 50 Mtoe (HighEff) in 2050. When also including the assumed sectoral trends for transport and industry of the 1.5TECH scenario (European Commission 2018a) (see footnote 41), total biomass consumption amounts to 120–122 Mtoe, which is well below the sustainable potential for bioenergy for the EU-27 of 196–335 Mtoe estimated by Panoutsou and Maniatis (2021).

49 In a meta-analysis of 139 studies, Sovacool et al. (2021) arrive at mean external costs for electricity supply

all negative externalities related to the processing of materials and manufacturing would need to be taken into account by a life cycle assessment, including those related to building insulation materials (Rodrigues and Freire 2021). In turn, there may also be significant positive externalities from energy efficiency, e.g. energy security in the sense of a reduced risk related to imported energy sources (Gillingham et al. 2009).

3

The magnitude of multiple impacts can be significant in cost-benefit analysis indicators such as the *ECS*. According to a screening of studies in Ürge-Vorsatz et al. (2016), the monetary impact of MIs in the building sector can be 0.2 to 3.2 times the value of the energy savings made. When applying the conservative end of this range to the *ECS* (see 'Figure 4'), the MediumEff scenario would clearly be cost-effective (1.54 bn EUR/a reduced costs compared to LowEff) while HighEff would remain cost-*in*effective (+0.23 bn EUR/a additional costs compared to LowEff). Hence, it is likely that the societal value of building efficiency measures is significantly undervalued in this study.

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

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

Eichhammer (2022) demonstrates that high energy prices have a significant effect on the cost-effectiveness of energy savings. To illustrate, using the values in 'Figure 5', the prices for coal, oil and gas would need to be +5% (MediumEff) and +68% (HighEff) higher over the period 2020–2050 than in the default trends (see 'Table 9') to make these scenarios cost-effective compared to LowEff, all else equal. Beyond short-term shocks, the long-term price trend for fossil fuels until 2050 may not necessarily go upward. In the sense of a macroeconomic rebound effect (Brockway

ranging from 2.9 ¢/kWh for wind power, through 5.3 ¢/kWh for PV, up to 14.5 ¢/kWh for coal – values that closely match their respective levelised cost of electricity (LCOE) (Lazard 2021).

et al. 2021), the wholesale prices for oil, gas and oil could decrease in response to significant global reductions in energy demand and large-scale deployment of renewable energies. Hence, long-term fossil fuel price trends could either improve or reduce the cost-effectiveness of energy efficiency measures.

Another limitation of this study is its restricted scope of relevant demand-side resources in the building sector that could contribute to both cost and emission savings (Mandel et al. 2022c). Apart from end-use energy efficiency, these also encompass energy sufficiency, i.e. strategies for reducing consumers' energy service needs while keeping utility constant (Thomas and Brischke 2015; Sorrell et al. 2020).[50] Another example is demand response. While this study did include price-based flexibility provision from both centralised and decentralised heat pumps as part of the ENERTILE model (Bernath et al. 2019), the scenario design does not allow the isolated effect of these actions to be determined for *ECS* and other outputs. The reported economic benefits of demand response generally involve lower, stable electricity prices (Paterakis et al. 2017) and related reductions in consumer bills (Brown and Chapman 2021).

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

3.4.2 Policy implications

Setting measurable targets for energy efficiency is key to keeping track of policy progress and guiding policy measures. Table 16 refers the ambition level of the three scenarios for the building sector to the energy efficiency target for final energy consumption set in the Energy Efficiency Directive (EED). For this purpose, projections for the transport and industry sectors were adopted from the *REG_MAX* scenario in the impact assessment accompanying the European Commission's proposal for a recast of the EED (2021c). Final energy consumption levels by 2030 in the scenarios lie roughly between the target set in the amended directive ('EED-2018') (European Union 2018b, Art. 3) and the one in the proposal for a recast EED ('EED-2021') (European Commission 2021e, Art. 4). The scenarios thus generally support a revision of the EED-2018 towards higher ambition levels of at least 35% in final energy terms.

50 One example of a sufficiency measure in the TECH scenario within the EUCalc model (EUCalc 2022; Pestiaux et al. 2019) is that encouraging a reduction in living space per person from an average of 49.5 m^2 to 43.4 m^2 across the EU could decrease final energy demand in the building sector in 2050 by 3.9%.

However, as described above, very ambitious levels of energy efficiency in buildings may lead to additional costs compared to the LowEff scenario. This is in contrast to studies that call for an energy efficiency target beyond 40% without considering the effects of escalating energy prices and multiple impacts.[51] In conservative terms, therefore, the ambition level of the EED-2021 proposal can be seen as a reasonable benchmark. Higher ambition levels could be reasonably justified on the grounds of multiple impacts beyond financial savings as well as on the grounds of higher wholesale energy prices.[52]

The findings of this study are also congruent with the goal in the European Commission's Renovation Wave strategy (2020a) to *"at least double the annual energy renovation rate of residential and non-residential buildings by 2030."* According to the Invert/Opt model, average renovation rates for the EU-27 over the period 2020–2050 range from 0.7% in the LowEff scenario, through 1.4% in MediumEff to 1.7% in HighEff (Table 12). The renovation rate in LowEff can be interpreted as a continuation of current trends (European Commission 2020c; Esser et al. 2019). Hence, the renovation rate in MediumEff corresponds to the current political ambition, with HighEff going beyond that ambition.

Table 16: Energy efficiency targets for 2030 in the Energy Efficiency Directive

		PRIMES-2007 baseline [d]	**PRIMES-2020 baseline [e]**
Energy efficiency target for final energy consumption in 2030 | % difference to baseline			
EED-2018 [a]	846 Mtoe	1,253 Mtoe | -32.5%	864 Mtoe | -2.1%
EED-2021 [b]	787 Mtoe	1,253 Mtoe | -37.2%	864 Mtoe | -9.0%
Scenario projections for 2030 [c] | % difference to baseline			
LowEff	800 Mtoe	1,253 Mtoe | -34.8%	864 Mtoe | -5.5%
MediumEff	792 Mtoe	1,253 Mtoe | -35.5%	864 Mtoe | -6.5%
HighEff	786 Mtoe	1,253 Mtoe | -36.0%	864 Mtoe | -7.2%

[a] Based on amended EED (European Union 2018b, Art. 3), excluding United Kingdom (European Union 2019b) | [b] Based on Commission proposal for EED recast (European Commission 2021e, Art. 4) | [c] Projections for industry and transport sectors based on REG_MAX scenario in Impact Assessment accompanying EED recast (European Commission 2021c) | [d] EU Reference Scenario 2007 (Capros et al. 2007) | [e] EU Reference Scenario 2020 (Capros et al. 2021)

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

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

52 Eichhammer (2022) assesses the effect of a 30% increase in wholesale energy prices and finds that this would legitimise a higher EU energy efficiency target of 42.3% (final energy) compared to PRIMES-2007.

3.5 Conclusion

This study set out to provide quantitative evidence for the relevance of the energy efficiency first (EE1st) principle in the EU by modelling the effect of moderate to ambitious end-use energy efficiency measures on an energy supply system that is transitioning towards net-zero GHG emissions. [53] Two major conclusions can be drawn from this work.

First, energy efficiency in buildings is crucial for a cost-efficient transition to a net-zero emissions energy system. Given the close similarity in energy system cost (*ECS*) between LowEff and MediumEff, it can be inferred that ambition levels for energy efficiency *below* LowEff are likely to result in *additional* costs. The LowEff scenario (21% reduction in final energy consumption for buildings in 2050 vs. 2020 levels) can thus be seen as the lower end of possible ambition levels for energy efficiency in buildings. This ambition level is significantly above the business-as-usual pathway of the EU Reference Scenario (10% reduction for buildings in 2050 vs. 2020) (Capros et al. 2021). A relevant issue for future research is how a 'NoEff' scenario with energy efficiency in buildings below LowEff would perform in terms of energy system cost and what risks this pathway involves with a view to the security of supply and the required expansion of renewables, among others.

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

In terms of policy implications, the findings of this work support a higher energy savings target in the EED of at least 35% in final energy terms compared to the PRIMES-2007 reference, as well

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

as a doubling of building renovation rates. While the modelling techniques applied do not allow a detailed analysis of policy measures, it is evident that each scenario pathway requires a combined approach of saving energy and decarbonising energy supply. As addressed in dedicated research (Pató and Mandel 2022; Mandel et al. 2022b), properly applying the EE1st principle requires electricity market reforms, incentive regulation for network companies, carbon pricing, financing schemes, and other actions.

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

4

Balancing heat saving and supply in local energy planning: insights from 1970–1989 buildings in three European countries

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4.1 Introduction

4.1.1 Background

Urban areas play a critical role in the European Union's (EU) transition towards a net-zero emissions energy system. About 75% of the EU's population currently lives in urban areas (Lavalle et al. 2018), a figure expected to rise to 84% by 2050 (United Nations 2018). Through local energy planning, municipal decision-makers can contribute to fossil-free urban energy systems, job creation, and other energy-related objectives (Johannsen et al. 2021; Neves et al. 2015; Herreras Martínez et al. 2022).

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In this context, residential and non-residential buildings are key, given their life cycles of 40 to 100 years (Abd Rashid and Yusoff 2015) and their share of 40% in EU-wide final energy consumption (Eurostat 2022b). Significant thermal energy saving potential exists for building envelope upgrades – especially for existing buildings, of which at least 75% are expected to still exist by 2050 (Esser et al. 2019). Resulting heat savings can reduce the size and associated investment required for both centralised district heating (DH) and decentralised heating solutions, as well as related infrastructures for heat, electricity, and gas (Mandel et al. 2023a; Zeyen et al. 2021). Hence, combinations of measures on the building envelope and technical systems can create synergies that lead to better outcomes regarding costs and energy performance than single measures (European Union 2012c).

With the 'energy efficiency first' (EE1st) principle laid down in the Governance Regulation (European Union 2018d), the EU aims to systematically prioritise energy efficiency solutions (e.g., building retrofits) whenever these cost less or provide more value to society than energy supply (e.g., DH system expansion) in meeting consumers' energy service needs. The principle can help avoid lock-in to long-lived energy infrastructures, ensure that energy service needs are met using the least-cost alternatives available, and thus contribute to a cost-efficient decarbonisation of the EU (Mandel et al. 2022c). As such, the concept of EE1st is closely related to that of smart energy systems (Mathiesen et al. 2015; Lund et al. 2017), as both concepts aim to combine and coordinate technological and behavioural solutions to achieve an optimal solution for the whole energy system.

4.1.2 State of research

As urban planners become more engaged in energy planning, they require robust modelling tools to support local energy strategy development and decision-making. The research literature features over 100 modelling tools for urban- to regional-scale energy system analysis (Yazdanie and Orehounig 2021), as described in a variety of review articles (Allegrini et al. 2015; Anderson et al. 2015; Ferrari et al. 2019; Keirstead et al. 2012; Manfren et al. 2011; Markovic et al. 2011; van Beuzekom et al. 2015). These tools differ in terms of purpose, technologies and energy end-uses considered, and levels of temporal and spatial detail.

A research line particularly relevant in the context of the EE1st principle deals with the techno-economic balance of energy savings and energy supply options (Delmastro and Gargiulo 2020; Milic et al. 2020; Romanchenko et al. 2020; Büchele et al. 2019; Ben Amer-Allam et al. 2017; Harrestrup and Svendsen 2014; Wu et al. 2017; Le Truong et al. 2014; Popovski et al. 2023; Mandel et al. 2023a; Zeyen et al. 2021; Kapsalaki et al. 2012; D'Agostino and Parker 2018; Connolly et al. 2014; Hansen et al. 2016). For example, analysing the city of Brasov (Romania), Büchele et al. (2019) show that heat savings of 58-78% compared to existing levels are more cost-effective than all assessed heat supply options. Similarly, for the case of Copenhagen (Denmark), Harrestrup and Svendsen (2014) find that it is slightly cheaper to invest in thermal retrofits that reduce heat demand by 65% before deploying new renewable DH supply. These studies generally indicate that reductions in building energy demand up to a certain level could involve lower overall cost than the expansion of energy supply options alone. This underscores the relevance of integrated urban energy planning in line with both the EE1st principle and smart energy systems.

However, some research gaps remain. Many of the above studies apply only to a selected context with specific climate conditions, energy resource potentials, and price levels (Delmastro and Gargiulo 2020; Milic et al. 2020; Romanchenko et al. 2020; Büchele et al. 2019; Ben Amer-Allam et al. 2017; Harrestrup and Svendsen 2014; Wu et al. 2017; Le Truong et al. 2014). In turn, relatively few studies apply the same approach to multiple contexts (Hansen et al. 2016; Kapsalaki et al. 2012; Popovski et al. 2023; Zeyen et al. 2021; D'Agostino and Parker 2018; Mandel et al. 2023a; Connolly et al. 2014), highlighting the need for systematic comparative analysis. Moreover, in terms of heating options, some of the studies focus exclusively on either centralised DH systems (Harrestrup and Svendsen 2014; Le Truong et al. 2014; Milic et al. 2020; Romanchenko et al. 2020) or decentralised building-integrated solutions (Wu et al. 2017; Kapsalaki et al. 2012), requiring integrated analysis to include all potentially cost-effective options. Finally, most studies focus on the private internal costs borne by building owners or utility companies (Delmastro and Gargiulo 2020; Milic et al. 2020; Romanchenko et al. 2020; Büchele et al. 2019; Harrestrup and Svendsen 2014; Wu et al. 2017; Popovski et al. 2023; Zeyen et al. 2021; Kapsalaki et al. 2012; D'Agostino and Parker 2018; Connolly et al. 2014). Apart from occasional adjustments to discount rates, they frequently overlook the societal perspective (Ürge-Vorsatz et al. 2016), also known as macroeconomic (European Union 2012c), that encompasses external costs such as air pollution. Incorporating the full societal implications of energy supply and savings options is fundamental to the EE1st concept, as it forms a normative benchmark for informed energy planning and policy-making (Mandel et al. 2022c).

4.1.3 Research objectives

Understanding the synergies between heat savings and supply in urban areas is crucial to determine sustainable, technically robust, and economically viable system configurations. This study aims to inform public policy through the application of spatially resolved building energy modelling. The analysis focuses on identifying potentially cost-efficient combinations of (i) building envelope renovation packages, (ii) decentralised heat supply, and (iii) centralised DH options.

For this purpose, a hypothetical case study is devised, featuring a generic urban district composed of residential, commercial, and educational buildings from the 1970-1989 construction period in need of major renovation - concerning both building envelopes and technical heating systems.[54] This situation prompts a benevolent urban planner in the year 2020 to determine which options (i-iii) should be prioritised. In evaluating these options, the study adopts a societal perspective, considering society's time preference and explicitly including external costs from direct greenhouse gas (GHG) and air pollution emissions, to align with broader socio-environmental interests.[55]

To account for the geophysical and economic heterogeneity across the EU, the generic urban district is analysed for country-specific conditions in Bulgaria (BG), Germany (DE), and Finland (FI). Differences thus result from climate conditions, current building energy performance, and price levels.[56] Given the hypothetical setting, the study addresses the question of how much the energy for space heating should be reduced through building retrofits and how it should be supplied in a building stock from the from the 1970-1989 construction period. In a sensitivity analysis, particular attention is paid to critical assumptions, such as the effect of supply temperatures on heat pump performance.

This study is structured as follows. Section 4.2 describes the methodology. Section 4.3 provides the numerical results. Section 4.4 discusses the methodological limitations and policy implications of the study. Finally, Section 4.5 concludes the study and suggests future research directions.

4.2 Methodology

The methodology adopted in this study is visualised in Figure 15, comprised of four steps. First, a generic urban district is defined (Section 4.2.1), which is analysed across the countries BG, DE, and FI. Second, the energy need for heating is calculated for each building within the urban district, according to three renovation packages (Section 4.2.2). Third, the costs of these renovation packages,

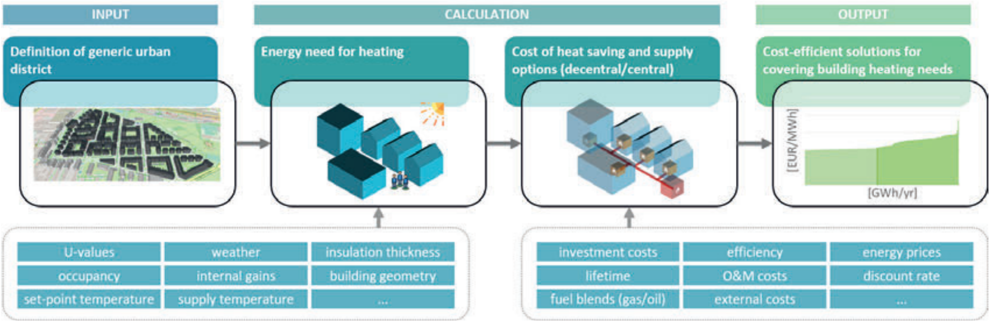
54 For the reference year 2020, the choice of the 1970-1989 period was justified by the typical 30-50 year renovation cycle of buildings (European Union 2012c). Additionally, this construction period represents around 28% of the EU dwelling stock (European Commission 2023).

55 GHG and air pollution emissions are not only classic externalities (Perman et al. 2011) but also significant multiple impacts in the energy efficiency discussion (Ürge-Vorsatz et al. 2016; Fawcett and Killip 2019). For the EU building sector in 2030, their monetary value has been estimated at 0.11 times the value of energy cost savings for GHG and 0.25 times for air pollution emissions (Thema et al. 2019).

56 To illustrate these aspects, average heating degree days (2010-2020) range from 2,432 (BG) to 5,390 (FI) (Eurostat 2022f). Average useful energy demand for space heating in residential buildings ($kWh/(m^2yr)$ ranges from 59 (BG) to 196 (FI) (Pezzutto et al. 2019). The consumer price level index for energy (EU_{27}=100) is between 56 (BG) and 120 (DE) (Eurostat 2022v).

as well as the costs of both decentralised and centralised heat supply options are determined (Section 4.2.3). Finally, cost-efficient combinations of these options are calculated (Section 4.3).

Figure 15: Methodology for determining cost-efficient combinations of building renovation measures and heat supply options



4.2.1 Definition of generic urban district

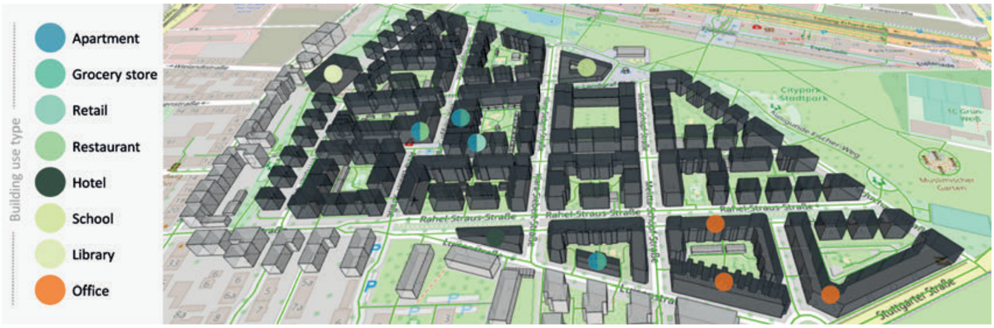
The generic urban district is characterised as a municipally owned city district of 15 hectares, built in the 1970-1989 construction period and inspired by the real district 'Citypark' in Karlsruhe, Germany.[57] It comprises 125 buildings ranging from 1 to 7 storeys, with a peak occupancy of around 11,000 people. As shown in Table 17, eight building use types are assumed in the district.

The City Energy Analyst (CEA) model[58] (Fonseca et al. 2016; ETH Zurich 2022) is used to generate a digital elevation model of the building topography in the generic urban district (Figure 16). The resulting building geometry data (footprint area, height, orientation) serves as an input for calculation of heating energy needs. Based on OpenStreetMap (2023), the CEA model also endogenously provides data on road lengths, which are relevant for the estimation of feasible district heating networks (Section 4.2.3).

57 Location: 49°00'08.3"N 8°25'02.5"E

58 CEA is a Python-based open-source model framework for the analysis and optimisation of energy systems in neighbourhoods and city districts (ETH Zurich 2022). This study uses CEA version 3.31.

Figure 16: Digital elevation model of the urban district by building use type



Source: Unless otherwise indicated, all shaded buildings are multi-family apartment buildings

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Table 17: Characterisation of generic urban district by building use type

	Conditioned floor area		Peak occupancy	
Use type	**[m^2]**	**[%]**	**[people]**	**[%]**
Apartment	181,716	79.6%	5,681	51.3%
Grocery store	1,168	0.5%	41	0.4%
Hotel	1,761	0.8%	102	0.9%
Library	6,584	2.9%	1,536	13.9%
Office	30,884	13.5%	2,057	18.6%
Restaurant	2,282	1.0%	133	1.2%
Retail shop	979	0.4%	27	0.2%
School	2,988	1.3%	1,494	13.5%
Total	**228,361**	**100.0%**	**11,071**	**100.00%**

4.2.2 Renovation packages and energy need for heating

The balance between building renovation and heating systems is examined by defining three renovation packages with varying energy performance requirements:[59]

- EXISTING: No thermal retrofits are applied. Buildings undergo usual refurbishment to maintain aesthetics, functionality, and safety, but without affecting thermal energy performance.

59 As per (Mandel et al. 2023a; Mazzarella 2015), 'retrofits' are here understood as the process of enhancing building energy performance, e.g., through insulation. 'Refurbishments', in turn, involve maintaining or upgrading building aesthetics, functionality, and safety without targeting energy performance. Lastly, 'renovation' comprises both retrofits and refurbishments.

- STANDARD: Light retrofit packages are applied to roofs, windows, walls, and floors, resulting in effective energy savings and reduced need for heat supply.
- ADVANCED: Deep retrofit packages, reflecting the best available options, are implemented to significantly improve building energy performance.

The thermo-physical properties of the individual buildings are based on the reference buildings of the TABULA building typologies (Ballarini et al. 2014; Loga et al. 2016; TABULA/EPISCOPE 2017), selecting multi-family buildings from around the 1970-1989 period. Table 18 presents the thermal heat transfer coefficients (U-value, $W/(m^2 \cdot K)$) and the added insulation thickness (*cm*) for each renovation package. The specific costs are described in Section 4.2.3.

To calculate the energy need for heating (European Union 2012c) associated with the defined renovation packages, the CEA model is applied to each of the 125 buildings defined in Section 4.2.1. As detailed in (Fonseca et al. 2016; Fonseca and Schlueter 2015), the model computes heating needs using an hourly single-zone resistance-capacitance model based on EN ISO 13790:2008. This essentially takes into account (a) heat losses from ventilation and transmission, and (b) heat gains from occupancy, solar radiation, and internal loads.

For this purpose, the model determines hourly occupancy schedules for the building use types listed in Table 17, utilising a dedicated occupant presence model described in Happle et al. (2020). This results in hourly ventilation rates, along with consumption values for appliances, lighting, and other energy services that affect internal gains, as summarised in Table B1. Solar heat gains are estimated in CEA based on hourly solar irradiation, topographic obstructions by surrounding buildings and atmospheric effects (Fonseca and Schlueter 2015). Weather files representing a typical meteorological year (2007-2021) for the locations of Sofia (BG), Berlin (DE), and Helsinki (FI) are obtained in EnergyPlus Weather (.epw) format from Climate.OneBuilding (2023).

Boundary conditions across countries and renovation packages are given in Table B2. Specifically, the set-point temperature in all buildings is set to 20 *°C* (Østergaard et al. 2022). Heating temperatures affect the performance of heat pumps. In EXISTING buildings, radiators with nominal supply/return temperatures of 70*°C*/55*°C* are assumed (Østergaard and Svendsen 2016). The original radiators are preserved in each renovation package. Due to lower heat loads and given typically oversized radiators in 1970-1989 buildings (Østergaard and Svendsen 2016; Østergaard et al. 2022), nominal temperatures in STANDARD and ADVANCED renovations are reduced to 60*°C*/50*°C* and 55*°C*/45*°C*, respectively, without compromising thermal comfort (Østergaard and Svendsen 2016; Brand and Svendsen 2013). Floor heating installation is not incorporated, given its potentially prohibitive renovation costs (IRENA 2021).

Table 18: Building characteristics by country, package and element

		Element by U-value [$W/m^2 K$] | Insulation added [cm] | Specific investment costs [$EUR2020/m^2$]			
Country	Package	Roof	Wall	Floor	Window
Bulgaria	EXISTING	0.59 W/m²K | - | -	0.93 W/m²K | - | -	1.29 W/m²K | - | -	2.63 W/m²K | - | -
	STANDARD	0.26 W/m²K | 8 cm | 29.18 EUR/m²	0.31 W/m²K | 8 cm | 38.06 EUR/m²	0.38 W/m²K | 7 cm | 17.52 EUR/m²	1.40 W/m²K | - | 79.80 EUR/m²
	ADVANCED	0.26 W/m²K | 8 cm | 29.18 EUR/m²	0.31 W/m²K | 8 cm | 38.06 EUR/m²	0.27 W/m²K | 10 cm | 19.14 EUR/m²	0.80 W/m²K | - | 109.29 EUR/m²
Germany	EXISTING	0.43 W/m²K | 6 cm | -	0.80 W/m²K | - | -	0.65 W/m²K | - | -	3.00 W/m²K | - | -
	STANDARD	0.17 W/m²K | 12 cm | 57.40 EUR/m²	0.21 W/m²K | 12 cm | 81.15 EUR/m²	0.26 W/m²K | 8 cm | 33.98 EUR/m²	1.30 W/m²K | - | 159.41 EUR/m²
	ADVANCED	0.09 W/m²K | 30 cm | 68.63 EUR/m²	0.12 W/m²K | 24 cm | 109.70 EUR/m²	0.20 W/m²K | 12 cm | 38.04 EUR/m²	0.80 W/m²K | - | 205.65 EUR/m²
Finland	EXISTING	0.17 W/m²K | - | -	0.33 W/m²K | - | -	0.27 W/m²K | - | -	2.04 W/m²K | - | -
	STANDARD	0.09 W/m²K | 20 cm | 58.52 EUR/m²	0.21 W/m²K | 5 cm | 60.49 EUR/m²	0.21 W/m²K | 4 cm | 28.06 EUR/m²	0.90 W/m²K | - | 184.23 EUR/m²
	ADVANCED	0.05 W/m²K | 50 cm | 76.08 EUR/m²	0.08 W/m²K | 30 cm | 116.30 EUR/m²	0.20 W/m²K | 45 cm | 67.14 EUR/m²	0.76 W/m²K | - | 196.37 EUR/m²

U-values and insulation thickness based on (Ballarini et al. 2014; Loga et al. 2016; TABULA/EPISCOPE 2017), using Sweden as proxy for Finland | Specific investment costs based on linear functions in Table B3, expressed per m^2 of component area; including materials, labour and professional fees; excluding general refurbishment costs (scaffolding, paint works, etc.) (Footnote 59)

4.2.3 Cost calculation

This section outlines the cost metrics for building renovation, decentralised, and centralised heat supply, as well as related energy and external costs. The analysis explicitly employs a societal perspective (Mandel et al. 2022c; Ürge-Vorsatz et al. 2016). Following standard cost-benefit analysis (Atkinson et al. 2018; Konstantin and Konstantin 2018a; Khatib 2014), this evaluation perspective features a low discount rate here set at 2%/yr, excludes taxes and subsidies as financial transfers within society, incorporates external costs in the form of climate and air pollution damages, and expresses present values in real terms (Eur_{2020}), excluding inflation.

Apart from the building structures, the study adopts a greenfield approach (van Beuzekom et al. 2015), which disregards any existing assets such as thermal networks. It also assumes that building renovation takes place all at once, rather than in stages (Maia et al. 2023). This corresponds to the narrative in Section 4.1 that at the time of analysis, both building envelopes and technical heating systems require significant renovation.

Building renovation

The specific costs of building renovation packages C_{ren} for a given country and building are calculated using Equation 2, where α is the annuity factor ($1/yr$) for a building element m, A is the element area

(m^2), I represents the specific initial investment costs (EUR/m^2)[60], and ΔQ denotes the useful energy savings compared to the EXISTING building state (MWh/yr). The discount rate is symbolised by δ, and the building element lifetime is indicated by n.

$$C_{ren} = \sum_m (\alpha_m \cdot A_m \cdot I_m) \,/\, \Delta Q \qquad [EUR_{2020}/MWh]$$

where Equation 2

$$\alpha_m = \frac{\delta}{1-(1+\delta)^{-n_m}} \qquad [1/yr]$$

The cost calculation follows this approach:

1) Linear cost function parameters are obtained from (Hummel et al. 2021; Hinz 2015) for DE in 2017 (Table B3).[61] For envelopes, the specific investment cost (EUR/m^2) is a function of added insulation (cm); for windows, the cost is a function of the U-value ($W/(m^2.K)$). The costs represent the sum of material costs, labour costs, and professional fees, excluding value added tax and miscellaneous charges.
2) Two adjustments are made to the data: (a) the values are transferred to BG and FI in 2017 (EUR_{2017}) using Eurostat's price level indices for construction (Eurostat 2022u); (b) the country-specific values are then adjusted to EUR_{2020} levels using construction cost indices (Eurostat 2022e).

The resulting specific investment costs by building element are given in Table 18. In line with the 'improvement' approach in Streicher et al. (2020), these values represent the additional *retrofit* costs to improve a building's thermal performance, excluding *refurbishment* costs (see Footnote 59) necessary for maintaining aesthetics and functionality (scaffolding, paint works, etc.). As per EN 15459-1, technical lifetime is set at 50 years for all insulation measures and 30 years for windows.

Decentralised heat supply

The specific costs for decentralised heating systems (C_{dec}) are calculated using Equation 3, dividing the present value of all expenses by the present value of energy needs for space heating (Q_h) and water heating (Q_w). I represents the initial investment costs, C_{ene} denotes energy costs (including auxiliary electricity needs), $C_{o\&m}$ refers to non-fuel-related operation and maintenance costs

60 Following Commission Delegated Regulation (EU) No 244/2012 (European Union 2012a), this study uses the term 'initial investment costs', although it is regarded as incorrect in accounting terms, as costs represent recurrent outlays, while investments (or capital expenditures) are non-recurrent capital outlays for future returns (Konstantin and Konstantin 2018a).

61 As discussed in Hummel et al. (2021), alternative national sources for renovation costs do exist (e.g. Fernández Boneta 2013) but tend to lack internal consistency. Therefore, the study adopts a common approach based on Germany's values.

(inspections, cleaning, etc.), and C_{ext} stands for external costs. Additionally, t is the annual time step, n indicates the technology lifetime, α is the annuity factor (see Equation 2), ρ is the energy price, and η represents the conversion efficiency.

$$C_{dec} = \left(I + \sum\nolimits_{t=1}^{n} \frac{C_{ene,t} + C_{o\&m,t} + C_{ext,t}}{(1+\delta)^t}\right) / \left(\frac{Q_H + Q_W}{\alpha}\right) \quad [EUR_{2020}/MWh]$$

where Equation 3

$$C_{ene,t} = \rho_t \cdot \frac{Q_H + Q_W}{\eta} \quad [EUR_{2020}]$$

Six decentralised technologies are considered: air-water heat pumps, biomass boilers (wood pellet and wood chip variants), gas boilers, ground-water heat pumps, and oil boilers. As reported below, boilers are analysed in terms of different fuel blends for gas (natural gas, biomethane, hydrogen, synthetic methane) and oil (fuel oil, biooil, synthetic fuel).

The technology data is largely based on the Danish Energy Agency's technology catalogue (DEA 2021c). It provides several observed technology variants from which linear functions for investment costs, efficiency and other variables can be derived. These functions are applied to each of the 125 buildings per renovation package, with nominal thermal capacity (kW_{th}) as the independent variable.

By default, all costs are given for Denmark in the year 2020, differentiated by equipment and installation. To transfer these costs to the case study countries, equipment costs are adjusted based on Eurostat's price level index for machinery (Eurostat 2022s). Likewise, installation costs are adjusted based on Eurostat's labour cost levels (Eurostat 2022q). Table 19 displays the resulting ranges for efficiency and other variables, while the complete parameters are provided in Table B4-Table B6.

Table 19: Techno-economic data for decentralised heat supply technologies

Technology	Efficiency [-]	Investment fix [$EUR_{2020}/unit$]	Investment variable [EUR_{2020}/kW_{th}]	Lifetime [yr]	O&M fix [$EUR_{2020}/kW_{th}/yr$]
Air-water heat pump	2.45-3.34 [c]	6,264-8,985	353.6-452.8	16-25	148.3-257.9
Biomass boiler	0.76-0.92	6,776-8,925	121.9-159.4	15-25	192.7-335.1
District heating substation [a]	0.95-1.00	1,798-2,861	21.8-30.2	20-30	19.0-33.0
Gas boiler	0.95-1.03	1,441-2,152	46.1-59.7	18-30	81.7-142.0
Ground-water heat pump [b]	3.19-3.88 [c]	8,957-15,105	324.9-523.6	18-40	116.1-201.9
Oil boiler	0.92-0.95	2,737-3,732	49.1-63.8	15-25	63.4-110.3

Aggregate ranges (min-max), see Table B4-Table B6 for details | [a] Indirect substation with heat exchanger (DEA 2021c) | [b] Shallow depth vertical collectors, assuming +30% investment cost compared to horizontal collectors solution (DEA 2021c) | [c] Seasonal performance factor for bivalent heat pump system with backup electric heater, see Equation 5

The coefficient of performance (*COP*) of heat pumps (*HP*) at each hour *h* largely depends on source temperature T_{source} and sink temperature T_{sink}. These temperatures vary over the year, influenced by climate and the nominal heat supply temperatures (Section 4.2.2). As per (DEA 2021c), heat pumps are typically designed to deliver sufficient heat output Q at T_{source} above -7°C (266 K) and T_{sink} below 55°C (328 K). Below -7°C, the heat pump would not provide adequate heat. Therefore, heat pumps are modelled as bivalent systems with a backup (*BU*) electric heater having an efficiency η_{BU} of 100%.

Based on the principles of the Carnot cycle and the exergetic efficiency of heat pumps $ø_{HP}$ (Fonseca et al. 2016), the hourly *COP* is derived bottom-up from the CEA model's hourly heating curves for each building, country and renovation package (Equation 4). This process distinguishes between space and water heating due to their different temperature profiles.

$$COP_{HP,h} = \left(1 - \frac{T_{source,h}}{T_{sink,HP,h}}\right)^{-1} \cdot \phi_{HP} \qquad [-] \qquad \text{Equation 4}$$

The annual performance entered as η in Equation 3 is expressed as the seasonal performance factor (*SPF*) (Lämmle et al. 2022) (Equation 5), i.e., including the energetic performance of the backup unit. For accuracy, $ø_{HP}$ is calibrated to the simulated *SPF* s for multi-family buildings in DE (Lämmle et al. 2022), yielding values of 0.37 for air-water and 0.41 for ground-water heat pumps.

$$SPF = \sum_h (Q_{HP,h} + Q_{BU,h}) \,/ \sum_h \left(\frac{Q_{HP,h}}{COP_{HP,h}} + \frac{Q_{BU,h}}{\eta_{BU}}\right) \qquad [-] \qquad \text{Equation 5}$$

As reported in Table 19 and Table B6, resulting mean *SPF* s, weighted by space and water heating needs, are in the range 2.45-3.34 for air-water and 3.19-3.88 for ground-water heat pump systems. The backup electric heater provides 1-10% of annual heat demand, depending on the country and renovation state.

Centralised heat supply

The costs for centralised district heating solutions are determined analogously to the decentralised solutions (Equation 3). The main difference is that the system elements (i.e., generation, pipes, water circulation pumps, substations) are valued separately and then aggregated.

Generation technologies include heat pumps (air source, deep geothermal), electrode boilers, gas boilers, and biomass boilers (wood chips, wood pellets, straw). Combined heat and power and seasonal heat storage technologies are not considered due to complex power system interactions requiring broader system boundaries. Based on (DEA 2021b), investment costs and other inputs are represented as linear functions, where the independent variable is the nominal thermal capacity (MW_{th}). Table B7-Table B9 provide the function parameters and Table 20 summarises this data.

Centralised heat pumps are typically designed for base load. Therefore, they are modelled as bivalent systems combined with either electric, gas or biomass peak boilers. As per DEA (2021b), the heat pumps are set to meet 85% of annual heat demand (MWh_{th}), which corresponds to 29-37% of the nominal thermal load (MW_{th}, see Figure 20), resulting in lower costs compared to a monovalent setup. The performance of centralised air source heat pumps follows the same approach based on hourly heating curves as for decentralised systems (see above). Efficiency data for geothermal heat pumps is based on DEA (2021b).

Indirect substations are considered as building connections, with costs reported in Table 19. The DH network layout, pipe diameters, and heat losses are endogenously determined in CEA. This involves a mixed-integer linear optimisation combined with a minimum spanning tree algorithm to determine the least-cost layout, subject to water pressure and velocity constraints, as detailed in Fonseca et al. (2016). Pipe costs are disaggregated by pipe diameters, listed in Table B10. Costs are based on (DEA 2021a; ETH Zurich 2022), using labour (Eurostat 2022q) and machinery price level indices (Eurostat 2022s, 2023c) to infer default values to EUR_{2020} price levels in BG, DE, FI. Pipe lifetime is set at 40 years (DEA 2021a). Specific investment costs for circulation pumps (EUR/MW_{el}) are based on (DEA 2021a), using the same price adjustments as for substations.

Table 20: Techno-economic data for centralised heat supply technologies

Technology	Efficiency [-]	Investment [$kEUR_{2020}/MW_{th}$]	Lifetime [yr]	O&M fix [$kEUR_{2020}/MW_{th}/yr$]	O&M variable [EUR_{2020}/MWh_{th}]
Air source heat pump	3.65-4.53 [b]	490-1,139	15-40	0.5-2.7	0.77-2.43
Electrode boiler	0.98-0.99	17-163	20-20	0.5-1.0	0.20-0.45
Gas boiler	0.93-1.05	23-230	25-25	0.5-2.3	0.26-1.80
Geothermal heat pump [a]	4.17-5.45 [b]	1,164-3,845	25-30	11.5-20.3	2.52-5.21
Straw boiler	0.88-1.04	382-977	20-35	22.2-53.8	0.25-0.79
Wood chip boiler	0.89-1.15	341-745	20-35	14.2-34.0	0.42-1.55
Wood pellet boiler	0.90-1.02	366-775	20-35	14.3-34.2	0.21-0.62

Aggregate ranges (min-max), see Table B7-Table B9 for details | [a] Compression heat pump with heat extraction from 1,200 m depth | [b] Seasonal coefficient of performance for 85% share in annual heat demand, excluding efficiency of peak boiler

Energy costs

Energy carrier costs are considered along two dimensions: (a) *supply scenarios* (business-as-usual, BAU vs. net-zero emissions by 2050, NetZero), and (b) to account for uncertainty in energy prices, low and high *price pathways* within these scenarios. For gas and oil, the fact that final users obtain them as mixes or blends (e.g., grid-based gas may consist of natural gas, biomethane, hydrogen, etc.) is taken into account. Consequently, fuel mixes are defined for the period 2020-2050 (Table 10), based on Hummel et al. (2023)

Detailed prices are given in Table B12-Table B13 for energy and network charges, respectively. Table 21 provides a summary across countries (BG, DE, FI), supply scenarios (BAU, NetZero), and price pathways (LOW, HIGH). Data is compiled from the IEA World Energy Outlook (2022), the EU Reference Scenario 2020 (Capros et al. 2021), the European Commission's Clean Planet for all study (European Commission 2018a), Eurostat (Eurostat 2022i, 2022l), and dedicated studies for bioenergy (Duić et al. 2017; van Nuffel et al. 2020) and synthetic fuels (Perner et al. 2018; Rademaekers et al. 2020). These values are net of taxes, levies and external costs and are expressed in EUR_{2020} using Eurostat's consumer price index (Eurostat 2022p). For electricity in 2020, an allowance price of 24.5 EUR/tCO_2 under the EU Emissions Trading System (EEX 2020) is subtracted to avoid double-counting of climate damage costs.

Table 21: Energy prices by energy carrier (EUR_{2020}/MWh)

		Energy		Network
Energy carrier type	**Energy carrier**	**2020**	**2050**	**2020-2050**
Biomass	Straw	21.55-27.66	23.18-37.02	2.75-3.94
	Wood chips	23.88-30.65	25.70-41.03	
	Wood pellets	31.50-40.43	30.07-48.02	
Electricity	Electricity	49.93-64.14	50.24-104.80	25.90-54.90
Gas	Biomethane	56.40-75.90	63.97-98.76	13.20-20.10
	Hydrogen	170.72-172.57	63.80-118.67	
	Natural gas	16.70-25.20	6.68-24.40	
	Synthetic methane	208.82-211.08	86.85-148.56	
Oil	Biooil	70.50-94.88	79.96-123.45	3.44-7.61
	Oil	54.09-76.16	18.81-104.85	
	Synthetic fuel	220.26-222.64	95.07-158.28	

Aggregate ranges across countries (BG, DE, FI), supply scenarios (BAU, NetZero), price pathways (LOW, HIGH), see Table B12-Table B13 for details | Prices excluding taxes/fees/levies and external costs

External costs

The external costs of heat supply are determined for air pollution and greenhouse gas emissions. These costs are based on a damage cost approach, which involves estimating the monetary value of the damages caused by specific pollutants on specific receptors (van Essen et al. 2019; Matthey and Bünger 2020). The pollutants considered include carbon dioxide equivalents (CO_2eq), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), particulate matter (PM), and sulphur dioxide (SO_2). Receptors include climate, human health, biodiversity, crops, and building materials (e.g. degradation of concrete structures). The emission scope involves direct emissions within the urban district, plus upstream emissions from grid-based electricity, corresponding to the 'geographic-plus' definition in (Ramaswami et al. 2011; Keirstead et al. 2012).[62]

62 Not considered are Scope 3 emissions, including 'grey' energy for the production of building elements (European Union 2012c).

As stated in Equation 6, external costs for a given country and heating technology at annual time step t are determined as the product of the emission factor ε [t/MWh_{th}], the value factor σ [EUR/t], and the energy use for space and water heating (see Equation 3) for all pollutants i and receptors j.

$$C_{ext,t} = \sum_{i=1} \sum_{j=1} \left(\varepsilon_{i,t} \cdot \sigma_{i,j,t} \cdot \frac{Q_H + Q_W}{\eta} \right) \quad [EUR_{2020}] \quad \text{Equation 6}$$

Emission factors ε for different fuels (e.g., natural gas) are based on (Lauf et al. 2023; EEA 2019) (Table B14). The greenhouse gas intensity of grid-based electricity is derived from Capros et al. (2021) and EEA (2023) for the BAU price scenario, while the NetZero scenario supposes a 95% reduction by 2050 compared to 2020 levels. The air pollution intensity of electricity is calculated by dividing total air pollution emissions (Eurostat 2023a) by final consumption (Eurostat 2022b). For 2050, this intensity is assumed to improve in the same way as the greenhouse gas intensity.

Value factors σ by air pollutant and receptor are obtained for DE from Matthey and Bünger (2020) (Table B16). Unit value transfer (van Essen et al. 2019) is applied for BG and FI, using an income elasticity of 0.8 in terms of PPP-adjusted GDP per capita (Eurostat 2023b). Based on recent evidence (Rennert et al. 2022), a social cost of carbon of 167 EUR_{2020} (185 USD_{2020}) per tonne of CO_2-equivalent is applied at a discount rate of 2% (Table B17). Table 22 summarises the resulting cost rates in *EUR* per *MWh* of final energy, i.e., the cross product of ε and σ.

Table 22: External cost rates (EUR_{2020}/MWh) by energy carrier type and emission type

	Air pollution		**Greenhouse gases**	
Energy carrier type	**2020**	**2050**	**2020**	**2050**
Biomass	2.24-7.75	2.24-7.75	0.06-0.07	0.06-0.07
Electricity	2.95-8.99	0.15-1.70	10.66-60.27	0.53-11.93
Gas	0.82-1.57	1.22-3.77	33.21	4.27-24.13
Oil	1.73-3.29	4.45-19.89	44.24	2.35-31.17

Aggregate ranges across countries (BG, DE, FI) and supply scenarios (BAU, NetZero). See Table B14-Table B17 for details

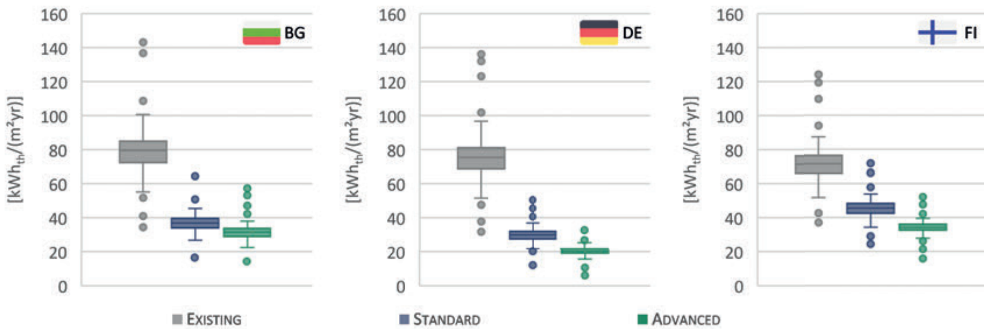
4.3 Results

The following sections present building energy performance (4.3.1), costs of decentralised (4.3.2) and centralised heating options (4.3.3), overall cost-efficient solutions (4.3.4), and a sensitivity analysis (4.3.5).

4.3.1 Building energy performance and renovation cost

As shown in Figure 17, the distribution of the specific energy performance for space heating (kWh_{th}/m^2yr) varies according to the renovation packages implemented across the 125 buildings. STANDARD and ADVANCED retrofits effectively reduce the buildings' thermal conductivity and, consequently, the energy need for heating. Median reductions are 61% (BG), 73% (DE), and 52% (FI) when comparing ADVANCED and EXISTING states. The lower outliers are mainly offices with high internal gains, while the upper outliers are detached apartment and school buildings. Median energy needs for sanitary hot water (data not shown) are between 19 and 21 kWh_{th}/m^2yr.

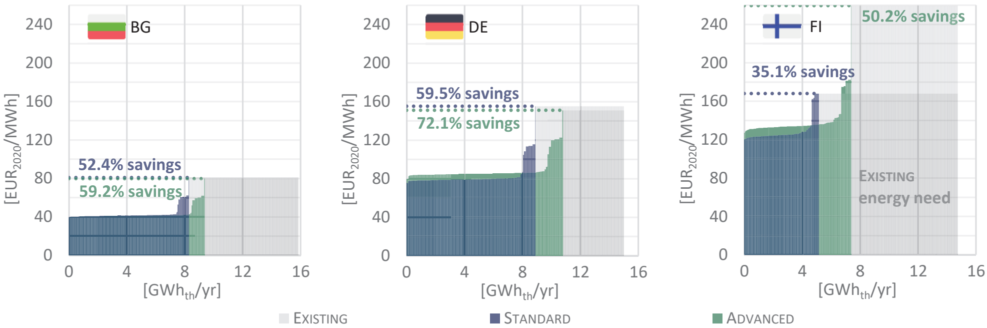
Figure 17: Specific energy performance for space heating by country and renovation package



n = 125 buildings by package, see Section 4.2.1-4.2.2 | *m²* of conditioned floor area

Figure 18 presents cost-potential curves of the useful energy savings for space heating. Cumulative saving potentials compared to the EXISTING package vary between 35% and 72%. Per *MWh* saved, Standard retrofits are cheaper than ADVANCED retrofits, but achieve lower energy savings. *Within* each country and package, cost differences result from occupancy and internal gains (Section 4.2.2), as well as the ratio of building envelope area to conditioned floor area. 87-88% of energy savings potentials come from apartments, 7-8% from offices, and the rest from other use types (data not shown).

Figure 18: Cost-potential curve of useful energy savings in space heating by renovation package



To understand what drives differences *across* countries, Table 23 decomposes the numbers from Figure 18 for the contrasting cases of FI and BG under the ADVANCED package. Three effects are considered:

- Climate conditions (1) moderately impact outcomes: warmer climates in BG yield less space heating savings and higher specific renovation costs compared to FI.
- U-values (2) strongly affect outcomes: according to Table 18, EXISTING buildings in BG have higher U-values and more ambitious retrofit options than in FI, enabling greater relative energy savings.
- Renovation cost levels (3) have the most substantial impact: lower labour and material costs make renovations more affordable in BG than in FI.

Table 23: Decomposition of building energy savings and renovation costs for the Advanced package in Finland (FI) and Bulgaria (BG)

Effect by country			Total savings in useful energy for space heating [MWh_{th}/yr] [d]	Weighted average building renovation costs [EUR_{2020}/MWh_{th}] [d]
(1) Weather [a]	(2) U-values [b]	(3) Renovation cost level [c]		
FI	FI	FI	7,404	139.80
BG	FI	FI	5,961	173.65
BG	BG	FI	9,387	110.27
BG	BG	BG	9,387	43.03

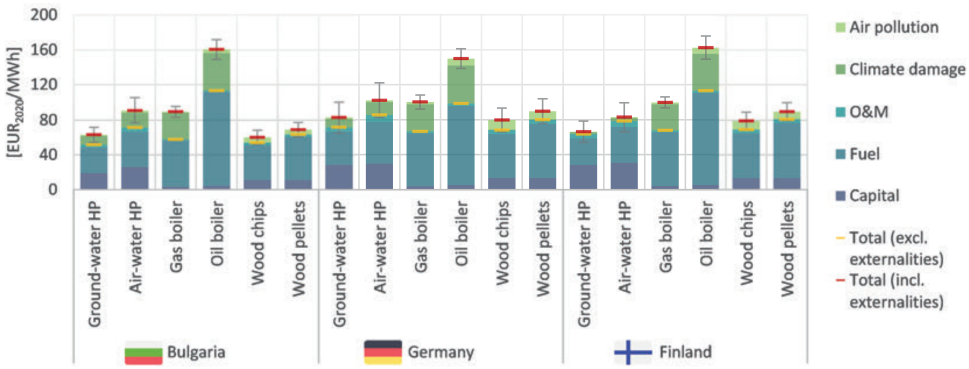
[a] Based on Climate.OneBuilding (2023), see Section 4.2.2 | [b] Based on TABULA/EPISCOPE (2017), see Table 18 | [c] Based on Eurostat (2022u), see Section 4.2.3 | [d] See Equation 2

4.3.2 Decentralised supply costs

Figure 19 shows the mean average specific costs for decentralised supply. For each country and technology, this covers 1,500 variants from two supply scenarios (BAU, NetZero), two price pathways (low, high), three renovation packages (Existing, Standard, Advanced), and 125 buildings.

Mean least-cost options in both BG and DE are wood chip boilers (60 and 80 EUR/MWh, respectively), and ground source heat pumps in FI (66 EUR/MWh). When adding external costs to capital, fuel, and O&M costs, biomass costs increase by 9-17%, heat pumps by 4-28%, gas by 48-55%, and oil by 42-52%. The standard deviation is high for heat pumps due to improving energetic performance after retrofits (Section 4.2.2). Despite higher total investments, specific capital costs for ground source heat pumps tend to be lower than for air source heat pumps, attributable to longer lifetimes (Table 19).

Figure 19: Mean specific costs for decentralised heating systems by cost type



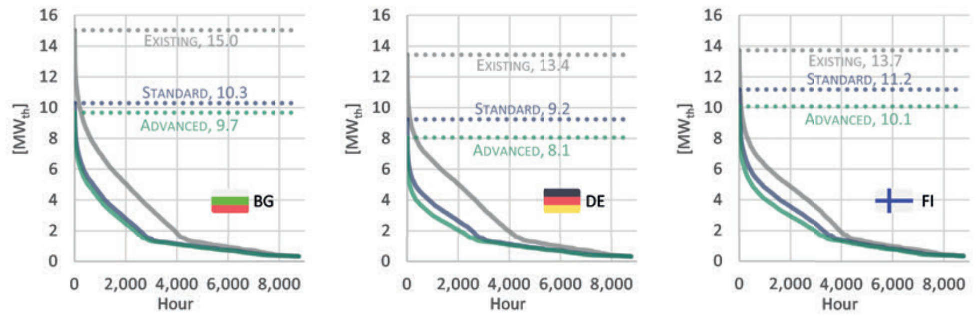
1,500 variants by country and technology (= 2 supply scenarios × 2 price pathways × 3 renovation packages × 125 buildings)

4.3.3 Centralised supply costs

Figure 20 shows the thermal load duration curve for centralised DH supply. When comparing the Advanced and Existing packages, peak load is reduced by 36% (BG), 40% (DE), and 27% (FI). For a calculated total network length of 5,040 m, linear heat densities (MWh_{th}/m) decrease from 5.10 to 2.90 (BG), 4.91 to 2.40 (DE), and 4.90 to 3.21 (FI) between Existing and Advanced packages (data not shown).

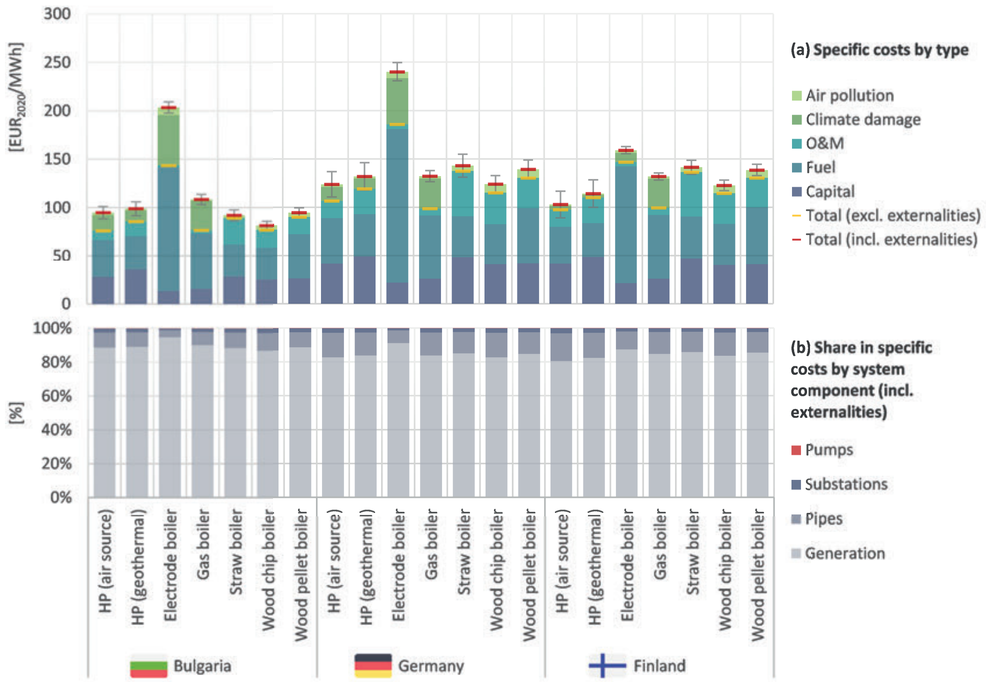
Figure 21a provides the mean average specific costs for centralised DH options across supply scenarios, price pathways, and renovation packages. Heat pumps are displayed in combination with peak boiler variants. Mean least-cost centralised solutions are monovalent wood chip boilers in BG (81 EUR/MWh), and air source heat pump systems in both DE and FI (124 and 103 EUR/MWh,

Figure 20: Thermal load duration curve for centralised district heating supply by renovation package



Including heat distribution losses as determined in the CEA model (Fonseca et al. 2016)

Figure 21: Mean specific costs for centralised district heating systems



12 base variants by country and technology (= 2 supply scenarios × 2 price pathways × 3 renovation packages); 60 variants for heat pumps (= 12 base variants × 5 backup boiler options)

respectively). Monovalent electrode boilers are generally the most expensive. As shown in Figure 21b, costs are dominated by generation, with specific pipe costs between 8.4 (BG) and 18.0 (DE) EUR/MWh. Costs for substations and pumps are negligible, accounting for 1-3% of overall specific costs.

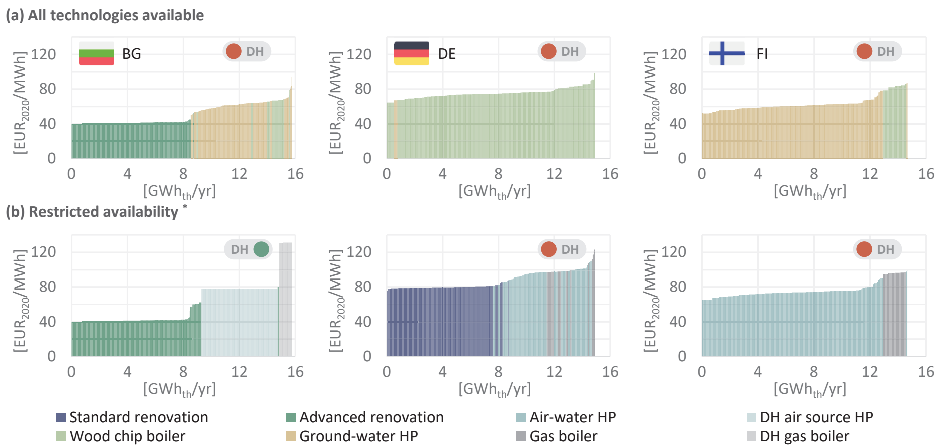
4.3.4 Cost-efficient solutions

A three-step heuristic optimisation is employed to balance energy demand reduction via building retrofits and supply via decentralised or centralised heat technologies. First, the least-cost mix of renovation packages (Figure 18) and decentralised options (Figure 19) is selected. Second, the least-cost combinations of renovation and centralised supply options (Figure 21) are determined. Finally, for each country, the lowest cost solution (decentral/central) is selected.

The costs of supply options are derived from mean specific costs across supply scenarios (BAU, NetZero) and price pathways (low, high). Two sets of least-cost solutions are determined. The first set (a) includes all heat supply technologies available. The second set (b) excludes biomass combustion, due to sustainability issues (e.g., deforestation), and ground source heat pumps, due to disruptive ground works in densely populated urban areas.

The results are presented in Figure 22 and Table 24. For set (a), 91% of the technical potential for retrofitting is utilised in BG, reducing annual costs by 8%. In contrast, no cost-effective retrofit measures are identified in DE and FI. Decentralised heating options are chosen in all three countries with a mix of wood chip boilers and ground-water heat pumps. These options are 20-27% cheaper than the least-cost centralised solution. Notably, ground-water heat pumps are also selected in FI's cold climate, attributable to both low electricity prices and low external costs.

Figure 22: Specific costs and share in useful energy demand of least-cost solutions



[*] No biomass; no ground source or geothermal heat pumps | Specific costs (*EUR/MWh*) as per Equation 2 and Equation 3, including external costs (climate, air pollution)

In set (b), significant differences emerge. Besides BG, cost-effective building retrofits are observed in DE, exploiting 75% of the technical potential and reducing total costs by 20% and 8% in BG and DE, respectively. In BG, centralised DH supply, based on an air-source heat pump and a backup gas boiler, is chosen, with minor cost savings of 2% compared to the decentralised solution. In DE and FI, decentralised air source heat pumps emerge as the major supply option.

Table 24: Detailed performance of least-cost solutions

Set [a]	Category	Performance indicator	Unit	Country: Bulgaria	Germany	Finland
(a) All technologies available	Total costs	Total discounted average costs	[EUR_{2020}/yr]	1,067,615	1,446,579	1,221,120
		Specific discounted average costs	[EUR_{2020}/MWh_{th}]	50.58	74.65	62.49
	Cost-effective savings through building retrofits [b]	Energy savings	[MWh_{th}/yr]	8,498	-	-
		Energy savings	[%]	53.6%	-	-
		Technical potential	[%]	90.5%	-	-
		Cost savings	[EUR_{2020}/yr]	87,896	-	-
		Cost savings	[%]	7.6%	-	-
	Heat supply	Supply type	[-]	Decentral	Decentral	Decentral
		Major technology	[-]	Ground source heat pump	Wood chips boiler	Ground source heat pump
		Share in heat supply	[%]	74.0%	98.9%	87.2%
		Cost savings vs. supply alternative (central/ decentral)	[%]	19.6%	23.7%	26.6%
(b) Restricted availability	Total costs	Total discounted average costs	[EUR_{2020}/yr]	1,327,191	1,727,459	1,473,722
		Specific discounted average costs	[EUR_{2020}/MWh_{th}]	60.39	87.11	75.42
	Cost-effective savings through building retrofits [b]	Energy savings	[MWh_{th}/yr]	9,387	8,042	-
		Energy savings	[%]	59.2%	53.6%	-
		Technical potential	[%]	100.0%	74.4%	-
		Cost savings	[EUR_{2020}/yr]	332,424	140,517	-
		Cost savings	[%]	20.0%	7.5%	-
	Heat supply	Supply type	[-]	Central	Decentral	Decentral
		Major technology	[-]	Air source heat pump	Air source heat pump	Air source heat pump
		Share in heat supply	[%]	85.0%	72.8%	87.2%
		Cost savings vs. supply alternative (central/ decentral)	[%]	2.3%	8.9%	11.5%

[a] Restricted availability: no biomass combustion, no ground source/geothermal heat pumps | [b] Compared to EXISTING renovation package (Section 4.2.2); energy savings in terms of useful energy for space heating

4

4.3.5 Sensitivity analysis

In order to evaluate the robustness of the results, a sensitivity analysis was conducted for technology set (b) in Table 24. Table 25 displays the outcomes of this analysis, focusing on three independent variables:

- the discount rate (1.5%, 2.0%, 2.5%, 3.0%), representing societal time preference and ethical considerations regarding the well-being of future generations;
- energy supply scenarios (BAU vs. NetZero) and price pathways (low vs. high);
- nominal heat supply/return temperatures, crucial for the efficient operation of heat pumps. The default Dynamic case considers temperature reductions for Standard and Advanced packages to 60/50°C and 55/45°C (Section 4.2.2), while Static maintains 70/50°C as from the Existing package.

Across the tested variants, air source heat pumps remain a fairly robust choice for heat supply. The discount rate affects not only default costs but also the long-term horizon of external climate damage, as represented by the social cost of carbon (Rennert et al. 2022) (Table B17). A higher discount rate lowers the present value of future damages, making gas boilers more cost-effective. Supply scenarios and price pathways have minimal effect on outcomes, which is attributed to the interlinked nature of these dimensions and discounting. Notably, the efficiency of heat pumps is significantly influenced by supply/return temperatures, becoming less cost-effective if not operated at low temperatures after renovation.

Table 25: Sensitivity analysis on cost-efficient solutions

<table>
<tr><th></th><th></th><th colspan="3">Dependent variables: [a]
Utilisation of technical potential for building retrofits [%] | Share of major decentral (⌂) or central (◉) supply technology in heat supply [%] |</th></tr>
<tr><th>Independent variable</th><th>Variant</th><th>Bulgaria</th><th>Germany</th><th>Finland</th></tr>
<tr><td rowspan="4">Discount rate</td><td>1.5%</td><td>100.0% | ◉ Air source HP (85%)</td><td>82.4% | ⌂ Air source HP (87%)</td><td>82.4% | ⌂ Air source HP (87%)</td></tr>
<tr><td>2.0% [b]</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (73%)</td><td>74.4% | ⌂ Air source HP (73%)</td></tr>
<tr><td>2.5%</td><td>99.2% | ⌂ Gas boiler (99%)</td><td>0.8% | ⌂ Gas boiler (99%)</td><td>0.8% | ⌂ Gas boiler (99%)</td></tr>
<tr><td>3.0%</td><td>91.8% | ⌂ Gas boiler (100%)</td><td>- | ⌂ Gas boiler (100%)</td><td>- | ⌂ Gas boiler (100%)</td></tr>
<tr><td rowspan="5">Supply scenario | price pathway [c]</td><td>Average(BAU, NetZero, Low, High) [b]</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (73%)</td><td>74.4% | ⌂ Air source HP (73%)</td></tr>
<tr><td>BAU | Low</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (55%)</td><td>74.4% | ⌂ Air source HP (55%)</td></tr>
<tr><td>BAU | High</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (70%)</td><td>74.4% | ⌂ Air source HP (70%)</td></tr>
<tr><td>NetZero | Low</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.6% | ⌂ Air source HP (75%)</td><td>74.6% | ⌂ Air source HP (75%)</td></tr>
<tr><td>NetZero | High</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (74%)</td><td>74.4% | ⌂ Air source HP (74%)</td></tr>
<tr><td rowspan="2">Heat pump supply/return temperatures [d]</td><td>Dynamic [b]</td><td>100.0% | ◉ Air source HP (85%)</td><td>74.4% | ⌂ Air source HP (73%)</td><td>74.4% | ⌂ Air source HP (73%)</td></tr>
<tr><td>Static</td><td>99.9% | ⌂ Gas boiler (99%)</td><td>72.3% | ⌂ Gas boiler (94%)</td><td>72.3% | ⌂ Gas boiler (94%)</td></tr>
</table>

[a] See Table 24 | [b] Default variant in Section 4.3.4, using technology set (b) | [c] See Section 4.2.3 | [d] See Sections 4.2.2-4.2.3

4.4 Discussion

The results highlight that the optimal balance between heat savings and supply varies contextually, influenced by technology availability, cost levels, and discount rates. Under certain conditions, building retrofits significantly lower costs; however, when labour and material costs are high, installing new heat supply without prior retrofitting may be more economically viable. Heat pumps, either decentralised or centralised, emerged as key options, even for non-retrofitted buildings in cold climates.

The findings align with existing literature: observed cost-effective heat energy savings of 0-60% versus current levels are consistent with EU estimates of 20-47% (Mandel et al. 2023a; Hummel et al. 2023) and local figures of 20-78% (Ben Amer-Allam et al. 2017; Büchele et al. 2019; Hansen et al. 2016; Harrestrup and Svendsen 2014; Milic et al. 2020; Romanchenko et al. 2020). The study supports the assertion that centralised DH may not consistently be more cost-effective than low-carbon decentralised options, with DH's optimal EU market shares in the literature at 5-45% (Manz et al. 2022). The importance of low-temperature heating is underlined, resonating with IRENA (2021) and Østergaard et al. (2022). This section discusses the study's policy implications (Section 4.4.1) and limitations (Section 4.4.2).

4.4.1 Policy implications

The proposed recast of the EU Energy Efficiency Directive (EED) (European Commission 2021e) emphasises the energy efficiency first (EE1st) principle, requiring decision-makers to determine solutions that yield cost-efficient outcomes for both individuals and society. Local authorities can address this principle through planning, zoning, financial incentives, and – as assumed in this study – the adoption of energy-efficient and low-carbon solutions in publicly owned buildings and energy infrastructures (Comodi et al. 2012).

This study illustrates the value of urban energy systems modelling as a decision support tool for identifying least-cost combinations of technical solutions. In this sense, Article 23(6) of the proposed EED recast (European Commission 2021e) would require Member States to carry out integrated heating and cooling planning for municipalities with a population exceeding 45,000. Denmark's experience (Chittum and Østergaard 2014) underscores the effectiveness of such planning to exclude options that are not economically viable, technologically feasible, and environmentally sustainable, while reducing risk for both suppliers and consumers.

However, major aspects of energy policy in the EU fall under the purview of regional or national governments, limiting the scope of action for local authorities (Comodi et al. 2012; Chittum and Østergaard 2014). In particular, national authorities face the challenge to create an enabling framework for decision-makers to adopt sustainable energy practices and technologies that benefit both their own interests and society as a whole.

Internalising external costs is the traditional economic approach to aligning private interests with societal goals (Perman et al. 2011). The results in Section 4.3.2 show that, on top of technology and energy expenses, gas boilers generate societal costs of 48 to 55%. In response, the recast EU Emissions Trading System (ETS) Directive (European Union 2023b) establishes a new ETS scheme covering the building and road transport sectors. This could incentivise private decision-makers to adopt efficient, low-carbon options like heat pumps.

To expedite building retrofits, the EU Energy Performance of Buildings Directive (EPBD) requires Member States to set minimum energy performance standards (MEPS) for new and existing buildings undergoing major renovation. The proposed EPBD recast aims to intensify these provisions, specifically targeting the worst-performing buildings (European Commission 2021f; Wilson 2022). As shown in this study, establishing MEPS necessitates a careful balance between decarbonising heat supply and reducing building heating needs, to ensure *"cost-optimal levels of minimum energy performance requirements"* (European Commission 2021f).

In sum, combining sound economic evaluation in local energy planning with comprehensive incentive structures is a promising strategy for fostering sustainable, resilient, and cost-efficient community energy systems in accordance with the EE1st principle.

4.4.2 Limitations

This study is subject to several limitations. First, in terms of technical detail, the analysis does not consider rooftop photovoltaic or solar thermal installations (IRENA 2020), nor does it endogenously represent increased power network costs in response to heat pump adoption (Romanchenko et al. 2020). It also disregards industrial excess heat potentials or seasonal energy storage in DH systems, potentially overestimating the cost of centralised heat supply (IRENA 2021; Manz et al. 2023). Moreover, the analysis uses yearly average electricity prices, which does not reflect the possibility of optimising heat pump operation during low-price periods using demand response strategies (Ben Amer-Allam et al. 2017; Yazdanie and Orehounig 2021).

Second, the study's hypothetical setup consists of a single urban district comprising generic reference buildings from the 1970-1989 construction period. In reality, the existing building stock in Europe is highly heterogeneous in terms of building types, construction periods, and renovation states (Esser et al. 2019; European Commission 2023). Consequently, the study's findings cannot easily be scaled to a national level.

Third, the analysis adopts a societal perspective, including external costs and excluding transfer payments while applying a low discount rate. This represents the viewpoint of benevolent municipal authorities who are shareholders in local energy utilities and public property owners (Comodi et al. 2012; Grundahl et al. 2016). However, to understand the specific effects for building owners, tenants, property developers, and heat utilities, a financial analysis (Bleyl et al. 2017; Konstantin and Konstantin 2018a) reflecting actual cash flow transactions, including all relevant taxes and subsidies, would be necessary. Any discrepancy between societal and financial calculations would indicate that the policy framework, including taxation levels, favours suboptimal solutions (Grundahl et al. 2016; Ben Amer-Allam et al. 2017).

Fourth, the analysis does not consider the practical feasibility of the proposed solutions. For instance, due to budget constraints, a staged building renovation approach could be more preferable (Maia et al. 2023; Maia et al. 2021). Technical constraints may include the availability of large-scale heat pumps for multi-family buildings, which often require custom solutions, unlike those in single-family buildings (DEA 2021c). Moreover, different countries have varying levels of experience with certain heat technologies, like the relatively mature heat pump market in Finland (EHPA 2023), which could influence practical implementation.

Finally, this study includes direct air pollution and climate change impacts as significant external costs. However, it does not fully capture all relevant externalities, such as noise pollution, which may be an issue for air source heat pumps (DEA 2021c). Moreover, the study could be broadened to include so-called multiple impacts (Ürge-Vorsatz et al. 2016; Thema et al. 2018), such as enhanced thermal comfort resulting from building retrofits, local job creation opportunities, and energy security considerations. Including these factors in the analysis could make the case for certain options, such as building retrofits, more attractive (Thema et al. 2019; Chatterjee and Ürge-Vorsatz 2021).

4.5 Conclusion

In this research, the potential for energy savings through building envelope retrofits and the role of decentralised and centralised heat supply technologies were investigated from a societal perspective, factoring in the external costs of greenhouse gas and air pollution emissions. This analysis encompassed a generic urban district in Bulgaria, Germany, and Finland, constructed during the 1970-1989 period. A heuristic optimisation approach was used to identify the least-cost combinations of these options.

The results suggest that the cost-effectiveness of retrofits is highly context-specific. In Bulgaria, deep retrofits are largely cost-effective. When excluding biomass combustion and ground source heat pumps due to sustainability and disruption concerns, respectively, renovation can yield up to 20% in annual cost savings and a 59% reduction in heat demand compared to existing levels. Conversely, in Germany and Finland, higher labour and material costs alter the economic balance: for instance, in Germany, retrofits may result in up to 8% cost savings with a 54% reduction in heating needs. Despite these varying conditions, both decentralised and centralised heat pumps emerged as key heat supply options, even for non-retrofitted buildings in the cold climates of Finland.

The study suggests that centralised district heating solutions may not consistently be more cost-effective than low-carbon decentralised options. However, it acknowledges the potential for cost reductions through model refinements, such as the integration of industrial excess heat potentials. Sensitivity analysis underlines the robustness of the overall findings, highlighting the significant impact of discount rates and the importance of low supply temperatures for efficient heat pump operation.

Policy implications include the need for balanced urban energy planning that integrates both energy-saving and supply measures. Effective local planning, coupled with supportive national policies, can facilitate the uptake of efficient low-carbon solutions. Future research should aim to integrate more technical model details and explore multiple impacts beyond classic externalities to provide a more comprehensive assessment of the heating transition in the building sector.

5

Towards effective implementation of the energy efficiency first principle: a theory-based classification and analysis of policy instruments

Mandel, Tim; Pató, Zsuzsanna (2023): Towards effective implementation of the energy efficiency first principle: a theory-based classification and analysis of policy instruments. Under review in *Energy Research & Social Science*

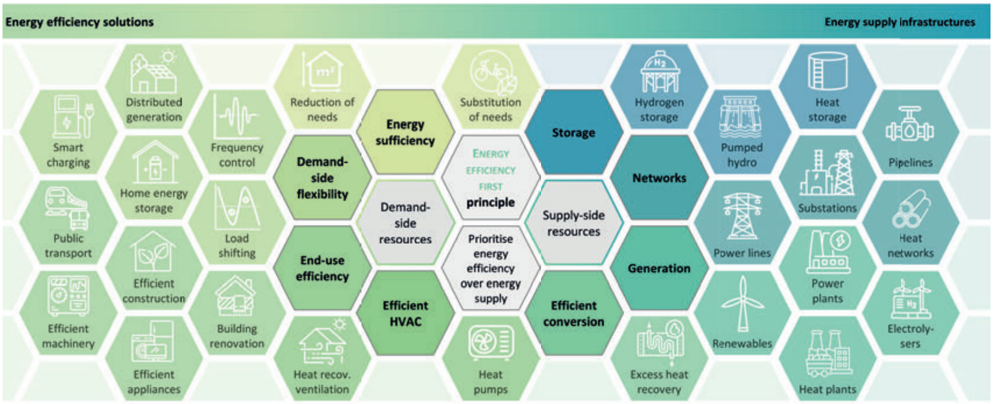
5.1 Introduction

5.1.1 Context

As part of its ambition to become a climate neutral economy by 2050 (European Union 2021b), the European Union (EU) has recently adopted the recast Energy Efficiency Directive (EED) (European Union 2023a). A key new element of this recast is Article 3, which requires Member States to assess, monitor, and report on the energy efficiency first (EE1st) principle in their policy and energy planning activities. Previously, the EE1st principle was formally defined in Article 2(18) of the EU Governance Regulation (European Union 2018d).[63]

The EE1st principle suggests that energy efficiency solutions, including not only traditional end-use energy efficiency, but also demand-side flexibility and efficient energy conversion in particular (Figure 23) (European Union 2018d, 2023a), are often the lowest cost options for providing energy services and contributing to wider societal goals. It therefore proposes that cost-effective energy efficiency solutions should be prioritised over new generation, network, and storage infrastructure for electricity, gas and heat. As such, the principle could contribute to a cost-efficient decarbonisation of the EU economy (Rosenow and Cowart 2019; Bayer 2015a), while also promoting economic growth, energy security, improved air quality, and other reported multiple benefits or co-benefits (IEA 2014a; Ürge-Vorsatz et al. 2016; Karlsson et al. 2020).

Figure 23: Conceptual overview of the energy efficiency first principle



See Mandel et al. (2022c) and European Union (2023) for definitions and detailed terminology discussions | HVAC: heating, ventilation, and air conditioning

63 *"'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions"* (European Union 2018d).

5.1.2 State of research

Previous studies have explored both the politics (Malmborg 2023a, 2023b, 2023c) and the conceptual foundations of the EE1st principle (Mandel et al. 2022c). Other studies have used energy systems modelling and cost-benefit analysis to demonstrate that energy efficiency can often cost-effectively reduce energy supply infrastructure needs in the EU's sustainable transition (Mandel et al. 2023a; Hummel et al. 2023; Zeyen et al. 2021). This line of research tends to address the energy planning aspects of EE1st (Footnote 63): it suggests that through robust model-based assessments and public deliberation, energy planners in areas such as local heating and cooling planning (Mandel et al. 2023b) could identify energy efficiency solutions that are projected to deliver the greatest net-benefits to society.

However, Article 3 of the EED is vague about how to proceed after determining an optimal energy efficiency level in high-level energy planning. Arguably, producers are unlikely to compromise their profits by reducing supply for the greater public good, just as consumers are unlikely to routinely adopt energy efficiency measures, as both largely follow private interests over societal ones (Mulder 2021). Bridging these two perspectives within EE1st essentially calls for public policy (Broc et al. 2022).

The EED's stance on appropriate EE1st policies remains unclear. In its recommendation on EE1st, the European Commission (European Union 2021a) outlines sectoral policies, ranging from dynamic pricing in electricity markets to financing schemes for building renovation. In the emerging EE1st research literature, Pató et al. (2019b) focus on electricity sector policies, highlighting market access rules for demand response and remuneration schemes for network operators to balance efficiency and supply solutions. Rosenow and Cowart (2019) discuss the EE1st principle in the UK, identifying instruments such as building codes.

Two major gaps remain in the current literature. First, the defining feature of policies for EE1st as opposed to traditional energy efficiency policy is unclear. Numerous articles (Trotta et al. 2018; Boza-Kiss et al. 2013; Bertoldi 2022; Markandya et al. 2015; Bertoldi 2020; Della Valle and Bertoldi 2022) and databases (ODYSSEE-MURE 2022; IEA 2015) have brought together policy instruments to promote energy efficiency, typically structured around (i) command and control (e.g. performance standards), (ii) pricing (e.g. grants), and (iii) information instruments (e.g. labels). Many of these instruments appear to be effective in terms of both energy and cost savings (Gillingham et al. 2018), raising the question of the added value of EE1st in the policy domain.

Second, relatedly, policy considerations for EE1st often lack firm grounding in economic and political theory, resulting in an ambiguous scope for action. Barriers to energy efficiency (Blumstein et al. 1980; Sorrell et al. 2000a; Brown 2001), as organised in numerous studies (Bertoldi 2022; Cagno et al. 2012; Cattaneo 2019; Eyre 1997; Langlois-Bertrand et al. 2015; Palm and Reindl 2018; Reddy 1991;

Schleich et al. 2016; Weber 1997; Wilson et al. 2015; Sorrell et al. 2000b), are occasionally given as the theoretical justification for EE1st policy (Rosenow and Cowart 2019; Pató et al. 2020a). The barriers concept, however, tends to focus on end-use energy efficiency, while demand-side flexibility and other relevant energy efficiency solutions (Figure 23) are organised in separate frameworks (Cardoso et al. 2020; Parrish et al. 2020; Sousa and Soares 2023). Moreover, the barriers concept faces criticism for analytical inaccuracies (Jaffe and Stavins 1994; Brown and Wang 2017; Schleich 2009; Golove and Eto 1996; Dennis 2006; Sanstad and Howarth 1994). For example, frequently mentioned barriers such as high upfront costs or perceived risk (e.g. Sorrell et al. 2000b) have been identified as normal market characteristics that do not inherently necessitate policy interventions (Sutherland 1994; Sanstad and Howarth 1994; Jaffe and Stavins 1994; Stadelmann 2017; Brown and Wang 2017).

In the context of EE1st policy, Mandel et al. (2022c) argue for market failures as a potentially more holistic, nuanced and consistent theoretical concept. Market failures are well established in economic theory (Krugman and Wells 2015; Mankiw 2017) and, unlike barriers, represent economic distortions rather than mere obstacles to energy efficiency. While the energy efficiency literature has recognised both overlaps and differences between the two concepts (Jaffe and Stavins 1994; Sorrell et al. 2000b; Brown and Wang 2017), a systematic account of genuine market failures relevant to EE1st policy, along with the corresponding policy instruments to address these market failures, is still missing.

5.1.3 Objective

This research aims to bridge the gap between the theoretical foundations of the EE1st principle and its practical policy implementation. Chapter 5.2 reviews the EE1st concept and explains how market failures create an economic imbalance between energy efficiency and energy supply. Chapter 5.3 classifies and describes policy instruments for applying EE1st, linking them to individual market failures, and thus offering a systematic roadmap for EE1st policy. Chapter 5.4 discusses the limitations of market failure theory and the scope for complementary policies. Finally, Chapter 5.5 summarises the main findings.

5.2 Theory: Well-functioning markets and market failures

This chapter presents insights from neoclassical, institutional, regulatory, and behavioural economics to provide a theoretical framework for the analysis of policy instruments in Chapter 3. Section 5.2.1 explains the concept of well-functioning markets as a benchmark for EE1st. Section 5.2.2 outlines the related concept of market failure. Section 5.2.3 presents market failures in different sectoral contexts.

5.2.1 Benchmark of well-functioning markets

The application of the EE1st principle can be straightforward in the case of public ownership. For example, benevolent local authorities that are shareholders in both local energy utilities and public housing could identify the least-cost mix of solutions according to Figure 23 and invest accordingly (Mandel et al. 2023b). However, the bulk of energy-related investment in the EU is privately owned by generators, suppliers, and consumers. Network companies vary in ownership – public, private, or mixed – and are all subject to regulation by national regulatory authorities. Taken together, as characterised by Golove and Eto (1996), this constitutes a 'market for energy services' in which, on the supply side, profit-driven producers deliver energy and energy-using equipment. On the demand side, consumers in households and businesses purchase energy and equipment, and make choices between using and saving energy.

Theoretically, in well-functioning markets, self-interest-driven individual actions collectively deliver economic efficiency (Mankiw 2017; Krugman and Wells 2015). Consumers adopt privately cost-effective energy efficiency solutions, and producers consider all technically viable options, including energy efficient alternatives, to maximise their profits. Economic efficiency can be understood as the normative benchmark for EE1st as, in fact, the principle does not unequivocally advocate for energy efficiency, but promotes these solutions only to the extent that they contribute to societal net-benefits (Mandel et al. 2022c).[64]

5.2.2 Market failure rationale for public policy

Figure 24 outlines the necessary conditions for well-functioning markets (Brown and Wang 2017; Mulder 2021; Perman et al. 2011): (A) no externalities, (B) free market entry, (C) effective regulatory oversight of natural monopolies, (D) perfect information, (E) zero transaction costs, and (F) rationality.[65] These conditions are not met in the EU energy services market, constituting market failures (Weimer and Vining 2017; Mandel et al. 2022c). For example, in electricity markets, demand-side flexibility cannot compete on equal footing with generation due to market entry restrictions (smartEn 2022b). Other market failures include the significant transaction costs in building renovation projects (Kiss 2016). As a result, energy efficiency levels are economically suboptimal, known as the energy efficiency gap (Brown and Wang 2017; Jaffe and Stavins 1994; Gillingham and Palmer 2014).

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64 "*The principle does not mean that energy efficiency is always a preferred option [...]*", but to "*consider actions in energy efficiency [...] on an equal footing with alternative actions to respond to a specific need or objective*" (European Union 2021a). Thus, EE1st acknowledges the criticism of economists (Sutherland 1994; Gunn 1997) that promoting energy efficiency per se is not a legitimate policy objective unless it contributes to economic efficiency.

65 Condition (C) is not a traditional characteristic of well-functioning markets, but a recognition that in modern energy markets network infrastructures are natural monopolies that require external regulation (Mulder 2021; Perez-Arriaga 2016).

Although all market failures represent barriers to energy efficiency, not all barriers qualify as market failures (Brown and Wang 2017; Sorrell et al. 2000b; Jaffe and Stavins 1994; Golove and Eto 1996). For example, high upfront costs for efficient technologies may hinder adoption (Bertoldi et al. 2021; Palm and Reindl 2018), but do not violate any conditions of well-functioning markets. Therefore, some economists contend that barriers are normal market characteristics and that addressing them through policy instruments would not improve economic efficiency (Sutherland 1994; Sanstad and Howarth 1994; Jaffe and Stavins 1994). Still, properly construed, many barriers can be reframed as market failures. For example, the barrier of hidden costs (Sorrell et al. 2000b) largely aligns with the market failure of transaction costs. Chapter 5.4 delves deeper into addressing non-market failure barriers.

In mainstream economics, public policy is warranted when societal benefits of tackling market failures outweigh implementation costs (Schleich 2009; Weimer and Vining 2017; Mulder 2021; Brown and Wang 2017). Addressing each failure with specific policy instruments aligns energy investments and system operation with the conditions of well-functioning markets, a strategy known as first-best policy, linked to the Tinbergen rule (Jenkins 2014; Gillingham and Palmer 2014; Fischer et al. 2021).[66] Consistent with the EE1st principle, the outcome of addressing market failures is not necessarily the adoption of energy efficiency, but the cost-efficient mix of solutions, whether energy savings or supply. Therefore, Mandel et al. (2022c) refer to this strategy as EE1st policies, rather than just energy efficiency policies (Trotta et al. 2018; Boza-Kiss et al. 2013; Bertoldi 2022; Markandya et al. 2015).

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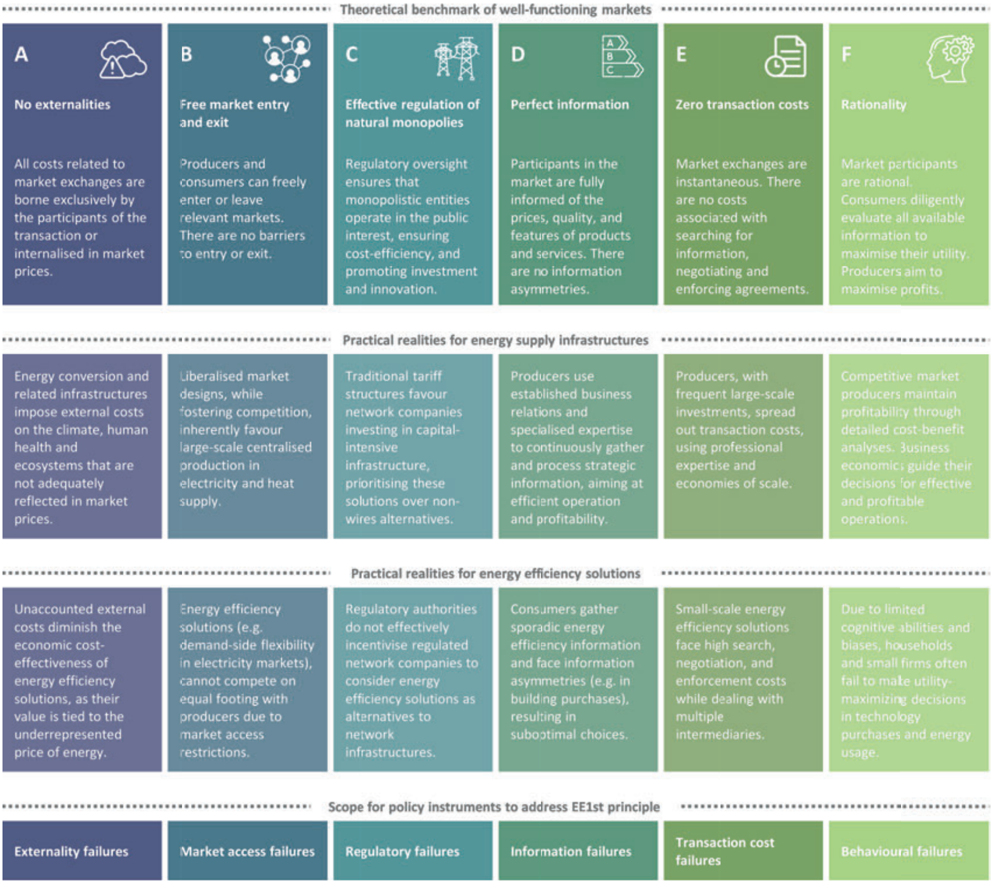
66 Tinbergen (1952) stated that addressing a certain number of market failures requires an equal number of policy instruments. This means that each market failure should be assigned a separate instrument to address it.

Figure 24: Theoretical benchmark and practical policy scope for implementing the energy efficiency first principle



Source: Authors' own, based on Brown and Wang (2017) and Mandel et al. (2022c)

5.2.3 Common market failures in the EU

The EU's energy services market exhibits numerous market failures. Based on the categorisation in Figure 24, the following sections illustrate how market failures affect the economic balance between energy efficiency and supply, highlighting specific but non-exhaustive sectoral examples.

Externality failures

Externalities are unintended side effects of an economic activity that affect other parties not involved in the activity (Krugman and Wells 2015; Weimer and Vining 2017). While the energy sector is dominated by the *negative externalities* of fossil fuels, such as greenhouse gas emissions (González Ortiz et al. 2020), there are also externalities from renewables, such as deforestation, water use and noise (Sovacool et al. 2021). These unaccounted costs create a systematic economic bias that diminishes the cost-effectiveness of energy efficiency solutions (Allcott and Greenstone 2012), as their value is tied to the underrepresented price of energy. Addressing this challenge entails internalising these external costs to reflect the true societal price of energy supply. Yet, in the EU, present mechanisms like emissions trading schemes (ETS) and carbon taxes have only internalised around 40% of these costs from electricity and heat supply (Smith et al. 2020).

A follow-on problem is *distortions in energy taxes and levies*. The EU's tax structure places disproportionately higher costs on electricity than on fossil fuels. In areas like space heating, the EU ETS imposes carbon charges on electricity consumers and users of large district heating networks, while fossil heating fuels such as natural gas remain largely untaxed (Rosenow et al. 2023). Moreover, levies, such as those to support renewable energies, are predominantly assigned to electricity. Such distortions not only deter the uptake of energy-efficient innovations like heat pumps but also conceal the temporal dynamics of energy and network use, impeding demand-side flexibility (Rosenow et al. 2023; Barnes and Bhagavathy 2020).

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Market access failures

Ease of market entry is key to fostering competition and innovation in markets (Krugman and Wells 2015). However, market design regulations can sometimes prevent new entrants from participating. While these regulations are often designed to ensure system reliability, they can inhibit competition and slow the uptake of innovative energy efficiency solutions. *Restricted market entry* is present in two major domains:

- Electricity markets: The EE1st principle highlights that demand-side flexibility is a system resource that can compete alongside traditional generation in electricity markets (Mandel et al. 2022c). Demand-side flexibility can contribute in real-time to energy markets, provide ancillary services for grid stability, and participate in capacity markets to ensure adequate power availability during demand peaks (Pató and Mandel 2022). However, despite its vast potentials[67], demand-side flexibility faces regulatory discrimination, including onerous eligibility criteria, tendering rules, and product designs (smartEn 2022b, 2023).
- District heating systems: Unlike electricity and gas, EU legislation does not mandate unbundling for district heating, resulting in typically integrated utilities. While heat networks are natural monopolies, this does not apply to heat production (Billerbeck et al. 2023). Industrial excess heat and renewable heat sources (solar, geothermal, etc.) have potential to supply, but market entry restrictions often impede their integration, limiting competition and improved efficiencies in heat production (Holzleitner et al. 2020; Bürger et al. 2019).

67 In 2030, full utilisation of demand-side flexibility in the EU could save EUR 4.6 billion (5%) in electricity system costs and reduce greenhouse gas emissions by 8%, compared to a scenario without demand-side flexibility (smartEn 2022a).

Regulatory failures

In the EU's unbundled market structure, networks operate as natural monopolies. To prevent monopolistic pricing and behaviour, they need to be regulated (Baldwin et al. 2012; Batlle and Ocaña 2016). The EE1st principle recognises that network capacity and reliability needs can be addressed using non-wires solutions (NWS) (Rosenow and Cowart 2019). These solutions can be more cost-effective and quicker to deploy than traditional infrastructure investments such as power lines or substations. Examples of NWS include temporary load shifting (demand response), permanent load reduction (end-use energy efficiency), distributed generation and advanced grid technologies such as grid management software and sensors (Chew et al. 2018; Dyson et al. 2018).

To procure NWS, network operators could issue tenders specifically seeking NWS to address identified grid constraints, contract third-party aggregators to curtail their energy use during peak periods or, in collaboration with retail energy providers, encourage the use of time-of-use network tariffs to shift consumer energy usage. However, unlike in the U.S. (Chew et al. 2018; Frick et al. 2021), NWS are not yet widely considered by EU network operators (Chondrogiannis et al. 2022), leaving untapped potential for cost savings and enhanced grid reliability. This represents regulatory failure (Baldwin et al. 2012; Mandel et al. 2022c), as the remuneration regime designed by the regulatory authorities largely affects the financial incentives of the regulated network operator to consider NWS.

The most common remuneration regime for electricity network operators in EU Member States is revenue or price cap regulation (CEER 2023), which places a cap on the tariffs the operator can charge. In theory, the operator has an incentive to reduce costs and improve productive efficiency since it can retain the profits it earns by operating below the cap (Mulder 2021; Rious and Rosetto 2018a). In practice, however, revenue cap regulation primarily motivates short-term cost savings to improve profitability, such as reducing line losses or optimising workforce management (Rious and Rosetto 2018a; Mulder 2021). Incentives are weak to adopt long-term NWS, which often involve upfront costs while savings from deferred capital projects are realised over many years.

The regulatory failure that network operators do not produce at the lowest possible cost can be classified as *X-inefficiency* (Weimer and Vining 2017). It can be attributed to misaligned regulatory incentives, favouring costlier traditional infrastructure upgrades over efficient, innovative NWS.[68] Specific misalignments include:

68 The underlying economic problem is information asymmetry in a principal-agent context: the regulator (principal) is trying to ensure the regulated network company (agent) operates efficiently and fairly, but the latter is primarily motivated by its own profit objectives and has more information about its operations than the regulator (Mulder 2021).

- CAPEX bias: Tariff regimes tend to favour capital expenditures (CAPEX) over operating expenses (OPEX), incentivising infrastructure investments over potentially more cost-effective NWS, which often fall under OPEX (Pató and Mandel 2022). Under revenue cap regulation, this bias can arise, for example, because a larger regulatory asset base leads to a higher cap and thus higher potential profits after costs.
- Lack of dedicated incentives for NWS: Revenue cap regulation strictly limits the tariffs operators can charge, without directly considering outcomes such as the smart grid deployment or service quality (Rious and Rosetto 2018a). Introducing performance metrics linked to financial rewards can ensure that operators not only maintain short-term cost efficiency but also meet desired operational benchmarks (Littell et al. 2018).
- Difficulty in setting the revenue cap: Given the information asymmetry between regulator and the network company, the challenge in revenue cap regulation is to set the cap close to the company's efficient average costs (Rious and Rosetto 2018a). If set too high, consumers pay excessively, whereas if set too low, the company might compromise service quality and disregard innovative solutions like NWS.

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Information failures

Information on energy efficiency solutions is generally asymmetric and incomplete (Ramos et al. 2015), creating another economic distortion. Producers, such as power plant operators, continuously gather information to make informed business decisions and to maintain profitability. In contrast, consumers have no such core business. They gather material on energy efficiency ad hoc and have to reconcile often conflicting information, resulting in suboptimal choices (Sorrell et al. 2000b; Rivas Calvete et al. 2016). Of particular concern to economists is asymmetric information, where one party in a transaction has more or better information than the other. Important market failures in this area include adverse selection and split incentives (Sorrell et al. 2000a; Sorrell et al. 2000b; Krugman and Wells 2015; Thollander et al. 2010; Leach 2010).

Adverse selection arises before a transaction occurs. One party has private information about some aspect of the product or themselves that the other party cannot observe. As a result, the uninformed party may make 'adverse' decisions (Giraudet 2020; Mulder 2021; Krugman and Wells 2015; Mankiw 2017). Examples include:

- Appliances: Manufacturers could label appliances as energy efficient without making significant improvements. Consumers, unable to differentiate, may become sceptical of all efficiency labels, hindering sales of genuinely efficient products (Thollander et al. 2010).
- Building energy performance: A seller may falsely claim that a building has high energy performance, but buyers, cautious about potential misinformation, reduce their willingness to pay, discouraging the sale of genuinely efficient buildings (Schleich 2009; Sorrell et al. 2000a).

- Electricity and network pricing: Electricity consumers do not have timely information about the real-time costs of electricity production. This can lead to suboptimal consumption patterns from a system-wide perspective. For example, if the price does not rise during peak demand hours when the marginal cost is high, consumers might use more electricity than is economically efficient (Gillingham et al. 2009; ACER/CEER 2021).
- Capital markets: Financial institutions may lack essential information on new, smaller-scale, demand-side resources (Zimring et al. 2013). Absence of historical data can make these investments appear riskier than larger, established projects such as network infrastructure. This information asymmetry, combined with high transaction costs (see below), can lead to higher, sometimes prohibitive, interest rates, particularly for low-income households and small businesses (McInerney and Bunn 2019; Zimring et al. 2013; Brown 2004).

Split incentives arise when two parties in a transaction face asymmetric information, misaligned incentives and transaction costs, leading one party to not invest in beneficial actions because the returns from such actions accrue to the other party, leading to suboptimal outcomes for both (European Union 2023a; Bird and Hernández 2012; Sorrell et al. 2000b; Linares and Labandeira 2010).

- Landlord-tenant problem: Landlords may avoid investing in energy efficiency measures if the investment cannot be passed on to the tenant, and vice versa, creating a misalignment between who pays for improvements and who benefits from energy savings (Gillingham et al. 2009; Bird and Hernández 2012).
- Corporate energy management: Facility managers might disregard energy efficiency measures if budgets and benefits are controlled by separate departments (Schleich 2009; Sorrell et al. 2000b).

Transaction cost failures

Transaction costs refer to costs associated with the exchange of goods or services that are not included in the market prices of the products (Mundaca et al. 2013; Lundmark 2022; Coase 1960). They can be broadly categorised as (1) search or due diligence costs (searching and assessing information); (2) negotiation costs (reaching an agreement on terms); and (3) enforcement costs (ensuring that the terms of the agreement are followed) (Kiss 2016; Brown and Wang 2017).

Transaction costs are a significant factor in energy systems. Often inaccurately referred to as 'hidden costs', they have long been argued to hinder the uptake of energy efficiency solutions (Schleich 2009; Jaffe and Stavins 1994; Stadelmann 2017). Their magnitude as a share of total investment costs has been estimated between 10% for efficient lighting technologies up to 25-50% for building insulation and efficient windows (Mundaca et al. 2013; Kiss 2016; Adisorn et al. 2021; Lundmark 2022).

While this magnitude is case- and context-specific, transaction costs tend to be higher for small-scale energy efficiency solutions than those for energy supply infrastructure (Mundaca et al. 2013; Sorrell et al. 2000b). One factor is the transaction frequency. Households make energy efficiency improvements infrequently and recover their transaction costs with a single purchase. Producers, in turn, make repetitive infrastructure investment decisions and can amortise their transaction costs through economies of scale (Sutherland 1991; Sorrell et al. 2000b). Another factor is the number of intermediaries. Building retrofits, for instance, involve many parties, including building owners, building developers, subcontractors, consultants and tenants (Kiss 2016), increasing the complexity of transactions (Mundaca et al. 2013). Finally, the characteristics of the transactors matter (Lundmark 2022). As detailed below, consumers often have limited cognitive capacity to process information, while producers can rely on professional expertise. Selected examples of transaction costs include:

- End-use energy efficiency investments: In building renovation and construction, especially, various actors with diverse interests temporarily work together. Transaction costs arise from finding reliable contractors, settling contractual terms with suppliers, and ensuring project specifications are met, making the process complex and protracted (Bertoldi et al. 2022; Kiss 2016; Palm and Reindl 2018).
- Demand response services: For residential or commercial energy consumers, participating in demand response entails transaction costs such as negotiating contracts, gathering and processing energy market information, maintaining technology, and ensuring regulatory compliance (IRENA 2019a; Burger et al. 2017). This can deter small-scale flexibility resources from actively engaging, despite potential benefits.
- Capital markets*:* Transaction costs are high for small-scale energy efficiency projects. These costs, which stem from due diligence activities like assessing creditworthiness, project feasibility, and regulatory environment, along with processing expenses such as legal fees and monitoring, can inflate the transaction costs per unit of capital for demand-side projects (Sorrell et al. 2000b; Golove and Eto 1996; Schleich 2009; Kreibiehl et al. 2022).

Behavioural failures

The benchmark of well-functioning markets suggests that agents are fully rational and make utility-maximising decisions. This implies that consumers would routinely invest in energy efficiency solutions and modify habits whenever long-term benefits outweigh costs. However, evidence from behavioural economics and psychology indicates that cognitive biases prevent consumers from making privately-optimal choices, even when given perfect information and appropriate incentive structures (Sorrell et al. 2000b; Linares and Labandeira 2010; Schleich 2009).[69] In contrast,

69 Although behavioural failures primarily affect households, they also occur in organisations, such as small businesses, especially where single individuals hold considerable decision-making power (IEA and UsersTCP 2020).

producers in competitive markets, such as power plants, have to make rational corporate decisions based on detailed cost-benefit analyses to maintain profitability (Mulder 2021).

There is a growing recognition of consumers' systematic deviations from the rational choice model, referred to as behavioural failures or anomalies (Saunders et al. 2021; Gillingham et al. 2018; Frederiks et al. 2015; Abrardi 2019).[70] Among the prominently observed behavioural failures is *bounded rationality*, which indicates the limited cognitive abilities of individuals to adequately process all available information. As a result, they rely on simple heuristics and rules of thumb to make decisions (Cattaneo 2019; Schleich et al. 2016; Stadelmann 2017). For example, when choosing a new appliance, households may consider the purchase price but overlook the running energy costs (Schleich et al. 2016; Stadelmann 2017).

Another well-documented behavioural failure is *loss aversion*, where individuals tend to prefer avoiding losses to achieving gains, leading them to undervalue long-term savings (Cattaneo 2019; Frederiks et al. 2015; Stadelmann 2017; Abrardi 2019; Gillingham and Palmer 2014). To illustrate, people may decide against otherwise cost-effective energy-efficient appliances because the immediate loss (purchase costs) is perceived as more significant than the gradual gains (energy cost savings) (Schleich et al. 2016).

The *status quo bias* captures the inherent preference among consumers to keep things the way they are, even if a change would be beneficial. This can deter them from adopting more energy-efficient technologies or behaviours (Schleich et al. 2016; Cattaneo 2019). For example, influenced by this bias, consumers may stick with traditional flat-rate electricity tariffs and resist switching to time-differentiated tariffs.

5.3 Practice: Policy instruments for energy efficiency first

This chapter identifies and discusses policy instruments to address the EE1st principle. Based on the theoretical framework established above, these are understood as formalised measures adopted by governing bodies or regulatory authorities to address specific market failures, intended to facilitate a level playing field between energy efficiency and supply in line with the EE1st principle.

The instruments are categorised by type of market failure (Figure 24) and detailed from Table 26 to Table 31, capturing their effects, potential challenges, and legal status in the EU. In total, twenty-

70 Over twenty-five behavioural anomalies in economic decision-making are documented in the literature (Shogren and Taylor 2008; Ramos et al. 2015). However, not all of these are conceptually sound, empirically significant and relevant to energy efficiency (Gillingham et al. 2018).

nine specific instruments are identified. However, this scope is not exhaustive and focuses primarily on energy efficiency solutions in the residential and services sectors, with less emphasis on industry and transport.

5.3.1 Internalising external costs (externality failures)

To correct the market failure of negative externalities and thus contribute to an economic balance between energy saving and energy supply, externalities need to be internalised, i.e. added to the market price (Krugman and Wells 2015) (Table 26). Two main instruments to price emissions are: the ETS, which sets a cap for emissions with prices determined by the market (ID A1), and the emissions tax, which sets the emissions price, allowing economic agents to decide on quantities (ID A2).

The EU has operated an ETS I for large-scale industrial and power generation units since 2005 (Erbach and Foukalová 2023). As a move towards the EU's target of reducing net greenhouse gas (GHG) emissions by 55% by 2030 relative to 1990 (European Union 2021b), the 2023 EU ETS Directive (European Union 2023b) not only reduces emission allowances but also introduces a separate ETS II, effective from 2027, covering road transport and building fuel use. To fully embody the EE1st principle, internalisation should go beyond GHG emissions to include other pollutants affecting air, water, and inducing noise (Sovacool et al. 2021). However, as discussed in Chapter 5.4, and contrary to neoclassical economics, pricing externalities is certainly not sufficient to implement EE1st.

A related need in pricing externalities is to rebalance taxes and charges (ID A3) so that electricity, as an energy carrier with inherent energy efficiency benefits, is appropriately priced relative to carbon-intensive fuels. The forthcoming ETS II addresses some of these imbalances in transport and buildings, as both electricity and fuels will be subject to carbon pricing. However, potential biases remain as Member States retain discretion over additional carbon taxes and excise duties. The planned recast of the Energy Taxation Directive (European Commission 2022c) aims to tackle this by removing outdated exemptions and reducing taxes that favour fossil fuels (Karaboytcheva 2022). Economically, efficient taxation would involve higher fossil fuel taxes and lower electricity taxes, reflecting their respective external costs. Levies, such as renewable energy incentives, should be redistributed from electricity consumers to the wider taxpayer base (Rosenow et al. 2023).

5.3.2 Enabling market access for energy efficiency solutions (market access failures)

Free market access for energy efficiency solutions is essential to stimulate competition and innovation. Table 27 lists relevant policy instruments. In electricity markets, non-discriminatory market access (ID B1) should enable the participation of demand-side flexibility, from heat pumps to electric vehicles and industry, so that these resources can compete on equal footing with traditional generators for a cost-efficient supply. The EU Electricity Market Regulation (European Union 2019e) has established clear rules to ensure the participation of these flexible resources, both individually and via aggregation (ID E3).

Yet, implementation is lagging behind. Balancing markets and ancillary services in many Member States maintain high technical requirements. Day-ahead and intraday markets often have long settlement periods or high minimum bid sizes. Capacity mechanisms and strategic reserves frequently have restrictive duration requirements or complex verification protocols, favouring traditional thermal generators over smaller flexibility resources (smartEn 2022b, 2023). Aside from market entry, full utilisation of demand-side flexibility also requires time-differentiated tariffs (ID D4) and independent aggregators (ID E3).

In district heating systems, third-party access (ID B2) promotes the integration of industrial excess heat as an energy efficiency solution (Bürger et al. 2019). The Renewable Energy Directive (European Union 2018a) mandates Member States to facilitate grid access when operators replace or expand existing capacity. However, the Directive contains numerous exemptions, allowing incumbent generators to refuse feed-in requests (Holzleitner et al. 2020). As a result, third-party access remains underdeveloped in many Member States (Bacquet et al. 2021; Billerbeck et al. 2023). A forthcoming revision of the Directive (European Commission 2021d) proposes mandatory access in systems >25 MW_{th}, with access conditions determined by regulators, indicating a more structured push towards heat producer competition.

5.3.3 Advancing non-wires solutions in network investment and operation (regulatory failures)

NWS present a potentially cost-effective yet underutilised alternative to traditional electricity network infrastructures in the EU. Table 28 reports on instruments to address the underlying regulatory failures. A primary hindrance to widespread NWS adoption is the CAPEX bias in established tariff regimes, which favours capital-intensive infrastructure investments over operational solutions like NWS. The total expenditure (TOTEX) approach (ID C1) integrates CAPEX and OPEX into one expenditure category, aiming to provide balanced regulatory treatment of all costs (Pató and Mandel 2022; Rious and Rosetto 2018b). This can level the playing field for NWS, which often fall under OPEX. While its application within EU Member States is limited, countries like the UK demonstrate its effective use in electricity distribution network regulation (Jamasb 2021).

Another issue is the lack of dedicated incentives for NWS adoption. Performance-based regulation (ID C2), which grants financial rewards for achieving specific metrics to reach certain socially desired goals, can potentially shift the focus away from conventional, capital-intensive solutions (Pató et al. 2019a; Littell et al. 2018). An extrinsic incentive to promote NWS is to mandate network operators to undertake feasibility studies (ID C3), comparing the technical and financial viability of infrastructures with NWS (Pató and Mandel 2022). For example, the Electricity Market Directive (European Union 2019d) requires the consideration of NWS in distribution network development plans.

Setting the cap under revenue cap regulation is another challenge. An incorrectly set cap can either constrain network operators, preventing innovative solutions like NWS, or allow excessive profits (Mulder 2021). Here, yardstick regulation (ID C4), which benchmarks a firm's performance against comparable entities, provides a robust mechanism for cap setting (Mulder 2021; Rious and Rosetto 2018a). This not only fosters operational efficiency but also supports the verification of metrics in performance-based regulation. Some Member States, notably Germany and the Netherlands, have begun integrating this approach (CEER 2023).

Together, these remuneration schemes are key for setting effective NWS incentives, as regulators have limited capacity to monitor every single network development project and verify compliance with the EE1st principle (ACER 2016). However, the instruments mentioned add complexity to traditional revenue cap regulation, requiring substantial technical expertise and financial resources in national regulatory authorities (Rious and Rosetto 2018a). Moreover, the promotion of NWS requires not only incentives for network operators, but also the involvement of consumers through dynamic network tariffs (ID D4), and the integration of aggregators (ID E3) (Pató and Mandel 2022). An actionable step might be introducing regulatory sandboxes (CEER 2022), allowing network operators to test and experiment with NWS without tight regulatory constraints.

5.3.4 Overcoming information asymmetries (information failures)

Major information failures revolve around adverse selection and split incentives. Table 29 lists corresponding policy instruments. Signalling instruments, such as labels (ID D1) and energy performance certificates (ID D2), can address adverse selection (Markandya et al. 2015). The proposed recast of the Energy Performance of Buildings Directive (EPBD) (European Commission 2021f; Wilson 2022) could enhance the stringency of building certificates across Member States. Mandatory energy audits (ID D3) enhance internal decision-making and signal commitment to energy efficiency to investors (Schleich 2009).

Yet, adverse selection goes beyond these classic examples. A continuing problem is electricity and network pricing, where average tariffs create information asymmetries between energy producers and consumers (Gillingham et al. 2009), leading to underutilisation of demand-side flexibility (Mandel et al. 2022c). While time-differentiated tariffs (ID D4) have been strengthened in EU electricity market legislation (European Union 2019e), they have mostly been applied to electricity generation and less so to network tariffs (smartEn 2022b).

Information asymmetries are also present in capital markets. Financial institutions, lacking experience with the intricacies of energy efficiency solutions, are heavily biased towards conventional large-scale energy infrastructure projects (McInerney and Bunn 2019; Zimring et al. 2013; Brown 2004). The recent EU Taxonomy Regulation (European Union 2020) marks a positive shift (ID D5), potentially encouraging investment in smaller, demand-side solutions. Meanwhile, the proposed Green Bond Regulation (European Commission 2021g) reflects a similar purpose (ID D6).

Addressing split incentives, particularly the landlord-tenant problem remains challenging due to its complex nature. Instruments such as revised rent and condominium laws (ID D7) could enable effective redistributions of investments and energy cost. Voluntary approaches, such as green leases (ID D8), offer flexibility in practical implementation (Castellazzi et al. 2017; Economidou and Bertoldi 2015; Bird and Hernández 2012). A notable addition to the proposed EPBD recast (European Commission 2021f) are building renovation passports (ID D9), providing a systematic guide to energy efficiency improvements, potentially signalling the added value of renovation to both landlords and tenants (Wilson 2022). Regarding split incentives in firms and organisations, mandatory energy management systems (ID D10) can help ensure continuous identification and monitoring of energy efficiency improvements.

5.3.5 Promoting small-scale demand-side transactions (transaction cost failures)

Transaction costs are true economic costs. As such, it may be privately optimal not to invest in energy efficiency if the transaction costs are too high relative to the anticipated energy savings (Sorrell et al. 2000b; Stadelmann 2017). However, given the benchmark of well-functioning markets and *societal* optimality, transaction costs provide a strong rationale for government intervention (Golove and Eto 1996; Sorrell et al. 2000b; Sanstad and Howarth 1994). Table 30 lists potential instruments.

To mitigate transaction costs associated with energy efficiency in small and medium-sized enterprises, the promotion of energy service companies (ESCOs) has proven effective (ID E1) (Schleich 2009). ESCOs offer contracting models, notably energy performance and energy supply contracts, where they finance, design and implement energy efficiency projects, then recoup their investments from the savings (Boza-Kiss et al. 2019). The ESCO market in the EU has experienced robust growth (Boza-Kiss et al. 2019), underscored by the EED's legal provisions for ESCO certification, monitoring, and regulation (European Union 2023a).

A related instrument gaining traction is one-stop shops (ID E2), which help to consolidate the design, material procurement, financing, and implementation services for building renovation and construction projects, thus reducing the transactional complexities of dealing with different service providers. In the EU, one-stop shops are increasing in number and activity, accounting for about 4-5% of renovation projects (Boza-Kiss et al. 2021), supported by new (European Union 2023a) and planned (European Commission 2021f) provisions.

In demand response programmes, aggregators (ID E3) consolidate numerous small-scale resources, forming a larger, more reliable asset. They reduce transaction costs for consumers through managing flexible resources, supplying enabling technologies, and overseeing financial settlements

(IRENA 2019a; Burger et al. 2017). Although aggregators have legal recognition in the EU (European Union 2019d), existing discriminatory market access rules (ID B1) result in their limited deployment across several Member States (smartEn 2023, 2022b).

In capital markets, high transaction costs often hinder small-scale energy efficiency investments. Financial institutions can address this by aggregating these loans into larger portfolios (warehousing) and converting them into tradable assets (securitisation) such as bonds (ID E4) (McInerney and Bunn 2019; Brown et al. 2019). This attracts large-scale institutional investors with broader, more diversified opportunities. The European Investment Bank and state-owned development banks have started using these mechanisms (European Investment Bank 2019).

5.3.6 Addressing cognitive biases in consumer decision-making (behavioural failures)

Behavioural failures prevent households and firms from adopting efficient and more flexible practices, highlighting the need for policy interventions (Häckel et al. 2017; Gillingham et al. 2018). Typically, these instruments are integrated as non-coercive motivational 'nudges' into information instruments (Section 5.3.4) (Schleich et al. 2016; Cattaneo 2019; Ramos et al. 2015). While nudges are often highly cost-effective, the energy savings they achieve tend to be modest (Gillingham et al. 2018). Table 31 shows proven behavioural instruments. The (IEA and UsersTCP) provide additional practical insights.

Addressing bounded rationality could involve simplification and framing of information (ID F1) (IEA and UsersTCP 2020; Frederiks et al. 2015). For example, the revised EU product energy labels use the A to G scale (European Union 2017), which consumers have found easier to understand than the former A+++ to G scale (IEA and UsersTCP 2020; Faure et al. 2021). Feedback mechanisms (ID F2), such as in-home displays linked to smart meters, can address bounded rationality by providing normative energy saving tips (IEA and UsersTCP 2020; Abrardi 2019; Zangheri et al. 2019). Peer comparison and social norms (ID F3) can stimulate positive competitive efforts (IEA and UsersTCP 2020; Andor and Fels 2018), such as through home energy reports (Saunders et al. 2021).

To address loss aversion, information can be restructured to emphasise the losses of inefficient behaviour (ID F4) (Cattaneo 2019; Abrardi 2019). For example, time-differentiated tariffs (ID D4) can be made more effective for load-shifting by stating on in-home displays 'Using your appliances during peak hours could cost you €2 per week. Shift to off-peak hours to avoid unnecessary losses!' (Abrardi 2019; IEA and UsersTCP 2020). Commitment and goal-setting programmes (ID F5) can leverage people's aversion to failing to meet self-set or publicly declared goals (IEA and UsersTCP 2020; Cattaneo 2019; Saunders et al. 2021; Abrardi 2019). For example, combining goal setting and social norms, 1,100 firms in the Netherlands effectively committed to voluntary energy savings of 8% over four years (IEA and UsersTCP 2020).

Table 26: Externality failures and corrective policy instruments

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Negative externa-lities		Energy conversion processes do not fully compensate for external costs they impose, leading to economic bias against energy efficiency solutions.	Emissions trading system	A1	Incentivises energy savings and/or fuel switches by capping total level of emissions, creating a market for allowances.	Complexity in design and administration; surplus allowances may reduce effectiveness; risk of emission leakage; regressivity affects low-income households disproportionately; politically sensitive.	ETS I (industrial and power sectors) since 2005; ETS II (road transport and buildings) from 2027.	(European Union 2023b)	(Dubash et al. 2022; Bertoldi et al. 2022; Ordonez et al. 2017)
			Emission taxes	A2	Incentivises energy savings and/or fuel switches by setting emission tax rate, letting economic agents decide on emission quantities.	Challenging to set optimal tax level; risk of emission leakage; regressivity affects low-income households disproportionately; politically sensitive.	Employed in 9 Member States, but potentially obsolete under ETS II.	(European Union 2003)	(Dubash et al. 2022; Bertoldi et al. 2022; Rosenow et al. 2023)
Distor-tions in energy taxes and levies		Disproportionate tax burden on electricity versus fossil fuels discourages adoption of efficient, electrically-powered solutions (e.g. heat pumps).	Balancing taxes and levies on fuels and electricity	A3	Aligns tax and levy burdens across energy carriers, potentially promoting efficient electric technologies. Reforms could include setting tax levels according to external costs.	Political opposition if perceived as disproportionately impacting certain demographics (energy poverty).	Ongoing revision with proposed restructuring of tax rates.	Proposal (European Commission 2022c)	(Rosenow et al. 2023; Karaboyt-cheva 2022)

Table 27: Market access failures and corrective policy instruments

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Restricted market entry	Electricity markets	Market access rules discriminate against demand-side flexibility to compete on equal footing with traditional generation.	Non-discriminatory market access for demand-side flexibility	B1	Removes undue regulatory restrictions to enable market participation from demand-side resources, both individually and via aggregators, thus improving competition.	Defining and enforcing non-discriminatory criteria; managing grid stability with increased demand-side participation.	Slow implementation of legal requirements for equal market access.	(European Union 2019e) Art. 6-8, 13, 20-22; (European Union 2019d) Art. 3	(Pató et al. 2019b; smartEn 2022b)
	District heating systems	Monopolies in district heat production lead to suboptimal outcomes in innovation, fossil-dependence, prices, and overall economic efficiency.	Third-party access in district heating systems	B2	Enables multiple heat producers to share network infrastructure to deliver heat, facilitating energy efficiency solutions (waste heat, heat pumps, renewable heat) and stimulating producer competition.	System management (maintaining supply/demand balance and temperature levels); setting and enforcing quality standards.	Inadequate legal provisions with various exemptions, subject to revision.	(European Union 2018a) Art. 24; proposal (European Commission 2021d)	(Holzleitner et al. 2020; Bürger et al. 2019; Billerbeck et al. 2023)

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Table 28: Regulatory failures and corrective policy instruments

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
X-inefficiency	CAPEX bias	Network operators choose expensive capital projects even when cheaper operational NWS exist because the regulatory framework allows them to earn a return on the former.	TOTEX approach	C1	By considering TOTEX, regulators can ensure that network operators consider all solutions (both capital-intensive and operational) on an equal footing. This can level the playing field for NWS, which often fall under OPEX.	Complexity of rate cases and regulatory reviews; risk of underinvestment in infrastructure; difficult classification of expenses under either CAPEX or OPEX.	Not explicitly mandated; limited experience across Member States.	(European Union 2023a) Art. 27; (European Union 2019d) Art. 32; (European Union 2019e) Art. 18	(Pató and Mandel 2022; Rious and Rosetto 2018b)
	Lack of dedicated incentives for NWS	Revenue cap regulation incentivises operators to cut short-term costs (e.g. maintenance/ repairs), but lacks specific incentives for adopting long-term NWS to enhance grid efficiency and innovation.	Performance-based regulation	C2	When operators achieve certain benchmarks (e.g. reduced peak load), they receive financial rewards, shifting focus from capital-intensive solutions to potentially more cost-effective NWS.	Determining measurable metrics; need for robust data verification; regulatory burden for monitoring system; potential network tariff volatility for consumers.	Not explicitly mandated; limited experience across Member States.	(European Union 2019e) Art. 18	(Littell et al. 2018; Pató et al. 2019a)
			Mandatory assessment of NWS	C3	Requires operators to conduct feasibility studies assessing technical/financial viability of NWS, and documenting assessments for transparency and accountability.	Biases or inconsistencies in analyses; upfront costs for assessment.	Robust legal provisions.	(European Union 2023a) Art. 27; (European Union 2019d) Art. 32, 51	(Pató and Mandel 2022)

Table 28: **continued**

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
X-inefficiency	Difficulty in setting the revenue cap	Regulators tend to set inadequate revenue caps, either constraining operators (hindering innovative solutions) or allowing excessive profits	Benchmarking (yardstick competition)	C4	Compares operator's performance to similar firms. Reduces information asymmetry by revealing potential discrepancies in reported data, ensuring more accurate cap setting.	Comparability across heterogeneous network operators (e.g. scale, demand levels, infrastructure age); data quality.	Not uniformly required, but applied in several Member States	(European Union 2023a) Art. 27; (European Union 2019d) Art. 32; (European Union 2019e) Art. 18	(Mulder 2021; Rious and Rosetto 2018

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Table 29: Information market failures and corrective policy instruments

Market failure outline			Policy response				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Adverse selection	Appliances	Sellers of energy-efficient products have more information about product's efficiency than buyers, leading to undervaluation of efficiency.	Labelling	D1	Provides standardised, credible information about energy efficiency, aiding consumers in making informed purchases.	Cost of verification and certification; potential misinterpretation by consumers.	16 product groups require an energy label.	(European Union 2017)	(Dubash et al. 2022; Markandya et al. 2015)
	Building energy perfor-mance	Sellers and builders of buildings have more information about their energy performance than potential buyers or tenants, skewing purchase decisions towards less efficient buildings.	Energy performance certificates	D2	Offers potential buyers or renters standardised, credible information about building's energy efficiency, facilitating more informed decisions.	Cost of verification and certification; potential misinterpretation by buyers.	Adopted in early 2000s. Must be issued for all buildings sold or rented.	(European Union 2010, 2018c) Art. 11-13	(Bertoldi et al. 2022; Markandya et al. 2015; Stromback et al. 2021)
	Energy perform-ance of small and medium-sized enterprises (SMEs)	SMEs lack comprehensive data about own energy performance, hindering both internal decision-making and external interactions financial institutions.	Energy audits	D3	SMEs obtain detailed insights into their energy consumption and potential efficiency improvements, also signalling their commitment to energy efficiency to investors.	Costs associated with audits; SMEs may not act on audit recommendations; variations in audit standards.	Required for enterprises with annual energy consumption >85 TJ.	(European Union 2023a) Art. 11	(Bertoldi et al. 2022; Giraudet 2020; Dubash et al. 2022)

Table 29: continued

Market failure outline			Policy response				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Adverse selection	Energy and network pricing	Producers know real-time costs of delivering energy, while consumers operate on averaged-out tariffs, leading to inefficiencies in consumption and grid usage.	Time-differentiated energy and network pricing	D4	Facilitates demand-side flexibility by reflecting marginal supply costs, incentivising consumers to shift electricity use, optimising infrastructure utilisation and investment.	Requires advanced metering devices; potential consumer unawareness of benefits; weak price signals due to electricity bill structure (ID A3).	Many design options, mostly applied to electricity tariffs, less so to network tariffs.	(European Union 2019e) Art. 11, 18; (European Union 2023a) Art. 27	(IRENA 2019b; ACER/CEER 2021)
	Capital markets	Financial institutions lack information to make informed investment decisions, leading to higher perceived risk and higher borrowing costs for small-scale energy efficiency solutions.	Standardisation framework for sustainable finance (EU Taxonomy)	D5	Standardised classification to assess sustainability of investments. Could redirect capital towards efficient demand-side solutions classified as sustainable.	Definition of universally accepted standards; potential for exclusion of certain activities or misclassification.	Taxonomy Regulation implemented in 2020, gradual definition of technical screening criteria.	(European Union 2020)	(Lucarelli et al. 2020)
			Certification of green bonds	D6	Provides investors with information to evaluate socio-environmental impact of investments, potentially redirecting capital towards efficient demand-side solutions. also signalling their commitment to energy efficiency to investors.	Incredibility of certificates due to risk of greenwashing unsustainable projects.	Growing market, but various certifications. Ongoing efforts for uniform and robust standards.	Proposal (European Commission 2021g)	(McInerney and Bunn 2019)

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Table 29: continued

Market failure outline			Policy response				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Split incentives	Landlord-tenant problem	Landlords have little incentive to invest in energy efficiency improvements when tenants pay energy bills, and vice versa.	Rent acts and condominium laws	D7	Establish conditions for redistribution of investments and energy cost savings of an energy efficiency upgrade.	Determining permissible rent increases; potential rent increases; burden on landlords to finance improvements.	Several Member States working on revisions of rent acts.	(European Union 2023a) Art. 22	(Castellazzi et al. 2017; Economidou and Bertoldi 2015)
			Contractual approaches (green leases)	D8	Voluntary counterpart to D7, aligning interests of landlords and tenants through negotiation.	Transaction costs for drafting and enforcing contracts.	Growing trend, especially in commercial properties.	n.a. (contractual in nature)	(Bird and Hernández 2012; Economidou and Bertoldi 2015)
			Building renovation passports	D9	Provides a step-by-step guide to energy efficiency upgrades, demonstrating potential net-benefits to both landlords and tenants.	Cost of creating the passport and keeping it updated.	Initiated in some Member States, envisaged under recast EPBD.	Proposal (European Commission 2021f) Art. 10	(Volt et al. 2020)
	Corporate energy management	Facility managers might not consider energy efficiency if budgets and benefits are controlled by separate departments.	Mandatory energy management systems	D10	Requires unified approach to energy management across departments and ensures continuous monitoring and improvement.	Implementation and maintenance cost; ensuring training and competency.	Required for enterprises with annual energy consumption >10 TJ.	(European Union 2023a) Art. 11	(Schützenhofer 2021)

Table 30: Transaction cost failures and corrective policy instruments

Market failure outline			Policy response				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Transaction costs	End-use energy efficiency investments	Energy efficiency projects (e.g. building renovation) involve significant transaction cost in terms of searching expertise, negotiating contracts, and ensuring compliance.	Energy service companies	E1	Reduce transaction costs by offering expertise, facilitating financing, serving as a single point of contact, and navigating regulations.	Difficulties in scaling; contractual complexity.	Mature ESCO market, particularly addressing SMEs.	(European Union 2023a) Art. 29	(Bertoldi et al. 2021; Boza-Kiss et al. 2019)
			One-stop shops	E2	Service providers offering integrated building renovation and construction solutions, consolidating tasks such as service provider search, negotiations, implementation, and post-project services.	Complexity in providing comprehensive services.	Small but growing market.	(European Commission 2021f) Art. 15; (European Union 2023a) Art. 22	(Bertoldi et al. 2021; Boza-Kiss et al. 2021)
	Demand response services management	Small-scale resources (residential/commercial) face transaction costs (information acquisition, regulatory compliance, etc.), hindering effective participation in electricity markets.	Aggregators for demand response	E3	Pool multiple small-scale resources, manage utilisation, facilitate enabling technology (e.g. automated control systems), and handle financial settlement process.	Standardisation issues related to data/technology compatibility.	Legally recognised but limited deployment due to market entry restrictions (ID B1).	(European Union 2019d) Art. 13, 17	(IRENA 2019a; Pató et al. 2019b; smartEn 2023)

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Table 30: continued

Market failure outline			Policy response				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Trans=action costs	Capital markets	Costs for due diligence, processing, and monitoring deter investment in small-scale, dispersed energy efficiency projects compared to large-scale supply-side energy infrastructures.	Warehousing & securitisation	E4	Financial institutions aggregate small-scale loans into larger portfolios (warehousing) and turn them into tradable financial assets (securitisation).	Default risk remains; still contingent on market demand for green asset-backed securities	Used by European Investment Bank and state-owned development banks.		McInerney and Bunn 2019; Brown et al. 2019; European Investment Bank 2019)

Table 31: Behavioural failures and corrective policy instruments

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Bounded rationality		People have limited cognitive resources to process all available information, leading to simplified decision-making.	Simplification and framing of information	F1	Transforms complex data into comprehensible formats, facilitating informed decisions.	Risk of oversimplification; potential misinterpretation by consumers.	Varies by jurisdiction; some mandates for information framing	(European Union 2023a) Art. 22; (European Union 2017)	(IEA and UsersTCP 2020; Faure et al. 2021)
			Feedback mechanisms	F2	Provides regular, structured feedback on energy, enhancing user awareness and response.	Might be ignored if too frequent or not actionable.	Often voluntary, but gaining popularity in smart grids.	(European Union 2023a) Art. 17-18; (European Union 2019d) Art. 18	(Zangheri et al. 2019)
			Peer comparison and social norms	F3	Demonstrates energy use in relation to peers, motivating efficient behaviours.	Privacy concerns; might not be motivational for all.	Generally voluntary, trial applications in some jurisdictions.		(Andor and Fels 2018)

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Table 31: continued

Market failure outline			Policy instrument				EU Implementation		
Market failure	**Context**	**Description**	**Instrument**	**ID**	**Effect**	**Potential issues**	**Status**	**Legal refs**	**Literature refs**
Loss aversion		Individuals tend to prefer avoiding losses to acquiring equivalent gains, making them undervalue gradual savings.	Loss-framed messages	F4	Emphasises potential losses from non-action, making certain behaviours more compelling.	Can be perceived as manipulative or cause undue stress.	Generally voluntary, trial applications in some jurisdictions.		(Abrardi 2019; IEA and UsersTCP 2020)
			Commitment and goal setting programmes	F5	Engages individuals or organisations by having them set targets, fostering accountability and motivation.	Risk of demotivation if goals are not met; might be perceived as burdensome.	Generally voluntary, trial applications in some jurisdictions.	(European Union 2023a) Art. 22	(Abrardi 2019; IEA and UsersTCP 2020)
Status quo bias		Preference for maintaining current state of affairs, even if change is beneficial.	Changes to the default options	F6	Makes beneficial efficient choices the default, e.g. through product standards.	Might be perceived as forceful or limiting consumer autonomy.	Some Ecodesign mandates for efficient default options.	e.g. (European Union 2019a) Art. 3 for dishwashers	(IEA and UsersTCP 2020; Cattaneo 2019)

Finally, addressing the status quo bias could involve changing default options in favour of the efficient choice (ID F6) (Cattaneo 2019; IEA and UsersTCP 2020). For example, changing thermostats' default set point temperature can increase energy efficiency in offices (Brown et al. 2013). Another example is setting the default programme for dishwashers to eco mode upon startup (European Union 2019a). Both of these can be mandated through product standards.

5.4 Discussion: Looking beyond market failure theory

Chapters 5.2-5.3 present the argument that EE1st policies should address specific market failures to level the economic balance between energy demand and energy supply. This brings into focus traditional energy efficiency policies (Trotta et al. 2018; Boza-Kiss et al. 2013; Bertoldi 2022; Markandya et al. 2015) that promote energy efficiency per se – in particular standards, such as building codes, energy efficiency obligation schemes (EEOS), and public financing instruments, such as grants and soft loans. Noteworthy, standards target a market outcome rather than a specific market failure (Sutherland 1996; Mandel et al. 2022c). Financing instruments are typically justified by high upfront costs, lack of private capital, and perceived risk (Bertoldi et al. 2021; Bertoldi et al. 2022), none of which represents deviations from the benchmark of well-functioning markets (Figure 24) and thus genuine market failures (Linares and Labandeira 2010; Ordonez et al. 2017).

One consideration for going beyond market failure theory in the context of EE1st is the practical constraints to policy implementation, as identified in Table 26-Table 31. For example, it is unlikely that behavioural failures in households can be eliminated entirely through 'first-best' EE1st instruments such as information framing (Stadelmann 2017). In consequence, there are more market failures than policies to realistically address them (Fischer et al. 2021). This is further complicated by the second best theorem (Lipsey and Lancaster 1956), which states that correcting only one market failure, while others continue to exist, may not increase welfare at all.

Given these constraints, simulations suggest that mandating energy efficiency through standards or savings obligations could result in greater welfare than emissions pricing and other 'first-best' policies (Tsvetanov and Segerson 2013, 2014). This justifies the EU's focus on building codes (Wilson 2022), product standards (Ragonnaud 2023), and EEOS (Fawcett et al. 2019). However, to avoid these 'second-best' instruments creating welfare losses, their stringency needs to be accurately calibrated to economically optimal levels of energy efficiency. This requires accurate ex-ante valuation of variables such as externalities and multiple impacts, transaction costs, rebound effects, and market heterogeneity – all of which are complex and uncertain (Bertoldi et al. 2022; Mulder 2021; Allcott and Greenstone 2012; Gillingham and Palmer 2014; Parry et al. 2014; Dubash et al. 2022). Therefore, while not shortcuts, these instruments are a logical complement to EE1st-targeted policies (Mandel et al. 2022c).

Another reason to look beyond market failure theory when addressing the EE1st principle is that the theoretical benchmark of well-functioning markets does not explicitly account for equity and resource distribution in society (Sorrell et al. 2000b). For this reason, (Ordonez et al.) advocate the use of grants, rebates, tax credits, subsidised loans and other public financing instruments targeted at low-income households to alleviate energy poverty, regardless of whether these actions resolve traditional market failures.

The challenge with financing instruments is to prevent free-riding (Cattaneo 2019), where incentives for actions that would occur regardless may render the instruments cost-ineffective for society (Gillingham et al. 2018; Markandya et al. 2015). Aligning incentives with the EE1st principle also involves correcting public financing imbalances between energy efficiency and supply, for example by integrating energy saving auctions and renewable energy auctions (Bertoldi et al. 2022). In summary, established instruments such as standards and public financing, despite not addressing specific market failures, have a vital role in the EU's energy and climate policy mix.

5.5 Conclusion

The research started from the premise that high-level energy planning alone is not sufficient to implement the EE1st principle, and argued for public policy to align private energy investment and operation decisions with societal interests. Chapter 5.2 provided a theoretical framework of how the EE1st principle can be addressed through policy instruments. Based on market failure theory, the EU's energy services market was shown to be inherently biased towards energy supply infrastructures over energy efficiency solutions, thus clearly disproving any remaining sceptics of an energy efficiency gap (Brown and Wang 2017).

The importance of addressing underlying market failures, such as externalities or transaction costs, with targeted policy instruments was highlighted. Rather than prescribing energy efficiency as a market outcome, EE1st policies aim to level the playing field between energy efficiency solutions and supply infrastructures. This theoretical framework thus broadens the scope for EE1st policies by suggesting what might appear to be supply-side policies, such as electricity market design, emissions pricing, and remuneration regimes for network companies.

Chapter 5.3 presented a non-exhaustive list of twenty-nine policy instruments to address individual market failures:

- *Externality failures* are well acknowledged, but require more stringent internalisation of external costs, including a broader emissions and sector scope for the EU ETS and related energy tax reforms.
- *Market access failures* are legally recognised, but national implementation has proven inadequate. In electricity markets, in particular, non-discriminatory market access is essential for demand-side flexibility to compete on equal terms with traditional generation for cost-efficient energy services.
- *Regulatory failures* are an emerging area of research. Regulated network companies need effective incentives to actively consider efficient non-wires solutions as alternatives to network infrastructure expansion. National regulatory authorities are increasingly exploring innovative instruments such as performance-based regulation, but consolidated evidence is still lacking.
- *Information market failures* are well addressed in some areas, such as product labelling. Others remain challenging, such as the limited uptake of time-differentiated energy and network tariffs to reduce information asymmetries between energy producers and flexible consumers.
- *Transaction cost failures* lead to significant 'hidden' costs for energy efficiency. Promising instruments include one-stop shops for building renovations, aggregation of demand-side flexibility resources, and the bundling of small-scale loans into larger portfolios for capital markets.
- *Behavioural failures* are increasingly recognised in the research literature, but not yet consciously incorporated into policy design. More research is needed to empirically confirm many supposed behavioural failures and to design targeted policy instruments to address them.

Chapter 5.4 discussed the limitations of market failure theory to inform the application of the EE1st principle. Challenges include the political economy and distributional concerns, highlighting the need for established energy efficiency-only policies, such as EEOS or public financing, that target a market outcome rather than specific market failures. The inherent complexity of public policy requires continued empirical evidence on policy outcomes, assessing cost-effectiveness, distributional effects, and multiple benefits (Dubash et al. 2022; Allcott and Greenstone 2012; Gillingham et al. 2018) as well as suitable instrument mixes (Rosenow et al. 2017b; Wiese et al. 2018; Kern et al. 2017). With the mandate of the recast EED, it remains to be seen how Member States will implement and report on the application of the EE1st principle in their upcoming national energy and climate progress reports.

6

Energy efficiency first in the power sector: incentivising consumers and network

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6.1 Introduction

Even though energy efficiency first (EE1st) is considered to be an established principle in European Union (EU) legislation, it is less so in the mind-set of actors across the energy value chain. Applying the simple idea behind EE1st consistently in decision making proved to be a major challenge so far. Mandatory reporting on EE1st, for example, does not go further than use of the term in the National Energy and Climate Plans submitted by Member States in 2020 (European Commission 2020b). However, the integration of demand-side resources is crucial for a quick and low-cost energy transition by reducing and flexing demand. The European Commission published a guidance to close this implementation gap (European Union 2021a).

EE1st is more and less than energy efficiency (Pató et al. 2019b). It is more than traditional energy efficiency programs in that its logic applies across many areas of energy policy making and energy investment that are not themselves primarily aimed at reducing energy use. This includes topics such as power market design, power and heat network planning, and resource adequacy assessments (Zondag et al. 2020). It is 'less' than an efficiency-only policy in that it does not command efficiency-only outcomes. EE1st requires decision-makers to thoughtfully consider demand-side resources as an alternative to supply-side resources prior to investment decisions and requires that those demand-side options be implemented whenever they are more cost-effective than the supply-side solutions they replace (Pató et al. 2019b; Pató et al. 2020a). Investing into generation and network infrastructure that can be avoided by demand-side options does not only mean unnecessary capital expenditures but often runs the risk of becoming stranded, especially in the case of fossil fuels (van der Ploeg and Rezai 2020).

EE1st is a new term but not a new concept. Integrated resource planning (IRP) of power systems that were introduced in the US to avoid the overbuilt of generation capacities and meet environmental goals at the same time recognised the role of demand-side options (Duncan and Burtraw 2018). The substitution of network investment with non-wires solutions[71] is an expanding practice in the US, especially in those states (mainly California and New York) where legislation requires utilities to consider these options in their development plans (Frick et al. 2021). Since 2008, the first FERC order (no. 719) on eliminating barriers to the participation of demand response in organised markets, federal regulation developed on distributed energy resources (DERs) (including demand response). Its latest Order 2222 (FERC 2020) tries to close the regulatory gap on DER aggregations participating in the wholesale energy, capacity and ancillary services markets (Brown and Chapman 2021).

71 Non-wire solutions are DERs that can be solicited by network companies (utilities) to defer network investment. DERs also include demand resources (such as energy efficiency, demand response), distributed supply (PV, micro CHP) and storage.

Even though the concept of demand-side resources includes demand response and end-use energy efficiency as well, in the power sector the former has special importance: supply and demand need to be maintained in constant balance (Cretì and Fontini 2019).[72] This second-by-second equilibrium increases the need for flexible load in a power system increasingly dominated by variable renewable generation, both for short-term operation and long-term system planning perspectives. Demand, that has been considered fixed in the past, is an important source of flexibility as consumers do respond to price signals (Faruqui et al. 2017). End-use energy efficiency is primarily relevant for a long-term perspective (deferring network infrastructure) as it means permanent load reduction.

Exploiting the untapped energy efficiency and demand response potential in Europe (Knoop and Lechtenböhmer 2017; Gils 2014; European Commission 2016d) would bring significant benefits. Buildings are the key source of demand response and remain so in the future. IEA forecast that building will have approximately twice as much flexibility potential in 2040 than transport, industry and agriculture together (IEA 2020a).

A swift power system transition relies on the active involvement of all actors and regulation has a prime role in realigning the interest of these actors to the goal of reaching a decarbonised European power system ahead of the 2050 economy-wide net zero target.[73] What are the key regulatory tools to activate consumers to offer their flexibility and DSOs to use this flexibility? This paper first discusses the multiple ways consumers can be a resource for the power system. Then it looks at key regulatory tools to incentivise a) consumers to supply and b) DSOs to use demand flexibility. The paper also provides some best practice illustrations of these regulatory tools. Our findings are based on the review of academic and policy literature, interviews with practitioners both in the EU and the US in the framework of the Enefirst project.[74]

6.2 Consumers as multiple power system resources

It is fundamentally a consumer choice that drives power systems both on the short, operational and the long, investment horizon. Consumers have discretion on how much electricity they consume and when. Naturally, this is a function of the level of desired energy service and his/her capabilities to acquire it in different ways (being able to finance energy efficiency investment for a lower bill

72 The US discussions usually consider demand-side resources together with distributed generation and small-scale storage together as DERs. The underlying rationale is that they appear jointly as net load for the power system.

73 The EU wants to achieve the carbon neutrality of the power sector by 2040 (European Commission 2020c). The International Energy Agency has demonstrated that respecting the Paris Agreements means reaching zero emissions in the power sector in industrialised economies by 2035 (IEA 2021a).

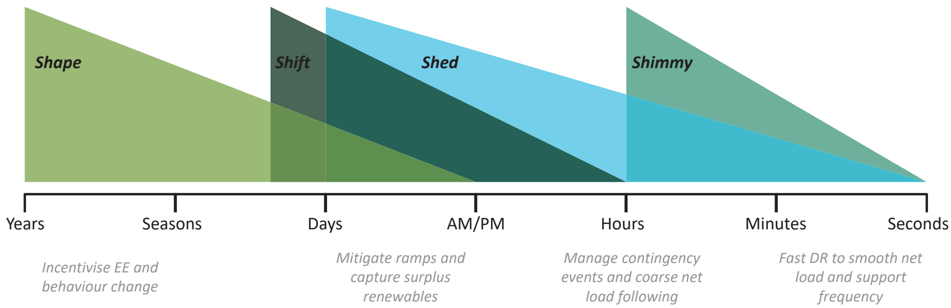
74 www.enefirst.eu

or invest into smart appliances to be able to sell his/her demand flexibility). These behind-the-meter investment decisions made by consumers include all energy consuming or generating assets such as space and water heating, electrical appliances, lighting, photovoltaics (PV), micro-storage, automation and smart meters allowing demand response. Due to self-consumption, the electricity generated by PVs and the consumption constitute the net load at the distribution system level.

Consumer choices have repercussions along the entire power supply chain. They alter the needed volume and timing of power supply, and the infrastructure generating and delivering it to the consumer. Hence, the policies and regulation influencing the energy use and production of end users have important upstream implications that needs to be considered systematically in those decisions to arrive at an optimal asset portfolio. Households that electrify their heating or change their internal combustion engine car to an electric one, for example, will use both the distribution network and the whole power system differently by the additional demand created and changing the load pattern depending on tariff design (Maier et al. 2019). In-front-of-the-meter infrastructure decisions – pertaining to generation, energy transmission and distribution, and utility scale storage – are taken by utilities, including both regulated network companies, and generators and storage owners operating under market conditions. Ideally, they all incorporate the behind-the-meter decisions of a multitude of consumers for efficient investment and operation. In particular, distribution system operators (DSO) can use consumer flexibility and energy efficiency to operate the grid more efficiently, reaching higher utilisation rate and minimise the needed grid expansion that needs to cope with additional load of heat and transport electrification.

Demand as a system resource does not stop at peak shedding at emergency situation that has been its major utilisation in the past but is capable of providing various services on different timescales at a continuous basis (Hledik et al. 2019). Figure 25 illustrates the various possible services provided by demand for the power system as a whole.

Figure 25: Services of demand-side resource in power systems at different timescales



Source: Alstone et al. (2017)

Shape captures demand-side resources that reshape the underlying load profile through relatively long-run price response and demand-side management (DSM) measures that results in structural changes to the stock of loads. For example, utilities or government can use energy audits, information provision or subsidies to incentivise consumer adoption of energy-efficient equipment (Gellings 2017). In the US, utilities are required to invest into energy efficiency in the framework of integrated resource planning (IRP) to provide a resource plan for least cost energy service (Gellings 2017). Energy efficiency obligation schemes (EEOS) in Europe, similarly, require suppliers or DSOs to achieve a predefined level of final energy savings among consumers (Fawcett et al. 2019). *Shift* represents demand response that induces the shift of energy consumption from times of high demand and tight grid capacity to times of day when there is surplus of renewable generation and/or grid is available. This can smooth net load ramps associated, for example, with the evening phase-out of solar generation. Shift technologies include, for example, behind-the-meter storage, rescheduling electric vehicle charging or pre-cooling with air conditioning and ventilation units (Michaelis et al. 2017). *Shed* describes loads that can occasionally be curtailed to reduce peak capacity and support the system in emergency or contingency events, without compensating the load reduction at another time. Examples are interruptible industry processes, advanced lighting controls, air-conditioner cycling, and behind-the-meter storage. *Shimmy* involves using loads to correct the real-time, continual gap between expected demand and actual demand at timescales ranging from seconds up to an hour by means of advanced lighting, fast response motor control, and EV charging, and more (Alstone et al. 2017). Whereas shedding load is usually a one-off reduction, shimmy is a continuous, bidirectional adjustment of load to follow net load changes and assist in frequency control. Even though each system service has its own typical timescale, they partly overlap: the power system can require both shedding for ramp management and shifting to match renewable production on an hourly basis.

6.3 Incentivising the consumer

Consumers are having more and more flexible assets such as electric vehicles and heat pumps. At the same time, their flexible use increasingly becomes hassle-free due to automation. Consumers are essentially interested in reducing their electricity bill without compromising their desired level of energy service. Stacking the various values the use of demand-side resources create for the power system and remunerating them is key in arriving at a high enough level of bill reduction to incentivise consumers to use them (Lazar and Colburn 2013).

6.3.1 To 'shape'

A fundamental tool to 'shape' load is to expose consumes to energy prices that are based on market fundamentals. Prices kept artificially low for residential consumers results in higher than optimal consumption and is a major impediment to energy efficiency improvements. Even with cost-reflective prices, the multitude of market and behavioural failures (Gillingham and Palmer 2014) justifies incentives and support for reaching an optimal level of energy efficiency investment. The involvement of utilities in energy use reduction depends on the market structure of the power sector. In the US, several states require utilities to reduce a certain amount of energy among their consumers (Gellings 2017). DSM programmes implemented by utilities mainly focuses on energy efficiency improvement in the residential and commercial sector. In the former, they provide incentives to switch to more efficient appliances (Aniti 2019). In Europe, most member states use energy efficiency obligation schemes (EEOS) that impose similar energy savings requirement on energy companies. The European legislation provides flexibility with regards to the obliged network companies or retailers but almost all countries opted for retailers (Broc et al. 2020; Fawcett et al. 2019). Even though network companies have better access to consumption data, retailers are better suited to extend their portfolio of activities with this new service both legally (network companies are not allowed to engage in competitive activities under European law) and also commercially to evolve into energy service companies. The experience with EEOS in Europe confirmed that this is a cost-effective way to reduce energy use (Rosenow and Bayer 2017; IEA 2017).

6.3.2 To 'shift' and 'shed'

As noted above, the way consumers use energy in terms of quantity and pattern of use over time has important ramification to the necessary level of generation and electricity network infrastructure. Any incentives altering consumer behaviour towards a pattern that limits the capacity expansion need for upstream infrastructure has a system level benefit to all consumers in the form of lower network tariffs and lower wholesale prices at peak periods. Price – as a key trigger of consumer behaviour – hence needs to reflect the marginal cost and thus scarcity of both of energy supply and network operation. In principle, prices must be low when there is abundant electricity supply and network capacity and high in tight periods.

Tariffs, both retail and network, need to be designed in a way that make the choices customers make to optimise their own bill consistent with the choices they would make to minimise system costs (Lazar and Gonzalez 2015). The energy component should reflect the changes in the scarcity or abundancy of electricity supply over time by moving away from a flat rate to time-differentiated tariffs (IRENA 2019b; Paterakis et al. 2017).[75] Such tariff designs are gaining foot in Europe, not independently from the fact consumers possessing smart meters are entitled to have at least one dynamic price contract offer, and every supplier with more than 200,000 consumers must have a time of use tariff offer for final consumers (European Union 2019d, Art 11(1)).[76]

75 Time-differentiated tariff has many designs (Faruqui et al. 2017). In practice it mostly means time-of-use tariffs.

76 Some further provisions strengthen the position of active consumers. It also contains an expedited supplier switching requirement (Directive Art 12(1)) and the entitlement of individual consumers to a smart meter even in the absence of a national rollout (Art 22).

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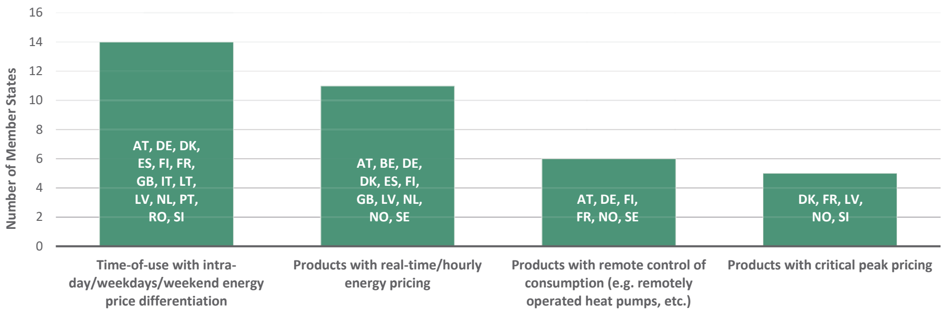
While time-of-use (ToU) and real-time pricing is mainly used to 'shift' load, remote control and critical peak pricing targets 'shedding' of load in those few hours when the system gets critically tight. The latest survey of ACER shows the variety of energy pricing designs in Europe (Figure 26).

Figure 26: Types of electricity products enabled by smart meters available in EU Member States and Norway, 2020



Source: ACER/CEER (2021)

Distribution network tariff design has been the subject of growing interest among regulators and academic experts recently as well (Brown and Sappington 2018; Pollitt 2018; ACER 2021). Key design questions relate to the format (energy, capacity, fixed or any combination), the temporal variability (flat or time-of-use with different granularity), and locational specificity (uniform or locational). Applying the scarcity argument to network charges implies that consumers pay for the network in proportion to their actual use and the associated costs they cause. Both flat volumetric and fixed charges (beyond the fixed charge of metering and billing) that are most often non-coincidental demand charges, are economically inefficient and promote consumption at times of stress on the grid and neutralise energy efficiency efforts (LeBel et al. 2020). As a result, growing (peak) demand drives excessive investment in underutilised grid infrastructure. A uniform fixed tariff tends to shift costs from the high-usage customers in a customer class to the low-usage ones (Kolokathis et al. 2018).

ACER (2021) reports a variety of design across the Member States: 3 Member States (MS) apply an energy-based only charge for all network users and 8 Member States apply a combination of energy-based and power-based charges for users. Other MS apply a combination of volumetric and fixed charges or differentiate between consumer groups in their tariff design. In most Member States, energy-based charges have a larger weight than power-based charges in the recovery of distribution costs. In 8 Member States, time differentiation is applied for both the power and energy-based component of the network charge.

The EU legislation is much less straightforward in its requirements on network tariff design than on electricity tariffs. It refers to the fixed cost for networks and even though fixed costs are not equal to fixed charges, this reference is easily interpreted as justification for a (higher) fixed tariff element. It does not align with the general requirement for network tariffs that *"shall neutrally support overall system efficiency in the long run through price signals to consumers and producers"* and *"shall not create disincentives for participation in demand response"* among others (European Union 2019e, Art 18(7)). Regulators shall only consider but not enforce "time-differentiated network tariffs when fixing or approving transmission tariffs and distribution tariffs or their methodologies" (European Union 2019e, Art 18(7)).

There are some examples for dynamic network charging. Radius, a Danish DSO serving about a million customers recently has extended its ToU tariff to residential consumers as well. It aims at shifting demand away from the winter peak period and avoid or limit expensive grid reinforcements. The ToU tariffs apply to consumers with smart meters who are connected to the low-voltage and parts of the medium-voltage network.[77] Spain introduced mandatory ToU network tariffs in June 2021 for all network users. The number of households on a two-period tariff increased from zero to 43% in 2021. The default energy tariff is a pass-through of wholesale prices (i.e., real-time tariff) and this, couples with the ToU network tariff sends strong price signal to consumers. Early evidence suggests that consumers have reacted to the price signal and have moved consumption from peak and flat hours to off-peak hours (González Bravo 2021).

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Consumers need to be informed and educated on ToU tariffs as they are new to them. The California Public Utilities Commission has, for example, ordered two customer guarantees as part of the rollout: customers receive a comparison of their ToU bill and what they would pay on their old tariff and a one-year bill guarantee that credits the difference if the bill increased.[78]

6.3.3 To 'shimmy'

Large-scale deployment of variable renewable generators changes the power system's ability to respond to imbalances in frequency.[79] Following a contingency event, the rotating masses of synchronous generators normally determine the immediate response to frequency imbalances. However, wind and PV are considered non-synchronous, as they have a power electronic interface with the grid, rather than a rotating mass (Tielens and van Hertem 2016; Dreidy et al. 2017). This

77 https://radiuselnet.dk/Elkunder/Priser-og-vilkaar/Tariffer-og-netabonnement/

78 https://www.utilitydive.com/news/california-utilities-prep-nations-biggest-time-of-use-rate-roll-out/543402/

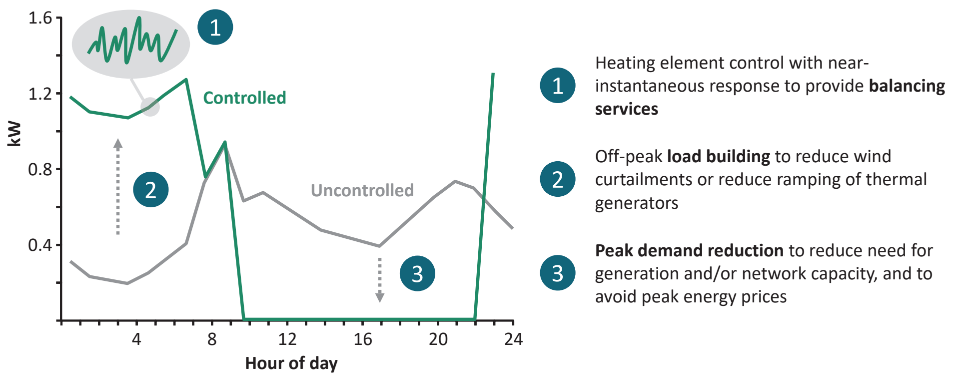
79 Frequency is the parameter of a power system that indicates whether there is an imbalance between active power generation and consumption. Sudden system failures or contingency events, such as the loss of a large generator, can cause frequency to go beyond accepted limits. These imbalances are addressed by activating power reserves, which are traded as ancillary services (IRENA 2017b; Pöller 2015).

means that they cannot generate electricity such that the frequency of the generated voltage, the generator speed and the frequency of the network voltage are in synchronism (IRENA 2017b). Frequency control as an ancillary service thus becomes increasingly valuable in the power system.

Demand response can serve as an alternative option to thermal generators for providing frequency stability services. Thermostatically based controllable loads such as refrigerators, air-conditioners, and ceiling heaters are suitable for such a service due to the short-term modulation of their aggregate power consumption. The thermostat modulates the power for cooling/heating to maintain the temperature nearly to the desired level. EVs as well can provide frequency response by the control of charging and discharging rates of vehicle-to-grid (Obaid et al. 2019). Batteries, as well, present a fast dynamic response to compensate the load variations in distribution networks (IRENA 2017a).

Several EU countries already allow for the use of load, alongside with batteries and pumped hydro storage in their balancing markets (Oureilidis et al. 2020). Water heaters, for example, can be easily converted to a system resource for frequency stability. The magnitude of this relatively untapped resource is significant: In 2019, water heating accounted for 12% or 86 Terawatt-hours of the EU's electricity use in households (Eurostat 2022g). They are traditionally used as thermal storage devices by delinking the time of demand for and generation of hot water: heating up water in the tank in periods of low overall power demand (e.g., at night). Water heaters, if equipped with modern control devices, can participate in frequency regulation and grid balancing services for the power system as well (Figure 27). These grid interactive water heaters can be controlled with near instantaneous response from the operator, and these additional benefits are increasingly valuable in markets with rapid fluctuations in supply due to the large share of renewable sources.

Figure 27: Water heating load profile



Source: Hledik et al. (2016)

In the framework of Figure 25, water heaters do not only 'Shift' but also 'Shimmy': not only to move energy consumption from peak times to times of day when there is a surplus of renewable generation, but also to use loads to provide near-instantaneous frequency control (Alstone et al. 2017). The net benefits of a conventional grid interactive tank (considering the extra cost of upgrading the heater) triple compared to when it is only used as thermal storage for peak shaving, mainly due to the benefit provided for frequency control (Hledik et al. 2016). This, however, can only materialise if market rules allow demand-side resources to participate in ancillary services markets.

Hawaii is a nice illustration of how a traditional utility demand response programme can be upscaled to provide a much larger rollout and more services with the involvement of third-party actors. As a response to the request of the regulator, Hawaiian Electric launched a competitive tender to procure approximately 16 MW of demand response, including 2.5 MW provided by grid-interactive water heating. A software-as-a-service platform called Grid Maestro monitors, analyses 5-minute, revenue-grade data and optimises smart water heaters through machine learning. Grid Maestro aggregates each heater's forecasts and load shift potential into a virtual power plant of grid interactive water heaters. Automated reporting and integrated ticketing simplify performance measurement and verification.[80]

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6.4 Incentivising the DSOs

It is not enough that consumers are incentivised to make use of their flexibility for the benefit of the power system, unless other actors make use of them. Once aggregated demand can participate in power markets on a level playing field, it becomes a direct competitor to generation, with markets coordinating the use of all these resources. Demand is an important resource to solve local network congestion as well. Distribution network companies traditionally forecast load changes and employ the 'fit-and-forget' approach to develop their network for serving peak load securely. It means that they forecast the peak load at various sections of the grid and invest into capacity upgrades (EURELECTRIC 2013). The regulator defines and covers the eligible cost of the DSO for maintaining network operations, at the same time incentivises them to provide this service at the lowest possible cost while maintaining service quality by leaving the savings from the maximum eligible cost at the DSO (revenue cap regulation).

Congestion management of the distribution network is a fundamentally new addition to the portfolio of DSOs. The use of demand flexibility is novel and (perceived to be) of higher delivery risk (Brown and Zhou 2019). Why would DSOs use demand resources instead of building more cables as in the past? If they would operate on a market, they would try any new cheaper option

80 http://www.shiftedenergy.com/technololgy/gridmaestro/

to gain on competitors. For network companies it is the regulator that needs to mimic the market and trigger change to save on consumers' bill. They have two key tools at disposal: the way DSOs are remunerated and network planning requirements to make sure that DSO do consider demand-side resources in providing for an efficient network.

6.4.1 By remuneration

National regulators set the rules by which the DSOs are remunerated. The dominant remuneration scheme used for electricity DSOs in Europe is the so-called revenue-cap regulation (CEER 2023). Under this regime, DSOs are motivated to reduce costs as the regulation decouples those costs from the revenue they are able to earn.[81] The regulator will assume an operational efficiency gain when setting a revenue cap and the DSO can increase its profits by achieving greater productive efficiency than this baseline over the price control period (Pató et al. 2019a; Rious and Rosetto 2018a).

A key barrier to use demand flexibility and energy efficiency in congestion management is that DSOs, in most remuneration regimes, have a direct incentive to relieve congestion with network capacity investment: they only earn a return on capital expenditures (CAPEX). At the same time, in the revenue cap regulation they are incentivised to reduce their operational expenditure (OPEX). Consequently, there is a disincentive for DSOs to engage in demand flexibility and end-use energy efficiency as they mainly involve OPEX and hence do not generate a return on investment (Rious and Rosetto 2018b). To incentivise the uptake of demand-side resources in the provision of network services, remuneration schemes should make DSO indifferent to the cost type, and hence the solution, they apply and place remuneration on total expenditure (TOTEX) rather than just on capital investments. As an addition, remuneration could reward DSOs with increased revenues for specified performance or, conversely, penalising them with reduced revenues for failure to perform (cf. Performance Based Regulations – PBRs) (Littell et al. 2018; Pató et al. 2019a).

In regulatory practice, the RIIO[82] scheme introduced in the UK in 2015 represents an important reference for PBR design for electricity DSOs in Europe. The preceding RPI-X framework, which is based on the retail prices index (RPI) minus expected efficiency improvements (X) focused on operational efficiency resulted in risk and innovation averse DSOs that were judged unfit for efficiently serving the consumers in the changing energy landscape (Mandel 2014; Jamasb 2021). The fundamental novelty of RIIO is that it recognises OPEX in a similar fashion to CAPEX, referred to as TOTEX incentive mechanism. This creates a powerful driver for DSOs to consider the deployment

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81 Decoupling is the term used in the United States to describe a revenue cap that breaks the link between sales volume and revenues (e.g. Sullivan et al. 2011)

82 RIIO stands for 'Revenue = Incentives + Innovation + Output', meaning that revenues of regulated network companies should be set to deliver Incentives for cost reduction, Innovation in order to provide new services to the benefit of network users, and Outputs to improve services to network users (Rious and Rosetto 2018b)

of demand-side resources alongside supply-side assets in providing network services. Moreover, RIIO applies a suite of incentives from the onset of the regulatory period to improve six outputs that are deemed to be relevant be the regulator (customer satisfaction, safety, reliability, conditions for connection, environmental impact, and social obligations). Performance brings financial rewards or penalty. The new framework, coined as RIIO-2, started in April 2021 and will run until 2026 for electricity DSOs. It introduces some novel features but keeps both the TOTEX approach and the performance incentives in place (Ofgem 2020). As such, RIIO regulation is viewed with much interest by regulators and network operators since it demonstrates new regulatory approaches (Rious and Rosetto 2018b).

6.4.2 By network planning requirements

Incorporating the EE1st principle in DSO planning and operation practices means to include demand-side resources on an equal footing with infrastructure options and, more specifically, to acknowledge that energy efficiency and demand response can possibly substitute for capital-intensive infrastructure assets. Planning is aimed at identifying investment needed for the reliable operation of the system for 15 to 20 years. The European legislation requires DSOs to publish their network development plans biannually (European Union 2019d, Art 32(3)).

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The planning and operation of power distribution networks is a cornerstone of decarbonisation. Electrification of heat supply and transport and the growing number of DERs such as PVs, demand response and storage connected to the distribution grid raises the question of how to integrate these DERs to the grid at the lowest cost? These changes in network use require the reconsideration of network planning. Demand-side resources, and DERs are general, need to be incorporated as viable, granular and probabilistic resources to be able to assess both their impact on grids but also their capability to contribute to the efficient grid operation by the flexibility they are able to provide (Mandel et al. 2020).[83] Smart grids[84] or Active Distribution Systems (ADSs) optimise the uses and flexibilities of the grid instead of passively operating it in order to limit the investment needed to serve the more volatile load (Figure 28).

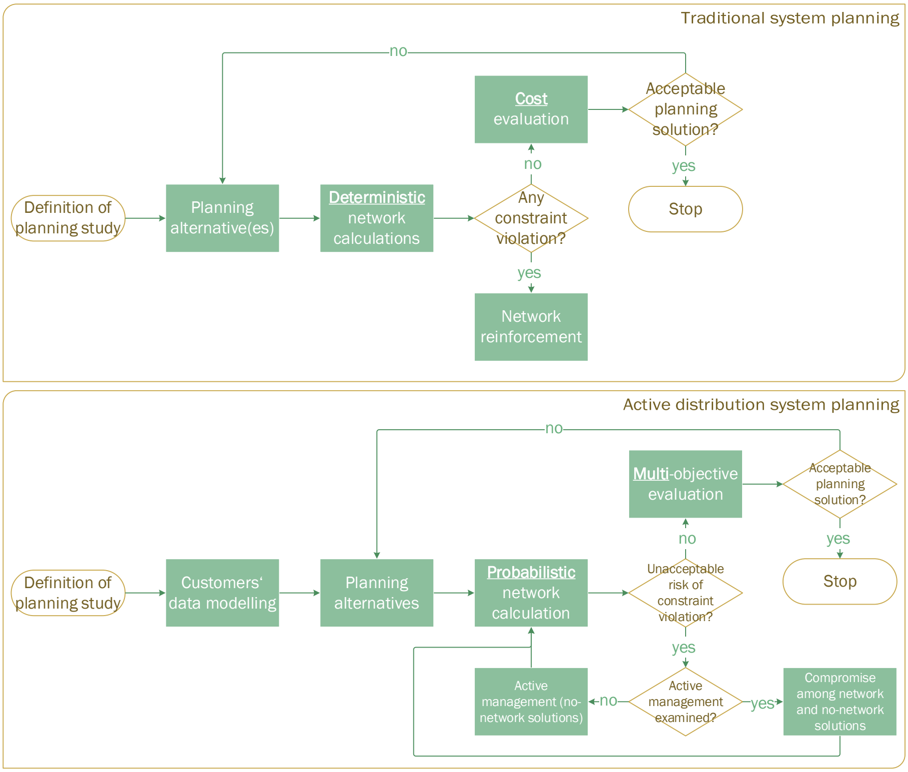
Traditional planning is based on the concept of a passive consumer and focuses where new loads will appear in the radial medium-voltage and low-voltage grid that is designed to distribute energy with a mono-directional flow of power from a substation to end-use customers. In distribution system planning, demand is exogenous and dominantly based on consumer/market information that is

83 For a good summary of the impact of DERs on distribution grids see (AEMO 2020).

84 A smart grid is an electricity network that integrates the behaviour and actions of all users connected to it (generators and/or consumers) while ensuring an economically efficient, sustainable power system with high levels of quality and security of supply and safety (CENELEC 2020). Beyond the US and Europe, for instance the Jeju Smart Grid demonstration project in South Korea has provided ample evidence on the practicability of the smart grid concept (Kim et al. 2016; Kang et al. 2018)

corrected statistically (Pilo et al. 2014). Assessment methods used are deterministic: the feasibility of connecting new customers requires the assessment of existing line capacity to incorporate them, referred to as hosting capacity analysis. These methods are mainly hourly power flow calculations for worst-case scenarios, in order to minimise risks (Silva 2017).[85] Once the planning study is defined, different planning alternatives are assessed against the load conditions in the planning time horizon. If there is no feasible planning alternative, then the network gets reinforced. Otherwise, the least-cost planning alternative is selected. When these studies include distributed generation, the same 'fit-and-forget' approach is applied: the relevant technical aspects of DER are considered but based on maximum generation/minimum demand scenarios that seldom characterise renewable generation. Demand-side integration and active distribution network options are not considered in general as alternatives to network capacity investments in the planning process.

Figure 28: Traditional vs. active distribution system planning process



Source: Pilo et al. (2014)

85 Power flow analysis is also used to give insights into the expected operation of a distribution grid by calculating the currents and losses in all the branches (lines, cables, and transformers), the voltage in load buses, the reactive power in generator buses and the active and reactive power in the (primary substation in a distribution grid for a given instance.

ADS planning uses stochastic assessment, from steady state to probability and risk, and from invisible to visible and controllable DERs. First, the alternatives are planned based on real, granular and verified consumer data that aggregates consumption, production and storage on a temporal basis resulting in 'net demand' profiles that approximate the future operation of the network more precisely than simply considering historical peak load. Flow analysis is not aimed at answering the binary question whether the network can integrate the forecasted load in the worst-case network state scenario but runs probability-based calculation to check if the predefined non-performance risk, i.e. the reliability level targeted is exceeded or not.[86] In case of foreseen operational problems, first ADS (or in other words non-wires) solutions are to be examined and only if they cannot solve the problems, network investment to be considered.

New general rules to network planning have been adopted in the European legislation in 2018 (Pató et al. 2019b). The Electricity Directive (European Union 2019d) requires Member States must *"provide the necessary regulatory framework to allow and provide incentives to DSOs to procure flexibility services, (...) in particular, from providers of distributed generation, demand response or energy storage and promote the uptake of energy efficiency measures, where such services cost-effectively alleviate the need to upgrade or replace electricity capacity"* (Art 32). DSOs, on the other hand, are required to procure these resources in a non-discriminatory and competitive way. As far as planning is concerned, distribution network development plans (published every two years) must provide transparency on the medium- and long-term flexibility services needed, and on the planned investments for the next five to 10 years (Art. 32).[87] Every two years national regulators need to monitor and assess the performance of network companies in relation to the development of a smart grid that promotes energy efficiency and the integration of renewable energy (Art. 59). The current European requirements set a solid framework both for integrating flexibility in operation and planning and hence a major step towards the implementation of the EE1st principle. The success of integrating demand in network planning rests in the national regulators that shall develop 1) detailed rules for appraising alternatives, 2) transparency rules compatible with data confidentiality (especially with location specific data) and 3) they have to enforce the least-cost principle and make network companies to scrutinise all alternatives in a systematic fashion and provide compelling evidence for the necessity of network reinforcement.

In the US, the California Public Utilities Commission (CPUC) introduced in 2018 the Distribution Investment Deferral Framework (DIDF) that is the process for identifying opportunities for DER to defer or avoid traditional distribution infrastructure investments (CPUC 2018a) and report annually. In addition, utilities need to provide a 10-year vision for their grid modernisation plans,

86 Quite similarly to generation adequacy, the level of acceptable risk should be based on the willingness of consumers/network users to pay for it.

87 Art. 40 and 51 (European Union 2019d) set similar requirements for TSOs.

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that not only justified the proposed investments based on lowest cost and highest benefits, but also would describe whether any investments could be met instead by DER. It broadened the scope of technologies including e.g. system analysis software and grid management systems, or sensors and controllers essential to maintain circuit stability and system reliability (CPUC 2018b). Solicitation for non-wire solutions in California were only partly successful. So far only 15 MW has been contracted in the three request-for-offer rounds launched (January 2019, 2020, and 2021) all ending up with in-front-the-meter storage solutions exclusively (Peterson and Golestani 2021).

6.5 Conclusions

EE1st is an important concept to minimise the cost of the energy transition by exploiting the end-use energy efficiency and demand response potential of end users. The simplicity of the concept, however, does not lend itself to simple implementation in the various energy sectors. The power sector is particularly relevant for the application of the EE1st principle for three reasons. First, the sector requires early decarbonisation by 2035–2040 to reach net-zero emissions for the whole economy by 2050. Second, electricity demand is to grow due to the electrification and heat and transport, which creates vast opportunities for applying the principle. Third, there is a constant need for equalling load and generation in the power system that places an increasing value on demand flexibility.

Demand-side resources can offer many system services with the advent of automation. As described in this paper through the 'shape-shift-shed-shimmy' framework, demand response is not confined to emergency load shedding in a few tight situations annually but a multiple resource that can be used 24/7 at various timescales. For one thing, implementing the EE1st principle in the power sector means that consumers need to able to offer their flexibility: to have flexible assets that are automated plus they have the right price incentives to sell them. Dynamic pricing of electricity – as requested by the EU legislation – is not enough if energy only makes up one-third of an average residential bills. Network tariffs, as well have to communicate grid conditions through dynamic price signals so that in tight periods the use of the network cost more. DSOs will not use demand flexibility if they are not required or incentivised. It is the role of the national regulators to require the consideration of demand-side resources in network planning and to incentivise them to integrate consumers in network operation. This requires the modernisation of network company remuneration schemes in almost all EU Member States. An EE1st compliant regulation is that guarantees that consumers can offer their flexibility and get compensated at market value and requires that DSOs use them whenever they provide more net benefit that network investment.

7

Applying the energy efficiency first principle based on a decision-tree framework

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7.1 Introduction

Energy efficiency first (EE1st) is an established principle for EU energy policy design. It emphasises the importance of exploiting demand-side resources in energy-related policy-making, system planning and investment, and has a broad scope encompassing the entire energy system. The EE1st principle is applied in multiple timeframes, from short-term investment planning to medium-term targets (for 2030) and long-term goals (for 2050) (Pató et al. 2020a). Since the European Commission's Communication of the Clean Energy for All Europeans policy package in 2016 (European Commission 2016b), the principle has been embedded in legislation with the package, as well as the policy initiatives for the Fit-for-55 Package (Boll et al. 2021)

Conceptually, the EE1st principle builds on a long history of what has been called integrated resource planning (IRP) or least-cost planning. These concepts were originally developed in the USA in the era of regulated, vertically integrated monopoly utilities (Krause and Eto 1988; Swisher et al. 1997). They were applied either to cases of investment allowances of new power plants, or rate setting, or energy system planning. The core was the analysis of benefits and costs of demand-side resources, including end-use energy efficiency and load management, on equal footing — or a 'level playing field' — with investing in and operating power plants and power grid expansions (CPUC 2001).

This is exactly the core of the EE1st principle. Such IRP concepts were introduced in the EU during the 1990s as well, but the advent of liberalisation of the electricity and gas markets made it difficult if not impossible to apply the concepts in the unbundled energy markets. Because in a market-based system, the government can only design policies to incentivise the decisions of market actors, instead of planning and implementing a vertically integrated system. Therefore, a study for the European Commission concluded (Thomas et al. 2000): *"The combination of unbundling and competition in wholesale and retail supply, renders IRP as a method of planning for matching demand forecasts and supply capacities less useful and feasible for most energy companies. For network operators, or for suppliers to non-eligible customers, an adapted form of IRP is still feasible. However, the methods developed under the IRP framework for integrated assessment of the cost-effectiveness of supply-side and demand-side options can still be used to analyse the most cost-effective options to provide to the customers the (genuine) energy services needed."* The study then proposed that governments and regulators were best suited to apply these methods, and then to create incentives for the market actors (e.g., energy companies) to implement the amount of energy efficiency that was found cost-effective (Thomas et al. 2000).

However, applying the EE1st principle is challenging for governments and regulators as well. One key reason is that, depending on the sector, it can involve multiple market actors with different interests, information and capabilities, for example, the actors from both demand- and supply-sides of the market, as well as the network operators and service providers in between. As a result, for the policymakers and regulators from multiple governance levels, it is challenging to incentivise all the market actors to fully exploit the demand-side resources.

To support applying the EE1st principle, this paper first contributes by identifying the most common elements across different cases based on a close review of the key areas (Pató et al. 2021). Second, we propose a decision-tree framework that can be flexibly constructed for different application cases based on the identified elements.

- First, the framework follows a decision-tree structure, which is located in a matrix with the following two dimensions: (1) general phases for planning and applying the EE1st principle for specific cases, including inception, preparation, validation, and implementation (Khatib 2014; Konstantin and Konstantin 2018b); and (2) involved decision-makers, which can be policymakers, regulators, and market actors (incl. energy suppliers, network operators, service providers, and consumers).
- Second, the key actions of the decision-makers in the different phases are also identified. For each action, we further provide a set of questions so that the decision-maker can identify the most relevant aspects when applying the EE1st principle in the given phase.

In Section "Literature review", we provide a literature review of the studies relevant to the EE1st principle and distinguish between two implementation approaches: decentralised market-based planning and centralised planning. In Section "Decision-tree framework", we introduce the methodology, identify the common elements in applying the EE1st principle in practice (incl. project phases, decision-makers, and actions of the decision-makers in different phases), and provide the general structure of the decision-tree. Section "Examples of applying the decision-tree framework" exemplifies how the decision-trees are constructed in specific cases by providing two examples: (1) planning for demand-response (DR) in the power sector, and (2) planning for a district heating system. At last, we conclude in Section "Building elements of the decision-tree framework".

7.2 Literature review

In general, EE1st is understood as a guiding principle for EU policy design in the energy sector. In essence, the principle states that so-called demand-side resources should be considered and prioritised whenever they are more or as cost-efficient in meeting stated objectives as alternative supply-side resources (Pató et al. 2020a).[88] The underlying rationale is that consumers in households

88 Formally, the EU Governance Regulation (European Union 2018d) defines EE1st as follows: "*'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means*

and firms do not demand electricity and other energy carriers as such, but the energy services derived from them (Bhattacharyya 2019; Kalt et al. 2019). This means that for a given energy service, e.g., thermal comfort, there are multiple resources, from the supply or demand-side as well as a combination of them, that can serve these needs.

On the one hand, supply-side resources refer to all technologies that convert energy to deliver energy services. This includes utility-scale assets, including renewable and non-renewable power plants, networks for power, gas and heat, as well as storage facilities. In a broader sense, supply-side resources may also comprise onsite energy conversion technologies like heat pumps and photovoltaic installations (Mandel et al. 2020). On the other hand, demand-side resources can be conceptualised as technologies and actions that reduce or shift final and useful energy demand. In essence, this includes end-use energy efficiency measures (e.g., thermal renovations in buildings) and demand-response (e.g., shifting appliance usage in response to hourly electricity tariffs) (Mandel et al. 2020; Rosenow and Cowart 2017). Energy service sufficiency (e.g., reduction of living space) is also being discussed as a dedicated demand-side resource (Mandel et al. 2020). At its core, the definition of EE1st principle suggests that the trade-off between demand- and supply-side resources for meeting demand of energy services is to be solved on a cost basis. The most adequate operationalisation here is not the private cost incurred by individuals and firms, but the cost to society (Mandel et al. 2020; European Union 2021a). In other words, EE1st as a principle of public policy is meant to prioritise demand- over supply-side resources to the extent that they minimise the net cost or maximise social welfare (cost-benefit analysis, CBA) from a societal perspective. This implies that the EE1st principle considers energy efficiency not as an end itself, but as a means of delivering energy services at the lowest possible cost to consumers. It also implies that costs borne by society are not solely composed of capital expenditures and operating expenses, but also a variety of social, economic, and environmental effects — referred to as multiple impacts or multiple benefits (IEA 2014a; Ürge-Vorsatz et al. 2016).[89] For example, Thema et al. (2018) identified and quantified a variety of multiple impacts associated with end-use energy efficiency measures in the EU, including reduced air pollution, job creation, increased labour productivity, and more.

The rationale behind the EE1st principle is thus inherently economic. As the EU aims to transform to a climate-neutral or net-zero economy by the year 2050, the EE1st principle can be viewed as a means to achieve a socially optimal or welfare-optimal deployment of end-use energy efficiency measures and other demand-side resources. As per the European Commission's guidelines on

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of cost-effective end-use energy savings, demand-response initiatives and more efficient conversion, transmission and distribution of energy, while still achieving the objectives of those decisions".

89 Ürge-Vorsatz et al. (2016) defines multiple impacts 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."*

EE1st (European Union 2021a), the principle should *"ensure […] that only the energy needed is produced and that investments in stranded assets are avoided in the pathway to achieve the climate goals"*.

This raises the question how the theoretical principle of EE1st is to be put into practice. In practical terms, the guidelines on the EE1st principle list a variety of available policy measures for different policy areas (Zondag et al. 2020). Similar measures have been proposed in Rosenow and Cowart (2017) and Pató et al. (2021). For example, for electricity systems, market access rules should enable demand-side resources to compete on an equal footing with generation in wholesale, capacity and ancillary service markets. This also requires dynamic electricity tariffs to incentivise consumers to implement DR activities. In turn, transmission and distribution (T&D) companies, as regulated monopolies, should be subject to guidelines and regulatory incentives to prioritise cost-effective demand-side resources over network investment.

Furthermore, in conceptual terms, Mandel et al. (2021) propose a distinction between two different planning approaches for implementing the EE1st principle in the EU.

- The first approach is decentralised/market-based, addressing consumers and producers in various competitive energy markets by resolving market and behavioural failures. To illustrate, average cost pricing is a commonly known market failure in economic theory because it hides the marginal cost of supply in the price signal conveyed to consumers. If the average cost are lower than the marginal cost at a point in time, this leads to overuse of generation and network capacities relative to the economic optimum (Gillingham et al. 2009). The deployment of dynamic tariffs can be an effective policy response to address this market failure.
- The second approach is centralised planning. Its key rationale is to address regulatory failures, that is, situations where governments or state agencies take regulatory measures that do not, at reasonable cost, produce desired outcomes for society (Baldwin et al. 2012). This covers the process of policy formulation, addressing misleading assumptions and methodologies in impact assessments (e.g., on discount rates). More narrowly, it also covers the design of regulatory price control regimes for regulated electricity, gas and district heating (network) companies. For example, incentive structures transitionally imposed on regulated companies by regulators have been associated with adverse effects on the cost of energy supply. Novel incentive designs, subsumed under the term performance-based regulation (Pató et al. 2019a), can create effective incentives for regulated companies to procure cost-effective demand-side resources as counterparts to supply-side capacity expansion and operation.

In summary, as indicated by the two approaches, the first step to apply the EE1st principle is to distinguish the application cases according to the underlining systems: market-based or price-regulated systems. The market structure decides how much the policymakers and regulators can be involved in the planning and decision-making processes, i.e., the implementation of the EE1st principle. Then, the policymaker and regulators should also (1) identify both supply- and demand-side actors (e.g., energy suppliers, network operators, consumers, service providers) and their potential actions; (2) design incentives following the EE1st principle, and (3) when possible, guide them through the processes by checking and approving their decisions.

7.3 Decision-tree framework

7.3.1 Methodology

In this paper, following the distinction between decentralised/market-based and centralised planning approaches in different systems, we explicitly define two types of EE1st principle application cases, as stated below.

- First are the policy-making cases, which refer to applying the EE1st principle in market-based systems, for example, motivating the households to (1) renovate their buildings for higher thermal efficiency; (2) adopt smart energy management system or buy DR services from providers in the market; etc.
- Second are the system planning and investment cases, which refer to applying the EE1st principle in price-regulated systems, for example, (1) by network operators in the energy system, e.g., T&D companies that are unbundled from the generation and retail (Lenz et al. 2019); or (2) in vertically integrated systems, e.g., district heating systems.

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The key difference between the two types of cases is the leverage of policymakers and regulators. In the policy-making cases, the policymakers and regulators can only design and implement policies to provide incentives for market actors. They need to anticipate the potential actions of market actors in the policy-making process, but they are not in the position to check or approve the investment decisions of the market actors. However, in the system planning and investment cases, the policymakers and regulators will be more deeply involved in the processes, including checking and approving the plans and decisions of the regulated actors.

At the same time, the two types of cases share similar groups of decision-makers and project phases. Based on a review of the key areas in which the EE1st principle can be applied (Pató et al. 2021), a common set of relevant decision-makers is summarised: policymakers, regulators, and market actors including energy suppliers, network operators, service providers, and consumers. For a specific application case, relevant decision-makers are chosen from this union set. Furthermore, shared project phases of different cases are summarised, including inception, preparation (design and planning), validation, and implementation (Khatib 2014; Konstantin and Konstantin 2018b). The planning of one application case of the EE1st principle is broken down as the actions of decision-makers in different project phases, which can be presented with a decision-tree.

The decision-tree approach is commonly used for example in project management. With a treelike diagram, it presents the core elements in the whole decision-making process: decision-makers, decision-points, actions of each decision-maker at each decision-point, and potential results. The approach can support project planning, communication, implementation, and control. Furthermore, such a general structure also provides the flexibility to consider project details and integrate other methodologies, so that the decision-tree approach can be used in different areas. Yao and Jaafari (2003) combined the real option and decision-tree approaches for project evaluation, to analyse the optimal strategies on risky projects in a chaotic commercial and tough regulatory environment. Harrison et al. (2018) developed a set of decision-trees to link the information from a survey, analysing *"why particular methods were selected to assess ecosystem service"*. Mock (1972) developed a methodological decision-tree to show how one can plan and control his/her research strategy in accounting studies.

Using the Microsoft Visio software, decision-trees are composed of shapes and flow-lines, with different shapes having different meanings. These mostly correspond to established standards defined by the International Organization for Standardization (ISO 5807/1985) and are outlined in Figure 29.

7.3.2 Building elements of the decision-tree framework

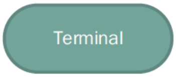
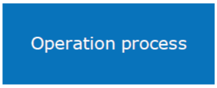
For applying the EE1st principle, the decision-tree approach shows its flexibility to capture the general decision-making structure that applies to different cases, as well as the detailed elements of specific cases. As introduced above, the elements fall into three groups.

First are the decision-makers that might be involved in the EE1st principle application cases, as summarised and defined in the following (European Union 2012b; Mulder 2021).

- Policymakers: (1) major institutions involved in the EU's standard legislative procedure, i.e., European Commission, European Parliament, Council of the European Union; (2) parliaments and administrative departments whose competencies extend over the whole territory (NUTS 0) of a Member State; (3) parliaments and administrative departments whose competencies extend over the regions (NUTS 1), provinces (NUTS 2) and municipalities (NUTS 3) of a Member State, respectively.
- Regulators: the public regulatory authorities or agencies designated at the national or regional level to set rules and ensure compliance, oversee the functioning of markets, and control tariffs in regulated market segments;
- Energy suppliers: the commercial producers of electricity, heat, and other commodities, as well as the legal entities that sell energy (electricity, heat, natural gas) to consumers;
- Network operators: entities responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution and transmission system in a given area for ensuring the long-term ability of the system to meet demands for electricity, heat, and natural gas;

- Service providers: the entities that provide management service (supporting consumers for both improved energy efficiency and DR), for example, the aggregators in the power system or dedicated energy service companies (ESCOs) who can increase the responding flexibility of consumers;
- Consumers: the customers in the industry, transport, residential, tertiary and agriculture sectors who purchase energy carriers for final use and invest in energy-using assets of a certain energy efficiency level.

Figure 29: Shapes for information display in the decision-tree

Shape	Description
	Represents the start or end point of the decision-tree.
	Indicates some particular operation proceeded by the decision-makers, for example, the policy-maker defining its policy target, or the energy supplier collecting information.
	Represents a point where specific checks are made. Lines coming out from the shape indicate different possible situations, i.e. yes or no, leading to different processes.
	Represent the flow of the sequence and direction of the process.
	Represents information entering or leaving the decision processes, for example, the cost data of demand-side options, or a report on demand- and supply-side costs.

Second, the project phases for the EE1st principle application cases include:

- Inception: the phase when the policymakers define the policy targets and the regulatory framework, based on which relevant decision-makers define the goals of their business. For system planning and investment cases, the regulators will check if the business goals comply with the targets defined by the policymakers;
- Preparation: the phase when the market or planning entities, including the energy suppliers, network operators, consumers, DR service providers, and other relevant decision-makers collect necessary information and systematically evaluate their options within a cost-benefit framework, which is defined by the regulatory authorities;
- Validation: the phase when the market actors propose their investment plan after the assessment and the regulatory authorities check the plan. However, such a phase only exists in the vertically

integrated sectors. In the market-based sectors, the entities do not need permits from the regulatory authorities when making investment decisions;

- Implementation: the phase when market entities implement the plans.

Third, the common actions of the decision-makers in the phases are identified, as shown in Table 32. The detailed introduction of each action is provided in Appendix B, where we list the most important questions to consider when applying the EE1st principle for each action.

In the next subsections, we follow the four project phases to explain the actions of the decision-makers, their meaning and their interlinkage. In Section “Examples of applying the decision-tree framework”, we further exemplify how to construct decision-trees for specific cases by providing two examples.

7.3.3 Project phases and actions of decision-makers

Project inception

To apply the EE1st principle in different areas, the policymakers need to define clear policy targets under the Paris agreement, and also identify the potential trade-offs among multiple targets or the sub-targets, for example, net-zero emissions by 2050, energy security, energy efficiency improvement, market integration, economic competitiveness and environmental protection, etc. (European Commission 2015; European Union 2021b; Zweifel et al. 2017). Then, the policymakers should define the regulatory framework and provide incentives to procure demand-side resources by integrating necessary policy instruments. The impacts of these policy instruments and the potential interactions among them should be identified.

Given the policy targets and the regulatory framework, the regulators will take local conditions and constraints into account and interact with relevant market actors. First, the regulators will define the market access rules for efficiency or DR solutions. Because under the current regulatory framework, some energy efficiency or DR improvement solutions may not be provided by the existing market actors. Therefore, access rules to relevant markets might have to be (re)defined to introduce new players. For example, in the case of a district heating system, additional to the system operator (i.e., heat supplier), new players such as potential waste heat providers can be introduced to the market. For the DR solutions, it could be the DR service provider (e.g., an aggregator), who coordinates the flexibility potential on the demand-side, reduces the peak demand, and further reduces the investment for the generation and network in the electricity system. In such cases, the regulatory authority should develop market access rules for new entrants.

On the other hand, according to the policy targets and regulatory framework, the company market actors will define their business or project goal based on their situations and decisions to make

(Bhattacharyya 2019; Mulder 2021). In some cases, public entities or state agencies may also be involved in an EE1st principle application case, directly participating in the system operation and are responsible for implementing the efficiency or DR programs, e.g., as DR service providers in the power system. Finally, under specific cases, companies from non-energy sectors may also be involved, for example, the industrial companies that provide waste heat to the district heating system.

In system planning and investment cases, the regulators should check the business or project goals proposed by the market actors. The aim is to ensure that the goals do not conflict with the policy targets and the market access rules, and besides, to ensure that there is space for the application of energy efficiency solutions on the demand-side. This should be an iterative process at an early stage and in particular, potential demand-side options should be specifically considered if they could contribute to achieving the business goals.

Project preparation

In the project preparation phase, the regulators should consider local conditions and constraints to define the cost-benefit-analysis (CBA) framework from a societal perspective. Apart from the energy savings, they should also look at wider costs and benefits which may not be easy to quantify

Table 32: General structure of the decision-tree for applying the EE1st principle

	Policymakers	Regulators	Market actors
Inception	(P1) define policy targets (P2) define regulatory framework	(R1) define market access rules for energy efficiency or DR solutions (R2) compliance check of business/project goal with policy targets and market access rules	(M1) define business/project goal
Preparation	-	(R3) define CBA method (R4) define policy and regulation details	(M2) define CBA method (M3) information collection (M4) energy service demand forecast (M5) identify other cost and risk
Validation	-	(R5) check the implementation plan and if relevant, approve it (R6) market monitor	(M6) systematic assessment (M7) propose implementation plan
Implementation	-	-	(M8) implement the plan, e.g., adopt energy-efficient technologies, provide designed service, make investment decisions, etc.

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or monetise (Atkinson et al. 2018; IEA 2014a; Thema et al. 2018; Ürge-Vorsatz et al. 2016), i.e., try to cover and meet all sustainable development goals (SDGs) with lower cost. Furthermore, the regulators should also define the policy and regulatory details,[90] so that the market actors can systematically assess their investment options accordingly.

For the actors in market-based systems, following the policy and regulation details, they will further define their own CBA method to guide a series of actions. The first action for project preparation is information collection. For example, the operator of a district heating system may collect information about the population or number of the dwellings in the relevant area, as well as information about potential heat providers from other sectors, e.g., industrial companies or data centres. Second, based on the collected information, the market actors need to forecast the energy service demand. The forecast should also look at possible further reductions in energy demand levels that could affect the viability and assessment of options. In the third step, the market actors will identify other potential costs and risks, as well as the "multiple (private) benefits" from other aspects (Killip et al. 2019). For example, when designing the contract for the consumers, the operator for a district heating system needs to consider the variation of fuel price, environmental cost, etc. The fourth step is a synthesis of the actions above, in which each market actor will do a systematic assessment of the various options for their business plan.

Project validation

The project validation phase is only relevant in system planning and investment cases. In this phase the market actors will propose their implementation plan to the regulators for a check. The plan should indicate how demand-side options are assessed, whether they have been discarded and under what conditions they could be implemented. From the perspective of regulators, they should evaluate if full advantage of the available demand-side options is taken, and the investment on the supply-side and networks are necessary to achieve the overall target. This is an iterative process and will lead to improvement until the plan is justified.

Project implementation

Finally, in the project implementation phase, the market actors will implement their plans, including making investment decisions (e.g., network operators), providing the designed services (e.g., DR service providers), or adopting energy-efficient technologies (e.g., consumers). The regulator will also monitor the market and punish the market actors who violate the regulations.

90 For some cases, the public authorities — policymakers and regulators — also need to do a series of analysis (e.g., reviewing the available options, forecasting the energy service demand, etc.) to support defining the benchmark or variables (e.g., subsidy, tax) of policy instruments.

7.4 Examples of applying the decision-tree framework

In this section, we provide two examples applying the decision-tree framework: (1) planning for demand response in the power sector Section ("Planning for demand-response in the power sector"), and (2) planning for a district heating system Section ("Planning for a district heating system"). The two examples correspond to the two types of EE1st principle application cases. In Section "Discussion", we summarise how to apply this framework to different cases and discuss its limitations.

7.4.1 Planning for demand-response in the power sector

Based on the development of information and communication technologies (ICTs) and smart measuring and planning devices, demand-response is playing a promising role for the future energy system. It improves the grid flexibility, increases the share of market, no vertically integrated utilities exist anymore, and it is the responsibility of the policymakers and regulators to evaluate the cost and benefit of DR measures from a societal perspective, and adopt them in their infrastructure investment plans.[91] For the electricity system planning, this evaluation includes an assessment of (1) whether future generation capacities will meet demand forecasts, and (2) how the grid expansion should be planned by the energy regulators and transmission and distribution system operators (TSOs and DSOs). Then, the policymakers and regulators ideally design policies which enable the market access for DR service providers and which motivate consumers to adopt relevant technologies.

In practice, the DR planning in the power sector could mean two situations below, with different roles for the central decision-maker, who is referred to as the "DR service provider":

- First, concerning the power markets — capacity, balancing, and wholesale markets — the DR service providers refer to large consumers, or aggregators (energy service companies, or virtual power plants operators) who could bid in these markets.
- Second, concerning the transmission and distribution network, DR service providers include two levels: (1) Transmission and distribution system operators under supervision of the regulator, offering incentives to the (2) providers of DR service.

In this example, we focus on the first situation, with DR service providers referring specifically to the aggregators, who provide DR services to the end-consumers (excluding large consumers). The other decision-makers identified in this real-life example include policymakers, regulators, and consumers. For such a market-based planning (i.e., policy-making) case, the policymakers

91 General planning is provided in the National Energy and Climate Plans (NECPs). More specific planning for network assets is prepared domestically in network development plans for transmission and distribution, as well as European-wide under the Ten-Year-Network-Development Plans (TYNDPs).

and regulators can only design policies to incentivise the DR service providers to enter the market and the consumers to adopt relevant technologies. Therefore, to support the policymakers and regulators to visualise and analyse potential actions and processes for policy-making decisions, the decision-tree is designed as shown in Figure 30.

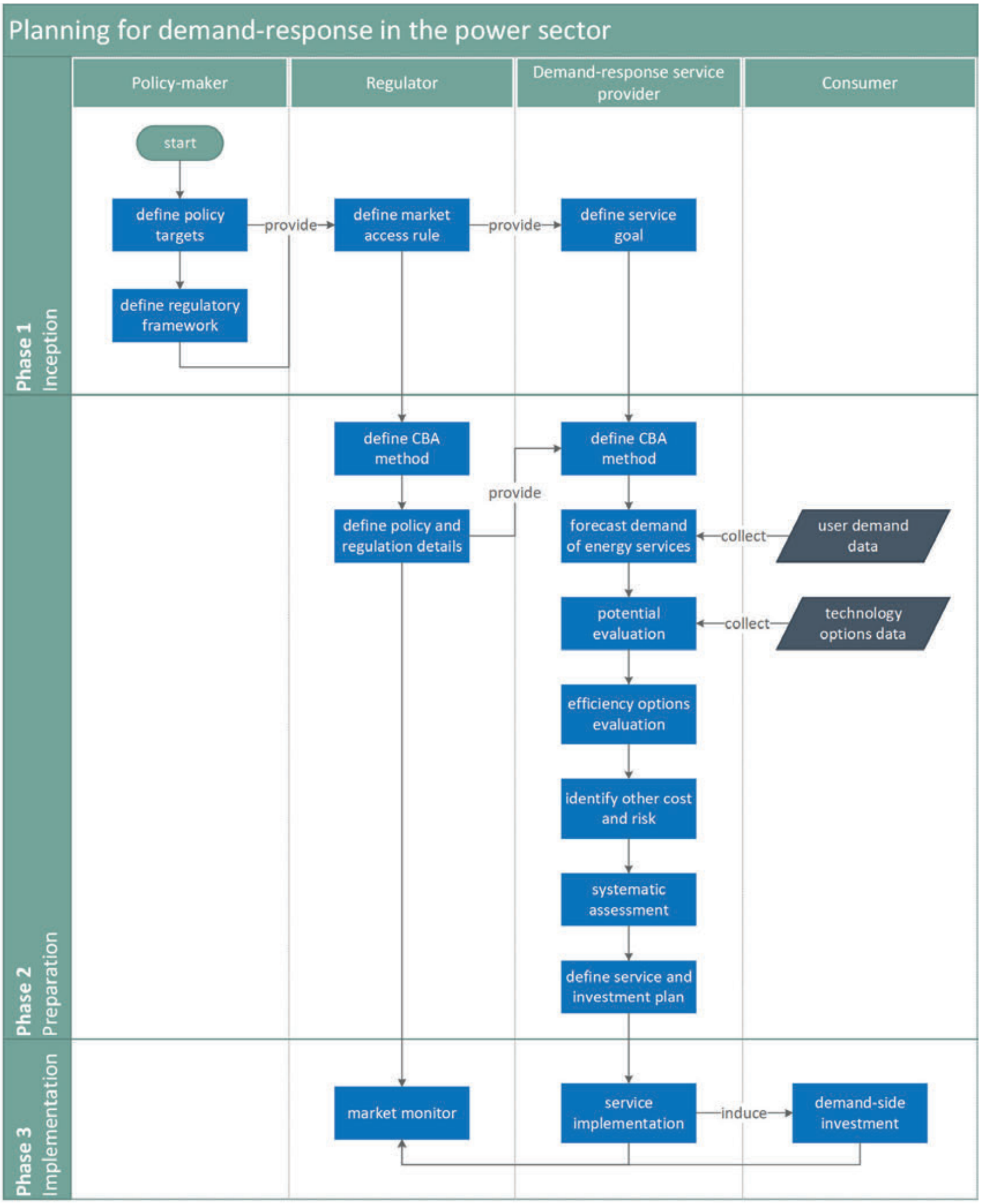
The whole planning starts with the policymaker defining the policy targets. As defined by the Electric Power Research Institute (EPRI): DR is the planning, implementation and monitoring of the utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., time pattern and magnitude of a utility's load (Paterakis et al. 2017). Facilitated by the energy management technologies and motivated by different kinds of DR programs, the targets include (1) reducing the peak of electricity demand, and (2) reducing the investment needed in generation, transmission and distribution networks and storage. Specifically, a policy target could be defined as, for example, "to develop x MW of DR that are prequalified for the balancing power markets".

The next action for the policymaker is to define a regulatory framework for planning the DR implementation, in which multiple policy instruments can be integrated. Policy instruments for DR in general include two categories: increasing storage options and reducing peak loads. The first one can for example be accomplished by providing grants for battery adoption, e.g., for battery electric vehicles that can be used as energy storage and which can feed energy back into the grid. The second one can be accomplished by incentivising investments, which make loads interruptible or through time-dependent power price programs, or network tariffs, to induce DR behaviours.

Given the policy targets and policy framework, the regulator will define market access rules for the DR service providers, to motivate them to enter the market. The rules should at least contain two aspects. First, it should contain the standard processes and contracts regulating their interaction with the electricity consumers, i.e., the companies or households who sell their flexibility of DR to them. The second aspect is about how the DR service providers are allowed to participate in the electricity market and the ancillary services markets.

Then, the regulator will define the CBA method from the societal perspective, based on which they define the policy and regulation details. This information will be provided to the DR service providers, based on which they will further define their own CBA method to systematically assess their investment options and services under the given regulatory and policy conditions, followed by a series of actions in the preparation phase. At last, based on a close review and assessment, the DR service providers will define their service plan and implement it, which further induces the investment by the consumers on energy storage, smart devices, etc. At the same time, the regulator will keep monitoring the market and respond to the violations.

Figure 30: Decision-tree of planning for DR in the power sector



7.4.2 Planning for a district heating system

District heating is generally considered as a key element for various objectives in energy policy. As pointed out, for example, in the EU Heating and Cooling Strategy (European Commission 2016a), district heating should help to reduce energy imports and dependency, to cut costs for households and businesses, and to deliver the EU's greenhouse gas emission reduction goal and meet its commitment under the Paris Agreement. From the EE1st perspective, three aspects are related to the analysis of a district heating system.

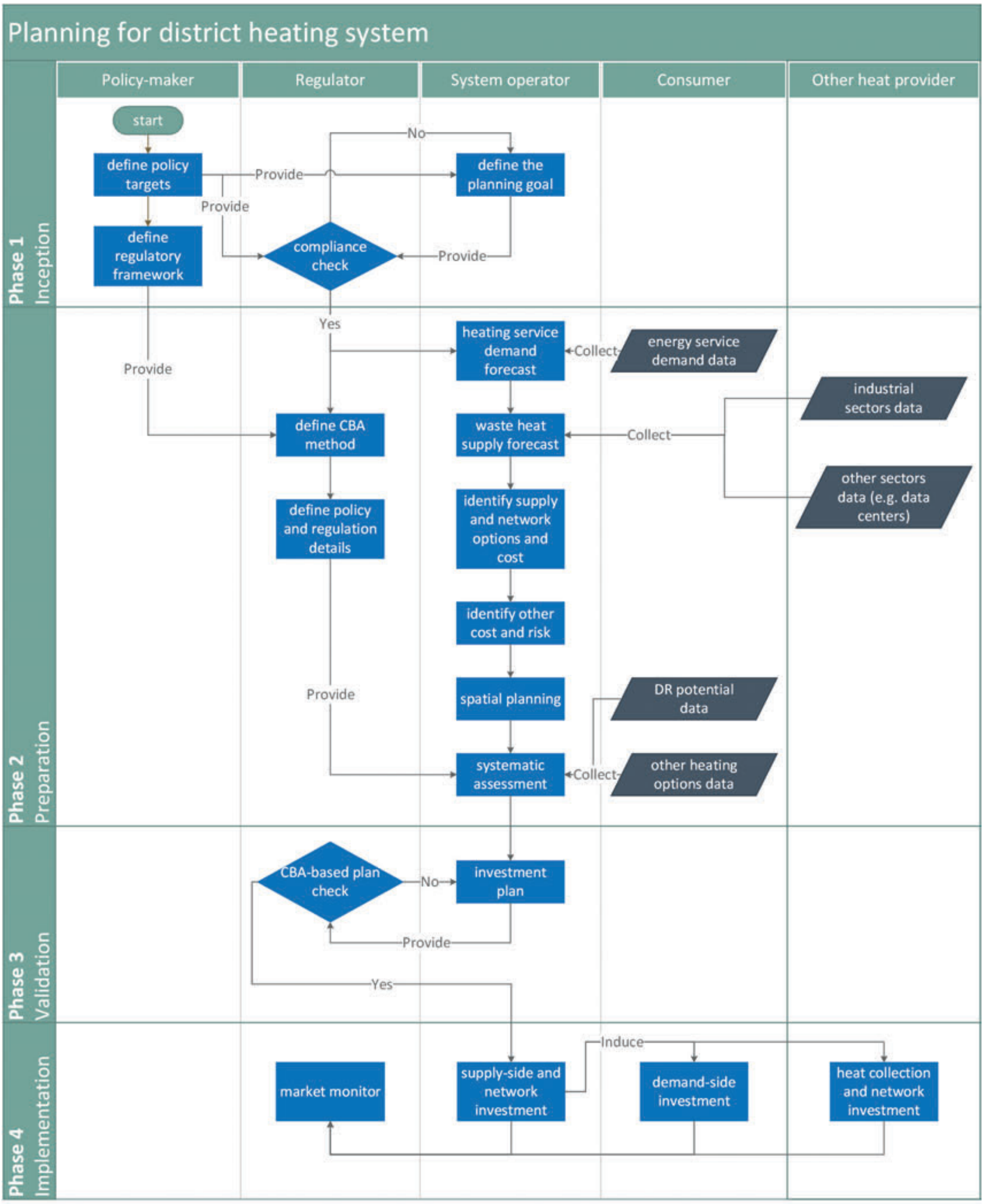
- First, when a district heating system is established, individual house boilers are replaced by a centralised more energy-efficient heating system or a combined heat and power system. So, conversion to district heating is thus an energy efficiency action by itself.
- Second, district heating provides flexibility for demand-side management. Through supporting technologies including information and communications, the peak demand of heat can be shaved, which reduces (1) the high pumping cost, (2) the risk of failure of the pipelines from large water velocities, and (3) the demand of production capacity. Besides, the capacity of the network to connect more buildings is also extended (Rutz et al. 2019). At last, it may also provide flexibility for the electricity sector if heat storage is used to optimise the power generation in a combined heat and power system.
- Third, however, district heating is an energy supply system. Therefore, end-use energy efficiency measures in buildings and production processes, which are supplied with heat from the district heating system, should be compared to and assessed against an expansion of the district heating system. Energy saved through energy efficiency measures with existing customers can be used to serve new consumers, i.e., efficiencies and reducing peak demand can be a business case as it allows more customers for a certain heat generation capacity.

Traditionally, district heating systems are vertically integrated systems, i.e. the system operator is responsible for both heat production and network operation and heat supply, as well as relevant investment decision-making.[92] Additionally, the industrial sectors can also be connected because they can collect waste heat and sell it to the network. In summary, district heating system planning is a good example for the second type of the EE1st principle application cases, i.e. system planning and investment. The policymakers and regulators are more deeply involved in checking and approving relevant planning and investment decisions. Correspondingly, the decision-tree for district heating system planning is provided as shown in Figure 31.

As shown in Figure 31, the project starts with policymakers defining policy targets. These may include reducing energy imports and dependency, cutting costs for households and businesses, and delivering greenhouse gas emission reductions. Then the district heating system operator will define its planning goal, which will be checked and approved by the regulator. This planning goal may differ according to the ownership arrangements of the DH system operator. Publicly owned

92 Competition on the generation side of district heating systems in Member States in the form of third party access is generally limited to voluntary arrangements between incumbent system operators and new suppliers, rather than full competition by statute (Bacquet et al. 2021)

Figure 31: Decision-tree of planning for district heating system



companies may prioritise societal concerns over profit maximisation, and vice versa for privately owned companies. The policymakers will also define the regulatory framework, based on which the regulator will define the CBA method and the policy and regulation details. While publicly owned companies can more easily adopt criteria favouring investments in demand-side resources,

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privately owned companies require regulatory oversight to control their performance in considering such resources in their investment and operation decision-making. Possible instruments for this purpose include the following: general regulatory oversight (closely supervise all costs and make all investment items subject to regulatory approval); price or revenue caps (set a ceiling that the operator is allowed to pass on to consumers relative to the opportunity costs of alternative demand-side investments); and performance-based regulation (reward the consideration of demand-side resources through financial incentives) (Zondag et al. 2020).

In this system planning and investment case, the regulator will directly interact with the system operator by checking and approving its decisions, so the system operator will follow the same CBA method defined by the regulator. Such a CBA method would define costs and benefits and to whom or what entity these items accrue. For example, from a consumer perspective, one would trade-off the costs for operating their heat supply as well as additional energy efficiency measures. Benefits would include the reduction in the customers' energy bills, financial incentives received and other non-monetary impacts (e.g., improved indoor air quality). More significant, however, in the context of EE1st is the societal perspective, comprising the costs and benefits experienced by all members of the local society in the vicinity of the district heating system. This perspective would take explicit account of multiple impacts and externalities occurring in the system. However, the system operator will collect information and go through a series of processes, then plan and systematically assess the investment decisions. After being checked and approved by the regulator based on the CBA method, the system operator will implement its plan, which will further induce the investment by consumers and potential heat providers from other sectors. At the same time, the regulator will keep monitoring the market.

7.5 Discussion

As shown in Section "Decision-tree framework" and the examples in Section "Planning for demand-response in the power sector" and "Planning for a district heating system", there are three key steps to use this framework to support applying the EE1st principle in practice.

- First, clearly define the application case, that is to define (1) the aim of the case, e.g., policy-making, or system planning and investment, and (2) which solutions, from both demand- and supply-sides, are involved in this case.
- Second, based on a clear definition, we identify which decision-makers are involved in the case, e.g., policymakers, regulators, or market actors. Then, given the focused solutions in this case, we select from the pre-identified actions, and construct the decision-tree.

Third, following the decision-tree, we go through the actions and the key questions for each of them (see Appendix B for a detailed list), review relevant studies to find answers and existing experiences, organise meetings and workshops for discussion, and finally form the project plan.

With this decision-tree framework, we aim to provide support for putting the EE1st principle in practice. We cover the most common elements in the EE1st principle application cases — decision-makers, phases, and actions — and thus aim to bring structure into the complex process of applying the principle. We further aim to summarise the most relevant and common questions for each action. Policymakers and regulators can flexibly apply the decision-tree to different cases in practice.

We tried to strike the balance between being general enough so that the decision-tree can be applied to the various cases and specific enough, so that the questions can really support decision-makers. Nevertheless, this approach comes with some limitations. First, and most importantly, the complexity of applying the EE1st principle lies in the fact that there is not one central planner who oversees the process and makes all the decisions for all relevant actors. Therefore, while we can visualise the process as a decision-tree, there is uncertainty as to whether the relevant actors will participate as expected, or whether they have sufficient leverage to deliver the actions identified. Second, application cases to the EE1st principle are manifold. We have therefore tried to design it in a very general way to fit many cases, yet elements might have to be added (e.g., additional decision-makers and actions) to capture more areas. Third, despite providing different questions for the different actions, those questions might not yet be detailed enough to fully guide the decision-making process and will have to be made more specific and in-depth for some cases. Furthermore, more hands-on information needs to be provided in the future, to really steer the decision-making process. Additional existing and to-be-developed tools might be linked to the various actions to support an evidence-based decision in the various steps.

Therefore, this decision-tree framework should be understood as a starting point, which provides a structure in the complex process, but which needs to be made, on one hand, wider so that it can be used in more application cases and on the other hand more specific, to be useful in each single case.

7.6 Conclusions

As an established principle for EU energy policy design, energy efficiency first emphasises the demand-side solutions in policy-making, energy system planning, and investment. However, there are various barriers to applying the principle, and one key barrier is the involvement of multiple market actors with different interests, especially in a market-based system. It is challenging for the policymakers and regulators to incentivise them to fully exploit the demand-side resources. In this paper, we developed a decision-tree framework to support applying the EE1st principle in practice.

Two different types of cases are distinguished according to the involvement depth of policymakers and regulators. For the cases from each type, the tool supports from different perspectives:

- For policy-making cases in the market-based decentralised systems, the tool can be used to visualise and analyse potential actions and processes for policymakers and regulators. They cannot check and approve the decisions of market actors, but can only design and implement policies to motivate their behaviours.
- For system planning and investment cases in the regulated (e.g., network and vertically integrated) systems, the tool can be used to organise the actions of all potential decision-makers in different cases, and also organise the whole decision-making processes in the project.

In general, this paper contributes to the application of the EE1st principle by defining and distinguishing different types of cases, identifying the most common elements (incl. decision-makers, project phases, and actions), and proposing a decision-tree framework than can be flexibly constructed based on the elements for different cases. Two examples are provided for further explanation and discussion. For some cases, the framework may need necessary extensions, for example, with new phases added, new decision-makers introduced, or new actions defined. Additionally, it might need to become more specific and hands-on to ensure the usefulness in each case. However, the overall framework can serve as a starting point by providing a systematic overview of the complex process to decision-makers.

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Conclusion

In this concluding chapter, Section 8.1 first provides a brief summary of the research objectives and questions. Section 8.2 then outlines the main research contributions, followed by a discussion of the limitations and research challenges in Section 8.3. Finally, Section 8.4 provides an outlook on future directions and implications of the research.

8.1 Synopsis of research objectives and questions

The energy efficiency first (EE1st) principle is based on the idea that energy efficiency is often the most sustainable and cost-effective means of meeting consumers' energy service needs (e.g. thermal comfort), and wider societal objectives (e.g. decarbonisation). Where this is the case, the principle suggests that energy efficiency solutions should be systematically prioritised over the development of relatively inefficient energy supply infrastructure. Since its inception in the mid-2010s, the EE1st principle has rapidly become part of European Union (EU) energy and climate policy. Initially appearing in brochures and policy briefs, it has been gradually integrated into EU strategies and legislation. A major milestone was the adoption of the recast Energy Efficiency Directive in late 2023 (European Union 2023a), Article 3 of which mandates the assessment, monitoring and reporting of the application of the EE1st principle in EU Member States.

Against this background, Chapter 1 provided a comprehensive review of the existing literature and identified three research gaps related to the EE1st principle. The first gap highlighted the lack of conceptual clarity surrounding EE1st. Prior to this research, the concept of EE1st had been largely absent from the peer-reviewed academic literature, leading to ambiguities and inconsistencies in its interpretation and terminology. Moreover, there was a tendency to equate EE1st with similar concepts from international contexts. This situation risked leading to a misunderstanding of the EE1st principle, thereby limiting its potential impact. This led to the formulation of the first research question (RQ 1): *How can the energy efficiency first principle be systematically conceptualised to clarify its meaning and distinguish it from related concepts?* Chapter 2 addressed this by providing a thorough conceptual exploration and analysis of the EE1st principle, thereby enhancing its clarity and delineating its practical scope.

The second research gap that was identified concerned the lack of quantitative evidence on the potential impacts of the EE1st principle. A key focus area has been the interplay between (a) the building sector, which includes residential, commercial, and public buildings with energy efficiency solutions such as building retrofits, and (b) the corresponding energy supply infrastructure, including generation, network and storage facilities for electricity, heat, gas, hydrogen and other energy carriers. Both sides involve significant economic costs and benefits, leading to RQ 2: *To what extent does prioritising energy efficiency in the building sector impact energy supply infrastructure requirements and energy system costs for a net-zero emissions transition in the EU?* This question was explored through

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two dedicated quantitative analyses in Chapters 3 and 4, which combined bottom-up energy system modelling with comprehensive cost-benefit analyses.

The third research gap that was identified involved the lack of practical guidance for the application of the EE1st principle by Member States and sub-national decision-makers. Despite initial recommendations from the European Union (2021), the recast of the Energy Efficiency Directive calls for more definitive and scientifically based guidance, in particular regarding the design of specific policy instruments for EE1st and its integration into strategic energy planning. Consequently, RQ 3 was formulated as follows: *How can the energy efficiency first principle be effectively applied in the European Union and its Member States through policy instruments and strategic energy planning?* Chapters 5 to 7 addressed this question using a combination of literature reviews, semi-structured interviews and the development of new supporting frameworks. The specific contributions of these chapters are detailed in the following sections.

8.2 Research contributions

This research makes three main contributions: an improved conceptual understanding and clarification of the scope of the EE1st principle (Section 8.2.1), quantitative evidence on the potential impacts of the EE1st principle on the building sector and energy supply (Section 8.2.2), and practical guidance on the application of the EE1st principle in EU energy and climate policy (Section 8.2.3).

8.2.1 Improving conceptual clarity and unravelling the scope of the energy efficiency first principle

The EE1st principle has emerged from grey literature and legal documents at the EU level. However, prior to this research, the principle had scarcely been represented in peer-reviewed literature, linking the concept to broader, multidisciplinary research on energy systems and energy policy. This lack of representation led to two major problems: a lack of clarity and consistency in terminology, and insufficient consideration of institutional and historical contexts.

The first issue revolved around the varying definitions of EE1st. Consistent terminology is essential for understanding, replication, comparison, and to prevent misinterpretation of concepts. When comparing the various existing definitions of EE1st in Table A1 (Appendix A), many terms become apparent that seem similar, but have different nuances, including energy efficiency solutions, demand-side resources, efficiency resources, or energy efficiency measures (Pató et al. 2020a; Rosenow et al. 2017a). This left unclear the exact scope of action of EE1st: does the principle target only classic end-use energy efficiency, does it also cover demand-side flexibility, and to what extent does it include efficient conversion and distribution of energy on the supply side?

To address this issue, this research reviewed the multidisciplinary literature on energy efficiency and reconsidered existing terminology. Chapter 2 provided a suite of definitions, summarised in Table A2. These definitions establish a general dichotomy between energy efficiency solutions on the one hand and energy supply infrastructure on the other. Energy efficiency solutions are further divided into demand-side resources (including end-use energy efficiency, demand-side flexibility, and energy sufficiency) and supply-side energy efficiency. Thus, in line with its official definition in EU legislation (see Chapter 1.1.2), the scope of EE1st is certainly broader than traditional end-use energy efficiency. Demand-side flexibility is arguably a more significant resource in electricity systems than permanent load reduction, a point thoroughly discussed in Chapter 6.

Yet, the exact scope of action for EE1st remained ambiguous. This is due to the relative nature of energy efficiency, which gains specificity when contrasting one technology's efficiency against another. For example, a combined cycle gas turbine has a higher fuel conversion efficiency than an open cycle gas turbine (DEA 2021b). Nevertheless, such superior efficiency does not automatically render it a primary focus of the EE1st principle. As elaborated in Chapter 2, system boundaries influence this focus. In a single building, thermal insulation is an end-use energy efficiency solution that can reduce the size and associated investment for heating solutions such as heat pumps. However, with broader system boundaries, such as the EU energy system, heat pumps also emerge as energy efficiency solutions when compared to alternatives such as gas boilers, taking into account the overall primary energy input to provide useful heat output.

To address this ambiguity, it might be best to conceive EE1st as an optimisation problem: the objective function is to minimise costs or maximise net benefits. The variables are the investments and operation of all available technological and behavioural options, subject to consumers' energy service needs (e.g. indoor comfort) and any other relevant objectives (e.g. decarbonisation). When framed this way, the focus of the EE1st principle is not to establish strict hierarchies of technologies based on their standalone energy efficiency. Instead, the primary focus is to identify and prioritise those solutions, whether particularly energy efficient or not, that deliver the highest net benefits.

Determining which costs and benefits to consider added another layer of ambiguity. A rational building owner, for example, would focus on private cost-effectiveness by estimating financial cash flows, 'hidden' transaction costs, and non-financial utility gains, such as improved thermal comfort after renovation. However, as highlighted in Chapter 2's literature review, the principle places greater emphasis on a wider societal perspective. Given its role within the EU legislative framework, the principle is unequivocally a matter of public policy, requiring policymakers to take into account broader impacts. Therefore, Chapters 3-4 employed a societal perspective in model-based analyses to approximate economically optimal levels of energy efficiency. Chapters 5–7 investigated reconciling private decisions with the wider public good through policy and planning instruments.

This research further distinguished between the terms 'cost-effectiveness' and 'cost-efficiency', which tend to be used interchangeably in the EE1st literature yet hold distinct nuances. Cost-efficiency is understood as the ratio of input costs to the level of energy service output, whereas cost-effectiveness indicates the absolute difference between costs and benefits. As such, cost-efficiency allows for an integrated cost comparison of energy efficiency solutions and energy supply infrastructure, taking into account the energy service delivered. This was demonstrated in Chapter 4's analysis, where both building retrofit measures and heat supply options were ranked based on their cost-efficiency (EUR/MWh_{th}) for providing the energy service of space heating (MWh_{th}).

In light of the above considerations, Chapter 2 offered a refined and substantiated definition of the EE1st principle: it is a decision principle for energy-related planning, investment and policymaking within given system boundaries, which prioritises energy efficiency solutions whenever they are more cost-efficient than energy supply infrastructures in meeting stated objectives. By bridging the gaps in the existing literature, and providing clarity on intricate terminologies, this research establishes a robust foundation for future research and the practical application of the principle.

The second issue concerned the institutional and historical context of the EE1st principle. At first glance, EE1st seems similar to certain regulatory practices in a number of U.S. states, including least-cost planning, integrated resource planning, and non-wires solutions. Chapter 2 contributed a systematic conceptual comparison of EE1st in the EU context and these related concepts, using the criteria of market structure, scope of energy vectors, and scope of costs and benefits.

In terms of market structure, the practices employed in the U.S. essentially require vertically-integrated utilities that own and operate energy supply infrastructures, and that are subject to regulatory oversight. Such a setting can facilitate the consideration of energy efficiency solutions. Conversely, beginning with the First Energy Package in 1995, the EU's energy markets have been largely unbundled and liberalised. The only regulated market activity left are network operators, due to their status as natural monopolies.

Consequently, the EU's context lacks direct leverage for regulatory authorities to apply the EE1st principle beyond these network companies. This raised the question how to deal with power plants, distributed generation, storage facilities, electrolysers and other supply-side infrastructures that exist within a liberalised or competition-based market framework. As argued throughout Chapters 5–7, this observation underscores the need for an appropriate incentive or policy framework to apply the EE1st principle beyond regulated market activities.

When considering the scope of energy vectors, i.e. the systems for transporting energy across locations, the EE1st principle in the EU context is also broader than the U.S. concepts, covering not only electricity, but extending to heat, natural gas, and hydrogen infrastructures. Moreover, the EU perspective is broader in assessing costs and benefits. The focus is on the societal perspective, aiming at solutions that are optimal for society as a whole, not just for utility customers. This implies a strong link to the concept of multiple impacts, which is essential to create a level playing field for both energy efficiency and energy supply. While the U.S. context may have provided some inspiration, the EE1st principle is clearly a unique concept with its own challenges and opportunities.

To conclude, this research into the origins, development, and practical implications of the EE1st principle addressed significant gaps. It offers an improved understanding of the EE1st principle, providing a clearer, broader, and more nuanced account of its scope and applications. The comparative analysis between the EU and U.S. contexts enhances the understanding of the principle's unique characteristics, which is important for identifying effective strategies for its application in different institutional and regulatory settings.

8.2.2 Examining the quantitative impacts of the energy efficiency first principle on buildings and energy supply

The building sector is an important focus for the EE1st principle, accounting for 40% of EU final energy consumption in 2019 (Eurostat 2022b) and 35% of energy-related greenhouse gas emissions (EEA 2021, 2022), taking into account emissions from electricity and heat used in buildings. This sector involves a wide range of technically feasible energy efficiency solutions, such as building retrofits, and energy supply infrastructures, such as gas networks with centralised or decentralised boilers. This raised the fundamental question of the extent to which energy efficiency solutions should be systematically prioritised over the development and operation of energy supply infrastructure and, consequently, whether there is significant scope for the EE1st principle in the EU.

Existing research has examined this issue, albeit largely without explicit reference to the EE1st principle. A number of specific research gaps were identified in this domain. First, many studies have overlooked the societal perspective, which, as established above, is integral to the EE1st concept. Second, there has been a clear underrepresentation of the multiple impacts that extend beyond traditional financial costs and benefits. Third, much of the existing research has been limited in its spatial scope and associated system boundaries, often focusing narrowly on specific EU Member States or local areas. Finally, the EU's goal of achieving net-zero greenhouse gas emissions by 2050 and its associated techno-economic challenges for energy systems have so far received limited attention in the relevant literature.

Chapter 3 provided a detailed analysis at the EU level, where each of the 27 EU Member States was modelled individually, taking into account mutual energy imports and exports. This chapter used a combination of temporally and spatially resolved bottom-up energy models, representing the sectors, individual technologies and processes that make up the overall energy system. Together, these models assessed the impact of different energy efficiency measures, from building envelope retrofits to efficient appliances, on an energy supply system transitioning to net-zero greenhouse gas emissions. Taking a societal perspective, the analysis assessed system performance based on energy system costs, defined as the total discounted costs of meeting the demand for energy services in buildings, including both financial (e.g. fuel costs) and external costs (see Section 8.3). In Chapter 3, the latter included the cost of air pollution damage from energy conversion, as this represents a significant multiple impact (Ürge-Vorsatz et al. 2016), with a monetary value previously estimated at 0.25 times the value of energy cost savings in the EU (Thema et al. 2019).

Several key insights can be drawn from Chapter 3. Ambitious energy saving measures have a significant impact on reducing the renewable supply capacity needed to meet the net-zero target. This implies potential reductions in the cumulative installed capacity of wind, photovoltaics, electrolysers and transmission grids, with implications for land use and public acceptance. Strategies to reduce final energy consumption in the buildings sector by 30% by 2050 compared to 2020 levels can be supported by the associated reduction in energy system costs. Meanwhile, it is important to keep the building sector efficiency improvement above 20% by 2050 compared to 2020 in order to avoid additional energy system costs. Taken together, these findings call for a considerably more ambitious energy savings trajectory for the building sector than the business-as-usual pathway under the EU Reference Scenario (Capros et al. 2021), which projects a 10% reduction in final energy consumption in buildings by 2050 compared to 2020.

Chapter 4, while maintaining certain analytical parallels with Chapter 3, applied more spatially resolved modelling techniques at the local level, examining a mixed-use urban district from the 1970–1989 construction period with approximately 10,000 residents. The study focused on the economic trade-offs and technical synergies between building retrofits and heat supply options, both building-integrated and district heating. For generalisability, the generic urban district was analysed for three European countries, each with different price levels, climatic conditions, and building stock characteristics. A dedicated sensitivity analysis was carried out to test the robustness of the results. In addition to air pollution, the monetised climate damage costs of greenhouse gas emissions were included as another multiple impact in the calculation of energy system costs.

Several key observations emerge from Chapter 4. The socially cost-optimal balance between heat savings and supply is influenced by various exogenous factors. For example, under favourable conditions – including low labour and material costs, cold winters, high fuel costs and high external costs – such as in Bulgaria, building retrofits can lead to cost savings of up to 20% while reducing useful heat demand by up to 60%. In contrast, in settings such as Finland, it may be more economically viable to install new heat supply without prior retrofitting, taking into account the external costs of air pollution and GHG emissions from energy conversion. A consistent theme is that heat pumps are an essential component for cost-efficient heat supply, whether in decentralised building-integrated systems or centralised district heating systems. As the data suggests, the performance of heat pumps is closely linked to flow temperatures: when these are too high, other heating systems, such as biomass boilers, may become economically preferable.

Synthesising the evidence from Chapters 3 and 4, a number of key conclusions are evident. There is an undeniable role for the EE1st principle in guiding the transition to a sustainable energy system in the EU. In particular, building retrofits emerge as a key energy efficiency solution. Such retrofits not only reduce the need for electricity, heat, gas and hydrogen infrastructure, but also offer potential cost reductions. In addition, heat pumps are identified as a key energy efficiency solution.

However, it is important to recognise that end-use energy efficiency measures may not always be more economically viable than new sustainable energy supply. In particular, building retrofits require significant upfront investments that must be recouped through reduced energy costs. This finding does not undermine the EE1st principle. Rather, as explained above, it highlights that the core of the principle is not simply the promotion of energy efficiency for its own sake, but rather the optimal mix of solutions that maximises net-benefits or minimises societal costs, taking into account not only traditional costs involving a financial transaction, but also multiple impacts.

These findings are widely consistent with the existing literature. Taking into account selected multiple impacts in the form of air pollution and greenhouse gas emissions, this research identifies potentially cost-effective energy savings in the building sector compared to current levels of 0-60%, depending on specific assumptions and local contexts. These figures are in line with Member State level estimates of 20-47% savings (Hummel et al. 2023; Langenheld et al. 2018; Hansen et al. 2016), and with local level findings suggesting 20-78% savings (Ben Amer-Allam et al. 2017; Büchele et al. 2019; Harrestrup and Svendsen 2014; Milic et al. 2020; Romanchenko et al. 2020), although these studies differ in terms of GHG reduction targets, perspective (private vs. societal) and corresponding discount rates, definition of costs and other relevant settings.

This research also highlights the technical synergies between building retrofits and low temperature heating systems such as heat pumps. In Chapter 3, sources such as solar thermal and deep geothermal energy also emerged as viable heat supply options, in line with the literature on low temperature heating and fourth/fifth generation district heating (Lund et al. 2021; IRENA 2021).

Another consistent theme in Chapters 3 and 4 is the moderate uptake of hydrogen and synthetic hydrocarbons in the transition to a net-zero emissions energy system. In the EU system-level analysis in Chapter 3, hydrogen produced using excess electricity is increasingly used as a storage solution to manage the variable nature of renewable electricity generation from 2030 onwards, which is consistent with similar model-based work (Zeyen et al. 2021). At the same time, in line with most of the literature (Rosenow 2024), the results suggest little scope for the direct use of hydrogen for heating in buildings. This is underlined by the local level analysis in Chapter 4, where boilers using different blends of natural gas, hydrogen and synthetic methane are largely outperformed by heat pumps, district heating and other alternatives in terms of both cost and energy efficiency.

Regarding policy implications, a balanced and strategic approach to energy planning in the scope of EE1st is essential. This approach should integrate both demand-side and supply-side solutions, in order to provide cost-optimal outcomes. The importance of this integrated perspective is increasingly recognised in the EU legislative framework, for example in Article 25(6) of the recast Energy Efficiency Directive (European Union 2023a) on local heating and cooling planning.

However, as detailed below, the challenge for policymakers is to reconcile the normative societal perspective of the EE1st principle with the actual private financial decisions of consumers and producers. This requires overcoming several market failures, ranging from regulatory disincentives and negative externalities to transaction costs. It also involves resolving behavioural anomalies and information problems so that consumers adequately consider the internal multiple impacts of their decisions, such as improved thermal comfort and productivity after building renovation. Overall, the pathway to a sustainable energy future in the EU requires a sensible balance between energy savings and renewable energy expansion, with the EE1st principle as a reasonable guiding principle. The building sector, with its nuances and complexities, remains central to this effort.

8.2.3 Providing guidance on the practical application of the energy efficiency first principle in strategic energy planning and policymaking

As discussed above, the EE1st principle has a number of conceptual intricacies and, as a result, its practical application has proved difficult for decision-makers. In particular, Member States have made only cursory reference to EE1st in their national energy and climate plans (European Commission 2020b), arguably due to a lack of guidance. While the European Commission has previously provided recommendations on the possible application of EE1st (2021), it can be expected that, in light of the new provisions in Article 3 of the recast Energy Efficiency Directive (European Union 2023a) (Table 2), clearer and more scientifically robust guidance will be needed.

From an academic perspective, three particular research gaps have been identified: first, the need to clarify the defining characteristics of EE1st policy as opposed to traditional energy efficiency policy, which is well established in the EU through command and control, pricing, and information instruments. Second, the need to develop a theoretically coherent policy intervention logic for EE1st. Previous justifications for EE1st policy have often referred loosely to the concept of barriers to energy efficiency, which has been criticised for analytical inaccuracies and for not clearly addressing the interplay between demand-side energy efficiency and energy supply. Third, the need to clarify how EE1st can be integrated into strategic energy planning.

In order to bridge the gap between the conceptual foundations of the EE1st principle and its practical application, two main approaches were proposed in Chapters 5-7. The first focused on strategic energy planning. This involves the integrated planning of energy efficiency solutions alongside energy supply infrastructures, supported by stakeholder engagement and quantitative analysis. The second approach concerned policy instruments. These are understood as formalised measures adopted by government bodies or regulatory authorities, designed to facilitate a level playing field between energy efficiency and energy supply in line with the EE1st principle.

Strategic energy planning has traditionally been the domain of network operators and energy utilities. With the development of EU and national legislation, the role of public authorities, including municipalities, has become increasingly significant. These authorities use strategic energy planning to work towards sustainable, reliable, resilient and affordable energy systems. A well-known example is Article 3 of Governance Regulation (European Union 2018d), requiring Member States to develop and implement national energy and climate plans that outline their strategies to meet EU energy and climate targets by 2030, based on planning and reporting frameworks.

As pointed out throughout Chapters 2-7, the application of the EE1st principle in strategic energy planning involves two main aspects. First, it requires an *integrated* assessment of energy supply and energy efficiency solutions (Figure 2), recognising that both can meet consumers' energy service needs. Traditional energy supply infrastructure planning, based on exogenous energy demand trends, needs to evolve to include energy efficiency solutions as active, endogenous system resources. The significance of integrated assessments is underlined by the quantitative studies presented in this work. For example, Chapter 4 showed that considering building retrofits alongside new heat supply in local energy planning could reduce energy system costs by up to 20%.

Second, a *fair* assessment of energy supply and energy efficiency solutions is essential. This requires taking into account all relevant costs and benefits, including the wider social, environmental, and economic impacts, particularly when a societal perspective is adopted in cost-benefit analysis. Chapters 3 and 4 acknowledged this by quantifying and monetising selected multiple impacts. In principle, through both integrated and fair planning, energy planners could identify energy efficiency solutions that are projected to deliver the greatest net benefits to society and invest accordingly. This was the idea behind the model-based study in Chapter 4, assuming municipal authorities that are major shareholders in both heat supply and housing companies.

However, strategic energy planning is a complex process. To provide a structured and systematic approach to planning, Chapter 7 introduced a novel decision tree framework. Derived from a review of management literature and the concept of EE1st, it incorporates two dimensions: planning phases, ranging from project inception to implementation, and decision-makers, ranging from policymakers to market actors. The framework uses common flowchart symbols to visually represent different decision paths and their potential outcomes, thereby breaking down complicated decisions and facilitating informed discussions among stakeholders.

To demonstrate its practical applicability, the framework was applied to two common planning situations. One is electricity network planning, illustrating when and how a distribution system operator could consider and assess non-wires solutions as alternatives to network capacity expansion. As shown in the decision tree, and detailed in Chapter 6, options for distribution system operators to procure energy efficiency solutions, including demand-side flexibility, could include solicitations, contracting with third-party aggregators, or collaborating with retail energy providers to incentivise time-of-use network tariffs to change consumers' electricity use patterns.

As such, the decision tree framework can serve as a planning tool to help identify least-cost combinations of energy efficiency and energy supply solutions, taking into account different constraints and objectives. Its effectiveness is enhanced when used alongside a broader toolkit of decision-making and cost-benefit modelling techniques within public deliberation processes.

However, strategic energy planning is not without limitations. It faces predictive uncertainty, political constraints influenced by changes in government and policy, and diverging ownership among stakeholders. To illustrate, while one entity may own a supply asset such as a heat plant, another may control energy efficiency solutions such as building renovations. Coordinating these different economic interests and stakeholders with the optimal outcome for the energy system and society as a whole requires not only strategic planning but also dedicated policy instruments.

A theoretical framework for the application of EE1st through policy instruments was outlined in Chapter 2 and expanded in Chapter 5. This framework is based on market failure theory, integrating findings from neoclassical, institutional, regulatory and behavioural economics. Central to the framework is the economic concept of well-functioning markets, which requires the fulfilment of six main conditions: (i) no externalities, (ii) free market entry and exit, (iii) effective regulation of natural monopolies, (iv) perfect information, (v) zero transaction costs, and (vi) rationality.

The concept of well-functioning markets serves as a normative theoretical benchmark for EE1st because, as summarised in Section 8.2.1 above, the principle does not unequivocally support energy efficiency, but rather societal net-benefits or economic efficiency. Market failures are understood as violations of the six formal characteristics of well-functioning markets. They result in economically suboptimal levels of energy efficiency, known as the energy efficiency gap. Based on this theoretical framework, Chapter 5 systematically examined common market failures in the EU energy system. An example is transaction costs: while producers tend to spread out transaction costs over recurring large investments, consumers were shown to face disproportionately high costs for infrequent small-scale energy efficiency investments such as building retrofits.

It was argued that policy intervention is justified when the societal benefits of addressing these market failures outweigh the implementation costs. Importantly, the outcome of addressing market failures under the EE1st principle is not necessarily the adoption of energy efficiency solutions, but rather a cost-minimising or welfare-maximising mix of solutions, whether energy savings or supply. Thus, Chapters 2 and 5 argued that this intervention logic should be referred to as EE1st policy.

Building on the theoretical framework, Chapter 5 introduced a novel classification and characterisation of policy instruments to address the EE1st principle. This study aimed to encompass policies that address the interaction between energy use in households, small and medium-sized enterprises and industry, and the corresponding energy supply infrastructures for electricity, gas, hydrogen and heat. Complementing this, Chapter 6 focused specifically on policy instruments in the power sector. This sector is crucial due to the increasing role of electrification in heating, transport and industry, and the need for flexible electricity use. Chapter 6 used semi-structured interviews with regulators, energy companies and researchers, combined with a literature review, to verify and refine policy guidelines. Taken together, the studies in Chapters 5 and 6 provide several key guidelines for effective implementation of the EE1st principle through policy instruments:

1) Network companies, as natural monopolies under regulatory oversight, need innovative financial incentives from regulatory authorities, such as performance-based regulation, to actively consider energy efficiency as an alternative to network infrastructure expansion.
2) All external costs of energy conversion and related infrastructure should be internalised into market prices to reflect impacts on climate, human health and ecosystems, possibly through an extension of the EU ETS in terms of sectors and emissions, together with energy tax reforms.
3) Energy efficiency solutions should have non-discriminatory market access where they can directly compete with traditional generation, e.g. for demand-side flexibility in electricity markets or for third party waste heat suppliers in large district heating systems.
4) Transaction costs are a significant 'hidden' cost for demand-side energy efficiency solutions and should be reduced as much as possible, e.g. by promoting one-stop shops for building renovation or aggregators for demand-side flexibility.
5) Information asymmetries are already well addressed in some areas, such as product labelling, but need to be tackled in others, e.g. by promoting time-differentiated energy and network tariffs to reduce information asymmetries between energy producers and flexible consumers.
6) Behavioural anomalies should be targeted so that consumers maximise their utility and take into account internal multiple impacts when making energy-related purchase and use decisions, e.g. through simplification and appropriate framing of information and other so-called nudges.

In this way, Chapters 5 and 6 highlight the defining feature of EE1st policy (Pató et al. 2019b): it is *broader* than traditional efficiency-only policy in that the market failure logic leads to important policy areas that are often not associated with energy efficiency, such as electricity market design, the regulation of network companies or emissions pricing. At the same time, it is *narrower* than traditional energy efficiency policy in that it does not command a market outcome, but promotes a market environment in which energy efficiency can emerge as a viable option.

Altogether, the framework provides a theoretically coherent explanation for the apparent economic imbalance between energy efficiency and energy supply while offering a practical intervention logic for policy instruments aimed at applying the EE1st principle. This complements the official guidance on EE1st by the European Union (2021), adding scrutiny and theoretical substance.

Importantly, this framework does not depart from the well-established concept of barriers to energy efficiency, but provides a nuanced reframing that aligns more consistently with economic theory, e.g. by interpreting the barrier of 'hidden costs' (e.g. Sorrell et al. 2000b) as the formal market failure of transaction costs. This approach simplifies the potential application of EE1st, showing its applicability across different energy sectors by highlighting common policy issues, such as market design that is relevant not only to electricity markets but also to district heating systems.

In sum, this research contributes to the practical application of the EE1st principle in energy planning and policymaking. By addressing conceptual intricacies and practical challenges, it provides a robust theoretical framework and actionable guidelines for integrating EE1st into both strategic energy planning and policy instruments. This helps to bridge the gap between theoretical understanding and practical implementation, providing an important groundwork for Member States and sub-national decision-makers to move from principle to practice.

8.3 Limitations and research challenges

This section critically examines the limitations of this research, focusing on the theoretical perspectives used to derive prescriptive policy guidance, the scope of energy efficiency solutions and sectors under EE1st, and the limitations of the quantitative models used, overall highlighting the research challenges to fully understanding and applying the EE1st principle.

Theoretical frameworks for understanding and addressing the EE1st principle

Theories are central to advancing understanding of emerging concepts, guiding research and integrating complex issues into coherent frameworks. In response to the lack of dedicated theoretical perspectives on EE1st in the existing literature, Chapters 2 and 5 developed a comprehensive framework based on market failure theory. This framework adopts the economic concept of well-functioning markets as a theoretical benchmark against which the application of the EE1st principle can be understood and assessed. Although it is an idealised construct, it provides a clear and coherent foundation for understanding the potential application of EE1st in the EU and was shown to be a valuable tool for deriving a comprehensive set of policy instruments.

However, over-reliance on market failure theory could lead to a policy mix that overlooks real-world complexities. For example, the concept of well-functioning markets focuses on economic efficiency but does not inherently address issues such as equity or distributional fairness. This suggests the need for public financing instruments such as grants or tax credits, that do not target specific market failures in the traditional economic sense, but address broader societal goals (Ordonez et al. 2017).

Socio-technical systems could provide a more nuanced understanding of EE1st beyond traditional economics (Fuenfschilling and Truffer 2014; Geels 2004). The multi-level perspective, a structured framework within socio-technical systems theory, could be particularly insightful (Geels 2018; Geels et al. 2017). It analyses interactions across three levels: *niches* (innovative practices and technologies), *regimes* (established practices, institutions, and regulatory frameworks), and *landscapes* (broader socio-economic trends). Applying the multi-level perspective to EE1st could reveal how established energy supply structures resist change and how niche innovations struggle for wider acceptance within the overarching socio-economic context (Sorrell 2015).

To illustrate, the multi-level perspective could suggest that successful demonstration projects and scientific evidence of benefits can help niche innovations, such as demand-side flexibility, to gain momentum. In addition, monitoring of EE1st applications in Member States could act as an effective feedback mechanism by influencing policy decisions at the regime level, thus facilitating the uptake of niche innovations and responding to landscape-level pressures, such as energy crises. In sum, practical application of the EE1st principle is a complex matter, involving not only technological innovation, but also changes in policy, institutions, societal values, and behaviours. A thorough understanding of this complexity is central to its effective practical application in the EU.

Scope of energy efficiency solutions

The quantitative studies in this work focused primarily on end-use energy efficiency, i.e. measures that increase the ratio of energy service output to final energy input. However, as highlighted in Section 8.2.1 and Figure 23, the scope of the EE1st principle is broader, including other solutions such as demand response and energy sufficiency, which could contribute to system-wide energy and cost savings (European Union 2023a, 2021a; Pató et al. 2020a).

Demand response involves changes in energy use by consumers in reaction to price changes or incentive payments. It is frequently highlighted in EE1st-related EU legislation (European Union 2021a) as it can help improve the efficiency and reliability of electricity systems. Although not the main focus, Chapter 3 took into account the provision of price-based flexibility through heat pumps, as detailed in Chapter 3.4.1. Meanwhile, many other technologies and applications in the building sector can provide demand response, such as electric water heaters. As shown in both theory and practice in Chapter 6, the inclusion of these applications could strengthen the case for EE1st. This requires more comprehensive modelling, including data on consumer price response, technology performance and detailed system operations (Boßmann 2015; smartEn 2022a).

Energy sufficiency, in turn, involves lifestyle and behavioural changes in the level of energy services required. The quantitative studies in Chapters 3 and 4 did not explicitly take this into account. Integration into energy system modelling could be achieved through exogenous assumptions reflecting lifestyle changes, such as the average floor area per household over time. However, there are challenges in assessing the costs and benefits of sufficiency to make it comparable to energy supply infrastructure and other technological solutions in the scope of EE1st. While some argue that sufficiency measures result in a loss of time or convenience (Alcott 2008), others suggest that they need not result in utility reduction (Sorrell et al. 2020). For example, well-designed smaller homes could provide the same utility as larger ones. Overall, further research into the potential of both demand response and energy sufficiency could provide further support for the EE1st principle.

Scope of energy demand sectors

As explained in Chapters 2 and 5, the EE1st principle is a holistic concept that aims to identify and prioritise cost-efficient energy efficiency solutions across all sectors of the energy system. The quantitative studies carried out in Chapters 3 and 4 primarily focused on the interaction between the building sector – including residential, commercial, and public buildings, with energy efficiency solutions such as building retrofits and efficient appliances – and energy supply, including electricity, heat, gas, and hydrogen infrastructures. This focus was justified by the building sector's significant share in final energy consumption and related greenhouse gas emissions.

While these studies made a compelling case for the EE1st principle, it is important to recognise potentials in other energy demand sectors. The industrial sector, in particular, offers substantial opportunities for energy efficiency through measures such as efficient processes and machinery (Kermeli et al. 2022), demand-side flexibility (Boldrini et al. 2024), and material efficiency (Cullen and Cooper 2022). In addition, Article 3(1) of the Energy Efficiency Directive (European Union 2023a) also highlights the transport sector, where energy efficiency solutions such as public transport systems could reduce the need for extensive transport infrastructure such as highways.

However, under the premise of a system transition to net-zero emissions by 2050, these sectors require continued quantitative evidence on the extent to which energy efficiency solutions are more cost-efficient compared to new energy supply infrastructure for electricity, hydrogen and other energy vectors. Moreover, to complement the insights provided in Chapters 5-7, there is a need for more targeted guidance on how to apply the EE1st principle in these sectors through strategic energy planning and dedicated policy instruments.

Integration of multiple impacts into cost-benefit analyses

In Chapters 3 and 4, the economic performance of energy efficiency and energy supply options was assessed using energy system costs. This metric includes discounted financial expenses such as fuel costs and integrates external costs associated with air pollution and greenhouse gas emissions. These external costs, affecting human health, ecosystems and the economy, were quantified using a damage cost approach (Matthey and Bünger 2020), covering both direct emissions (Scope 1) and indirect emissions associated with energy supply (Scope 2) (WRI 2015). Thus, Chapters 3 and 4 recognised that energy efficiency has multiple impacts, also known as wider benefits or co-benefits (Reuter et al. 2020; Fawcett and Killip 2019; Ürge-Vorsatz et al. 2016), beyond the private financial costs reflected in the cost of energy production and use.

Multiple impacts can be *external*, affecting individuals not directly involved in the energy-related activity. Chapter 4 showed that the external costs of air pollution and greenhouse gas emissions significantly shift the economic balance in favour of energy efficiency. For example, these external costs add 48-55% to the technology and energy costs for gas boilers, and 4-28% for heat pumps, depending on the country and the development of the electricity supply mix. These analyses could be further strengthened by including additional external impacts such as water and noise emissions or land use associated with many renewable energy supply options (Sovacool et al. 2021).49 Ideally, a comprehensive comparison should also take into account indirect emissions from the extraction and production of materials such as building insulation (Scope 3) (Rodrigues and Freire 2021).

Multiple impacts can also be *internal*, affecting only the decision-makers themselves. For example, improvements in insulation, heating, ventilation and cooling systems can enhance the quality of living and working environments, contributing to better health and productivity (Chatterjee and Ürge-Vorsatz 2021). These comfort-related impacts can be monetised using willingness-to-pay methods and integrated into cost-benefit analyses as utility gains (benefits) alongside financial expenses (costs) (Thema et al. 2019).[93] It is important to note, however, that internal impacts are

93 A related conceptual challenge in multiple impacts research is handling direct rebound effects, i.e. situations where efficiency improvements lead to increased consumption of the same service. While many argue these effects reduce the cost-effectiveness of energy efficiency measures (Brown and Wang 2017),

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not always benefits. As discussed in Chapter 5, transaction costs, including information search, negotiation and perceived hassle, can be significant for infrequent demand-side energy efficiency solutions. The magnitude of these costs can be as high as 25-50% of the total investment for measures such as building insulation and retrofits (Lundmark 2022; Adisorn et al. 2021; Kiss 2016).

Overall, rigorous quantification of these intangible costs and benefits is essential to ensure a level playing field between energy efficiency and energy supply options in cost-benefit analyses. Recent research has made significant progress in quantifying multiple impacts in physical terms (Reuter et al. 2020) and monetising them (Suerkemper et al. 2022). However, ongoing research needs to address the context dependency of multiple impacts in terms of the specific technological, demographic and economic circumstances in which these impacts occur (Ürge-Vorsatz et al. 2016). In addition, there is a need for careful analysis of impact overlaps to avoid double counting and the potential overestimation of net impacts, especially in the case of macroeconomic impacts such as increases in gross domestic product or employment, for example using impact pathway mapping approaches (Suerkemper et al. 2022; Ürge-Vorsatz et al. 2016).

Economic versus financial analysis

The studies in Chapters 3 and 4 adopted an economic analysis, also known as societal perspective (Ürge-Vorsatz et al. 2016; Sartori et al. 2015). In line with the principles of cost-benefit analysis, this perspective essentially involves applying a low discount rate, excluding taxes, subsidies and other financial transfers within society, and including significant external costs, thus serving as an EE1st benchmark with a level playing field for energy efficiency and energy supply solutions.

However, three major research needs remain. First, additional financial analysis is needed that takes into account the actual cash flows of implementing decision-makers, such as building owners or network companies. This type of analysis is crucial for policy guidance: if a project is financially viable for the decision-maker but has a net negative impact on society, it indicates that the broader policy framework needs rectification (Grundahl et al. 2016). Beyond policy guidance, dedicated financial analyses for different income groups or regions would provide insights into the distribution of costs and benefits within society, revealing potential equity issues (Atkinson 2015).

Second, multiple impacts, such as the comfort of building occupants depending on the state of building renovation, need to be factored into both the financial and the economic analysis, as discussed above. Finally, thorough financial corrections are needed to ensure that costs and benefits are accurately compared in the economic and financial analyses, respectively (Konstantin and Konstantin 2018a). In particular, as discussed in the economic analyses in Chapters 3 and 4, a

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others propose they offer added utility (Bertoldi et al. 2022; Brugger et al. 2021). For instance, building retrofits might enhance comfort and health, potentially balancing utility and additional costs.

complete exclusion of all relevant transfer payments requires dedicated input data collection and analysis, for example on the exact share of labour and payroll taxes in building renovation costs.

Model resolution

Chapters 3 and 4 used bottom-up energy system models to examine future developments in energy consumption and production. These models provide a high degree of temporal and spatial resolution. For example, the ENERTILE model used in Chapter 3 estimates renewable energy potentials based on a grid with an edge length of 6.5 km and represents system operation at hourly resolution. However, there are certain limitations in terms of technical resolution.

With regard to the modelling of electricity and gas distribution network infrastructures, both quantitative studies assumed linear relationships between energy demand and network costs. This simplified approach does not adequately capture the complexity of Europe's geographically dispersed networks or the complex operational dynamics and constraints, such as pressure and flow constraints in natural gas and hydrogen networks. More accurate analysis would require dedicated network models with significantly improved technical resolution (Guelpa et al. 2019).

Likewise, the modelling overlooked the potential for excess or waste heat in district heating systems. This important energy efficiency solution involves the collection and reuse of heat from various sources, such as industrial processes and data centres. However, methodological challenges include representing the temporal and spatial variability of excess heat supply, distances between heat sources and potential consumers, data availability issues, and technical complexities such as the different temperature levels provided (Manz et al. 2023; Papapetrou et al. 2018).

8.4 Outlook

When the EE1st principle was first introduced, it appeared primarily in brochures and policy briefs. This initial presentation led to certain conceptual ambiguities and practical misconceptions, with lingering concerns that EE1st would be reduced to a short-lived slogan (Teffer 2018; Coalition for Energy Savings 2015). Despite these initial challenges, the uptake and integration of the principle into the EU policy framework has been remarkable. The EU Governance Regulation (European Union 2018d) provided not only a legal definition for the EE1st principle but also introduced preliminary monitoring requirements. While this may not have led to widespread recognition in all Member States (European Commission 2020b), it has certainly raised the visibility of the principle.

The significance of the EE1st principle was further underlined in the recast Energy Efficiency Directive (European Union 2023a). This is evident in the inclusion of an Article 3 dedicated entirely to the EE1st principle, which is placed even before the EU's headline energy savings target. As detailed in Table 2 (Section 1.1), Article 3 places several new provisions on the Member States. These include the assessment of energy efficiency solutions, the promotion of comprehensive cost-benefit analysis methodologies, and enhanced monitoring and regular reporting on EE1st. This prominence within the Energy Efficiency Directive is likely to enhance awareness of the EE1st principle among Member States, as they are tasked with integrating these legal provisions into their national frameworks. Nonetheless, challenges remain. Potential implementation issues are already becoming apparent, highlighting a clear need for further research and analysis.

One issue is the assessment of energy efficiency solutions and supply alternatives. Article 3(1) of the Directive requires Member States to ensure that energy efficiency solutions *"are assessed in planning, policy formulation and major investment decisions"* regarding both *"energy systems"* and *"non-energy sectors"*. Assuming that this provision involves not only a technical feasibility analysis, but more importantly a cost-benefit analysis from a societal perspective – as inferred from Recitals 16 and 17 of the Directive – this work has identified further research needs for effective application.

In particular, a comprehensive social cost-benefit analysis requires the inclusion of all relevant impacts beyond the direct financial expenses to ensure a fair comparison between energy efficiency and energy supply options. As discussed in Section 8.3, this involves accurately valuing welfare by considering all utility gains (benefits) of a project or policy and subtracting all negative impacts (costs). This issue is well recognised in relation to multiple impacts, referred to in the Directive as *"wider benefits"*. While recent work has made significant progress in quantifying multiple impacts in physical units and monetising them (e.g. Suerkemper et al. 2022), more consistent aggregation of interrelated impacts is needed to avoid double counting and potential overestimation of net impacts (Thema et al. 2019). There is also a continued need for empirical data on multiple impacts, taking into account their context dependency in terms of geographical location, economic conditions, social attitudes and other factors (Ürge-Vorsatz et al. 2016).

Additionally, relating to Article 3(5)(b) of the Directive, an important aspect in cost-benefit analysis is the assessment of distributional impacts and energy poverty. While cost-benefit analysis typically aims to represent net welfare, it may not distinguish between those who benefit and those who are disadvantaged (Atkinson and Mourato 2008). Linking the EE1st principle to the topic of energy justice (Baker et al. 2019; Heffron and McCauley 2018), which refers to the fair and equitable distribution of the benefits and burdens in the energy system transition, could provide valuable insights. Taken together, there is a need for comprehensive quantitative evidence to facilitate the assessment of energy efficiency solutions under the provisions of the Energy Efficiency Directive.

Another potential issue is the practical application of the EE1st principle once cost-efficient energy efficiency solutions have been identified through high-level assessments and strategic energy planning. Typically, the ownership arrangements in the energy system lead to economic actors having no private incentive to make investments or use energy according to the social optimum. For example, a power plant company has no inherent interest to reduce production output for the collective benefit, and similarly, consumers may not consider wider external impacts in their purchasing and energy use decisions unless they are given appropriate incentives.

The legal text of the Directive is notably silent on this aspect. It only requires Member States under Article 3(5)(d)(ii) to include in their national energy and climate progress reports *"a list of actions taken to remove any unnecessary regulatory or non-regulatory barriers to the implementation of the energy efficiency first principle and of demand-side solutions [...]"*. This research has provided a robust theoretical framework and actionable guidance on appropriate policy instruments to address what are referred to here as market failures rather than barriers, going beyond the traditional energy efficiency policy triad of standards, public financing and information instruments.

As discussed above, these instruments should particularly address incentive mechanisms for regulated network companies, market design in electricity and district heating systems, pricing of externalities and targeted reduction of transaction costs. These mechanisms are not new, but they have not previously been framed in the context of system-wide energy efficiency and the EE1st principle. While recent legal provisions such as Article 27 of the Directive, which requires national regulatory authorities to apply EE1st in the regulation of gas and electricity infrastructure, provide some grounds for optimism, it remains to be seen how these provisions will be implemented.

Alongside the practical application of the EE1st principle, there is an ongoing need for robust monitoring and ex-post evaluation of their outcomes, using criteria such as cost-effectiveness and multiple impacts (Dubash et al. 2022). In addition, policy mixes need to be better understood, taking into account their comprehensiveness (how well the mix covers all relevant aspects related to EE1st), coherence (how well different policies work together) and consistency (how stable the policies are over time) (Rogge and Reichardt 2016; Rosenow et al. 2017b). Moreover, integrating multi-level governance approaches in EE1st could enhance policy effectiveness through coordinated action across different government levels (Oikonomou and Eichhammer 2021).

In conclusion, the EE1st principle has the potential to facilitate an economically viable, robust and equitable transition to a net-zero emissions energy system in the European Union by 2050. The mandate provided by the recast Energy Efficiency Directive, combined with the current political momentum, creates a window of opportunity for implementing action. It remains to be seen how Member States will interpret, implement and report on the application of the EE1st principle in their forthcoming national energy and climate progress reports. The effectiveness of these implementations will be a key factor in achieving the EU's ambitious energy and climate goals.

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List of abbreviations

ACER	Agency for the Cooperation of Energy Regulators
ADS	Active distribution system
CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CEA	City Energy Analyst
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide-equivalents
CPUC	California Public Utilities Commission
CSP	Concentrated solar power
DER	Distributed energy resource
DH	District heating
DR	Demand response
DSM	Demand-side management
DSO	Distribution system operator
EE	Energy efficiency
EE1st	Energy efficiency first
EED	Energy Efficiency Directive
EEOS	Energy efficiency obligation scheme
EPBD	Energy Performance of Buildings Directive
ESC	Energy system costs
ESCO	Energy service company
ESD	Energy Services Directive
ETS	Emissions trading system
EU	European Union
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic information system
HVAC	Heating, ventilation, and air conditioning
ICT	Information and communications technologies
IEA	International Energy Agency
IRP	Integrated resource planning
LCP	Least-cost planning
LED	Light-emitting diode
MEPS	Minimum energy performance standards

MI	Multiple impact
MS	Member State
NECP	National energy and climate plan
NH_3	Ammonia
NMVOC	Volatile organic compounds without methane
NO_x	Nitrogen oxides
NWS	Non-wires solutions
OPEX	Operating expenses
PBR	Performance-based regulation
PM	Particulate matter
PV	Photovoltaics
RES	Renewable energy sources
RPI	Retail price index
SDG	Sustainable Development Goal
SME	Small and medium-sized enterprise
SO_2	Sulphur dioxide
TEN-E	Trans-European Networks for Energy
TOTEX	Total expenditures
TOU	Time of use
TSO	Transmission system operator
TYNDP	Ten Year Network Development Plan
UK	United Kingdom
U.S.	United States

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List of research articles

This thesis is based on the following peer-reviewed research articles:

Chapter 2 Mandel, Tim; Pató, Zsuzsanna; Broc, Jean-Sébastien; Eichhammer, Wolfgang (2022): Conceptualising the energy efficiency first principle: insights from theory and practice. In *Energy Efficiency* 15 (6), pp. 1–24. DOI: 10.1007/s12053-022-10053-w.

Chapter 3 Mandel, Tim; Kranzl, Lukas; Popovski, Eftim; Sensfuß, Frank; Müller, Andreas; Eichhammer, Wolfgang (2023): Investigating pathways to a net-zero emissions building sector in the European Union: what role for the energy efficiency first principle? In *Energy Efficiency* 16 (4), pp. 1–29. DOI: 10.1007/s12053-023-10100-0.

Chapter 4 Mandel, Tim; Worrell, Ernst; Alibaş, Şirin (2023): Balancing heat saving and supply in local energy planning: insights from 1970–1989 buildings in three European countries. In *Smart Energy* 12, p. 100121. DOI: 10.1016/j.segy.2023.100121.

Chapter 5 Mandel, Tim; Pató, Zsuzsanna: Towards effective implementation of the energy efficiency first principle: a theory-based classification and analysis of policy instruments. Under review in *Energy Research & Social Science*.

Chapter 6 Pató, Zsuzsanna; Mandel, Tim (2022): Energy Efficiency First in the power sector: incentivising consumers and network companies. In *Energy Efficiency* 15 (57), pp. 1–14. DOI: 10.1007/s12053-022-10062-9.
Author's contributions: Investigation, writing of original draft, review and editing, visualisation

Chapter 7 Yu, Songmin; Mandel, Tim; Thomas, Stefan; Brugger, Heike (2022): Applying the Energy Efficiency First principle based on a decision-tree framework. In *Energy Efficiency* 15 (6). DOI: 10.1007/s12053-022-10049-6.
Author's contributions: Conceptualisation, investigation, writing of original draft, review and editing, visualisation

Appendices

A Definitions

Table A1: Existing definitions of the energy efficiency first principle

Reference	Definition
Cowart (2014)	"However, Europe's top-line energy and economic goals can be met more reliably, at lower cost, and with lower environmental burdens if our traditional focus on supply-side solutions is reversed. We need to require a rigorous exploration of less expensive demand-side resources before more expensive supply-side commitments are locked into place. This is the policy called 'Efficiency First'."
Coalition for Energy Savings (2015)	"Energy efficiency first' is the principle of considering the potential for energy efficiency first in all decision-making related to energy. Where energy efficiency improvements are shown to be most cost-effective, considering also their role in driving jobs and economic growth, increasing energy security and reducing climate change, these should be prioritized."
Bayer et al. (2016a)	"Efficiency First is the fundamental principle around which the EU's energy system should be designed. It means considering the potential value of investing in efficiency (including energy savings and demand response) in all decisions about energy system development — be that in homes, offices, industry or mobility. Where efficiency improvements are shown to be most cost-effective or valuable, taking full account of their co-benefits, they should be prioritized over any investment in new power generation, grids or pipelines, and fuel supplies."
Rosenow et al. (2017a)	"Efficiency First is a principle applied to policymaking, planning and investment in the energy sector. Put simply, it prioritizes investments in customer-side efficiency resources (including end-use energy efficiency and demand response) whenever they would cost less, or deliver more value, than investing in energy infrastructure, fuels, and supply alone."
European Union (2018)	"'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions."
Pató et al. (2020a)	"'Efficiency First' gives priority to demand-side resources whenever they are more cost effective from a societal perspective than investments in energy infrastructure in meeting policy objectives. It is a decision principle that is applied systematically at any level to energy-related investment planning and enabled by an 'equal opportunity' policy design."

Table A2: Key definitions developed or adopted in this research

Term	Definition
Building sector	The total final energy consumption in the sectors households and commercial & public services, excluding the industry sector
Cost-effectiveness	The difference between the present value of cash outflows (costs) and cash inflows (benefits) over a specific period, expressed in Euros. It is utilised for assessing the absolute profitability of an investment, essentially evaluating whether benefits outweigh costs.
Cost-efficiency	The ratio of input costs to the level of useful energy output, expressed in Euros per unit of output. It is employed to assess the relative costs of different assets, facilitating the identification of alternatives that offer the greatest output for the least expense.
Demand response	*"the change of electricity load by final customers from their normal or current consumption patterns in response to market signals […], or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market […], whether alone or through aggregation"* (European Union 2019d, Art. 2(20)) Synonyms: demand-side flexibility, system flexibilities
Demand-side flexibility	*"'Demand-side flexibility' means the capability of any active customer to react to external signals and adjust their energy generation and consumption in a dynamic time-dependent way, individually as well as through aggregation. Demand-side flexibility can be provided by smart decentralised energy resources, including demand management, energy storage, and distributed renewable generation"* (smartEn 2022a).
Demand-side resources	A subset of energy efficiency solutions that includes technological and behavioural measures to reduce, shift, or manage consumer energy consumption, covering *end-use efficiency, demand-side flexibility, and energy sufficiency*.
End-use energy efficiency	Technologies or practices to minimise the amount of energy consumed by distinct end-use sectors or devices, whilst maintaining the output level of energy service provided. End-use sectors typically include residential, commercial, industrial, and transportation sectors.
Energy efficiency	*"The ratio of output of performance, service, goods or energy, to input of energy"* (European Union 2012b, Art. 2(3a)).
Energy efficiency first	A decision principle for energy-related planning, investment and policymaking within given system boundaries that prioritises demand-side resources and supply-side energy efficiency whenever these are more cost-efficient in meeting decision objectives than default supply-side resources.
Energy efficiency solutions	Technologies, processes and practices designed to reduce the amount of energy required to provide the same level of energy service, comprising demand-side resources and supply-side energy efficiency.
Energy service	*"the physical benefit, utility or good derived from a combination of energy with energy-efficient technology or with action"* (European Union 2012b, Art. 2(9)).
Energy sufficiency	Changes in behaviours and lifestyles leading to a reduction in final energy consumption. Unlike end-use energy efficiency, which improves the ratio of output to energy input, energy sufficiency involves altering the level of utility or energy service demanded.
Multiple impacts	The economic, social and environmental impacts resulting from implementing *energy efficiency solutions*, which are not direct private benefits or costs involving a financial transaction. Synonyms: multiple benefits, wider benefits, co-benefits, non-energy benefits

Table A2: Continued

Policy instrument	Concrete tools or techniques of governance that address policy problems. Synonyms: policies
Supply-side energy efficiency	Technologies and practices aimed at enhancing the energy conversion efficiency in the production, transmission, distribution, and storage stages of energy. It aims to increase the ratio of final energy output to the input of primary or secondary energy.
Supply-side resources	Technologies that generate, transmit, distribute and store energy to meet customers' energy demand, including utility-scale generation, networks and pipelines, and utility-scale storage.

B Supplementary material for Chapter 4

B.1 Building renovation

Table B1: Internal loads by building use type

Parameter	Unit	Building use type							
		Apartment	**Grocery**	**Hotel**	**Library**	**Office**	**Restaurant**	**Retail**	**School**
Occupancy density	m^2/p	30.0	8.0	15.0	5.0	14.0	2.0	8.0	3.0
Peak sensible heat load of occupants	W/p	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Peak spec electrical load | Appliances	W/m^2	8.0	2.0	8.0	2.0	7.0	2.0	2.0	4.0
Peak specific electrical load | Lighting	W/m^2	2.7	21.3	2.7	6.9	15.9	6.9	33.3	14.0
Peak specific electrical load | Cooling rooms	W/m^2	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
Peak specific electrical load | Server rooms	W/m^2	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Peak specific daily fresh water consumption	$l/d/p$	140.0	30.0	160.0	0.0	60.0	45.0	30.0	30.0
Peak specific daily hot water consumption	$l/d/p$	35.0	2.0	40.0	0.0	3.0	15.0	2.0	2.0

Source: ETH Zurich (2022) | *p* person; *l* litre; *d* day

Table B2: Boundary conditions for calculation of building energy need for heating in the CEA model

Category	Parameter	Setting
Building materials and envelope	Construction type	Internal heat capacity per unit of air conditioned area C_m=16500 [J/Km^2]
	Airtightness	Air exchanges per hour at 50 *Pa* pressure *n*_50=3 [1/*h*]
	Solar shading	Shading coefficient rf_{sh}= 0.08
	Glazed area to façade area ratio	0.2 (North), 0.15 (East), 0.2 (South), 0.15 (West)
Space heating	Set-point temperature	T_{set}=20°C
Water heating	Nominal supply temperature	High temperature water with T_w=60°C
Ventilation	Ventilation type	Window ventilation with night flush

Source: ETH Zurich (2022); TABULA/EPISCOPE (2017)

Table B3: Linear function parameters for specific investment costs of building renovation measures in Germany

Component	Renovation type [a]	Cost function parameters in form [ ]			
		Variable [x]	Constant [ ]	Additional cost [ ]	Other costs [b]
Roof	Refurbishment	Insulation thickness [*cm*]	118.00 [EUR/m²]	-	16.7%
	Retrofit		174.00 [EUR/m²]	0.70 [EUR/(cm·m²)]	
Floor	Refurbishment		0.00 [EUR/m²]	-	
	Retrofit		29.00 [EUR/m²]	1.14 [EUR/(cm·m²)]	
Wall	Refurbishment		37.00 [EUR/m²]	-	
	Retrofit		96.00 [EUR/m²]	2.67 [EUR/(cm·m²)]	
Window	Refurbishment	U-value [W/m^2K]	201.00 [EUR/m²]	-	22.5%
	Retrofit		538.28 [EUR/m²]	-111.54 [EUR/(W/m²K)·m²)]	

Source: Hummel et al. (2021); Hinz (2015) | a Refurbishment: maintenance of building aesthetics/safety, without addressing energy performance; retrofit: improvement of building energy performance, see Footnote 59 | b Share of miscellaneous taxes and charges not related to materials, labour or professional fees

B.2 Decentralised heat supply

Table B4: Technical parameters for decentralised heat supply technologies

Technology	Linear function expressed as f (x) = n+m.x, where x is the nominal thermal capacity (kW_{th})									
	Efficiency [-]				Lifetime [yr]				Aux. electricity [kWh_{el}/yr]	
	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]	[m]	[n]
Air-water heat pump	a				0.104	17.3	25	16	b	
Biomass boiler	0.0001	0.83	0.92	0.76	0.0066	18.6	25	15	4.8	371.1
District heating substation	0.0001	0.97	1.00	0.95	0.0080	23.5	30	20	1.6	76.9
Electric heater	0.0000	1.00	1.00	1.00	0.0307	23.1	30	25	0.0	0.0
Gas boiler	0.0001	0.97	1.03	0.95	0.0160	30	40	18	1.6	92.1
Ground-water heat pump	a				0.0126	23.6	40	18	b	
Oil boiler	0.0000	0.93	0.95	0.92	0.0004	19.9	25	15	3.3	60.5

Source: DEA (2021c) | [a] Endogenous estimation of seasonal performance factor *SPF*, see Equation 5 | [b] Included in

Table B5:		**Economic parameters for decentralised heat supply technologies**			
Technology	**Country**	**Linear function expressed as f(x) = n + m • x, where is the nominal thermal capacity (KW_{th})**			
		Investment [EUR_{2020}]		**O&M fix [EUR2020/Yr]**	
		[m]	[n]	[m]	[n]
Air-water heat pump	BG	354	6,264	3.8	148
	DE	420	8,529	6.6	253
	FI	453	8,985	6.7	258
Biomass boiler	BG	122	6,776	1.0	193
	DE	148	8,322	1.7	329
	FI	159	8,925	1.8	335
District heating substation	BG	22	1,798	0.1	19
	DE	28	2,769	0.1	32
	FI	30	2,861	0.1	33
Electric heater *	BG	155	-	0.1	14
	DE	208	-	0.1	24
	FI	220	-	0.1	25
Gas boiler	BG	46	1,441	0.5	82
	DE	55	2,059	0.9	140
	FI	60	2,152	0.9	142
Ground-water heat pump	BG	325	8,957	2.3	116
	DE	508	14,763	3.9	198
	FI	524	15,105	4.0	202
Oil boiler	BG	49	2,737	1.0	63
	DE	59	3,506	1.7	108
	FI	64	3,732	1.7	110

Source: DEA (2021c), cost adjustments as described in Section 4.2.3 | * Backup heater for heat pump systems without base investment

Table B6: **Seasonal performance factor SPF of decentralised heat pump systems: space heating alone (and combined with water heating)**

Type	Country	Renovation package		
		EXISTING	**STANDARD**	**ADVANCED**
Air-water heat pump	BG	2.28 (2.61)	2.40 (2.92)	2.51 (3.03)
	DE	2.34 (2.70)	2.58 (3.14)	2.76 (3.34)
	FI	2.01 (2.45)	2.12 (2.67)	2.18 (2.81)
Ground-water heat pump	BG	3.27 (3.50)	3.47 (3.66)	3.79 (3.88)
	DE	3.01 (3.31)	3.28 (3.58)	3.67 (3.83)
	FI	2.81 (3.19)	2.94 (3.30)	3.19 (3.51)

SPF for bivalent heat pump system with backup electric heater, shown as the mean energy-weighted average for 125 buildings per country and renovation package | See Equation 5

B.3 Centralised heat supply

Table B7: **Technical parameters for centralised heat supply technologies**

Technology	Linear function expressed as f(x) = n + m • x, where is the nominal thermal capacity (MW_{th})							
	Efficiency [-]				Lifetime [Yr]			
	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]
Air source heat pump	*				1.643	7.5	40	15
Electrode boiler	0.0003	0.98	0.99	0.98	0.000	20.0	20	20
Gas boiler	0.0126	0.94	1.05	0.93	0.000	25.0	25	25
Geothermal heat pump	0.0854	3.81	5.45	4.17	0.339	22.7	30	25
Straw boiler	0.1801	-0.08	1.04	0.88	11.746	-42.8	35	20
Wood chip boiler	0.1687	-0.01	1.15	0.89	6.688	-15.8	35	20
Wood pellet boiler	0.1825	-0.09	1.02	0.90	16.140	-68.1	35	20

Source: DEA (2021b) | * Endogenous estimation of seasonal coefficient of performance, see Section 4.2.3 and Equation 4

Table B8: **Economic parameters for centralised heat supply technologies**

Technology	Country	Linear function expressed as f(x) = n + m • x, where is the nominal thermal capacity (MW_{th})											
		Investment [$keur_{2020}/MW_{th}$]				O&M fix $keur_{2020}/MW_{th}$ [yr]				O&M var [EUR_{2020}/MWh_{th}]			
		[m]	[n]		[min]	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]
Air source heat pump	BG	27.7	354	913	490	0.07	0.26	1.53	0.51	0.04	0.51	1.38	0.77
	DE	27.7	465	1,049	586	0.11	0.44	2.66	0.89	0.07	0.89	2.39	1.33
	FI	31.0	492	1,139	632	0.12	0.45	2.71	0.90	0.07	0.90	2.43	1.35
Electrode boiler	BG	4.2	22	126	17	0.00	0.52	0.56	0.51	0.00	0.22	0.26	0.20
	DE	5.2	23	151	18	0.00	0.91	0.98	0.89	0.00	0.39	0.44	0.36
	FI	5.6	26	163	20	0.00	0.92	0.99	0.90	0.00	0.39	0.45	0.36
Gas boiler	BG	12.9	1	145	23	0.08	0.50	1.28	0.51	0.08	0.17	1.02	0.26
	DE	20.1	-3	222	31	0.14	0.88	2.22	0.89	0.14	0.30	1.78	0.44
	FI	20.7	-3	230	33	0.14	0.89	2.26	0.90	0.14	0.30	1.80	0.45
Geothermal heat pump	BG	116.5	639	2,909	1,164	0.00	11.50	11.50	11.50	0.03	2.42	2.95	2.52
	DE	145.0	761	3,588	1,417	0.00	19.98	19.98	19.98	0.05	4.21	5.13	4.38
	FI	155.1	820	3,845	1,522	0.00	20.30	20.30	20.30	0.05	4.27	5.21	4.45
Straw boiler	BG	137.2	-352	559	382	7.05	-15.51	30.47	22.19	0.17	-0.64	0.45	0.25
	DE	224.4	-522	960	678	12.25	-26.94	52.93	38.55	0.29	-1.12	0.78	0.44
	FI	229.8	-543	977	686	12.44	-27.36	53.77	39.15	0.30	-1.14	0.79	0.44
Wood chip boiler	BG	56.9	36	461	341	2.49	0.91	19.27	14.21	0.21	-0.72	0.88	0.42
	DE	89.2	57	723	534	4.32	1.58	33.48	24.69	0.37	-1.26	1.52	0.73
	FI	91.9	59	745	550	4.39	1.60	34.01	25.08	0.38	-1.28	1.55	0.75
Wood pellet boiler	BG	146.9	-436	495	366	5.98	-18.29	19.37	14.31	0.17	-0.70	0.35	0.21
	DE	222.3	-659	748	553	10.39	-31.78	33.66	24.87	0.29	-1.21	0.61	0.37
	FI	230.3	-683	775	573	10.55	-32.28	34.19	25.26	0.29	-1.23	0.62	0.37

Source: DEA (2021b), cost adjustments as described in Section 4.2.3

Table B9: Seasonal coefficient of performance for centralised air source heat pumps

Technology	Country	Renovation package		
		EXISTING	STANDARD	ADVANCED
Air source heat pump	BG	3.76	4.20	4.47
	DE	3.80	4.25	4.53
	FI	3.65	4.06	4.31

COP for 85% share in annual heat demand, excluding efficiency of peak boiler, see Equation 4

Table B10: Techno-economic data for district heating network pipes

Variable	Pipe code	Internal diameter [m]	Country		
			BG	DE	FI
Specific investment costs [EUR_{2020}/m]	DN20	0.022	294	556	572
	DN25	0.029	298	563	579
	DN32	0.037	318	601	618
	DN40	0.043	329	621	639
	DN50	0.055	372	704	724
	DN65	0.070	404	764	786
	DN80	0.083	463	876	901
	DN100	0.107	572	1,081	1,112
	DN125	0.133	687	1,299	1,336
	DN200	0.210	986	1,864	1,918
	DN250	0.263	1,320	2,496	2,568
	DN300	0.313	1,654	3,129	3,219
	DN350	0.344	1,989	3,762	3,870
	DN400	0.394	2,323	4,393	4,519
	DN450	0.445	2,658	5,026	5,170
Lifetime [Yr]	-	-	40	40	40
Variable O&M[EUR2020/MWh_{th}]	-	-	0.62	2.13	2.24

Source: DEA (2021a); ETH Zurich (2022), with cost adjustments as described in Section 4.2.3 | O&M operation and maintenance

B.4 Energy costs

Table B11: Average energy carrier mix for gaseous and liquid fuels in the EU

Energy carrier type	Supply scenario	Energy carrier	Share 2020	Share 2050
Gas	BAU	Biomethane	1.4%	30.0%
		Hydrogen	0.0%	2.0%
		Natural gas	98.6%	68.0%
		Synthetic methane	0.0%	0.0%
	NETZERO	Biomethane	1.4%	77.0%
		Hydrogen	0.0%	10.0%
		Natural gas	98.6%	3.0%
		Synthetic methane	0.0%	10.0%
Oil	BAU	Biooil	0.5%	30.0%
		Oil	99.5%	70.0%
		Synthetic fuel	0.0%	0.0%
	NETZERO	Biooil	0.5%	85.0%
		Oil	99.5%	5.0%
		Synthetic fuel	0.0%	10.0%

Source: 2020 values based on EU average fuel mix Eurostat (2022b); 2050 values based on Hummel et al. (2023)

Table B12: Energy carrier prices by country, supply scenario and price pathway

Energy carrier type	Energy carrier	Country	Price ( ) by supply scenario and price pathway in year 2020 (2050)				Source
			BAU		NETZERO		
			HIGH	LOW	HIGH	LOW	
Biomass	Straw	BG	21.55 (26.91)	21.55 (23.18)	21.55 (29.40)	21.55 (26.91)	(Duić et al. 2017)
		DE	26.12 (32.61)	26.12 (31.16)	26.12 (34.80)	26.12 (32.61)	
		FI	27.66 (34.54)	27.66 (32.89)	27.66 (37.02)	27.66 (34.54)	
	Wood chips	BG	23.88 (29.82)	23.88 (25.70)	23.88 (32.59)	23.88 (29.82)	(Duić et al. 2017)
		DE	28.93 (36.14)	28.93 (34.52)	28.93 (38.56)	28.93 (36.14)	
		FI	30.65 (38.27)	30.65 (36.45)	30.65 (41.03)	30.65 (38.27)	
	Wood pellets	BG	31.50 (34.92)	31.50 (30.07)	31.50 (38.15)	31.50 (34.92)	(Duić et al. 2017)
		DE	38.17 (42.31)	38.17 (40.42)	38.17 (45.14)	38.17 (42.31)	
		FI	40.43 (44.81)	40.43 (42.66)	40.43 (48.02)	40.43 (44.81)	
Electricity	Electricity	BG	64.14 (67.82)	64.14 (64.57)	64.14 (104.80)	64.14 (83.39)	(Eurostat 2022i; European Commission 2018a; Capros et al. 2021)
		DE	57.41 (60.70)	57.41 (57.79)	57.41 (93.68)	57.41 (74.58)	
		FI	49.93 (52.53)	49.93 (50.24)	49.93 (78.62)	49.93 (63.52)	

Table B12: Continued

Gas	Biome-thane	BG	75.90 (90.41)	75.90 (77.87)	75.90 (98.76)	75.90 (90.41)	(van Nuffel et al. 2020; Duić et al. 2017)
		DE	71.40 (85.06)	71.40 (81.26)	71.40 (90.75)	71.40 (85.06)	
		FI	56.40 (67.18)	56.40 (63.97)	56.40 (72.01)	56.40 (67.18)	
	Hydro-gen	BG	170.72 (117.40)	170.72 (82.60)	170.72 (82.60)	170.72 (63.80)	(Perner et al. 2018)
		DE	171.11 (117.66)	171.11 (82.78)	171.11 (82.78)	171.11 (63.95)	
		FI	172.57 (118.67)	172.57 (83.49)	172.57 (83.49)	172.57 (64.49)	
	Natural gas	BG	16.70 (16.17)	16.70 (11.07)	16.70 (11.07)	16.70 (6.68)	(Eurostat 2022l; IEA 2022)
		DE	25.20 (24.40)	25.20 (16.71)	25.20 (16.71)	25.20 (10.08)	
		FI	23.10 (22.37)	23.10 (15.32)	23.10 (15.32)	23.10 (9.24)	
	Synthetic methane	BG	208.82 (146.97)	208.82 (109.02)	208.82 (109.02)	208.82 (86.85)	(Perner et al. 2018)
		DE	209.29 (147.30)	209.29 (109.27)	209.29 (109.27)	209.29 (87.04)	
		FI	211.08 (148.56)	211.08 (110.20)	211.08 (110.20)	211.08 (87.79)	
Oil	Biooil	BG	94.88 (113.01)	94.88 (97.33)	94.88 (123.45)	94.88 (113.01)	(Hummel et al. 2023)
		DE	89.25 (106.33)	89.25 (101.58)	89.25 (113.43)	89.25 (106.33)	
		FI	70.50 (83.98)	70.50 (79.96)	70.50 (90.01)	70.50 (83.98)	
	Fuel oil	BG	74.62 (102.74)	74.62 (64.89)	74.62 (64.89)	74.62 (25.96)	(Rademaekers et al. 2020; IEA 2022)
		DE	54.09 (74.47)	54.09 (47.03)	54.09 (47.03)	54.09 (18.81)	
		FI	76.16 (104.85)	76.16 (66.22)	76.16 (66.22)	76.16 (26.49)	
	Synthetic fuel	BG	220.26 (156.59)	220.26 (116.61)	220.26 (116.61)	220.26 (95.07)	(Perner et al. 2018)
		DE	220.76 (156.94)	220.76 (116.87)	220.76 (116.87)	220.76 (95.28)	
		FI	222.64 (158.28)	222.64 (117.87)	222.64 (117.87)	222.64 (96.09)	

Prices excluding taxes/fees/levies and external costs

Table B13:	Network and fuel handling charges by energy carrier type		
Energy carrier type	**Country code**	**EUR_{2020}/MWh**	**Source**
Biomass	BG	2.75	(Duić et al. 2017)
	DE	3.68	
	FI	3.94	
Electricity	BG	25.90	(Eurostat 2022i)
	DE	54.90	
	FI	37.80	
Gas	BG	13.50	(Eurostat 2022l)
	DE	13.20	
	FI	20.10	
Oil	BG	3.44	(Duić et al. 2017)
	DE	7.12	
	FI	7.61	

B.5 Emissions

Table B14:	Emission factors (g/kWh_{th}) by fuel and pollutant				
Pollutant type	**Greenhouse gas**	**Air pollution**			
Fuel | Pollutant	**CO_2-eq**	**NMVOC**	**NOX**	**PM**	**SO_2**
Biomethane	25.471	0.013	0.208	0.001	0.001
Biooil	0.930	0.010	1.017	0.024	0.001
Hydrogen *	-	-	-	-	-
Municipal waste	1.449	0.001	0.176	0.001	0.012
Natural gas	201.909	0.002	0.074	-	0.001
Oil	267.062	0.005	0.150	0.003	0.008
Straw	0.341	0.003	0.259	0.083	0.016
Synthetic fuel *	-	0.010	1.017	0.024	0.001
Synthetic methane *	-	0.013	0.208	0.001	0.001
Wood chips	0.431	0.009	0.360	0.073	0.016
Wood pellets	0.390	0.006	0.310	0.067	0.018

Source: Lauf et al. (2023); EEA (2019) | * Assumption

Table B15: Emission factors for grid-based electricity ( ) by country, scenario, year and pollutant

Pollutant type			**Greenhouse gas**	**Air pollution**					
Country	**Supply scenario**	**Year**	**CO_2-eq**	**NH_3**	**NMVOC**	**NOX**	**PM_{10}**	**$PM2_{.5}$**	**SO_2**
BG	BAU	2020	362.0	0.000	0.019	0.346	0.006	0.005	0.767
		2050	43.8	0.000	0.002	0.042	0.001	0.001	0.093
	NETZERO	2020	362.0	0.000	0.019	0.346	0.006	0.005	0.767
		2050	18.1	0.000	0.001	0.017	0.000	0.000	0.038
FI	BAU	2020	64.0	0.000	0.012	0.136	0.007	0.002	0.054
		2050	19.5	0.000	0.004	0.041	0.002	0.001	0.016
	NETZERO	2020	64.0	0.000	0.012	0.136	0.007	0.002	0.054
		2050	3.2	0.000	0.001	0.007	0.000	0.000	0.003
DE	BAU	2020	314.0	0.001	0.011	0.319	0.007	0.006	0.143
		2050	71.6	0.000	0.003	0.073	0.002	0.001	0.033
	NETZERO	2020	314.0	0.001	0.011	0.319	0.007	0.006	0.143
		2050	15.7	0.000	0.001	0.016	0.000	0.000	0.007

Source: EEA (2023); Capros et al. (2021); Eurostat (2023a), see Section 4.2.3

Table B16: Value factors by receptor, emission source, and air pollutant

Receptor	Emission source	Value factor by pollutant ($EUR_{2020/t}$)						
		NH3	NMVOC	NO_X	PM	PM_{10}	$PM_{2.5}$	SO_2
Health damage	Energy supply	13,131 to 25,000	683 to 1,300	6,093 to 11,600	262.6 to 500.0	12,238 to 23,300	17,386 to 33,100	7,038 to 13,400
	Buildings	13,026 to 24,800	683 to 1,300	8,719 to 16,600	998 to 1,900	43,018 to 81,900	61,087 to 116,300	8,141 to 15,500
Biodiversity losses	-	6,298 to 11,990	-	1,444 to 2,750	-	-	--	556.8 to 1060.0
Crop damage	-	-190.0 to -99.8	525.3 to 1000.0	446.5 to 850.0	-	-	-	170.0 to -89.3
Material damage	-	-	-	73.5 to 140.0	-	-	-	336.2 to 640.0

Source: van Essen et al. (2019); Matthey and Bünger (2020) | Ranges across countries (BG, DE, FI)

Table B17: Social cost of carbon by discount rate

Receptor	Emission source	Discount rate	EUR_{2020}/tCO_2eq	USD_{2020}/tCO_2eq
Climate damage		3.0%	72	80
		2.5%	106	118
		2.0%	167	185
		1.5%	277	308

Source: Rennert et al. (2022)

C Supplementary material for Chapter 7

In this section, we provide further explanation for the common actions of the decision-makers that are listed in Table 32, including a short introduction and the most important questions to consider when applying the EE1st principle for each action. As shown in Table 32, four market actors are merged into one group, including energy suppliers, network operators, consumers, and DR service providers, because several actions are shared among them.

C.1 Policymakers

(P1) Define policy targets
For a specific application case, the policymaker should define the policy targets following the EE1st principle and consider the interactions among them. Then, the policymakers should provide the targets to the regulatory authorities and other relevant decision-makers for further steps.

For this process, the following questions are involved: (a) What policy targets are usually applied under the specific case? (b) How can these targets be measured? (c) What are the potential trade-offs among these targets?

(P2) Define regulatory framework
Based on the targets defined in the first step, the policymaker should also define the regulatory framework to support the application of EFF principle, i.e., to provide incentives to procure demand-side resources by integrating necessary policy instruments. Specifically, incentives need to be provided for the system operator in the vertical integrated systems, or energy suppliers and energy service providers in the market-based systems, to promote the use of demand-side resources.

Relevant questions include the following: (a) What policy instruments can be applied to achieve the policy targets listed in the first step? Are there interactions among these policy instruments? (b) What are the existing experiences with these policy instruments? What are the barriers for implementation? (c) For the specific case under consideration, what are the advantages and disadvantages of the policy instruments?

C.2 Regulators

Following the policy targets and regulatory framework defined by the policymakers, the regulators take local conditions and constraints into account and interact with relevant decision-makers at a micro-level, by checking their business goals and implementation plan, and by defining more detailed cost-benefit-analysis (CBA) method and necessary rules. Four relevant actions of regulators are identified as follows.

(R1) Define market access rules for efficiency or DR solutions

Under the current regulatory framework, some energy efficiency or DR improvement solutions may not be provided by the existing decision-makers. To implement the EE1st principle, new players who provide efficiency or DR solutions should be introduced to the relevant markets by defining access rules for them. For example, in the case of a district heating system, additional to the system operator new players such as potential waste heat providers have to be able to access the market. For the DR solutions, it could be the DR service provider (e.g., an aggregator), who improves the flexibility of demand-side, reduces the peak demand, and further reduces the investment for the supply-side or network in the electricity system.

For such cases, the regulatory authority should provide the rules that make this possible. Relevant questions include the following: (a) Concerning the case under consideration, are there any other players that can enhance the energy efficiency or DR flexibility of consumers, or provide energy from waste collection, etc.? (b) If there are these kind of players, what are the current barriers for them to implement a more energy efficiency solution or access the market? (c) How can the potential contribution from these decision-makers be evaluated, and are there any costs for letting them in the system? (d) How should the responsibilities be shared for the achievement of the main objectives of the project? (e) What are the existing experiences of the application of energy efficiency solution in a specific area?

(R2) Compliance check

Based on the policy targets provided by the policymaker, the regulatory authority should check the business/project goals proposed by the market entities. The aim of this process is to ensure that the business/project goals do not conflict with the policy targets defined by the policymakers and the market access rules, and besides, to ensure that there is space for the application of energy efficiency solutions on the demand-side.

This should be an iterative process at an early stage of the decision-making process that should lead to consideration of increasing energy efficiency in the business goals and ensuring that energy-efficient solutions could be eligible for a given initiative. In particular, potential demand-side options, should be specifically considered if they could contribute to achieving the business goals.
For this process, the regulatory authorities need to answer the following: (a) Are there potential conflicts between the business/project goals and the targets defined by the policymakers? (b) Given the scope and goals of the business/project, is it possible to incorporate efficiency or DR solutions?

(R3) Define CBA method

The CBA method for applying the EE1st principle should be defined from a societal perspective. Apart from the energy savings, it should also look at wider benefits which may not be easy to quantify or monetize, and the benefit should be evaluated from a societal cost and benefit perspective, beyond the market entity perspective.

Relevant questions include the following: (a) What are the available investment options for the market entities on the supply-side and the network for the specific initiative? (b) What are the options on the demand-side that can improve the energy efficiency or DR flexibility, and reduce the investment on the supply-side or the network? (c) For these options, how can their costs and benefits be evaluated? (d) How can the contribution of cost-effective investments to the policy targets be assessed?

For some cases in non-energy areas (e.g., construction of a data centre) the evaluation of investment options should also consider their impact on the energy consumption, and see if the more energy-efficient options can be integrated. Relevant questions include the following: (a) Given the policy targets or business goals, what are the available options, especially the energy efficiency options? What are the impacts on energy consumption of various investment options? (b) How can the cost and benefit of these options be evaluated from the societal perspective? (c) If and where can data be obtained and compared?

(R4) Define policy and regulation details

Based on the policy targets and regulatory framework defined by the policymaker, the regulators should take local conditions and constraints into account to develop the CBA method from a societal perspective, and then define the policy and regulation details to motivate the behaviour of market actors and to monitor the market in the implementation phase.

(R5) Implementation plan check

Following the CBA method provided in the earlier step, for system planning and investment cases, the regulatory authorities should check the plans proposed by the decision-makers following the EE1st principle. They should evaluate if full advantage of the available energy efficiency options is taken, and the investment on the supply-side and networks are necessary to achieve the overall target. This is an iterative process and will lead to improvement until the EE1st principle is fully applied in the planning. Relevant questions are the same as for the action "(R3) Define the CBA method".

(R6) Market monitor

Based on the policy and regulation details defined previously, the regulator should monitor the market and deal with the violations.

C.3 Market actors

The "Market actors" here include energy suppliers, network operators, consumers, and DR service providers. Additionally, in some cases, it also includes public entities or state agencies, which directly participate in the system operation and are responsible for implementing the EE or DR programs, for example, as DR service providers in the power system. At last, under specific cases, some decision-makers from non-energy sectors may also be included, for example, the industrial companies that provide waste heat to the district heating system. Here we put all these decision-makers together because they share several similar actions. The union set of their actions is introduced as follows.

(M1) Define business/project goal

Under a specific EE1st principle case, some market actors need to define their business or project goals based on the policy targets defined by the policymaker. For different market actors in different cases, the emphasis of the goal can be different. For the generation companies in the electricity market, the goal is more about maximizing the profit, while for the operator of a district heating system, the goal may be more about the improvement of energy efficiency, and the cost and benefit is evaluated more from a societal perspective.

In system planning and investment cases, the goals defined by the market actors will be checked by the regulatory authorities, to see if they are consistent with the policy targets, and if necessary efficiency options can be included in the following stages. For the action "define business/project goal", relevant questions include the following: (a) What are the implications of targets defined by the policymakers on the business or project? Are there any conflicts? (b) Is it possible to incorporate efficiency or DR options within the business or project?

(M2) Define CBA method

When applying the EE1st principle in the market based systems, the societal CBA method will be specified by the regulators. The market entities will also define their own CBA method based on the given regulatory framework and policy instruments, to systematically assess the investment options. The impact of policy instruments will be taken into consideration, and the investment on the supply-side or network may be reduced.

Relevant questions include the following: (a) How will the regulatory framework and policy instruments influence the cost and benefit of the business or project? How will they influence the decisions of other relevant decision-makers? How will they influence the final equilibrium among all decision-makers? (b) Are there any demand-side options that can be applied to reduce the investment on the supply-side or network? How are they influenced by the policy instruments?

(M3) Information collection

For further steps, the market actors need to collect the necessary information. For example, the operator of a district heating system may collect information about the population or number of the dwellings in this area, as well as their location, to forecast the demand of district heating. Additionally, he may also collect the information about potential heat providers from other sectors, e.g., industrial companies or data centres. At last, the system operator also needs to collect information about the cost of heat sources and pipelines, thermal insulation of buildings, social benefit of the district heating system (energy saving, pollution reduction, etc.), to systematically evaluate the cost and benefit of the system and to fully apply the EE1st principle.

Relevant questions of this action include the following: (a) What are the factors that influence the demand of the business or project under discussion? (b) What is the cost of potential investment options in the supply capacity or network? (c) Are there any other decision-makers that can be involved for a higher overall efficiency? (d) How can we collect such information with enough details and reliability?

(M4) Energy service demand forecast

To apply the EE1st principle in the energy field, all the relevant market actors, especially the ones active on the supply-side and network operation, will forecast the energy service demand. Additionally, for the vertically integrated systems, the task of forecasting could also be upon the regulatory authority. Based on this forecast of energy service, in the following steps they will evaluate the available options based on the CBA method defined before. The forecast should also look at possible further reductions in energy demand levels that could affect the viability and cost-benefit assessment of options.

Relevant aspects to consider include the following: (a) What is the energy service demand for the business or project under discussion? What is the amount of energy service? What does its load-profile look like? (b) Will there be demand reduction led by efficiency improvements or DR options in the future? What is the implication on the system planning or investment decision today?

(M5) Identify other cost and risk

To evaluate the costs and benefits of system planning, investment decision, or a policy design, one also needs to identify other potential costs and risks and consider them. For example, when designing the contract for the consumers, the operator for a district heating system needs to consider the variation of fuel price, environmental cost, etc.

Relevant questions include the following: (a) Are there any other factors that will influence the cost benefit analysis of the business or project under discussion? For example, the variation of fuel price, environment cost, etc. (b) What are the influencing sensitivities of these factors?

(M6) Systematic assessment

Based on all the information collected, including costs of various available options, the forecast of energy service demand, and identified uncertainties and risks, the decision-makers will systematically assess all the available options based on the CBA method. Following the EE1st principle, the demand-side options are included and all the options are treated equally. Relevant questions at this phase include the following: (a) What are the systematic costs and benefits of the system plan or investment decision? (b) What is the final investment decision on supply-side capacity, networks, and demand-side options?

(M7) Propose the implementation plan

In the system planning and investment cases, based on the systematic assessment of all options, the market actors will propose their plans to the regulators for a check. The plan should indicate how energy efficiency and DR options are assessed, whether they have been discarded or selected and under what conditions they could be implemented. This is an iterative process and will lead to improvement until the plan is justified. This action does not indicate other specific questions.

(M8) Implementation

At last, after all the actions above and receiving approval from the regulatory authorities (if necessary), the market actors will implement their plans at last, including adopting energy-efficiency technologies, providing the designed service, making investment decisions, etc. This action does not indicate other specific questions.

Wetenschappelijke samenvatting

Achtergrond

Energie-efficiëntie verwijst naar de verhouding tussen nuttige output en fysieke energie-input. Aan de vraagzijde van het energiesysteem betekent het verbeteren van de energie-efficiëntie het verminderen van de hoeveelheid energie die nodig is door handelswijzen zoals het ontwerpen van energie-efficiënte gebouwen die het comfort binnenshuis behouden en tegelijkertijd het energieverbruikdfsd minimaliseren, of het gebruik van warmtepompen als een efficiënter alternatief voor traditionele verwarmingssystemen. Aan de aanbodzijde omvat dit het opwekken en transporteren van finale energie met minder primaire of secundaire energie-input, zoals het gebruik van efficiënte systemen voor stadsverwarming en -koeling, of het verminderen van lijnverliezen in transmissie en distributie. Het omvat ook flexibiliteit aan de vraagzijde om het energiegebruik aan te passen in reactie op de leveringsvoorwaarden, waardoor de algehele systeemefficiëntie wordt verbeterd.

Verbetering van de energie-efficiëntie in de hele energiewaardeketen wordt algemeen erkend als een belangrijke strategie om de kosten van het energiesysteem te verlagen en klimaatverandering aan te pakken. Het wordt ook steeds meer erkend als een manier om de afhankelijkheid van energie-import te verminderen, banen te creëren, de luchtkwaliteit te verbeteren en andere zogenaamde 'multiple impacts' of 'co-benefits' op te leveren. In reactie hierop richt de Europese Unie (EU) haar energie- en klimaatbeleid al lange tijd op het verhogen van de energie-efficiëntie. De Green Deal-strategie van de Europese Commissie, die in 2019 is geïntroduceerd, bevestigt opnieuw de noodzaak van energie-efficiëntie om de langetermijndoelstelling van de EU te halen, namelijk een broeikasgasemissieniveau van netto nul in 2050, zoals vastgelegd in de Europese klimaatverordening. Beleid en maatregelen in de EU en haar lidstaten omvatten regelgeving die energie-efficiëntieverbeteringen verplicht stelt, stimulansen voor energie-efficiënte technologieën en programma's om gedragsveranderingen in energiegebruik aan te moedigen.

Uit empirische gegevens en academische discussies over de zogenaamde 'energy efficiency gap' blijkt echter dat de EU niet genoeg investeert in energie-efficiëntie in vergelijking met nieuwe opwekkings-, netwerk- en opslaginfrastructuur. Om deze onevenwichtigheid aan te pakken, is onlangs het energie-efficiëntie-eerstbeginsel (EE1st-beginsel) geïntroduceerd in het EU-beleidsdebat. Dit beginsel is gebaseerd op het idee dat energie-efficiëntie vaak de meest duurzame en kosteneffectieve manier is om te voldoen aan de behoeften van de consument op het gebied van energiediensten (bijv. warmtecomfort) en bredere maatschappelijke doelstellingen (bijv. decarbonisatie). Waar dit het geval is, suggereert het beginsel dat oplossingen voor energie-efficiëntie systematisch voorrang moeten krijgen op de ontwikkeling van een relatief inefficiënte infrastructuur voor energievoorziening. Als zodanig zou het EE1st-beginsel een effectieve en betaalbare decarbonisatie van het energiesysteem in de EU kunnen vergemakkelijken.

In een opmerkelijk korte tijd is het EE1st-beginsel een belangrijk element geworden van het energie- en klimaatbeleid van de EU. Begonnen halverwege de jaren 2010 met brochures van niet-gouvernementele organisaties, is het geleidelijk geïntegreerd in EU-strategieën en -wetgeving. Een mogelijke mijlpaal was de goedkeuring van de herschikte richtlijn inzake energie-efficiëntie eind 2023, die de beoordeling van energie-efficiëntieoplossingen in plannings-, beleids- en investeringsbeslissingen, het toezicht op de toepassing van het EE1st-beginsel en de rapportage over EE1st in het kader van de EU-Governanceverordening vereist.

Onderzoeksvragen

Ondanks de snelle opkomst in het politieke debat in de EU is het EE1st-beginsel nog niet uitgebreid onderbouwd en ondersteund door academisch onderzoek. Op basis van een grondig onderzoek van de bestaande literatuur identificeert hoofdstuk 1 van dit werk drie belangrijke onderzoekshiaten.

Ten eerste mist het EE1st-beginsel conceptuele duidelijkheid. Het concept is grotendeels ontleend aan grijze literatuur en wetgevende teksten, maar is nauwelijks terug te vinden in de peer-reviewed academische literatuur. Dit leidt tot dubbelzinnigheid en inconsistentie in de terminologie en het begrip. Er is ook een tendens om EE1st gelijk te stellen aan vergelijkbare regelgevende praktijken in de Verenigde Staten (VS), zoals 'integrated resource planning'. Hierdoor bestaat het risico dat het EE1st-concept verkeerd wordt begrepen of wordt gereduceerd tot een slogan, waardoor de praktische impact ervan mogelijk wordt beperkt. Dit motiveert de eerste onderzoeksvraag (OV):

OV 1: Hoe kan het energie-efficiëntie-eerstbeginsel systematisch geconceptualiseerd worden om de betekenis ervan te verduidelijken en het te onderscheiden van verwante concepten?

Ten tweede is er een gebrek aan kwantitatief bewijs over de potentiële effecten van het EE1st-beginsel in de transitie van de EU naar netto nul emissies. Een belangrijk gebied om rekening mee te houden is de interactie tussen de bouwsector, die residentiële, commerciële en openbare gebouwen omvat, en de bijbehorende infrastructuur voor energievoorziening, waaronder opwekkings-, netwerk- en opslagfaciliteiten voor elektriciteit, warmte, gas en waterstof. Uiteindelijk brengen zowel oplossingen voor energie-efficiëntie als infrastructuur voor energievoorziening economische kosten en baten met zich mee, wat leidt tot de tweede onderzoeksvraag:

OV2: In welke mate heeft het prioriteren van energie-efficiëntie in de bouwsector invloed op de infrastructuurvereisten voor energievoorziening en de kosten van energiesystemen voor een netto-nul-emissietransitie in de EU?

Ten slotte ontbreekt het aan praktische richtlijnen voor de mogelijke toepassing van het EE1st-beginsel door lidstaten en subnationale besluitvormers. Hoewel de Europese Commissie in 2021 enkele aanbevelingen heeft gedaan, vraagt de herschikking van de richtlijn inzake energie-efficiëntie om meer definitieve en wetenschappelijk onderbouwde richtlijnen. Twee specifieke kwesties zijn het ontwerp van specifieke beleidsinstrumenten voor EE1st en de integratie van EE1st in strategische energieplanning. Dit leidt tot de derde onderzoeksvraag:

OV 3: Hoe kan het energie-efficiëntie-eerstbeginsel effectief worden toegepast in de Europese Unie en haar lidstaten door middel van beleidsinstrumenten en strategische energieplanning?

Zoals hieronder samengevat, worden deze onderzoeksvragen behandeld in zes specifieke hoofdstukken (2-7), die elk een afzonderlijk onderzoek vertegenwoordigen dat de ingewikkelde aspecten van het EE1st-beginsel onderzoekt. Daarmee levert dit onderzoek drie belangrijke bijdragen.

Bijdrage 1: Verbetering van de conceptuele duidelijkheid en ontrafeling van het toepassingsgebied van het energie-efficiëntie-eerstbeginsel

Hoofdstuk 2 gaat in op de vraag wat het EE1st-beginsel betekent en hoe het zich verhoudt tot andere verwante concepten door de multidisciplinaire literatuur over energie-efficiëntie en beleid kritisch te bekijken en erover na te denken. Dit levert een duidelijker onderscheid op tussen oplossingen voor energie-efficiëntie en infrastructuur voor energievoorziening. Oplossingen voor energie-efficiëntie worden verder gecategoriseerd in middelen aan de vraagzijde – waaronder energie-efficiëntie bij het eindgebruik, flexibiliteit aan de vraagzijde en energiesuppiciëntie × en energie-efficiëntie aan de aanbodzijde, zoals efficiënte stadsverwarming en -koeling.

Dit conceptuele werk onderstreept dat de reikwijdte van EE1st verder gaat dan energie-efficiëntie bij het eindgebruik, met name in het elektriciteitssysteem waar flexibiliteit aan de vraagzijde belangrijker wordt geacht dan permanente vermindering van de belasting, een punt dat in hoofdstuk 6 uitvoerig wordt besproken. Bovendien, hoewel EE1st relevant kan zijn in het private domein, bijvoorbeeld voor een bedrijf dat mogelijkheden voor energie-efficiëntie wil identificeren, is het fundamenteel een kwestie van overheidsbeleid, gericht op het leveren van die oplossingen, of ze nu bijzonder energie-efficiënt zijn of niet, die het grootste nettovoordeel voor de maatschappij opleveren.

Alles bij elkaar suggereren de bevindingen dat EE1st niet gericht is op het opstellen van strikte hiërarchieën van oplossingen op basis van hun stand-alone energie-efficiëntie. In plaats daarvan kan EE1st het best worden opgevat als een optimalisatieprobleem: de objectieve functie is het minimaliseren van de maatschappelijke kosten of het maximaliseren van de netto baten, rekening houdend met de investeringen en werking van alle beschikbare technologische en gedragsopties, met inachtneming van de behoefte aan energiediensten van de consument en bredere maatschappelijke doelstellingen. Deze herconceptualisering leidt tot een verfijnde definitie van EE1st als een besluitvormingsbeginsel voor energiegerelateerde planning, investeringen en beleidsvorming binnen gegeven systeemgrenzen, waarbij prioriteit wordt gegeven aan energie-efficiënte oplossingen wanneer deze kostenefficiënter zijn dan nieuwe infrastructuur voor energievoorziening om zowel aan individuele als collectieve behoeften te voldoen.

Hoofdstuk 2 vergelijkt EE1st ook systematisch met verwante concepten uit de VS, waaronder 'least-cost planning', 'integrated resource planning' en 'non-wires solutions'. Er komen drie belangrijke verschillen naar voren. In tegenstelling tot een groot deel van de VS zijn de energiemarkten in de EU ontbundeld en geliberaliseerd, wat betekent dat regelgevende instanties beperkte directe invloed hebben om EE1st toe te passen, behalve voor netwerkbedrijven vanwege hun natuurlijke monopoliepositie. Dit wijst op de noodzaak van een geschikt beleids- en planningskader voor energiecentrales, opslagfaciliteiten en andere concurrerende marktactiviteiten om het beginsel toe te passen. Bovendien is de reikwijdte van EE1st in de EU breder: het omvat niet alleen elektriciteit, maar ook warmte-, gas-, waterstof- en zelfs waterinfrastructuur. Tot slot heeft EE1st in de EU een duidelijke maatschappelijke focus, gericht op oplossingen die optimaal zijn voor de maatschappij als geheel, niet alleen voor klanten van nutsbedrijven.

Samengevat verbetert dit onderzoek het begrip van het EE1st-beginsel door een duidelijkere en meer genuanceerde beschrijving te geven van de terminologie en de reikwijdte ervan. Deze basis staat centraal in zowel de kwantitatieve analyses in de hoofdstukken 3 en 4 en de praktische richtlijnen voor EE1st in de hoofdstukken 5 tot 7.

Bijdrage 2: Onderzoek naar de kwantitatieve effecten van het energie-efficiëntie-eerstbeginsel op gebouwen en energievoorziening

Hoofdstukken 3 en 4 gaan in op de vraag hoe een systematische prioritering van energie-efficiëntie-oplossingen in de bouwsector van invloed is op de infrastructuurvereisten voor energievoorziening en de kosten van het energiesysteem voor een netto-nul-emissietransitie in de EU. Door middel van temporele en ruimtelijk opgeloste bottom-up modellering van het energiesysteem leveren deze studies robuust kwantitatief bewijs voor EE1st.

In het bijzonder in hoofdstuk 3 worden scenario's onderzocht met verschillende ambitieniveaus voor de renovatie van gebouwen en efficiënte producten, waarbij het effect op de elektriciteits-, warmte- en waterstofvoorziening wordt beoordeeld onder netto nul emissies in 2050. De studie modelleert elk van de 27 EU-lidstaten, rekening houdend met wederzijdse energie-import en -export. De kosten van het energiesysteem zijn de belangrijkste prestatie-indicator en omvatten traditionele financiële kosten en externe kosten, zoals kosten veroorzaakt door luchtvervuiling. Hoofdstuk 4 volgt een vergelijkbare analytische logica, maar richt zich op het lokale niveau en onderzoekt een stadswijk met gemengd gebruik. De studie beoordeelt de afwegingen tussen gebouwrenovaties en opties voor warmtelevering, zowel gebouwgeïntegreerd als stadsverwarming, in verschillende lidstaten, met een speciale gevoeligheidsanalyse om de robuustheid en generaliseerbaarheid van de bevindingen te testen.

Samen laten hoofdstuk 3 en 4 zien dat energie-efficiëntie in de gebouwensector de behoefte aan energievoorzieningsinfrastructuur in de net-nul systeemtransitie, waaronder windturbines, elektrolysers, stadsverwarming en bijbehorende netwerken, aanzienlijk kan verminderen. Vanuit een kostenperspectief geeft hoofdstuk 3 aan dat een vermindering van het finaal energiegebruik in de bouwsector met 30% in 2050 ten opzichte van 2020 gerechtvaardigd kan worden door netto kostenbesparingen, een traject dat aanzienlijk ambitieuzer is dan de huidige trend van energiebesparingen bij ongewijzigd beleid. Hoofdstuk 4 nuanceert deze bevindingen door te laten zien dat de kostenoptimale balans tussen warmtebesparing en warmtevoorziening afhangt van verschillende exogene factoren, waaronder arbeids- en materiaalkosten, klimatologische omstandigheden, energieprijzen en de omvang van externe kosten. Onder gunstige omstandigheden kan de aanpassing van gebouwen leiden tot aanzienlijke kostenbesparingen, terwijl het in andere contexten economisch haalbaarder kan zijn om koolstofarme verwarmingssystemen, zoals warmtepompen, te installeren zonder voorafgaande renovatie. In plaats van het EE1st-beginsel tegen te spreken, onderstreept dit inzicht de essentie ervan: energie-efficiëntie niet alleen omwille van de energie-efficiëntie bevorderen, maar streven naar een optimale mix van alle beschikbare opties die de nettovoordelen maximaliseert.

Deze studies identificeren ook technische synergieën, met name tussen lagere aanvoertemperaturen in gebouwen na renovaties en de energetische prestaties van lagetemperatuurverwarmingssystemen. Warmtepompen en thermische zonne-energiesystemen komen naar voren als cruciaal voor goedkope warmtelevering, zowel in gedecentraliseerde gebouwgeïntegreerde systemen als in gecentraliseerde stadsverwarming van de vierde generatie. De studies wijzen ook op een gematigd gebruik van waterstof en synthetische koolwaterstoffen, voornamelijk als opslagoplossing om de variabele aard van hernieuwbare energieën in de elektriciteitsvoorziening te beheren.

Daarom levert dit onderzoek verschillende bijdragen. Het biedt een systematische beschouwing van het maatschappelijk perspectief, met aandacht voor discontovoeten, overdrachtsbetalingen en externe kosten zoals de uitstoot van luchtverontreiniging. Hierdoor wordt de ondervertegenwoordiging van multiple impacts aangepakt, hoewel verder onderzoek nodig is om meer van deze effecten op te nemen in dergelijke kosten-batenanalyses (KBA's). Bovendien levert dit onderzoek, door het toepassen van systematische vergelijkende analyses, generaliseerbaar bewijs over EE1st, rekening houdend met de EU-doelstelling van netto nul broeikasgasemissies tegen 2050 en de bijbehorende modelleringsuitdagingen wat betreft het weergeven van flexibiliteit en behoeften aan sectorale koppeling. Dit onderstreept het belang van het EE1st-beginsel in de EU, dat oproept tot een verstandig evenwicht tussen energiebesparing en uitbreiding van het aanbod van hernieuwbare energie om een duurzame, robuuste en kostenefficiënte transitie naar een energiesysteem met netto nul-emissies mogelijk te maken.

Bijdrage 3: Een leidraad bieden voor de praktische toepassing van het energie-efficiëntie-eerstbeginsel bij energieplanning en -beleidsvorming

Hoofdstukken 5 tot 7 gaan in op de vraag hoe EE1st effectief kan worden toegepast in de EU en haar lidstaten. In deze studies worden twee belangrijke mechanismen voor de toepassing van EE1st onderzocht. Het eerste is strategische energieplanning, die tot doel heeft een optimale mix van energie-efficiënte oplossingen en infrastructuur voor energievoorziening te identificeren, ondersteund door betrokkenheid van belanghebbenden en kwantitatieve analyse. Hoewel energieplanning van oudsher het domein is van netwerkbeheerders en nutsbedrijven, is het in toenemende mate een verantwoordelijkheid geworden van overheidsinstanties, waaronder gemeenten, bijvoorbeeld bij de ontwikkeling van nationale energie- en klimaatplannen in het kader van de EU-Governanceverordening.

Zoals beschreven in hoofdstuk 7 vereist strategische energieplanning volgens het EE1st-beginsel een geïntegreerde beoordeling van zowel de infrastructuur voor energievoorziening als oplossingen voor energie-efficiëntie, waarbij erkend wordt dat beide kunnen voldoen aan de behoeften aan energiediensten van de consument en bredere maatschappelijke doelstellingen. Het vereist ook een faire beoordeling die rekening houdt met alle relevante kosten en baten, met inbegrip van meervoudige sociale, economische en milieueffecten. Met het oog op de praktische complexiteit van strategische energieplanning, wordt in hoofdstuk 7 een nieuw kader met beslissingsboom geïntroduceerd. Dit kader biedt een gestructureerde aanpak voor het navigeren door ingewikkelde planningsbeslissingen door een visuele weergave te bieden van beslissingspaden en mogelijke uitkomsten. Als zodanig kan dit kader dienen als hulpmiddel in een bredere gereedschapskist van beslissingsondersteunende technieken voor zowel publieke als private planners, waarbij de praktische toepasbaarheid wordt gedemonstreerd aan de hand van veelvoorkomende planningssituaties zoals de planning van elektriciteitsnetwerken.

Een belangrijke uitdaging bij strategische energieplanning is echter dat de verschillende middelen aan de vraag- en aanbodzijde van het energiesysteem meestal in handen zijn van verschillende belanghebbenden, die eerder particuliere dan collectieve maatschappelijke belangen nastreven. Om deze uiteenlopende belangen af te stemmen op een collectief optimaal resultaat zijn niet alleen planning, maar ook specifieke beleidsinstrumenten nodig.

Daarom is het tweede onderzochte mechanisme het beleidsinstrumentarium, opgevat als formele maatregelen van overheidsinstanties of regelgevende autoriteiten om een gelijk speelveld te creëren voor energie-efficiënte oplossingen en infrastructuur voor energievoorziening in overeenstemming met het EE1st-beginsel. In antwoord op het gebrek aan academische literatuur over EE1st, wordt in hoofdstuk 5 een uitgebreid theoretisch kader ontwikkeld voor de toepassing ervan door middel van beleidsinstrumenten, waarbij inzichten uit de neoklassieke, institutionele, regelgevings- en gedragseconomie worden geïntegreerd. Centraal in dit kader staat het concept van goed functionerende markten dat, in lijn met de conceptuele basis in hoofdstuk 2 dient als normatief ijkpunt voor EE1st. Dit concept suggereert een beleidsinterventielogica die marktfalen aanpakt wanneer de maatschappelijke baten van overheidsinterventie opwegen tegen de kosten van beleidsimplementatie.

Gebaseerd op deze logica wordt in Hoofdstuk 5 een nieuwe classificatie en karakterisering van meer dan vijfentwintig beleidsinstrumenten om EE1st aan te pakken. Deze variëren van regelgevende interventies en marktontwerp tot emissieprijzen en aggregatiebedrijfsmodellen, elk gericht op specifieke tekortkomingen van de markt. Als aanvulling hierop geeft hoofdstuk 6 gericht op beleidsinstrumenten in het elektriciteitssysteem, wat cruciaal is gezien de toenemende rol van elektrificatie en flexibiliteit aan de vraagzijde. Er worden bijvoorbeeld innovatieve stimuleringsmechanismen voorgesteld, zoals 'performance-based regulation', voor netwerkbedrijven om alternatieven aan de vraagzijde in overweging te nemen in plaats van traditionele netwerkuitbreiding.

Deze studies leveren dus verschillende bijdragen. Ze gaan verder dan het gangbare concept van 'barriers to energy efficiency' en bieden een theoretisch genuanceerder kader voor de alomvattende toepassing van EE1st. Dit houdt in dat niet alleen energie-efficiëntie bij het eindgebruik wordt geïntegreerd, maar ook flexibiliteit aan de vraagzijde en efficiënte energieomzetting als belangrijke oplossingen voor energie-efficiëntie in het EE1st-concept. Daarnaast verduidelijken deze studies de reikwijdte van EE1st-beleid, waarbij ze benadrukken dat de toepassing ervan een brede beleidsrespons vereist die verder gaat dan de traditionele portefeuille van energie-efficiëntiebeleid door beleid te integreren dat wellicht wordt verward met beleid aan de aanbodzijde, zoals het design van de elektriciteitsmarkt of de regulering van netwerkbedrijven. Op deze manier voegt dit onderzoek kritisch onderzoek en theoretische onderbouwing toe aan de bestaande richtlijnen. Dit grondwerk kan lidstaten en subnationale besluitvormers helpen EE1st effectief toe te passen en van principe naar praktijk te brengen.

Vooruitblik
De herschikte richtlijn inzake energie-efficiëntie heeft nieuwe bepalingen voor de lidstaten geïntroduceerd, waaronder de beoordeling van energie-efficiëntieoplossingen, de bevordering van uitgebreide KBA-methodologieën en regelmatige monitoring van het EE1st-beginsel. Deze toegenomen aandacht zal waarschijnlijk het bewustzijn van het EE1e-beginsel onder de lidstaten aanzienlijk vergroten. Er blijven echter nog verschillende onderzoeksbehoeften bestaan.

Wat de grondslagen van EE1st betreft, biedt dit onderzoek een coherent theoretisch kader waaruit een uitgebreide reeks praktische beleidsinstrumenten kan worden afgeleid. Vertrouwen op dit kader alleen kan echter complexiteiten in de echte wereld over het hoofd zien. Andere theorieën, zoals 'socio-technical systems' en het 'multi level perspective', zouden een genuanceerder begrip van EE1st kunnen opleveren door te verklaren hoe gevestigde energievoorzieningsstructuren zich verzetten tegen verandering en hoe niche-innovaties in energie-efficiëntie, zoals flexibiliteit aan de vraagzijde, vechten voor bredere acceptatie.

Wat de kwantitatieve gegevens over EE1st betreft, heeft dit onderzoek zich voornamelijk gericht op energie-efficiëntie bij het eindgebruik. Het EE1st-concept omvat echter ook flexibiliteit aan de vraagzijde en energiesuppiciëntie, die verder onderzoek verdienen. Hoewel dit onderzoek zich heeft gericht op de interactie tussen de bouwsector en de energievoorziening, is er bovendien behoefte aan meer gegevens over de mogelijkheden van EE1st in de industriële sector bij de transitie van de EU naar netto nul emissies. Bovendien gebruiken de KBA's die in dit onderzoek zijn uitgevoerd de kosten van het energiesysteem, inclusief geselecteerde externe kosten zoals luchtvervuiling, als een belangrijke prestatie-indicator. Toekomstig onderzoek moet gericht zijn op het opnemen van een breder scala aan 'multiple impacts', zoals arbeidsproductiviteit en energiezekerheidseffecten, waarvoor empirische gegevens nodig zijn voor monetarisering en kaders om dubbeltelling van effecten te voorkomen. Tot slot is er, als aanvulling op de economische analyses vanuit een maatschappelijk perspectief in dit onderzoek, behoefte aan specifieke financiële analyses die de verdelingseffecten over verschillende demografische groepen onderzoeken.

Met betrekking tot de praktische toepassing van het EE1st-beginsel biedt dit onderzoek bruikbare richtlijnen voor beleidsinstrumenten en strategische energieplanning. Deze toepassing vereist robuuste ex-post evaluaties van de genomen maatregelen, wat op zijn beurt vraagt om uitgebreide monitoring- en rapportageprocessen. Er is ook behoefte aan een beter begrip van beleidsmixen, rekening houdend met de collectieve impact en compatibiliteit van verschillende beleidsinstrumenten.

Concluderend kan worden gesteld dat het EE1st-beginsel het potentieel heeft om een economisch levensvatbare, robuuste en rechtvaardige transitie naar een energiesysteem met netto nul emissies in de EU tegen 2050 te vergemakkelijken. Het huidige politieke momentum biedt de mogelijkheid om effectieve maatregelen te nemen. Het valt echter nog te bezien hoe de lidstaten het EE1st-beginsel zullen interpreteren, implementeren en rapporteren. De effectiviteit van deze implementaties zal cruciaal zijn voor het behalen van de ambitieuze energie- en klimaatdoelstellingen van de EU.

Wissenschaftliche Zusammenfassung

Hintergrund

Energieeffizienz bezeichnet das Verhältnis zwischen nutzbarem Output und physischem Energieinput. Auf der Nachfrageseite des Energiesystems umfasst die Verbesserung der Energieeffizienz die Verringerung des Energiebedarfs durch Maßnahmen wie die energieeffiziente Gestaltung von Gebäuden, die den Komfort in Innenräumen aufrechterhalten und gleichzeitig den Energieverbrauch minimieren, oder den Einsatz von Wärmepumpen als effizientere Alternative zu herkömmlichen Heizsystemen. Auf der Angebotsseite umfasst sie die Erzeugung und Übertragung von Endenergie mit geringerem Einsatz von Primär- oder Sekundärenergie, z. B. durch den Einsatz effizienter Fernwärme- und Fernkältesysteme oder die Verringerung von Leitungsverlusten bei der Übertragung und Verteilung. Sie umfasst auch die nachfrageseitige Flexibilität, um den Energieverbrauch an die Versorgungsbedingungen anzupassen und so die Gesamteffizienz des Energiesystems zu verbessern.

Die Verbesserung der Energieeffizienz in der gesamten Energiewertschöpfungskette ist weithin als Schlüsselstrategie zur Senkung der Kosten des Energiesystems und zur Bekämpfung des Klimawandels anerkannt. Sie wird auch zunehmend als Mittel zur Verringerung der Abhängigkeit von Energieimporten, zur Schaffung von Arbeitsplätzen, zur Verbesserung der Luftqualität und zur Erzielung anderer sogenannter ‚multiple impacts' oder ‚co-benefits' anerkannt. Vor diesem Hintergrund hat die Europäische Union (EU) ihre Energie- und Klimapolitik seit langem auf die Verbesserung der Energieeffizienz ausgerichtet. Die 2019 vorgestellte Green Deal Strategie der Europäischen Kommission bekräftigt die Notwendigkeit der Energieeffizienz, um das langfristige Ziel der EU zu erreichen, bis 2050 netto keine Treibhausgasemissionen mehr zu verursachen, wie es in der europäischen Klimarechtsverordnung festgelegt ist. Zu den etablierten Politiken und Maßnahmen in der EU und ihren Mitgliedstaaten gehören Verordnungen, die Verbesserungen der Energieeffizienz vorschreiben, Anreize für energieeffiziente Technologien und Programme zur Förderung von Verhaltensänderungen beim Energieverbrauch.

Empirische Daten und akademische Diskussionen über die sogenannte Energieeffizienzlücke zeigen jedoch, dass die EU im Vergleich zu neuen Erzeugungs-, Netz- und Speicherinfrastrukturen zu wenig in Energieeffizienz investiert. Um dieses Ungleichgewicht zu beheben, wurde kürzlich das Prinzip ‚Energy Efficiency First' (EE1st) in die politische Debatte der EU eingebracht. Dieses Prinzip basiert auf der Idee, dass Energieeffizienz oft der nachhaltigste und kostengünstigste Weg ist, um die Bedürfnisse der Verbraucher nach Energiedienstleistungen (z. B. thermische Behaglichkeit in Innenräumen) und übergeordnete gesellschaftliche Ziele (z. B. Reduzierung des Treibhausgasausstoßes) zu erfüllen. Wo dies der Fall ist, besagt das Prinzip, dass Energieeffizienzlösungen systematisch Vorrang vor dem Ausbau einer relativ ineffizienten Energieversorgungsinfrastruktur haben sollten. Auf diese Weise könnte das EE1st-Prinzip eine effektive und kostengünstige Dekarbonisierung des EU-Energiesystems erleichtern.

In bemerkenswert kurzer Zeit hat sich das EE1st-Prinzip zu einem Schlüsselelement der EU-Energie- und Klimapolitik entwickelt. Es begann Mitte der 2010er Jahre mit Broschüren von Nichtregierungsorganisationen und wurde nach und nach in EU-Strategien und -Gesetze integriert. Ein potenzieller Meilenstein war die Verabschiedung der neugefassten Energieeffizienzrichtlinie Ende 2023, welche die Bewertung von Energieeffizienzlösungen bei Planungs-, Politik- und Investitionsentscheidungen, die Begleitung der Anwendung des EE1st-Prinzips und die Berichterstattung über EE1st im Rahmen der EU-Governance-Verordnung vorschreibt.

Forschungsfragen

Trotz seines rasanten Aufstiegs in der politischen Debatte in der EU wurde das EE1st-Prinzip noch nicht umfassend wissenschaftlich fundiert und begleitet. Auf Grundlage einer ausführlichen Untersuchung der bestehenden Literatur werden in Kapitel 1 dieser Arbeit drei wesentliche Forschungslücken identifiziert.

Erstens mangelt es dem EE1st-Prinzip an begrifflicher Klarheit. Das Konzept stammt größtenteils aus der sogenannten grauen Literatur sowie aus Gesetzestexten, ist aber in der von Experten begutachteten wissenschaftlichen Literatur kaum vertreten. Dies führt zu Unklarheiten und Inkonsistenzen in der Terminologie und im Verständnis. Es besteht auch die Tendenz, EE1st mit ähnlichen Regulierungspraktiken in den Vereinigten Staaten (USA), wie z. B. ‚Integrated Resource Planning', gleichzusetzen. Damit besteht die Gefahr, dass das EE1st-Konzept missverstanden oder auf einen Slogan reduziert wird, was seine praktische Wirkung einschränken könnte. Dies motiviert die erste Forschungsfrage:

Forschungsfrage 1: Wie kann das ‚Energy Efficiency First'-Prinzip systematisch konzeptualisiert werden, um seine Bedeutung zu klären und es von verwandten Konzepten abzugrenzen?

Zweitens mangelt es an quantitativen Daten über die potenziellen Auswirkungen des EE1st-Prinzips auf den Wandel der EU hinzu Treibhausgasneutralität. Ein wichtiger Bereich ist die Wechselwirkung zwischen dem Gebäudesektor – einschließlich Wohn-, Gewerbe- und öffentlichen Gebäuden mit Energieeffizienzlösungen wie Gebäudesanierungen – und der entsprechenden Energieversorgungsinfrastruktur, einschließlich Erzeugungs-, Netz- und Speicheranlagen für Strom, Wärme, Gas, Wasserstoff und andere Energieträger. Letztlich sind sowohl Energieeffizienzlösungen als auch die Energieversorgungsinfrastruktur mit volkswirtschaftlichen Kosten und Nutzen verbunden, was zur zweiten Forschungsfrage führt:

Forschungsfrage 2: Inwieweit wirkt sich eine Priorisierung der Energieeffizienz im Gebäudesektor auf die Anforderungen an die Energieversorgungsinfrastruktur und die Energiesystemkosten für eine Systemwende zur Treibhausgasneutralität in der EU aus?

Darüber hinaus fehlt es an praktischen Leitlinien für die mögliche Anwendung des EE1st-Prinzips durch die Mitgliedstaaten und subnationale Entscheidungsträger. Während die Europäische Kommission im Jahr 2021 eine Reihe von Empfehlungen vorgelegt hat, werden im Zuge der Neufassung der Energieeffizienzrichtlinie klarere und wissenschaftlich fundierte Leitlinien benötigt. Zwei wesentliche Aspekte sind die Gestaltung spezifischer Politikinstrumente für EE1st und die Integration von EE1st in die strategische Energieplanung. Daraus leitet sich die dritte Forschungsfrage ab:

Forschungsfrage 3: Wie kann das ‚Energy Efficiency First'-Prinzip in der Europäischen Union und ihren Mitgliedstaaten mittels politischer Instrumente und strategischer Energieplanung wirksam umgesetzt werden?

Wie im Folgenden zusammengefasst, werden diese Forschungsfragen in sechs eigenen Kapiteln behandelt (2-7) behandelt, die jeweils separate Studien darstellen, welche die verschiedenen Aspekte des EE1st-Prinzips untersuchen. Damit leistet diese Forschungsarbeit drei wichtige Beiträge.

Beitrag 1: Verbesserung der begrifflichen Klarheit und Konkretisierung des Anwendungsbereichs des ‚Energy Efficiency First'-Prinzips

Kapitel 2 befasst sich mit der Frage, was das EE1-Prinzip bedeutet und wie es mit anderen verwandten Konzepten zu vergleichen ist, indem es die multidisziplinäre Literatur über Energieeffizienz und Politik kritisch überprüft und reflektiert. In dieser Studie wird zunächst eine klarere Unterscheidung zwischen Energieeffizienzlösungen und Energieversorgungsinfrastruktur getroffen. Energieeffizienzlösungen werden weiter unterteilt in nachfrageseitige Ressourcen – einschließlich Endenergieeffizienz, nachfrageseitige Flexibilität und Energiesuffizienz – sowie angebotsseitige Energieeffizienz, wie effiziente Fernwärme und -kälte.

Diese konzeptionelle Arbeit unterstreicht, dass der Anwendungsbereich von EE1st über die klassische Endenergieeffizienz hinausgeht, insbesondere im Stromsystem, wo nachfrageseitige Flexibilität als bedeutsamer angesehen wird als permanente Lastreduktion, ein Thema, das in Kapitel 6 ausführlich behandelt wird. Darüber hinaus kann EE1st zwar im privaten Bereich von Bedeutung sein, z. B. für ein Unternehmen, das nach Möglichkeiten zur Verbesserung der Energieeffizienz sucht, doch ist es im Wesentlichen eine Frage der öffentlichen Politik, die darauf abzielt, diejenigen Lösungen ⨯ ob besonders energieeffizient oder nicht – bereitzustellen, die den größtmöglichen volkswirtschaftlichen Nettonutzen bringen.

Insgesamt zeigen die Ergebnisse, dass es bei EE1st nicht darum geht, strikte Hierarchien von Maßnahmen gemäß ihrer jeweiligen Energieeffizienz aufzustellen. Stattdessen ist EE1st am besten als Optimierungsproblem zu verstehen: Die Zielfunktion besteht darin, die gesellschaftlichen Kosten zu minimieren bzw. den Nettonutzen zu maximieren, wobei die Investitionen und der Betrieb aller verfügbaren Technologie- und Verhaltensoptionen zu berücksichtigen sind und der Bedarf der Verbraucher an Energiedienstleistungen sowie übergeordnete gesellschaftliche Ziele erfüllt werden müssen. Diese Sichtweise führt zu einer verfeinerten Definition von EE1st als einem Entscheidungsprinzip für energiebezogene Planung, Investitionen und politische Entscheidungen, das Energieeffizienzlösungen immer dann Vorrang einräumt, wenn sie bei der Erfüllung individueller und kollektiver Bedürfnisse kosteneffizienter sind als die Energieversorgungsinfrastruktur.

In Kapitel 2 wird EE1st auch systematisch mit verwandten Konzepten aus den USA verglichen, darunter ‚Least-Cost Planning', ‚Integrated Resource Planning' und ‚Non-Wires Solutions'. Dabei werden drei wesentliche Unterschiede deutlich. Anders als in weiten Teilen der USA sind die Energiemärkte in der EU entflochten und liberalisiert, was bedeutet, dass die Regulierungsbehörden nur begrenzten direkten Einfluss auf die Anwendung von EE1st haben, mit Ausnahme der Netzunternehmen aufgrund ihres natürlichen Monopolstatus. Dies zeigt, dass die Anwendung des Prinzips einen angemessenen politischen und planerischen Rahmen für Kraftwerke, Speicher und andere Marktaktivitäten erfordert. Darüber hinaus ist der Anwendungsbereich von EE1st in der EU weiter gefasst und umfasst nicht nur Strom, sondern auch Wärme, Gas, Wasserstoff und sogar Wasserinfrastrukturen. Schließlich hat EE1st in der EU einen starken volkswirtschaftlichen Fokus und zielt auf Lösungen ab, die für die Gesellschaft als Ganzes und nicht nur für die Kunden eines Energieversorgungsunternehmens optimal sind.

Zusammenfassend lässt sich sagen, dass diese Forschungsarbeit das Verständnis des EE1-Prinzips durch eine klarere und differenziertere Darstellung seiner Terminologie und seines Anwendungsbereichs verbessert. Dies bietet die Grundlage sowohl für die quantitativen Analysen in den Kapiteln 3 und 4 als auch für die praktischen Leitlinien zu EE1st in den Kapiteln 5 bis 7.

Beitrag 2: Untersuchung der quantitativen Auswirkungen des ‚Energy Efficiency First'-Prinzips auf Gebäude und Energieversorgung

In den Kapiteln 3 und 4 wird untersucht, wie sich eine systematische Priorisierung von Energieeffizienzlösungen im Gebäudesektor auf die Anforderungen an die Energieversorgungsinfrastruktur und die Energiesystemkosten für Systemwende zur Treibhausgasneutralität in der EU auswirkt. Durch zeitlich und räumlich aufgelöste Bottom-up-Energiesystemmodellierung liefern diese Studien robuste quantitative Evidenz zu EE1st.

So werden in Kapitel 3 Szenarien mit unterschiedlichen Zielvorgaben für die Gebäudesanierung und effiziente Geräte untersucht und deren Auswirkungen auf die Strom-, Wärme- und Wasserstoffversorgung unter dem Ziel der Treibhausgasneutralität im Jahr 2050 bewertet. In der Studie werden alle 27 EU-Mitgliedsstaaten unter Berücksichtigung der gegenseitigen Energieimporte und -exporte modelliert. Die Energiesystemkosten sind der zentrale Leistungsindikator, der sowohl traditionelle finanzielle Kosten als auch externe Kosten, z. B. durch Luftverschmutzung, umfasst. Kapitel 4 folgt einer ähnlichen analytischen Logik, konzentriert sich jedoch auf die lokale Ebene und untersucht ein gemischt genutztes Stadtquartier. Die Studie bewertet die Zielkonflikte zwischen Gebäudesanierung und Wärmeversorgungsoptionen, sowohl gebäudeintegriert als auch mit Fernwärme, in verschiedenen Mitgliedstaaten, einschließlich einer eigenen Sensitivitätsanalyse, um die Robustheit und Verallgemeinerbarkeit der Ergebnisse zu überprüfen.

Zusammengenommen zeigen diese Studien, dass die Energieeffizienz im Gebäudesektor den Bedarf an Energieversorgungsinfrastruktur für die Wende hin zu Treibhausgasneutralität, einschließlich Windturbinen, Elektrolyseuren, Fernwärme und den dazugehörigen Netzen, erheblich reduzieren kann. Unter Kostengesichtspunkten wird in Kapitel 3 gezeigt, dass eine Senkung des Endenergieverbrauchs im Gebäudesektor um 30 % bis 2050 gegenüber 2020 durch Nettokosteneinsparungen gerechtfertigt werden kann. Kapitel 4 präzisiert diese Ergebnisse, indem es zeigt, dass das kostenoptimale Gleichgewicht zwischen Energieeinsparung und Energieversorgung von einer Vielzahl exogener Faktoren abhängt, darunter Arbeits- und Materialkosten, klimatische Bedingungen, Energiepreise und die Höhe der externen Kosten. Unter günstigen Bedingungen können Gebäudesanierungen zu erheblichen Systemkosteneinsparungen führen, während es in anderen Kontexten wirtschaftlich sinnvoller sein kann, kohlenstoffarme Heizsysteme wie Wärmepumpen zu installieren. Diese Erkenntnis steht nicht im Widerspruch zum EE1st-Prinzip, sondern unterstreicht dessen Kern: Es geht nicht darum, Energieeffizienz um ihrer selbst willen zu fördern, sondern eine optimale Kombination aller verfügbaren Optionen einzusetzen, die den Nettonutzen maximiert.

Diese Studien zeigen auch technische Synergien auf, insbesondere zwischen reduzierten Vorlauftemperaturen in sanierten Gebäuden und der Energieeffizienz von Niedertemperatur-Heizsystemen. Wärmepumpen und solarthermische Anlagen erweisen sich als wesentliche Elemente für eine kostengünstige Wärmeversorgung, sei es in dezentralen gebäudeintegrierten Systemen oder in zentralen Fernwärmesystemen der vierten Generation. Die Studien deuten auch auf einen moderaten Einsatz von Wasserstoff und synthetischen Kohlenwasserstoffen hin, vor allem als Speicherlösung zur Regelung der fluktuierenden Stromerzeugung aus erneuerbaren Energien.
Damit leistet diese Arbeit einen wichtigen Beitrag. Sie bietet eine systematische Betrachtung der volkswirtschaftlichen Perspektive unter Berücksichtigung von Diskontierungssätzen, Transferzahlungen und externen Kosten wie z. B. Luftschadstoffemissionen. Damit wird der unzureichenden Berücksichtigung von ‚multiple impacts' begegnet, wenngleich weitere Forschung erforderlich ist, um mehr dieser Effekte in Kosten-Nutzen-Analysen einzubeziehen. Darüber hinaus liefert diese Forschung durch die Anwendung systematischer vergleichender Analysen verallgemeinerbare

Erkenntnisse über EE1st unter Berücksichtigung des EU-Ziels von Treibhausgasneutralität bis 2050 und der damit verbundenen modelltechnischen Herausforderungen bei der Abbildung von Sektorkopplung und Flexibilitätsanforderungen. Dies unterstreicht die Bedeutung des EE1st-Prinzips in der EU, welches ein sinnvolles Gleichgewicht zwischen Energieeinsparungen und dem Ausbau erneuerbarer Energien fordert, um eine nachhaltige, tragfähige und kosteneffiziente Wende zur Treibhausgasneutralität zu ermöglichen.

Beitrag 3: Leitlinien für die praktische Anwendung des ‚Energy Efficiency First'-Prinzips in der Energieplanung und -politik

Die Kapitel 5 bis 7 befassen sich mit der Frage, wie das EE1st-Prinzip in der EU und ihren Mitgliedstaaten wirksam umgesetzt werden könnte. In diesen Studien werden zwei Hauptmechanismen für die Anwendung von EE1st untersucht. Der erste ist die strategische Energieplanung, die darauf abzielt, einen optimalen Mix aus Energieeffizienzlösungen und Energieversorgungsinfrastruktur zu ermitteln, basierend auf der Einbeziehung von Interessengruppen und quantitativen Analysen. Während die Energieplanung traditionell in den Zuständigkeitsbereich von Netzbetreibern und Versorgungsunternehmen fiel, ist sie zunehmend in die Verantwortung von Behörden, einschließlich Kommunen, übergegangen, beispielsweise bei der Entwicklung nationaler Energie- und Klimapläne im Rahmen der EU Governance-Verordnung.

Wie in Kapitel 7 beschrieben, erfordert die strategische Energieplanung gemäß dem EE1st-Prinzip eine integrierte Bewertung sowohl der Energieversorgungsinfrastruktur als auch der Energieeffizienzlösungen, wobei zu berücksichtigen ist, dass beide den Bedarf der Verbraucher an Energiedienstleistungen und weitergehende gesellschaftliche Ziele erfüllen können. Darüber hinaus ist eine faire Bewertung erforderlich, bei der alle relevanten Kosten und Nutzen, einschließlich der sozialen, ökologischen und wirtschaftlichen ‚multiple impacts', berücksichtigt werden. Angesichts der praktischen Komplexität der strategischen Energieplanung wird in Kapitel 7 ein neuer ‚decision tree'-Ansatz vorgestellt. Dieser Ansatz bietet einen strukturierten Zugang zu komplexen Planungsentscheidungen, indem er Entscheidungswege und mögliche Ergebnisse visuell darstellt. So kann dieser Ansatz als Teil eines breiteren Instrumentariums von Entscheidungsunterstützungstechniken sowohl für öffentliche als auch für private Planer dienen, wobei seine praktische Anwendbarkeit anhand gängiger Planungssituationen wie der Planung von Stromnetzen demonstriert wird.

Eine zentrale Herausforderung für die strategische Energieplanung besteht jedoch darin, dass sich die verschiedenen Komponenten auf der Angebots- und Nachfrageseite des Energiesystems in der Regel im Besitz unterschiedlicher Akteure befinden, die naturgemäß eher private als kollektive gesellschaftliche Interessen verfolgen. Um diese unterschiedlichen Interessen und Akteure auf ein kollektiv optimales Ergebnis auszurichten, bedarf es nicht nur der Planung, sondern auch geeigneter politischer Instrumente.

Der zweite untersuchte Mechanismus sind daher Politikinstrumente, die als formale Maßnahmen verstanden werden, welche von Regierungs- oder Regulierungsbehörden ergriffen werden, um gleiche Wettbewerbsbedingungen für Energieeffizienzlösungen und Energieversorgungsinfrastrukturen im Einklang mit dem EE1st-Prinzip zu schaffen. Als Antwort auf den Mangel an wissenschaftlicher Literatur zu EE1st wird in Kapitel 5 ein umfassendes theoretisches Framework für die Umsetzung von EE1st mittels politischer Instrumente entwickelt, das Erkenntnisse aus der neoklassischen, institutionellen, ordnungspolitischen und verhaltenswissenschaftlichen Ökonomie integriert. Im Zentrum dieses Frameworks steht das Konzept gut funktionierender Märkte, das in Anlehnung an die konzeptionellen Grundlagen in Kapitel 2 als normativer Maßstab für EE1st dient. Dieses Konzept legt nahe, dass Marktversagen politisch behoben werden sollte, wenn der gesellschaftliche Nutzen einer staatlichen Intervention die Kosten der Politikumsetzung übersteigt.

Basierend auf dieser Logik wird in Kapitel 5 eine neue Klassifizierung und Charakterisierung von mehr als 25 Politikinstrumenten vorgestellt, die das EE1st-Prinzip adressieren. Diese reichen von regulatorischen Eingriffen und Marktdesign bis hin zur Bepreisung von Emissionen und Geschäftsmodellen zur Aggregation, die jeweils auf ein spezifisches Marktversagen abzielen. Ergänzend werden in Kapitel 6 Politikinstrumente im Stromsystem diskutiert, das angesichts der zunehmenden Bedeutung von Elektrifizierung und nachfrageseitiger Flexibilität von entscheidender Bedeutung ist. So werden etwa innovative Anreizmechanismen wie eine leistungsbasierte Regulierung vorgeschlagen, um Netzbetreiber dazu zu bewegen, nachfrageseitige Alternativen zum konventionellen Netzausbau in Betracht zu ziehen.

Diese Studien leisten somit mehrere Beiträge. Sie gehen über das vorherrschende Konzept der Energieeffizienzhemmnisse hinaus und bieten ein theoretisch fundierten Rahmen für die umfassende Anwendung von EE1st. Dazu gehört, dass nicht nur Endenergieeffizienz, sondern auch nachfrageseitige Flexibilität und effiziente Energieumwandlung als zentrale Energieeffizienzlösungen in das EE1st-Konzept einbezogen werden. Darüber hinaus verdeutlichen diese Studien den Umfang der EE1st-Politik, indem sie hervorheben, dass dessen Umsetzung einen breit angelegten politischen Handlungsansatz erfordert, der über das traditionelle Bündel von Energieeffizienzmaßnahmen hinausgeht und auch Maßnahmen umfasst, die fälschlicherweise als angebotsseitige Maßnahmen angesehen werden könnten, wie z. B. das Strommarktdesign oder die Anreizregulierung von Netzbetreibern. Auf diese Weise fügt diese Forschung den existierenden Leitlinien der Europäischen Kommissionen eine genauere Prüfung und theoretische Substanz hinzu. Diese Grundlagen können den Mitgliedsstaaten und Entscheidungsträgern auf subnationaler Ebene helfen, das EE1st-Prinzip effektiv anzuwenden und vom Prinzip zur Praxis zu gelangen.

Ausblick

Mit der Neufassung der EU-Energieeffizienzrichtlinie wurden neue Anforderungen an die Mitgliedstaaten gestellt, darunter die Bewertung von Energieeffizienzlösungen, die Förderung umfassender Kosten-Nutzen-Analysen und das regelmäßige Monitoring des EE1st-Prinzips. Dies dürfte das Bewusstsein für das EE1st-Prinzip in den Mitgliedstaaten deutlich erhöhen. Es besteht jedoch weiterhin Forschungsbedarf.

Im Hinblick auf die Grundlagen von EE1st bietet diese Forschung ein schlüssiges theoretisches Framework, aus dem sich eine Vielzahl praktischer Politikinstrumente ableiten lässt. Wenn man sich jedoch nur auf dieses Framework verlässt, besteht die Gefahr, dass relevante Aspekte übersehen werden. Andere Theorien, wie sozio-technische Systeme und die Mehrebenenperspektive, könnten ein differenzierteres Verständnis von EE1st liefern, indem sie erklären, wie sich Energieversorgungsstrukturen dem Wandel widersetzen und wie Nischeninnovationen im Bereich der Energieeffizienz, wie z. B. nachfrageseitige Flexibilität, um eine breitere Akzeptanz kämpfen.

Was die quantitative Evidenz zu EE1st betrifft, so konzentriert sich diese Arbeit in erster Linie auf die Endenergieeffizienz. Das EE1st-Konzept umfasst jedoch auch nachfrageseitige Flexibilität und Energiesuffizienz, die weiterer Forschung bedürfen. Darüber hinaus konzentriert sich diese Arbeit auf die Wechselwirkungen zwischen dem Gebäudesektor und der Energieversorgung. Es besteht jedoch Bedarf an weiteren Erkenntnissen über das Potenzial von EE1st im Industriesektor als Teil der Systemwende der EU hinzu Treibhausgasneutralität. Darüber hinaus basieren die in dieser Arbeit durchgeführten Analysen auf Energiesystemkosten, einschließlich ausgewählter externer Kosten wie Luftverschmutzung, als Schlüsselindikator. Künftige Forschungsarbeiten sollten ein breiteres Spektrum an sozioökonomischen Effekten einbeziehen, wie z. B. Arbeitsproduktivität und Energieversorgungssicherheit, für die empirische Daten zur Monetarisierung und Leitfäden zur Vermeidung von Doppelzählungen benötigt werden. Zudem sind finanzwissenschaftliche Analysen erforderlich, die Verteilungseffekte auf verschiedene demographische Gruppen untersuchen.

Im Hinblick auf die praktische Anwendung des EE1st-Prinzips bietet diese Forschungsarbeit eine handlungsorientierte Anleitung für politische Instrumente und strategische Energieplanung. Diese Anwendung erfordert solide Ex-post-Evaluierungen der ergriffenen Maßnahmen, was wiederum umfassende Monitoring- und Berichterstattungsprozesse voraussetzt. Außerdem ist ein besseres Verständnis von Policy-Mixes erforderlich, wobei die kollektiven Auswirkungen und die Kompatibilität verschiedener politischer Instrumente berücksichtigt werden müssen.

Zusammenfassend lässt sich sagen, dass das EE1st-Prinzip das Potenzial hat, eine wirtschaftlich tragfähige, nachhaltige und gerechte Wende hin zu einem treibhausgasneutralen Energiesystem in der EU bis 2050 zu schaffen. Die derzeitige politische Dynamik bietet die Möglichkeit, wirksame Maßnahmen zu ergreifen. Es bleibt jedoch abzuwarten, wie die Mitgliedstaaten das EE1st-Prinzip interpretieren, umsetzen und über dessen Anwendung berichten werden. Dies wird entscheidend für die Erreichung der ehrgeizigen Energie- und Klimaziele der EU sein.

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The 'energy efficiency first' (EE1st) principle has become a key element of the European Union's (EU) strategy to transition to a net-zero emissions energy system. This principle advocates prioritising energy efficiency solutions, such as building retrofits, when they cost less or provide greater societal benefits than traditional energy supply infrastructure, such as power plants. Despite its inclusion in the EU Governance Regulation and the recast Energy Efficiency Directive, the implementation of the EE1st principle across Member States faces both conceptual and practical challenges. This research makes three main contributions: First, it provides a thorough investigation of the theoretical foundations of the EE1st principle through a combination of literature review and conceptual analysis, thereby integrating the principle into the broader research literature and clarifying its implications for EU policymaking. Second, it analyses the quantitative effects of the principle using energy systems modelling and cost-benefit analyses, examining the balance between energy savings in the building sector and the associated energy supply needs for electricity, heat, and hydrogen in the EU's net-zero transition. Finally, based on a literature review of economic theory and semi-structured interviews, the research provides policy guidance by categorising potential policy instruments and presenting a decision tree framework to facilitate energy planning. Altogether, this research highlights the critical role of the EE1st principle in moving the EU towards net-zero emissions by providing conceptual clarity, empirical evidence, and actionable guidance.

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