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Review and guidance for quantitative assessments of demand and supply side resources in the context of the Efficiency First principle

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EXECUTIVE SUMMARY

« Efficiency First » (E1st) is a compelling principle of energy planning as it seeks to provide a socially optimal deployment and operation of demand and supply side resources. In practice, however, taking explicit account of E1st in system planning and policy design is a complex planning exercise that is subject to uncertainties. Energy models play a vital role in making these complexities and uncertainties tangible and in enabling decision-makers to make informed decisions on policy design, future technology and infrastructure investment, as well as system operation. Existing models are diverse in terms of objectives, geographical scopes, technologies and energy sectors considered, spatiotemporal resolutions and other properties. Yet, given the novelty of the concept of E1st in the political and academic debate, at present there are only few model-based studies that make explicit reference to the E1st principle and to its implications for quantitative modelling. Against this background, the **objective of this report** is to provide modellers and policymakers with a comprehensive guidance on conceptual implications and on existing quantitative approaches for assessing demand and supply side resources in the light of the E1st principle.

With respect to the **conceptualization of E1st for quantitative modelling**, this report recapitulates the definition of the E1st principle adopted in ENEFIRST and highlights implications of four particular aspects within this definition. Most fundamentally, the E1st principle requires an explicit comparison of demand and supply side resources. Second, planning and policy objectives provide a common functional unit for these assessments. Third, cost-effectiveness is one important decision criterion for the selection and prioritization of resource options that can be assessed through cost-benefit analysis (CBA) and other appraisal techniques. Finally, the E1st principle presupposes a societal perspective, which implies, inter alia, the inclusion of multiple impacts to represent the long-term social welfare effects of different resources.

Following this conceptual background, this report provides a thorough description of **existing modelling approaches** associated with the concept of E1st. First, it introduces two paradigms of quantitative assessments for E1st. While the **normative paradigm** investigates what resources should be adopted to reach an anticipated vision of the future, the **exploratory paradigm** seeks to project the actual adoption of demand and supply side resources. Second, it provides considerations on modelling E1st at different **levels of analysis**: national, utility, and buildings. It thereby shows that there is no universal model for representing E1st and that each model-based assessment is nested in a trade-off between data needs and computational complexity versus robustness and credibility of the model outcomes. Finally, the report discusses **three challenges** to modelling the trade-off between demand and supply side resources with respect to the E1st principle: *(1)* to capture a broad array of **multiple impacts** and to monetize them, where possible; *(2)* to apply **social discount rates**, unless a model aims to simulate actual technology adoption behaviour; *(3)* to ensure sufficient **model detail** to represent the true costs of supply-side resources and the value of demand-side flexibility options.

To conclude, this report advances the nascent field energy modelling in the context of the E1st principle. As such, it provides the methodological foundation for several upcoming reports in the ENEFIRST project:

- **Energy system analysis for EU-27:** Model-based assessment of the contribution of demand side resources in the buildings sector to achieve EU climate targets for the year 2050;
- **Five local case studies for urban areas:** Model-based assessment of the contribution of demand side resources in residential and non-residential buildings to achieve local planning and policy objectives.

1 INTRODUCTION

« Efficiency First » (E1st) is a principle in energy system planning that prioritizes investments in energy efficiency, demand response and other demand side resources whenever these are more cost-effective from a societal perspective in meeting planning objectives than generators, networks and other supply-side assets. In a previous ENEFIRST report (Pató et al. 2020), the E1st principle is shown to bear resemblance Least-Cost Planning (LCP), Integrated Resource Planning (IRP), and other existing concepts of energy planning. However, the report also highlights unique features of E1st that go beyond existing concepts:

- E1st is not limited to power system planning, but addresses the entire **energy system –** i.e., demand-side planning in all end-use sectors (buildings, industry, transport) versus supply-side planning concerning all energy carriers for final energy use (electricity, gas, district heating, oil products, etc.);
- It advocates decision-making from a **societal perspective**, which includes the explicit consideration of multiple impacts in determining costs and benefits of demand and supply side resources;
- Its **time horizon** is not restricted to energy utilities' short-term business planning, but applies to various time frames – from short-term system operation to medium-term and long-term investment planning.

From a theoretical viewpoint, the E1st principle is compelling in a way that it seeks to maximize social welfare and meeting planning objectives by optimizing the deployment of various resources. Yet from a practical perspective, taking explicit account of E1st in system planning and corresponding policy design is a complex planning exercise that is subject to **uncertainties** (Santori et al. 2015). Broadly speaking, the aggregate adoption of demand side resources (e.g. energy efficiency measures) depends on demographic dynamics (e.g. population growth), economic trends (e.g. growth in gross domestic product, GDP), weather and climate conditions (affecting the demand for heating and cooling), existing regulatory provisions, technology costs, energy carrier prices, and manifold consumer preferences. In turn, the deployment of supply side assets (e.g. distribution network upgrade) is affected by fuel price dynamics, political decisions about the discontinuation of certain types of energy sources (e.g. coal-fired power plants), technology costs and the system of incentives (e.g. subsidies on renewable energy sources), environmental requirements imposing additional costs to energy production, market structure, utility regulation and more.

In consideration of **uncertainties**, along with high levels of **complexity** in the energy system, **energy models** play an indispensable role in system planning, its operation as well as policy formulation (Blok and Nieuwlaar 2016; Connolly et al. 2010).[1] Designed by engineers, economists and planners, these models operate upon input data and assumptions, so called exogenous variables. Based on these variables, target values are calculated through the model, referred to as endogenous variables. Taken together, the numerical assumptions and calculations result in a range of possible trajectories and target states that can

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[1] Some researchers suggest a distinction between energy models and modelling tools (IRENA 2017). A model is then referred to as a set of mathematical equations with parameters, equipped with an algorithm to solve the equations. Modelling tools are referred to as graphical interfaces in a software package that help users handle the equations and data of a model. In this report, we refrain from this distinction and use the general term 'energy models' to cover both aspects – mathematical foundation and graphical interfaces.

assist decision-makers in making informed decisions on future technology investment, system operation as well as policy design (Behn and Byfield 2016; Blok and Nieuwlaar 2016; DeCarolis et al. 2012).[2]

In recent years, there has been a high level of activity in the development of energy models, with many new models and features emerging in the academic literature. Various researchers have attempted to provide comprehensive **reviews of existing energy models**. To highlight some, Ringkjøb et al. (2018) present a thorough review of 75 modelling tools currently used for energy and electricity systems, ranging from small-scale power system analysis tools to global long-term energy models. At a local level, Ferrari et al. (2019) consider 17 modelling tools for local energy planning in urban areas to evaluate the potentials and combinations of different energy technologies. At a global scale, Krey et al. (2019) conduct a comprehensive review of integrated assessment models, used to explore the interface between energy, land, food, water and climate. It is evident from these review studies that energy models are diverse in terms of objectives they address, regional scopes, technologies and energy sectors considered, spatiotemporal resolutions and other properties.

Given the novelty of the E1st principle in the political and academic debate, there are hardly any **dedicated quantitative assessments explicitly relating to the E1st principle**. For the case of the German power sector, Wünsch et al. (2014) assess the economic benefits of energy efficiency measures by calculating across scenarios the total costs of the electric power system, including power generation and electrical grids at the distribution and transmission levels. The key finding of this study is that saving one kilowatt-hour (kWh) of electricity would lead to reduced electrical system costs of between 11 to 15 euro cents by 2035, depending on the exogenous assumptions. For the German buildings sector, Langenheld et al. (2018) investigate the cross-sectoral effects of building efficiency measures on total economic cost of heat supply, under the constraint of meeting climate targets for the year 2050. They find that strategic planning for enhanced energy efficiency in buildings, along with a boosted deployment of heat pumps, would provide the most economical solution to meeting energy service demands as well as climate targets.

Note that besides the few dedicated quantitative assessments for E1st, there is ample experience with **quantitative assessments for the related U.S. practices of LCP and IRP**. For example, Swisher et al. (1997) present tools and methods for projecting energy demand and calculating costs in the context of IRP. Duncan and Burtraw (2018) provide general thoughts on quantifying the value of demand side resources in IRP. Eto (1990) gives an overview of modelling tools for IRP and elaborates on the complexities of demand and supply side resource quantification. In the context of the early interest for LCP and IRP in Europe in the 1990s (Pató et al. 2020) before the liberalization of the electricity and gas markets, Dreher et al. (1999) propose an energy-emission modelling approach for the development of LCP/IRP strategies for electric utilities in Germany. Overall, however, as the E1st principle has unique features that distinguish it from other existing practices, it also requires dedicated conceptual considerations and quantitative approaches.

Against this background, the **objective of this report** is to provide a comprehensive methodological review and guidance for the conceptualization and model-based quantification of the E1st principle. As such, it

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[2] The merits of using energy models to inform policymaking and energy investment are discussed comprehensively in research literature. For instance, Mai et al. (2013) elaborate on how models and scenarios are used to guide decision making under uncertainty. Moreover, they describe typical pitfalls in interpreting modelling outcomes and underline that scenarios are not expected to predict the future.

informs analysts and policymakers engaged in energy system planning and policy design about existing approaches and challenges in assessing the trade-off between demand and supply side resources for a given planning case.

To substantiate this report, a series of 18 **semi-structured interviews** (Bryman 2012) was conducted with experts in the fields of energy systems modelling and policy design. Interviewees were acquired from intergovernmental organizations such as the International Energy Agency (IEA), network operators represented by the European Network of Transmission System Operators (ENTSO-E), research institutes (e.g. Wuppertal Institute), and other institutions. Presented in the Annex of this report, interviewees were asked a series of predefines questions about the E1st principle and its relation to different aspects of quantitative modelling. Given the semi-structured design of the interviews, interviewers were given latitude to ask further questions in response to what are seen as significant replies and to adjust the emphasis of the interview at their discretion. Overall, the interviews were used to both challenge and substantiate the findings in this report. Note, however, that the information and views set out in this report are those of the authors and do not necessarily reflect the opinion of the interviewees.

This report is structured as follows. **Chapter 2** provides a conceptual background to quantitative assessments of the E1st principle. Based on the principle's definition adopted in the ENEFIRST project, it describes the principle's major implications for model-based assessments of demand and supply side resources. Subsequently, **Chapter 3** describes established modelling approaches that can be used to provide quantitative assessments of the E1st principle at different levels of analysis. In addition, it discusses three methodological challenges that such model-based assessments are likely to face and provides possible avenues and recommendations for addressing them in practice. Finally, **Chapter 4** concludes this report.

2 BACKGROUND: CONCEPTUALIZATION OF THE E1ST PRINCIPLE FOR QUANTITATIVE MODELLING

The purpose of this chapter is to provide a detailed conceptual understanding of the major implications of the concept of E1st for quantitative energy modelling. Based on the definition of the E1st principle developed in the first report of the ENEFIRST project (Pató et al. 2020), this chapter elaborates on several aspects of E1st that are critical for any quantitative model-based appraisal related to it. **Figure 1** recapitulates the definition of E1st developed in the project.[3]

> **'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 planning and 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.

Figure 1. Definition of the E1st principle adopted in the ENEFIRST project.

Source: Authors' own, based on (Pató et al. 2020).

Four particular aspects of this definition are highlighted in the following. Each of these aspects has important implications for carrying out quantitative assessments in line with the E1st principle: demand side resources vs. energy infrastructure (**Section 2.1**); planning and policy objectives (**Section 2.2**); cost-effectiveness (**Section 2.3**); and societal perspective (**Section 2.4**).

2.1 Demand vs. supply side resources

Systematic assessments and comparisons of demand and supply side resources are the unique feature of the E1st principle. As discussed in a previous report of the ENEFIRST project (Pató et al. 2020), this is what essentially differentiates the principle from long-established practices of focusing on energy efficiency in isolation by means of economic and regulatory programs while disregarding the cost implications of these programs on the supply side of the energy system (e.g. avoided network infrastructure costs). In turn, a comparison of different energy supply options without including demand side options also would not

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[3] As elaborated on in (Pató et al. 2020) multiple definitions of the principle have been brought forward by different institutions and legislations, most notably the EU Governance Regulation (EU, 2018/1999, Art. 2.18).

qualify as an assessment of the E1st principle. For example, the Levelized Cost of Energy (LCOE) method has been used for numerous purposes of cost evaluation of renewable and non-renewable power supply options (Hansen 2019), however, while leaving aside demand side resources and thus not reflecting the E1st principle. To illustrate the concept of E1st, **Figure 2** provides a taxonomy of demand and supply side resources that are typically relevant in contemporary energy systems planning.

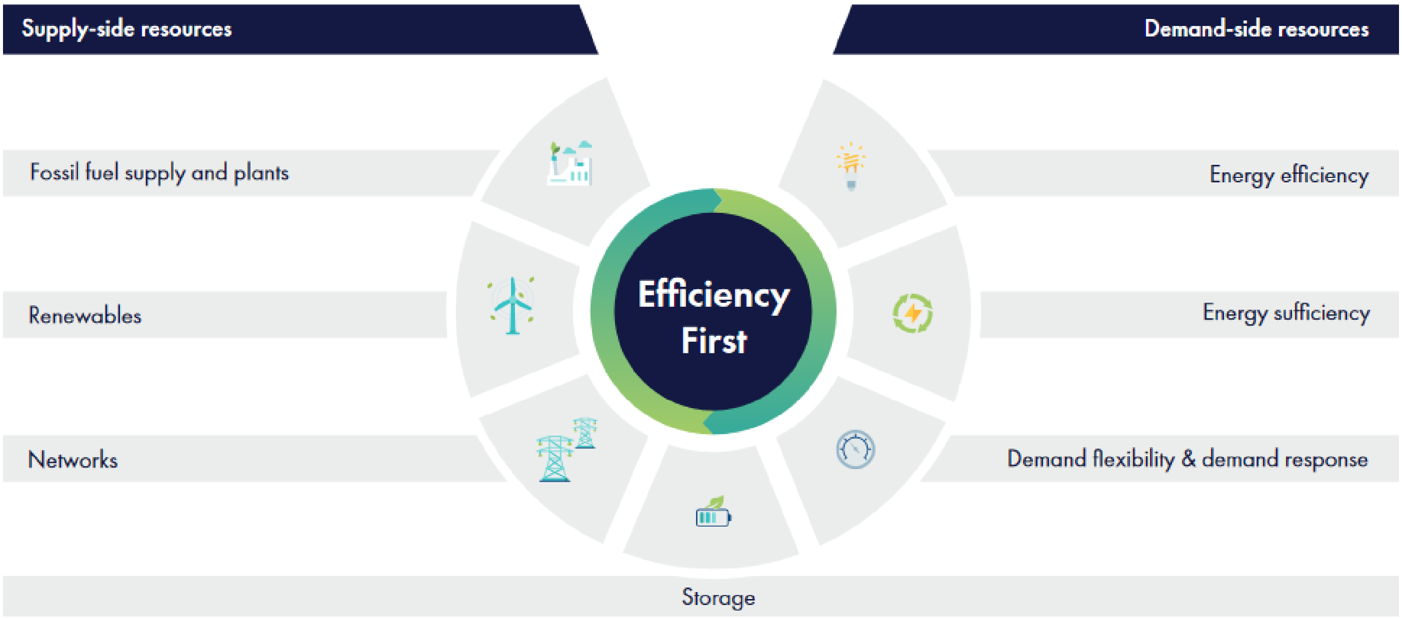

Figure 2. Taxonomy of supply- and demand-side resources in the context of the E1st principle.
Source: Authors' own.

On the demand side, **energy efficiency** is an essential resource. As energy is used to fulfil human needs, the energy efficiency of an activity may be defined as the degree to which given energy services (i.e. human needs) are fulfilled with a minimum amount of energy.[4] **Energy sufficiency** can also be considered an important demand side resource. It means any changes that permanently reduce energy services, for example behaviour changes for a lowered indoor temperature in buildings or a reduced travelling distance, regulations requiring lights to be off after a given night hour in commercial buildings, adapting minimum energy performance standards to favour smaller appliances or lighter vehicles, and more. Finally, **demand flexibility & demand response** means the change of load by final customers from their normal or current consumption patterns in response to market signals (European Union 2019). It may take different forms depending on consumers' consumption volumes and patterns. There is an established distinction between explicit demand response (consumers commit their flexibility upfront to markets or system operators in return for an incentive payment) and implicit demand response (consumers choose to shift their energy use in response to variable prices) (EURELECTRIC 2015; IRENA 2019).

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[4] An illustrative example is the energy efficiency improvement of lighting: A candle has a light production of less than 1 lumen (lm) per watt; incandescent lamps were a major improvement (approximately 15 lm/W), but modern LED lights provide even greater efficiency (100 lm/W and more) (Blok and Nieuwlaar 2016).

On the supply side, the taxonomy refers to various energy production and conversion processes. **Fossil fuel supply and plants** means thermal power plants, boilers, cogeneration, heat pumps (power-to-heat) and other equipment that do not run entirely on renewable energy carriers. **Renewables** comprise, for example, wind turbines, solar photovoltaics (PV), concentrated solar power (CSP), geothermal energy, and other established and emerging technologies. **Networks** are used to transport and distribute power, gas, and heat, which includes wires, poles, substations, pipelines, and other assets.

Storage means technologies to defer the final use of energy to a moment later than when it was generated (European Union 2019), such as batteries, gas and thermal storage, but also technologies which convert electric energy into fuel such as hydrogen and methane (power-to-gas). They are indicated on both sides of the taxonomy to highlight their various applications, ranging from large utility-scale infrastructures to behind-the-meter battery storage that can enable demand flexibility.

Note that overall, the supply side in this taxonomy comprises both i) utility scale supply technologies (e.g. gas-fired power plant) but also ii) supply technologies used onsite by consumers (e.g. heat pump). **We thus here apply a definition of the E1st principle giving priority to end-use efficiency** (i.e. limiting the needs in investments in supply technologies or infrastructures). In other contexts, distributed energy resources (DER) – such as behind-the-meter batteries or rooftop solar PV – are referred to as demand side resources because their use occurs beyond utility-scale/commercial energy conversion activities, and when operated for own use, they can reduce the needs in networks and large-scale generation (e.g. Dyson et al. 2018). Likewise, supply-side efficiency (e.g. use of CHP – Combined Heat and Power, excess heat utilization, reduced losses in networks) can be complementary ways to optimize energy systems, reducing primary energy consumption. Either way, the scope of demand and supply resources to be considered in a quantitative assessment of the E1st principle is contingent on the scope of the project. This matter of **planning and policy objectives** is elaborated on in the following section.

2.2 Planning and policy objectives

E1st is not merely about assessing the costs and benefits of demand and supply side resources, but about making these assessments in the context of given objectives. These can be, for example, developing new capacity to meet increasing demand in an urban area, improving technical reliability and security of energy supply, tackling energy poverty or reducing greenhouse gases and pollutant emissions produced by the energy sector (Santori et al. 2015). These examples can be broken down into **planning objectives** and **policy objectives**.

The most fundamental planning objective is to meet energy needs by providing **energy services** in a given society or economy. An energy service is defined as the result of human activity obtained through the use of energy and satisfying a human need. Examples of energy services are heating or lighting a certain area of working space, travelling a certain distance, or producing a certain amount of steel (Blok and Nieuwlaar 2016; Pfenninger et al. 2014). Energy services are often grouped by **end-uses**. For example, the various electrical appliances used in households (e.g. refrigerator for energy service of perishable food storage, washing machine for energy service of getting clean clothes) are typically grouped into the end-use of lighting and electrical appliances (Eurostat 2013).

Quantitative assessments of the E1st principle may focus on one or several end-uses and evaluate the societal costs and benefits for providing these end-use via different combinations of demand and supply side resources. For example, one may evaluate whether investments in thermal refurbishments of buildings are more cost-effective than an upgrade of a local district heating network in providing the end-use of space heating (adequate indoor temperature). According to the sector under consideration (residential, commercial and public services, industry), the scope of end-uses and demand and supply side resources differs. To illustrate the significance of different end-uses, **Figure 3** shows the final energy demand for the residential sector in the EU-27 by end-use and energy carrier.

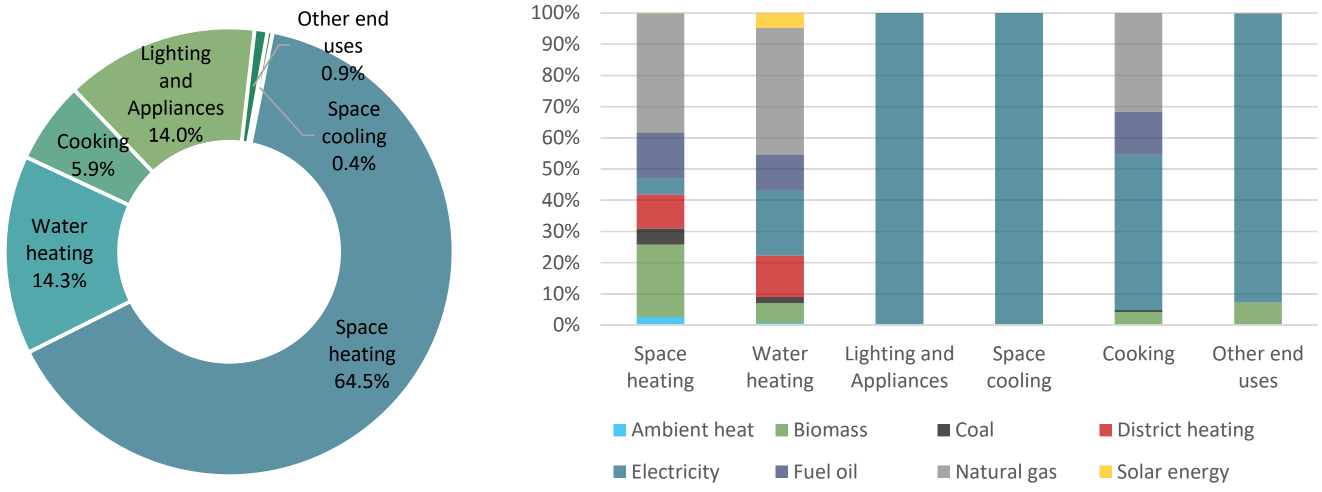

Figure 3. Final energy demand in the EU-27 residential sector by end-use and energy carrier in 2017.

Source: Authors' own, based on (Eurostat 2020).

As seen in the left-hand chart, space and water heating together account for about 79% of residential energy demand in the EU-27 and thus represent a critical research object for quantitative assessments of the E1st principle. Another important end-use is lighting and appliances. Quantitative assessments of the E1st principle may here evaluate energy efficiency and demand response as demand side resources against the costs of power generation, networks, and storage facilities on the supply side. Moreover, as illustrated in the right-hand chart, the end-uses differ by the range of energy carriers, and thus range number of supply side resources, potentially involved in the assessment. For example, comprehensive assessments of E1st for space and water heating would not only need to consider infrastructures for electricity provision, but also for district heating and gas as grid-bound infrastructures. Such multi energy carrier assessments are thus inherently more complex than assessments which involve only electricity as a single energy carrier (e.g. lighting and appliances) (Guelpa et al. 2019).

In assessments of the E1st principle, **policy objectives** may complement the general planning objective of providing energy services. For example, assessments of the societal costs for providing space heating in an urban settlement may be supplemented by the constraint that each resource configuration must meet a given greenhouse gas emission reduction target. The assessment would thus identify those demand and supply resources that are most cost-effective in providing energy services while complying with the policy objective. Depending on the research object, policy objectives included in quantitative assessments of the E1st principle will certainly differ. At the EU level, the Commission's Energy Union Strategy (European Commission 2015) comprises a set of five key objectives: i) security of supply, ii) internal energy market, iii) energy efficiency, iv) decarbonisation, and v) innovation. In turn, local energy planning may be, for example, more driven by local pollution reduction targets and local employment.

To conclude, an essential property of quantitative assessments for E1st is not just the comparison of demand and supply side resources but also the presence of a common functional unit in terms of planning and policy objectives. In the absence of such common objectives, the costs of different resources are hardly comparable and thus provide little support for investment decisions. Comparisons based on different scopes could create bias in informing decision-making. Next, the following section elaborates on the E1st aspect of 'cost-effectiveness'.

2.3 Cost-effectiveness

Cost-effectiveness can be considered the most significant aspect of the E1st definition. It is also one of ample latitude for interpretation. In general economic terms, **cost-effectiveness** is about judging all positive (**benefits**) and negative (**costs**) welfare effects of an investment option and to select those investments for which total benefits exceed total costs. The underlying appraisal technique is **cost-benefit analysis** (CBA) (Santori et al. 2015; Jordan and Turnpenny 2015).[5]

More specifically, in the context of the E1st principle, applying CBA means to systematically calculate the costs and benefits of all relevant demand side resources (e.g. thermal refurbishment of building) and all relevant supply side resources (e.g. district heating generation, networks, and storage assets). This **scope of resources** depends on the planning context, geographic location, renewable energy potentials and other factors. In any case, to take adequate account of the E1st principle, the scope of resources must not be limited to different supply side resources (e.g. district heating system based on biomass or heat pump) but must explicitly include a set of demand side options that can comply with planning and policy objectives.

Under consideration of CBA, the E1st principle postulates that demand side resources must be prioritized whenever they are more cost effective (i.e. create greater benefits) than alternative supply side options. Suppose that there are $i = 1 \dots n$ competing demand and supply side resources and t time steps [a], with corresponding investments I [EUR], benefits B [EUR], costs C [EUR], discount rates r [%/a], and technology lifetimes n [a]. The selection of demand and supply side resources for a given planning case can then be written in the form of net present values (NPV):

$$NPV_i = -I_i + \sum_{t=1}^{n} \frac{B_{i,t} - C_{i,t}}{(1 + r_i)^{t_i}}$$

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[5] It is arguable whether CBA should be the only one input to making recommendations about decisions on investments and policies in the context of the E1st principle. As pointed out by Atkinson et al. (2018), there is a significant array of other appraisal techniques that can substantiate or complement CBA and add different facets of evidence relevant to the decision-making process. For example, multi-criteria analysis (MCA) provides a coherent framework for scoring and weighting various decision relevant parameters relating to "cost-effectiveness" but also "equity" and "administrative simplicity and governance" and others. As such, MCA may go further than CBA, which can only include such parameters to the extent these can be reflected in robust monetary valuation. Another relevant appraisal technique for cost-benefit practitioners are participatory approaches that can be particularly useful for projects where lack of participation can easily create public opposition. The list of appraisal techniques can be continued with cost-effectiveness analysis (CEA), risk assessment, and environmental assessment. See (Atkinson et al. 2018; Santori et al. 2015; Jordan and Turnpenny 2015) for a detailed discussion of these different appraisal techniques.

The NPVs could be ranked to select as many resources needed to fit the total demand for energy services $\bar{E}$ [e.g. m² of heated living space in buildings] through summation of the energy services provided by the individual resources E_i:

$$Rank\ by\ NPV_i\ \ s.t. \sum_i E_i = \bar{E}$$

This formulation is deceptively simple as there are a number of critical properties that are inherent to every CBA. The general challenge is to have a **common numerical basis** for comparing benefits (B) and costs (C), which involves assigning monetary values to impacts of demand and supply side resources (Atkinson et al. 2018). *What* costs and benefits should be within the scope of a CBA essentially depends on the perspective taken (societal vs. private) and is discussed in the following section. In addition, the question arises *how* and by what methods to quantify and monetize the multiple impacts of demand and supply side resources. As a general challenge to modelling the E1st principle, this issue is dealt with in detail in **Chapter 3.3.1**.

Another important property is the **discounting of costs and benefits**. Costs and benefits will accrue over time and the general rule in CBA is that future costs and benefits are weighted so that a unit of benefit or cost in the future has a lower weight than the same unit of benefit or cost now. Note that this discounting is unrelated to the effect of inflation, which, by using *real* instead of *nominal* money terms, is usually netted out in CBA to ensure that values are comparable from year to year (Atkinson et al. 2018). As a second challenge to modelling the E1st principle, the topic of selecting appropriate discount rates is elaborated on in **Chapter 3.3.2**.

Finally, CBA acknowledges that future costs and benefits will not be known with certainty. In applying the E1st principle via CBA it is therefore important to take into account **risk and uncertainty**. A risk context is where costs and benefits are not known with certainty, but a probability distribution is known. Uncertainty in turn is different in a way that there is no known probability distribution (Atkinson et al. 2018). In practice, this means that, if the context is one of uncertainty, quantitative assessments of the E1st principle should, at the very least, be accompanied by sensitivity analyses (Saltelli et al. 2004). The CBA is then computed with different values of the parameters about which there is uncertainty. If least-cost mix of demand and supply side resources remains largely unaffected by these variations, the analysis is said to be robust.

2.4 Societal perspective

The E1st principle postulates that costs and benefits are evaluated from a societal perspective, which needs to be distinguished from a private perspective. Broadly speaking, from a **societal perspective**, net economic effects of the implementation of demand and supply side resources, i.e. social welfare gains or losses, are assessed. In other terms, the societal perspective may be easily defined as all costs and benefits accruing to the society as a whole.[6] In turn, the **private perspective** assesses the profitability of

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[6] Quantitative assessments of the E1st principle would typically work with national or local boundaries, so that 'society' can be equated with the sum of all individuals in these territories. However, in the case of environmental indicators in CBA, the boundaries may need to be set more widely, for example in the case of greenhouse gas emissions (Atkinson et al. 2018).

demand and supply side resources as well as its financial viability for the asset owner and some key stakeholders (Ürge-Vorsatz et al. 2016; Santori et al. 2015).[7] Taking either of the two perspectives in CBA and quantitative assessments of the E1st principle has important implications.

The societal and private perspective have common features and differences concerning the accounting of the **costs and benefits** associated with demand and supply side resources (**Table 1**). The fundamental costs in both perspectives are the investment and operation and maintenance (O&M) costs associated with the construction, modernization or improvement of the supply and demand side resources. Typical investment costs are technological installations and land acquisition. O&M costs can be differentiated between variable and fixed costs, depending on whether they vary with the quantity of energy produced/distributed or not. Fixed O&M costs usually include labour costs, periodic fixed maintenance and repairing costs, insurance costs, and other general overheads. The most relevant variable O&M costs are energy fuel costs, variable overheads, or the cost of greenhouse gas (GHG) emission allowances purchased within the European Emission Trading System (ETS) (Santori et al. 2015).

Table 1. Benefits and costs of societal and private evaluation perspectives.

Source: Authors' own, based on (Ürge-Vorsatz et al. 2016; Santori et al. 2015; Bhattacharyya 2019).

Evaluation perspective	Benefits	Costs
Societal	Direct benefits for society, e.g. ▪ additional employment ▪ increased competitiveness ▪ increased energy security ▪ impacts on social welfare ▪ …	(Incremental) costs of demand and supply side resources (excl. taxes and other transfers) Negative externalities Other costs for society, e.g. ▪ policy implementation costs ▪ transaction costs
Private	Subsidies and other transfers Direct benefits for investors/end-users, e.g. ▪ comfort gains ▪ noise reduction ▪ increased building value ▪ health improvements ▪ …	Incremental costs of demand and supply side resources (incl. taxes) Investment risk Other costs for investors/end-users, e.g. ▪ transaction costs ▪ opportunity costs

In the accounting of investment and O&M costs, both perspectives must account for **transfer payments** between different parties. Economic theory suggests, from a societal perspective, that these payments should not be considered either a cost or a benefit because they cancel each other out. Taxes and subsidies are usually considered transfer payments that do not represent real economic costs or benefits

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[7] Besides this general distinction between societal and private perspective, energy utilities and regulators in the U.S. have been active since the late 1980s in defining a set of five cost-effectiveness tests to evaluate the costs and benefits of demand side measures against alternative supply side options from different perspective (CPUC 2001; Woolf et al. 2012). In essence, these tests disaggregate the private perspective by considering costs/benefits accruing to utilities (Program Administrator Test), to consumers who receive energy efficiency incentives (Participant Test), and to consumers who do not benefit from incentives but may need to pay higher tariffs (Ratepayer Impact Test). Overall, these tests are less applicable to the EU context because of a different tradition of the state being the entity that implements demand side programs instead of utilities, as well as the absence of vertically-integrated utilities that can pass on costs incurred to the consumers.

for society as they involve merely a transfer of control over certain resources from one group in society to another (Santori et al. 2015; Woolf et al. 2012). The societal perspective should thus consider prices net of value added tax (VAT), as well as net of direct and indirect taxes.[8] In turn, taxes and subsidies remain in the private perspective to reflect actual cash flows accruing to stakeholders.

Another difference is the **accounting of multiple impacts**. One major category of multiple impacts are **direct benefits**, referring to impacts generated on consumers due to the use of demand or supply side resources, which are relevant for society, but for which a market value is not available (Santori et al. 2015). From the societal perspective, examples of direct benefits are economic effects such as the creation of jobs and additional growth and the increase in competitiveness and innovative strength, combating energy poverty, increasing energy security, and more (IEA 2015). However, direct benefits can also arise for the private investor, for example in the form of greater living comfort, a higher property value, better air quality, a better environment at the workplace (e.g. through a more pleasant indoor climate or lighting). When multiple impacts do not occur in the transactions between the producer and the direct users of the project services but fall on uncompensated third parties, these impacts are defined as **externalities**. In other terms, an externality refers to any cost or benefit that spills over from the resources towards other parties without monetary compensation (Santori et al. 2015). **Box 1** presents an overview of typical externalities in the context of energy systems planning. By definition, externalities are not taken into account by investors in the private perspective – unless a tax or other mechanism has been designed to reflect these externalities, e.g. a carbon tax to take account of the GHG emissions. For the societal perspective, however, their consideration is crucial to assess welfare effects for the entire society.

Moreover, there are **other costs** that are considered differently in the two perspectives. Important for the societal perspective are policy implementation costs, e.g. for building codes. This includes expenditures by the government and public authorities to design, plan, administer, deliver, monitor, and evaluate these programs. These policy implementation costs are irrelevant for the private perspective. However, both perspectives may consider transaction costs, e.g. the costs for determining suitable demand and supply side resources for the given planning and policy objectives.

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[8] In some cases, indirect taxes (or subsidies) are intended as a correction for externalities, e.g. taxes on NO_X emissions to discourage negative environmental externalities. In these cases, it is justified to include these taxes (subsidies) in the CBA, provided that they adequately reflect the underlying marginal costs. However, the appraisal should avoid double counting (e.g. including both energy taxes and estimates of full external environmental costs) (Santori et al. 2015).

Box 1. Examples of environmental externalities.

Source: (Santori et al. 2015).

Air pollution: Emissions of localized air pollutants (e.g. SO_2, NO_X, PM, VOC, mercury and other heavy metals) negatively impact human health, generate loss of crops, and affect ecosystems. It is relevant to various forms of thermal generators, e.g. power plants, cogeneration plants, and boilers.

Greenhouse gas emissions: Fuel combustion or production process emissions emit greenhouse gases (GHG) into the atmosphere. The impact of GHG emissions is worldwide due to the global scale of the damage caused, thus it is irrelevant where the GHG emissions take place.

Soil contamination: Industrial activity, agricultural chemicals or improper disposal of waste may cause contamination of soil. It can have effects on production, consumption and human health.

Noise: Noise emissions can affect activities and human health. It is mainly relevant for supply side infrastructures in proximity of densely populated areas.

Water pollution: When pollutants are discharged directly or indirectly into water bodies without adequate treatment to remove harmful compounds, water bodies can be contaminated, e.g. lakes, rivers, oceans, aquifers and groundwater.

Ecosystem degradation: Supply side infrastructures can increase habitat fragmentation and contribute to deterioration of diversity, loss of habitats and species.

Landscape deterioration: This refers to a loss of recreational or aesthetic value through the construction of infrastructures.

Finally, another key difference between the societal and the private perspective is the level of the **discount rate** applied to costs and benefits occurring at different times. The private perspective implies a **financial discount rate** (FDR), while the societal perspective requires a **social discount rate** (SDR). The FDR reflects the opportunity cost of capital[9] from the perspective of businesses, utilities and private investors and takes into account the risk of the anticipated future cash flow being less than expected (Santori et al. 2015). In turn, the SDR reflects the opportunity cost of capital from an inter-temporal perspective for society as a whole. In other terms, it is about the social view of how future benefits and costs are to be valued against present ones. A SDR of zero means that equal weights are given to costs and benefits occurring at any moment, i.e. that today's and future consumptions are indifferent to the point of view. A positive discount rate, on the contrary, indicates a preference for current over future consumption, whereas the opposite applies if the discount rate is negative (Santori et al. 2015). In practice, based on these considerations, the SDR (typically 3-7%) is much lower than the FDR (typically 7-25% for energy projects). Chapter 3.3.2 presents the selection of an appropriate discount rate as one of three principal challenges in quantitative assessments of the E1st principle.

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[9] When private investors commit capital to an investment project, they have an implicit cost deriving from sacrificing a return to another project. In other words, the resources employed have an opportunity cost. Thus, to induce the investment, the expected return should be at least as high as the opportunity cost of funding (Santori et al. 2015).

To conclude this chapter, the theoretical notion of the E1st principle has various implications for quantitative modelling. Most fundamentally, the E1st principle requires an explicit **comparison of demand and supply side resources**. Planning and policy **objectives** provide a common functional unit for these assessments. **Cost-effectiveness** is one major decision criterion for the selection and prioritization of resource options and, through the method of CBA, has distinct methodological features, including monetization and discounting of costs and benefits. Finally, the E1st principle presupposes a **societal perspective** in the assessment of demand and supply side resources, which implies, inter alia, the inclusion of multiple impacts to represent the net social welfare effects of different resources. Following these conceptual considerations, **Chapter 3** describes existing modelling approaches that can provide quantitative assessments demand and supply side resources at different planning levels and discusses methodological challenges in the light of the E1st principle.

3 RESULTS: APPROACHES AND CHALLENGES IN QUANTITATIVE ASSESSMENTS OF THE E1ST PRINCIPLE

As described previously, energy models are an indispensable tool for decision-makers in government and utilities to make informed decisions on technology adoption and investment, operation decisions, as well as policy design in the light of the E1st principle. Following the conceptual background provided above, this chapter sets out to describe existing modelling approaches associated with the concept of E1st. **Section 3.1** introduces two **paradigms of quantitative assessments** for E1st – normative and exploratory – and associates these paradigms with general types of **energy models**. **Section 3.2** takes a more in-depth look at how to assess the E1st principle at various **levels of analysis**: national level, utility level, and buildings level. Finally, **Section 3.3** presents three **methodological challenges** that quantitative assessments of E1st may be confronted with regardless of paradigms or levels of analysis: capturing multiple impacts, selecting discount rates, and modelling the deployment and operation of supply side resources.

3.1 Paradigms of quantitative assessments

The E1st principle grants priority to demand side resources whenever they are more cost-effective for society than supply side alternatives. From an analytical viewpoint, under consideration of the complexities and uncertainties of energy systems, the principle gives rise to two major research directions, referred to here as **paradigms of quantitative assessments for E1st**.[10]

One the one hand, it is worth investigating what demand and supply side resources *should* be adopted over time to reach an anticipated vision of the future. We refer to this as the **normative paradigm** to E1st. In other terms, this paradigm is based on a predefined future target state of the energy system as the basis for retrospectively determining which developments or measures are most beneficial from a societal viewpoint to achieve this state. To illustrate, Langenheld et al. (2018) run four coupled energy models to investigate what combinations of energy efficiency measures in buildings and supply-side investments can provide least-cost trajectories for the country of Germany to reach its climate targets for the years 2030 and 2050. The authors model a set of 5 scenarios that are all configured to reach these targets, ranging from a distinct focus on end-use efficiency in buildings to one centred on power-to-gas to cut emissions. Their analysis is substantiated by a semi-quantitative appraisal of multiple impacts. The study finds that the scenario with enhanced energy efficiency in buildings and boosted deployment of heat pumps would provide the most cost-effective pathways for the country to reach its long-term climate targets. As such, the normative paradigm to modelling E1st can help decision-makers identify priorities for policy design and technology investment, along with specific opportunities and risks associated with different pathways.

On the other hand, quantitative assessments might investigate what demand and supply side resources *could* or are likely to be adopted over time in response to socio-economic conditions. We designate this as

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[10] This distinction is closely associated with categories of scenarios brought forward in literature. Scenarios are commonly defined as a range of possible future situations that, in contrast to forecasts and stochastic models, reach further into the future and disregard from any statement as to the probability of a development (Behn and Byfield 2016). In the context of energy systems, IRGC (2015) distinguishes (a) forecast-based/reference, (b) exploratory, (c) normative, and (d) hybrid scenarios. In adopting the exploratory and normative categories, we here aim to provide a simple dichotomy of possible research direction in the light of the E1st principle.

the **exploratory paradigm** to E1st. In contrast to the normative paradigm, the target state in this paradigm is unknown before the energy models are run. It thus serves to estimate the actual adoption of demand and supply side resources in response to boundary conditions (exogenous variables) – including policies, energy prices, technology availability, and other variables. An example of the exploratory paradigm to E1st is the European Commission's analysis for its long-term climate policy vision "A Clean Planet for All" (European Commission 2018a, 2018b; Duwe et al. 2018). Based on the energy-climate-economy models PRIMES, GAINS, GLOBIOM, GEM-E3 and E3Me, this analysis computes a series of eight scenarios to analyse possible pathways for emissions reductions in the EU. Each of the scenarios features different levels of GHG emission reductions reached by 2050 as well as a different technology focus – ranging from energy efficiency (*EE*), to hydrogen (*H2*), circular economy (*CIRC*) and others. To outline to findings of the study, greater ambition towards end-use energy efficiency in the *EE* scenario – based on more frequent modernisation, digital smart solutions, labels, and more efficient appliances – is projected to reach an 80% GHG emission reduction by 2050. In turn, the scenario *1.5 LIFE* shows that a balanced combination of various resource options, along with stronger circular economy and significant lifestyle changes can reach net-zero emissions (100% reduction) by 2050, with total system costs being only slightly higher than in the *EE* (European Commission 2018a)[11]. As such, the exploratory paradigm can help identify the possible future performance and limitations of single resource options and thus drive decision-makers to investigate alternative portfolios of demand and supply side resources in the light of E1st.

These two paradigms of quantitative assessments for E1st can be associated with different **types of energy models (Figure 4)**. Following Pfenninger et al. (2014), one can distinguish (i) energy system optimization models, (ii) energy systems simulation models, and (iii) power systems and electricity market models. Certainly there are numerous ways to categorize energy models (Herbst et al. 2012; Ringkjøb et al. 2018), these three however provide a reasonable appraisal in the context of E1st.[12]

Energy system optimisation models are associated with the *normative paradigm* and use optimization methods to provide projections of how the system should evolve to reach given objectives. The most common optimization method is linear programming, with an objective function that is either maximised or minimised (e.g. minimize total system cost), subject to a set of constraints (e.g. balancing the supply and demand in the grid). More advanced methods include mixed-integer linear programming (MILP) that forces certain variable to be integral. Optimisation models can also be non-linear with objective function or constraints that are non-linear (Ringkjøb et al. 2018). MARKAL is probably the most widely used general purpose energy system optimization model. With addition of another optimization model (EFOM, Energy Flow Optimization Model), it evolved into TIMES (The Integrated MARKAL-EFOM System). Other established system optimization models include MESSAGE and OSeMOSYS.

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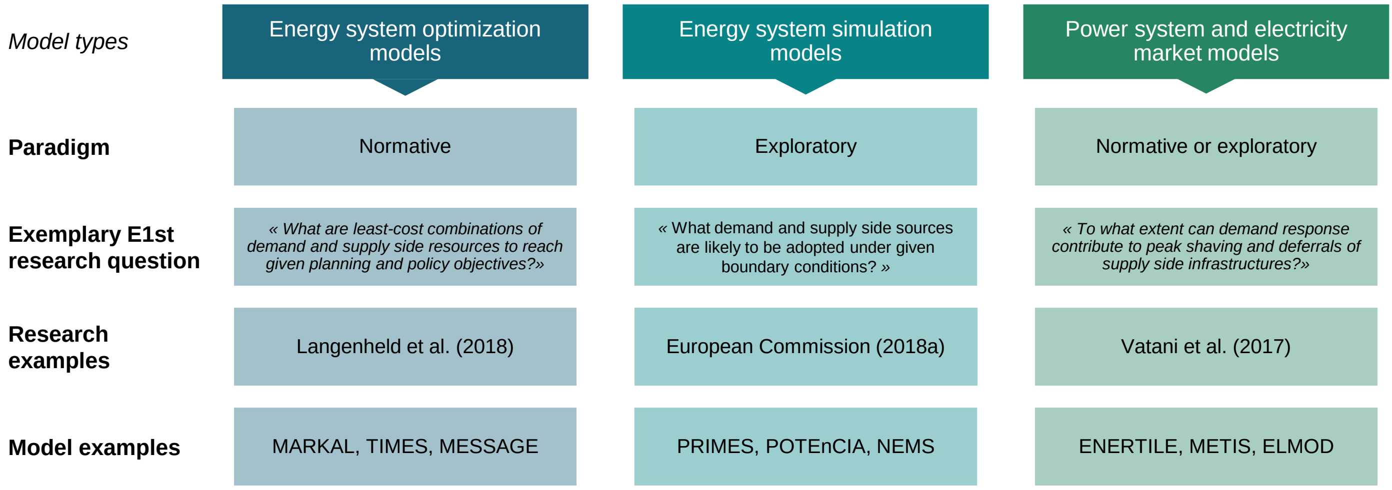
[11] Total system costs in the EC's analysis essentially comprise capital costs (e.g. for energy infrastructure) and operational costs (e.g. fuel purchase). They do not include any monetized multiple impacts, which, arguably, might alter the outcomes of the analysis.

[12] Note that, as E1st addresses all major energy system infrastructures, one would also need to consider dedicated models for gas and district heating and cooling systems – in addition or in conjunction with the type of 'power system and electricity market models' indicated here. Characteristics of DHC systems are frequently incorporated in power system models (e.g. ENERTILE). For a more detailed account, the reader is referred to alternative references concerning dedicated modelling techniques for gas and DHC systems (see e.g. Guelpa et al. 2019).



Model types	Energy system optimization models	Energy system simulation models	Power system and electricity market models
Paradigm	Normative	Exploratory	Normative or exploratory
Exemplary E1st research question	*« What are least-cost combinations of demand and supply side resources to reach given planning and policy objectives?»*	« What demand and supply side sources are likely to be adopted under given boundary conditions? »	*« To what extent can demand response contribute to peak shaving and deferrals of supply side infrastructures?»*
Research examples	Langenheld et al. (2018)	European Commission (2018a)	Vatani et al. (2017)
Model examples	MARKAL, TIMES, MESSAGE	PRIMES, POTEnCIA, NEMS	ENERTILE, METIS, ELMOD

Figure 4. Major energy model types in the context of E1st.
Source: Authors' own.

Energy system simulation models follow the *explorative paradigm* to examine how the system is likely to evolve under given policies, technology costs, and other variables. In contrast to the often rigid mathematical formulation of energy system optimization models, these simulation models can be built modularly and incorporate a range of simulation methods, such as logit formulas or agent-based simulation (Pfenninger et al. 2014; Greening and Bataille 2009). An important examples of energy system simulation models is PRIMES, which is used to project the long-term economic, energy, climate and transport impacts of the existing EU policy framework in the EU Reference Scenarios (Capros et al. 2016). POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment), developed by the EU's Joint Research Centre (JRC) allows for an assessment of the impact of different policy instruments on the EU energy system. The U.S. Energy Information Administration's NEMS (National Energy Modelling System) model consists of a number of submodules that are used to produce the Annual Energy Outlook. LEAP (Low Emissions Analysis Platform), developed at Stockholm Environment Institute, is also an established model for integrated energy planning and climate change mitigation assessment.

Power systems and electricity market models focus primarily on the electricity system and can follow either the normative or the exploratory paradigm. These models are often used within utilities and other power sector businesses to make decision ranging from investment planning to operational strategies such as generator dispatch (Pfenninger et al. 2014). In contrast to general simulation and optimization models, power system models are characterized by more detail and attention to temporal and spatial variation, as a key property of a functioning power system is a constant balance between supply and demand. Closely related are electricity market models, but instead of primarily focusing on physical properties and load on the grid, they are concerned with the processes in increasingly liberalized electricity markets. Examples for large power systems models include ENERTILE, METIS, PLEXOS and WASP. ENERTILE is a mixed-integer linear programming modelled developed at Fraunhofer ISI with detailed representation of different power generators, the transmission grid, as well as capacity expansion. An example of an electricity market model is ELMOD, which considers different use cases ranging from market design to investment decisions. Vatani et al. (2017) provide a research example of electricity market modelling in the context of E1st. Using a mathematical model, the authors show that using demand response as a demand side resource in capacity markets can effectively defer costly transmission upgrade.

Overall, quantitative assessments of the E1st principle can follow several research directions in terms of paradigms. Each of these paradigms requires different model types and approaches, depending on the scope of the research. Note that, in practice, there are various nuances to different models, including the fact that categorizations of model types can never fully account for all particularities and features. Based on these general considerations, the following section provides an in-depth overview of established quantitative modelling approaches at different planning levels.

3.2 Levels of analysis

This section presents how the E1st principle can potentially be modelled at different levels of analysis. It considers the national level (**Section 3.2.1**), the utility level (**Section 3.2.2**), and the buildings level (**Section 3.2.3**). Each of the levels features its own methodological and practical particularities with respect to the assessment of demand and supply side resources. Given the complexity of the energy system, these sections highlight that there is no universal model or modelling approach for representing the E1st principle. Instead, each model is subject to an inherent trade-off between data needs and computational complexity on the one hand, and robustness and credibility of the model outcomes on the other.

3.2.1 National level

In the context of the E1st principle, quantitative modelling at the national level is concerned with identifying what portfolios of demand and supply side resources can reach planning and policy objectives at least cost for the entire society and to evaluate what policies, technology costs and other boundary conditions are necessary to reach these desired future outcomes.[13] Depending on the scope of the analysis, such quantitative assessments need to account for a multitude of possible demand and supply side resources. On the demand side, consumers in the buildings, industry and transport sector face innumerable investment options, ranging, for example, from thermal retrofits in buildings, to efficient processes in industry sectors, to modal shifts in transportation. On the supply side, nations feature various energy infrastructures – e.g. for electricity, gas, district heating and oil – that all exhibit distinct investment options in terms of energy conversion and storage units as well as network infrastructures (Guelpa et al. 2019).

As such, there is a wide **variety of models** that can be used for quantitative assessments of demand and supply side resources at the national level. Hall and Buckley (2016) review the prevalent usage of energy models in the United Kingdom and categorise 22 existing models according to structure, model detail, and mathematical approaches. Ringkjøb et al. (2018) analyse 75 models for energy and electricity systems with large shares of renewables. Pfenninger et al. (2014) provide a general backdrop to the use of energy models in national and international policymaking and suggest four broad categories of models, based on several dichotomies: simulation vs. optimization; investment planning vs. system operation; snapshots vs. pathways. There is a wealth of miscellaneous review studies that help identify clusters of model

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[13] While this section primarily accounts for the national level, it is noteworthy that models with regional scopes (e.g. European Union) typically build upon national boundaries and aggregate outputs to reflect the region as a whole. Likewise, transnational modelling (e.g. power flows across EU countries) requires, at the very least, a geographical resolution at the national level to account for generation potentials and other dynamics. The findings from this section are thus also highly relevant for the European level.

approaches, as well as their individual characteristics (Connolly et al. 2010; Després et al. 2015; IRENA 2017; Tozzi and Jo 2017).

It is apparent from these reviews that models adapt an increasingly integrated representation of the formerly detached energy infrastructures of electricity, gas, and heat. Referred to as **sector coupling** (Oberle et al. 2020; Stephanos and Höhne 2018), electric heat pumps and electrode boilers are projected to be used in district heating systems; gas networks can transport hydrogen and synthetic methane produced from renewable-based electrolysis; cogeneration power plants generate both heat to district heating networks and electricity through electric grids. Quantitative assessments of demand and supply side resources that aim to account for national system boundaries are thus subject to increasing levels of complexity in adequately capturing these dynamics. As further elaborated on in the discussion of methodological challenges in **Section 3.3**, in order to properly reflect these dynamics, it is imperative for models to account of the unique properties of variable renewable energies and the requirements and possibilities for flexibility options they bring about.

Within the concept of E1st, **demand response** is considered a key demand side resource and flexibility option (**Section 2.1**), which thus calls for consideration in energy models at national and subordinate levels. One the one hand, there are various empirical studies that test the impact of demand response programs on the electricity market, the electricity, and the load shifting behaviour of consumers. For example, Di Cosmo et al. (2014) analyse how Irish households respond to different time-of-use (TOU) tariffs at different times of the day (peak, day and night), and in conjunction with different information stimuli. On the other hand, informed by empirical findings, there are dedicated modelling studies on aggregate potentials and limitations of demand response at different levels of analysis. For instance, Gils (2014) provides a model-based assessment of the theoretical demand response potential in Europe, with particular attention given to temporal availability and geographic distribution of flexible loads.

The **diffusion of end-use efficiency technologies** and corresponding levels of energy demand are another key concern for quantitative modelling of the E1st principle. At national and more aggregate levels, there is a longstanding distinction between top-down and bottom-up approaches to projecting future energy demand (Bhattacharyya 2019; Herbst et al. 2012; IRGC 2015; Zweifel et al. 2017). The **top-down approach**, also known as econometric approach, consists of correlating past energy demand for a given fuel with other variables –such as fuel prices, prices of substitutes, income, and other factors – by means of detailed regression analyses of past data. Future energy demands for specific fuels are then related to the predicted growth of these variables, reflected in an overall demand function. Its major shortcoming is that it features no explicit representation of end-use technologies (e.g. different lighting options) and, as such, is unsuitable for quantifying cost-optimal resource portfolios in the light of the E1st principle. In turn, the **bottom-up approach**, also referred to as process approach, shifts the estimation process away from fuel consumption itself to an understanding and quantification of the technologies that consume energy. Its underlying idea is that final energy is only an intermediary good, which is used by energy-converting devices and appliances to provide useful energy and, eventually, a particular energy service. In practice, quantitative assessments of demand side resource in the context of E1st are contingent on bottom-up approaches to determine individual end-use efficiency technologies, their costs and multiple impacts.

Major bottlenecks in model usage for quantitative assessments of demand and supply side resources at national levels are **data needs** and **computational complexity** (Després et al. 2015; Pfenninger et al. 2014). Data needs arise from a high degree of technological detail, resulting in lengthy parametrisation and calibration processes.[14] Computational complexity depends on the scope and detail of demand and supply side resources considered. As elaborated on in the discussion of methodological challenges in **Section 3.3**, models taking detailed account of the temporal and spatial properties of VRE (Variable renewable energies) frequently run linear or mixed-integer optimisation methods that are numerically complex and thus time-intensive. Parametrisations and other methods can limit some of the time requirement for model runs, however, this comes at the expense of robustness and transparency of the model outcomes. This trade-off between data needs and computational complexity on the one hand, and robustness and credibility of the model outcomes on the other is further discussed in the following sections.

3.2.2 Utility level

Utilities are concerned with **planning and operating supply-side infrastructures** that are used to produce, transform and transport energy. Incorporating the E1st principle in utility 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 substitute for capital-intensive infrastructure assets. Infrastructures for electricity, gas, and district heating have different characteristics and face different technical challenges and, as such, the technological aspects and modelling approaches are different (see e.g. Guelpa et al. 2019).[15] In general terms, modelling by utilities is aimed at identifying investment needed for the reliable operation of the system for 15-20 years and it is usually updated annually. This includes on the one hand the replacement of aging assets, on the other the development of generation, network, and storage capacities to be able to serve the future needs as demanded by the current and future users of the network.

The planning and operation of **power distribution networks** from the perspective of system operators is a highly relevant topic that is highlighted in the following. Electrification of heat supply and transport, in addition to demand growth driven by economic advancement in some EU countries and the growing number of distributed energy resources (DERs) such as PVs, demand response and storage connected to the distribution grid places this second aspect of network development into the spotlight: how to serve all this demand and how to integrate these DERs into the grid at the lowest cost? These already ongoing and further anticipated changes in distribution network use require the reconsideration of network planning. Demand-side resources 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. Smart grids[16] or **Active Distribution Systems (ADSs)** optimize the

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[14] For example, the widely used MARKAL model has been applied to the U.S. with over 4,000 technologies depicted, which creates major efforts for data collection and implementation (Greening and Bataille 2009).

[15] From a modelling viewpoint, district heating, gas, and electricity infrastructures present similarities and differences. Modelling of gas and heat systems has some similarities but the dynamics are different as gas is a compressible fluid while water in a DHC system is uncompressible. As such, pipelines can serve as a storage medium for gas, while in the case of DHC networks only the thermal capacity of the fluid can be exploited. The dynamics of power modelling are significantly different due to the different nature of its physical properties. In this case, the unpredictability of the generation is the key issue to be modelled in order to solve problems related to imbalance and losses (Guelpa et al. 2019).

[16] A smart grid is an electricity network that can integrate, in a cost-efficient manner, the behavior and actions of all users connected to it (generators and/or consumers). This behavioral control ensures an economically efficient, sustainable power system with high levels of quality and security of supply and safety (CEN-CENELEC-ETSI, “Smart grids,” 2017).

uses and flexibilities of the grid instead of passively operating it in order to limit the investment needed to serve the more volatile load.

Traditional planning is based on the concept of a passive consumer and is largely focusing on figuring out 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 – according to the global industry survey conducted by (Pilo et al. 2014) – it is dominantly based on consumer/market information that is corrected statistically and demand scenario analysis. No targeted tools are developed for demand response, energy efficiency and distributed resource forecasting, i.e. the focus is on traditional demand forecast.

Assessment methods used are **deterministic**: the feasibility of connecting new customers requires the assessment of existing line capacity to incorporate them (hosting capacity analysis). These studies are often power flow calculations (generally on an hourly basis) for worst-case scenarios, in order to minimize risks (Silva 2017).[17] When these studies include distributed generation, the same 'fit-and-forget' approach is applied: the relevant technical aspects of DER is considered but based on maximum generation/minimum demand scenarios that seldom characterize renewable generation. Demand-side integration and active distribution network options are not considered in general by utilities as potential alternatives to network capacity investments in the planning process.

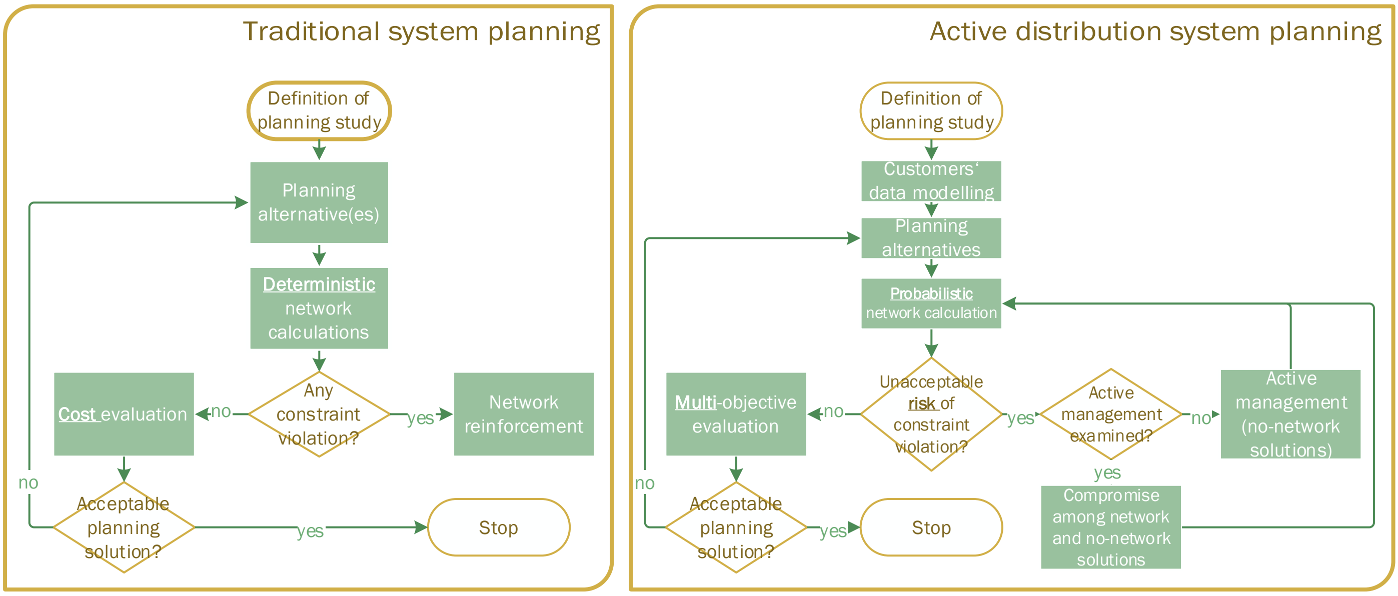

Figure 5. Traditional vs. active distribution system planning process

Source: (Pilo et al. 2014)

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[17] 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.

In contrast to traditional planning, **ADS planning** means changing from deterministic (without considering uncertainties) to stochastic assessment, from steady state to probability and risk, and from invisible to visible and controllable DERs. Figure 5 illustrates the difference between the two planning processes. 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 describe the future operation of the network more precisely. 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 is exceeded or not.[18] All developed alternatives needs to be technically sound and – naturally include demand resource options as well. In case of foreseen operational problems, first ADS solutions are to be examined and only if they cannot solve the problems, network investment to be considered. This logic give priority to ADS solutions. This seems to be on implementation logic of the E1st idea – that in itself does only require the equal treatment of supply and demand options – factoring in the difficulties of integrating all the demand resource benefits and the network company regulation that incentivize these companies to invest in CAPEX (Pató et al. 2019). In case of no constraint violation, all alternatives for network development should be considered based on a multi-objective analysis: each alternative to a specific problem.

On the one hand ADS helps to identify the challenges associated by widespread DER use such as high fluctuations in network power flow causing unpredictable changes in the voltage profile, reverse flows challenging existing safety devices etc. More importantly, from the point of view of E1st, their better representation sheds light on them as grid resources: assets that are not owned by the network company, similar to wires and poles, but can be made of good use for the benefits of all network users, primarily through avoiding unnecessary costly infrastructure investments.

3.2.3 Buildings level

Planning for E1st at the buildings level means to consider different demand and supply side resources and to evaluate which of these resources are most cost-effective to meet energy service demand (e.g. space and water heating) and overarching policy objectives (e.g. reduction of local air pollution). For example, planning a new urban district may evaluate the costs and benefits of enhanced thermal insulation, energy-efficient electrical appliances and demand response as demand side resources against those of distributed energy supply technologies (e.g. rooftop PV), district heating and cooling systems, installation of thermal storages, and other supply-side resources. Ideally, such analysis is conducted from a societal perspective, i.e. taking explicit account of externalities, direct benefits and other multiple impacts. However, it is important to acknowledge that consumers make their actual investment decisions from a private perspective. Models at the buildings level thus need to address socially optimal pathways, along with projections on the actual technology adoption by consumers. Any gap between the two can then serve policymakers to design instruments, which incentivise consumers to move from their purely private to socially optimal outcomes.

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

There are various existing models for energy planning at the level of **single buildings, urban areas, and even entire building stocks** across a nation. Manfren et al. (2011) reviews 14 models addressing the issues of distributed generation in buildings and demand response. Markovic et al. (2011) classify 13 models for urban energy planning according to different planning phases: 'geography models' for the assessment of RES availability, building characteristics, and local infrastructure; 'energy models' to simulate local system operation; and 'evaluation models' to assess environmental impacts, life cycle aspects and other socio-economic concerns. Ferrari et al. (2019) provide a comprehensive review of 17 models for urban energy planning, classifying them according to their temporal resolution (e.g. hourly), ease of use (user-friendly interface vs. advanced models targeted on academic researchers) and type of license (free vs. commercial).

Building scale models can also be broadly distinguished according to the two paradigms of quantitative assessments for E1st introduced in **Section 3.1**. Following the **normative paradigm**, there are models that use optimisation methods to reflect cost-optimal pathways for urban development. For example, Dias et al. (2019) use the TIMES_EVORA model to explore optimal solutions for meeting 2030 greenhouse gas emission reduction targets in a municipality in Portugal, subject to households' budget constraints for the acquisition of more efficient technologies (e.g. electrical appliances).

In turn, following the **exploratory paradigm**, there are buildings models that simulate energy-relevant decisions in the building stock in response to energy prices, technology costs and availability, policy instruments, and other boundary conditions. For example, the Invert/EE-Lab model (cf. Hummel et al. 2020) simulates the effects of different policy packages on the total energy demand, energy carrier mix, CO_2 reductions and costs for space heating, cooling, hot water preparation and lighting in buildings. The general challenge for simulation approaches at the buildings level is to refrain from modelling decision-makers (building owners, tenants, etc.) as fully rational agents with perfect information. As further elaborated on below in the discussion of discount rates (**Section 3.3.2**), in order to provide robust projections, models need to take into account the heterogeneous preferences of decision-makers, along with their partly irrational behaviour and external barriers (e.g. lack of capital) they face in making investment decisions for building retrofits and other resources (Schleich et al. 2016).

Besides adequate modelling of investment decision-making, there are further **challenges to quantitative assessments of E1st at the buildings level**. One challenge concerns the issue of single heating zones, meaning that models assume homogenous heating of the whole building without consideration of partial heating (e.g. higher temperature in living room vs. bedroom). This simplification of homogenous heating is generally attributable to a lack of empirical data, along with higher computational complexity for multi-zone models when evaluating building stocks for entire regions or countries. Another challenge is the choice between static vs. dynamic approaches for calculating useful energy demand of buildings. Static approaches do not factor in the thermal mass building components, saving e.g. solar energy during the day and emitting it during the night, providing a form of thermal storage for heating but also for cooling. As shown in Reilly and Kinnane (2017), the static approach can underestimate the energy used in cold climates by a factor 2.65 compared to a dynamic approach. Again, computational complexity and data needs limit the use of the more sophisticated dynamic over the static approach.

These sections presented methodological and conceptual considerations on modelling the E1st principle at the national, utility, and buildings levels. In the following, this report discusses three methodological challenges that quantitative assessments of E1st may face regardless of the level of analysis.

3.3 Methodological challenges

As the previous chapters have shown, practical assessments of the trade-off between demand and supply side resources for a given planning case require sophisticated energy models. To ensure that sound implications are drawn from these assessments in policy design and system planning, policy-makers and analysts require an understanding of the assumptions that go into any one particular modelling result (Pfenninger et al. 2014). For this purpose, this section examines three methodological challenges that quantitative assessments and models face in the light of the E1st principle: capturing the **multiple impacts** of demand and supply side resources (**Section 3.3.1**), selecting appropriate **discount rates** (**Section 3.3.2**), and ensuring **spatiotemporal detail** in modelling the deployment and operation of supply side resources (**Section 3.3.3**). In discussing these challenges, we present possible avenues and recommendations for addressing them in quantitative modelling. This overview makes no claim to being exhaustive with respect to the challenges that modellers can potentially face. Yet, the challenges presented here have been informed by expert interviews and substantiated with existing literature to ensure practical relevance.

3.3.1 Capturing multiple impacts

The concept of multiple impacts (also referred to as "co-benefits", "multiple benefits", "non-energy benefits")[19] has evolved as a field of analysis showing that the impacts of energy system transformations go hand-in-hand with many other societal and economic effects. In **cost-benefit analysis (CBA)**, the size of multiple impacts can be significant. According to a screening of 52 monetized case studies on energy efficiency measures in (Ürge-Vorsatz et al. 2016), in 63% of the cases, the value of the multiple impacts were equal or greater than the value of energy savings. 30% of these case studies featured multiple impacts valued three times more than the energy savings, and in about 25% of the cases, the multiple impacts were more than four times the energy savings.

Quantified values of multiple impacts already play some **role in policymaking**. For example, as part of the 2017-2018 Clean Energy for all Europeans Package (Winter Package), the European Commission carried out impact assessments for the amendment of the Energy Efficiency Directive (2012/27/EU; (EU) 2018/2002) (European Commission 2016b) and the Energy Performance of Buildings Directive (2010/31/EU; (EU) 2018/844) (European Commission 2016a). These assessments explicitly included multiple impacts, such as macro-economic impacts, social impacts including affordability issues, environmental effects and health impacts. However, multiple impacts typically play only a secondary role in such assessments and are captured only selectively (Thema et al. 2019; Ürge-Vorsatz et al. 2016).

With regard to quantitative assessments of the E1st principle, the general challenge is to integrate the assessment of multiple impacts into CBA in a methodologically and theoretically consistent manner. A first sub-challenge is a comprehensive **coverage of multiple impacts**. If only a subset of them is assessed in the decision-making framework, this can result in biases. As such, it is typically not sufficient to only

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[19] The literature features a broad array of terms synonymous or similar to 'multiple impacts', such as co-benefits, multiple benefits, ancillary benefits, indirect costs, adverse side-effects, risks, etc. See Thema et al. 2019 and Ürge-Vorsatz et al. 2014 for a review of these terms. In this report, we refer to the term 'multiple impacts' as it is does not indicate whether an impact is positive or negative.

integrate benefits into such CBA, because in order to avoid a positive bias all other indirect costs (risks, adverse side-effects, transaction costs, hidden costs, etc.) also need to enter the decision-making process. Equally, when only costs or risks are accounted for, it may create a negative bias, and the multiple benefits need to be integrated into the analysis to maintain a balanced assessment (Ürge-Vorsatz et al. 2016).

Monetization of multiple impacts is a second sub-challenge (Thema et al. 2019; Ürge-Vorsatz et al. 2016; Atkinson et al. 2018). As a starting point of quantitative assessments in the context of E1st, expressing impacts in their respective physical units (e.g. tonnes of air pollutants) may already allow for a comparison and discussion of different policy and investment options and their respective impacts. However, in order to perform a CBA, indicators need to be monetized. While established monetisation approaches are available for most impacts (e.g. economic impacts and energy security), there are some where monetization remains a challenge because of ethical concerns and other controversies (particularly health-related impacts). To mitigate these controversial aspects, it is generally recommended to report multiple impacts in terms of their physical units to at least allow for a general appraisal and to allow decision-makings to make a considered decision (Santori et al. 2015; Ürge-Vorsatz et al. 2016).

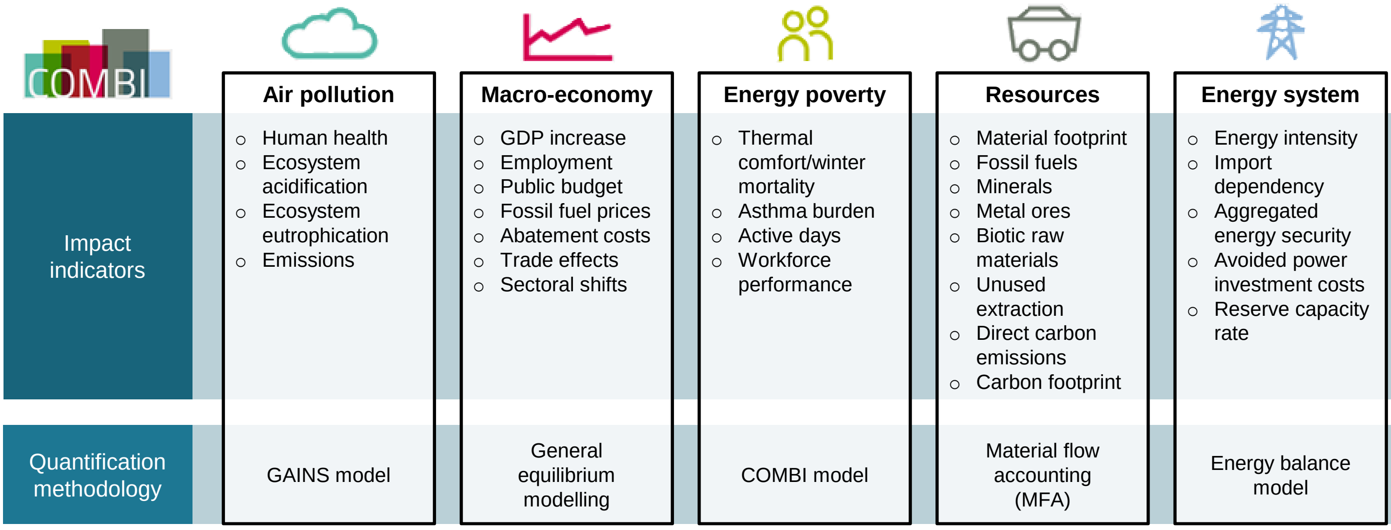
Against this background, significant progress has been made in recent years to quantify multiple impacts and to integrate them into CBA. Altogether, this constitutes a disperse field of research, with different coverage across sectors, countries, and technologies. A seminal piece in this field is the IEA's report on the classification and quantification of multiple impacts (IEA 2015). Further significant attempts to review integrate existing methodologies on the quantification of multiple impacts into single frameworks are provided by Ürge-Vorsatz et al. (2016) and Thema et al. (2019). In practice, different types of multiple impacts require different assessment approaches. For example, to assess the impacts of air pollution, researchers often apply so-called marginal co-benefit estimates or detailed models for specific pollutants, sectors, and recipients. To provide a detailed account of existing work on the assessment of multiple impacts, **Box 2** summarizes the innovations and methodological approach of the **COMBI project**.

Box 2. Innovations and approach of the COMBI project.

Source: Authors' own, based on (Thema et al. 2019).

The European Horizon 2020 research project COMBI ("Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe") aimed to integrate the state of knowledge for multiple impacts into one consistent framework as well as to develop and apply adequate methodologies for impact quantification and monetisation. The COMBI research ended up with a framework of 32 impact indicators covering the categories of air pollution (with ecosystems and human health impacts), macro-economic impacts (aggregate demand/GDP, employment, energy price effects), energy poverty (human health), resource impacts (fossil fuels, metals, minerals, biotic materials and unused extraction and carbon footprint), and productivity, and energy system impacts (security and system impacts).

This framework was applied to a set of scenarios for the EU to assess multiple impacts in the year 2030 that result from energy efficiency investments that are additional to a reference scenario. The scenarios were bottom-up funded, with 21 energy efficiency improvement actions in the buildings, transport and industry sectors (see University of Antwerp 2018). High-resolution stock models are used to quantify energy savings and investment costs. Using detailed quantification methodologies per indicator (e.g. GAINS model for air pollution), multiple impacts were quantified by EU member state and by single energy efficiency improvement action.



	Air pollution	Macro-economy	Energy poverty	Resources	Energy system
Impact indicators	○ Human health ○ Ecosystem acidification ○ Ecosystem eutrophication ○ Emissions	○ GDP increase ○ Employment ○ Public budget ○ Fossil fuel prices ○ Abatement costs ○ Trade effects ○ Sectoral shifts	○ Thermal comfort/winter mortality ○ Asthma burden ○ Active days ○ Workforce performance	○ Material footprint ○ Fossil fuels ○ Minerals ○ Metal ores ○ Biotic raw materials ○ Unused extraction ○ Direct carbon emissions ○ Carbon footprint	○ Energy intensity ○ Import dependency ○ Aggregated energy security ○ Avoided power investment costs ○ Reserve capacity rate
Quantification methodology	GAINS model	General equilibrium modelling	COMBI model	Material flow accounting (MFA)	Energy balance model

Figure 6. Multiple impact indicators and quantification methodologies used in the COMBI project.

Source: Authors' own, based on (Thema et al. 2019).

As summarized in (Thema et al. 2019), the COMBI project finds that energy efficiency improvement actions not only yield energy and greenhouse gas emission savings, but also imply substantial multiple impacts. With a conservative estimate, multiple impacts sum up to a size of at least 50% of energy cost savings, with substantial impacts coming from e.g., air pollution, energy poverty reduction and economic impacts. The project thus clearly demonstrates how the inclusion of multiple impacts can substantially alter CBA results. In turn, omitting multiple impacts in CBA reduces the cost-effectiveness of energy efficiency actions below their actual value, leading to sub-optimal levels from a societal perspective.

To conclude, reliable quantifications of multiple impacts are a precondition for decision-makers to take informed decisions with regard to the trade-off between demand and supply side resources (Thema et al. 2019), but also with respect to policy design and implementation in selecting instruments and targets that maximize social welfare in line with the E1st principle. Overall, it remains a challenging task for science and policy to understand the causality and extent of multiple impacts. Further developments in this field, both theoretical and empirical, are needed in order to broaden the range of multiple impacts considered in actual decision-making (Santori et al. 2015; Ürge-Vorsatz et al. 2016).

3.3.2 Selecting discount rates

Discounting is an omnipresent subject in economics and, arguably, one of the most debated issues in energy systems modelling.[20] Discount rates are used to attribute a weight to future cash flows, which makes them a key parameter in quantitative assessments of demand and supply side resources with different upfront cost and subsequent cash flows. As outlined in **Chapter 2**, a rough distinction can be made between **the financial discount rate** (FDR), reflecting time preference and risk from the perspective of businesses, utilities, and private investors, and the **social discount rate** (SDR), reflecting these attributes from the point of view of society.[21]

The general **effect in modelling**, and thus quantitative assessments of demand versus supply side resources, is that the higher the discount rate, the less significant appear future cash flows. High discount rates tend to be detrimental to energy efficiency measures, such as building retrofits, whereas they tend to favour fossil-fuel based supply technologies, which have relatively low upfront costs but high fuel and operational costs (Riley 2015). As a result, depending on the discount rate, beneficial demand side actions may not be undertaken in light of quantitative assessments and model-based CBAs. As the E1st principle postulates, assessments of demand and supply side resources should be made from a societal perspective. This raises the question whether using a SDR is the panacea for such assessments and what, in fact, would be a fair discount rate in line with the E1st principle. To address this matter, it is worth considering what exactly discount rates are used for in model-based assessments of demand and supply side resources. **Figure 7** provides an overview of two major **use cases for discount rates** in quantitative assessments of the E1st principle, along with typical rates used and their respective methodological challenges.

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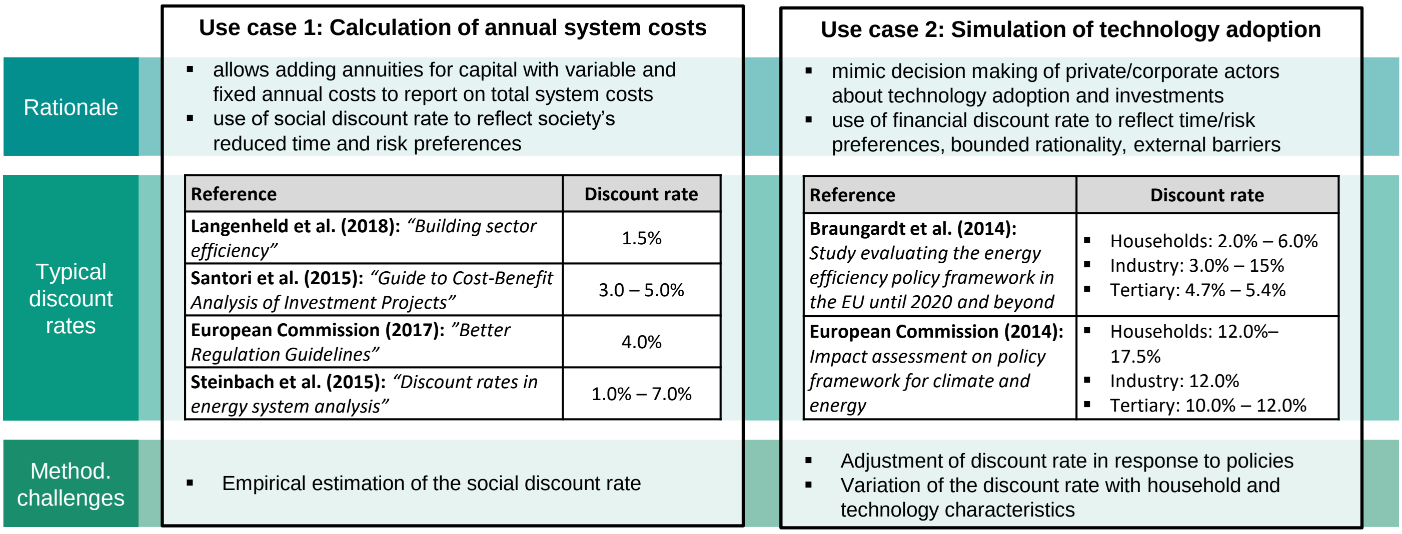
[20] For instance, labelled as the "battle of the discount" rates (Riley 2015), the European Commission has been criticized for having used a high discount rate of 17.5% for modelling the cost-effectiveness of energy efficiency measures in its impact assessment of the 2030 energy targets (European Commission 2014). As argued by Riley (2015) and Dupuy (2015), this caused such measures to appear too unattractive to be promoted. While the discount rates for households have been lowered in subsequent impact assessments, the underlying debate remains.

[21] Note that, in a perfectly competitive economy and under equilibrium, the FDR coincides with the SDR, which would correspond to the financial market interest rate. However, since capital markets are distorted, this does not apply in practice (Santori et al. 2015).



Use case 1: Calculation of annual system costs

Rationale

- allows adding annuities for capital with variable and fixed annual costs to report on total system costs
- use of social discount rate to reflect society's reduced time and risk preferences

Typical discount rates

Reference	Discount rate
Langenheld et al. (2018): *"Building sector efficiency"*	1.5%
Santori et al. (2015): *"Guide to Cost-Benefit Analysis of Investment Projects"*	3.0 – 5.0%
European Commission (2017): *"Better Regulation Guidelines"*	4.0%
Steinbach et al. (2015): *"Discount rates in energy system analysis"*	1.0% – 7.0%

Method. challenges

- Empirical estimation of the social discount rate

Use case 2: Simulation of technology adoption

Rationale

- mimic decision making of private/corporate actors about technology adoption and investments
- use of financial discount rate to reflect time/risk preferences, bounded rationality, external barriers

Typical discount rates

Reference	Discount rate
Braungardt et al. (2014): *Study evaluating the energy efficiency policy framework in the EU until 2020 and beyond*	Households: 2.0% – 6.0% Industry: 3.0% – 15% Tertiary: 4.7% – 5.4%
European Commission (2014): *Impact assessment on policy framework for climate and energy*	Households: 12.0%–17.5% Industry: 12.0% Tertiary: 10.0% – 12.0%

Method. challenges

- Adjustment of discount rate in response to policies
- Variation of the discount rate with household and technology characteristics

Figure 7. Use of discount rates in quantitative assessments of the E1st principle.

Source: Authors' own, based on (Steinbach and Staniaszek 2015; Hermelink and Jager 2015).

The most fundamental use case is the **calculation of total annual system costs**, which, as an aggregate indicator, serves to identify the most cost-effective resource configurations. To calculate yearly costs, investment expenditures need to be annualized to account for the fact that investments that are made before the time period under consideration ends are only partially considered in the calculations. This is being done by transforming upfront investment into equal annual instalments ("annuities") of capital expenditures (CAPEX) over the investment's lifetime or depreciation period.[22] The higher the discount rate, the higher the weight of CAPEX compared variable and fixed operating expenditures (OPEX) and other monetized impacts, which tends to make energy efficiency investments unattractive in assessments of competing demand and supply side resources. In essence, the E1st principle takes the perspective of a benevolent central planner who aims to identify the most cost-effective mix of demand and supply-side resources on behalf of all member of society. As such, for the calculation of system costs, the modelling literature generally approves the use of a social discount rate (SDR), reflecting society's reduced time preference for societal payback as well as reduced investment risk (Steinbach and Staniaszek 2015; Dupuy 2015; Riley 2015).

This leaves the **question what SDR to select** for a given assessment in the light of the E1st principle. Ideally, the SDR is empirically estimated for the country or region under consideration, for which different established approaches exist.[23] Another option is to draw upon existing assessments. Either way, there is

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[22] Using the equivalent annuity cost method, the annual capital expenditures (annuities) of an investment are calculated by multiplying the initial investment I with the capital recovery factor α that is a function of the discount rate r and the investment lifetime n. The capital recovery factor is written as $\alpha = \frac{r}{1-(1+r)^{-n}}$ (Blok and Nieuwlaar 2016).

[23] There are two established approaches to estimating the SDR (Santori et al. 2015). The social rate of time preference (SRTP) approach supposes that the government should consider the welfare of both current and future generation and solve an optimal planning programme based on individual preferences for consumption. The rates of government bonds or other low risk securities are often used as proxies for the SRTP while the Ramsey growth model (Ramsey 1928) provides an empirical approach for its estimation. In turn, the social rate of return on private investments (SRRI) considers the SDR equal to the marginal social opportunity cost of funds in the private sector. In practice, public

a variety of different rates in practice today. To mention a few, the "Better Regulation Guidelines" (European Commission 2017), used to inform the European Commission's impact assessments, recommends a SDR of 4%. The European Commission's "Guide to Cost-Benefit Analysis of Investment Projects" (Santori et al. 2015) suggests a SDR of 5% for public investment projects in Cohesion countries and 3% for other Member States.

Another use case for discount rates in model-based assessments is the **simulation of technology adoption**. As introduced in **Section 3.1**, quantitative assessments of the E1st principle may either take a prescriptive (optimization approaches) or a descriptive perspective (simulation approaches). In simulation approaches, discount rates are applied as a behavioural parameter that governs decision-makers' actual technology choices – based on their various preferences, bounded rationality and barriers faced in their day-to-day decisions (Steinbach and Staniaszek 2015; Schleich et al. 2016). In other terms, these approaches are conceived to assess individual decision-making and policy impacts as close as possible to reality in order to avoid under- or over-estimation of the costs and difficulties of transformations towards meeting targets and transition objectives (Capros et al. 2016).

Using a SDR to simulate individual decision-making is, arguably, inappropriate as it is likely to be too low to accurately forecast behaviour, which thus can be misleading for purposes of policy making and strategic planning (Capros et al. 2016). Instead, the use of a FDR is warranted for which it is intuitively clear that it should be adjusted to account for differences in decision-makers. For energy-related investments in industry and services firms, the discount rate would essentially be the **internal rate of return** required to trigger an investment.[24] For utilities that are state-owned or subject to regulation by the state (e.g. power networks), the **regulated rate of return** is often used as discount rate (Capros et al. 2016). More controversial is the discount rate used to mimic households' investment behaviour, occasionally referred to as the **implicit discount rates (IDR)** (Schleich et al. 2016). In addition to opportunity costs, time preference, and risk preference as the major constituents of discount rates, IDRs also reflect external barriers to energy efficiency, e.g. imperfect information, capital constraints or the landlord-tenant (split-incentive) problem.[25] IDRs are usually empirically derived from observed technology choices and econometric models for certain countries and, less frequently, socio-economic groups (Schleich et al. 2016).

As IDRs are used to simulate households' future behaviour, the major **methodological challenge is to adjust them in response to prospective policies measures**. In the absence of strong policies to support energy efficiency, households tend to be uninformed and unreasonably sceptical about the benefits of

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agencies in the EU primarily use the SRTP to estimate the SDR for public investment projects (Santori et al. 2015). Recent advances in discounting theory have focused on the use of declining discount rates to evaluate public projects, a practice that is now commonplace in several EU countries, including France and Denmark (Atkinson et al. 2018).

[24] An established proxy for this is the capital asset pricing method, which takes into account both the costs of capital and the riskiness of the investment. In some cases, the Weighted Average Cost of Capital could also be used (European Commission 2017).

[25] Schleich et al. (2016) present a comprehensive framework of the underlying factors of the IDR for household adoption of energy efficient technologies, based on behavioural economics literature. They disentangle the IDR into (i) preferences (such as time and risk preferences), (ii) predictable (ir)rational behaviour (i.e. bounded rationality, rational inattention, and behavioural biases, such as present bias or status quo bias); and (iii) external barriers to energy efficiency (e.g. split incentives, lack of information or lack of capital).

saving energy – that is, they exhibit high implicit discount rates (Dupuy 2015). However, directed policies can lower the IDR by adequately targeting the external barriers to energy efficiency. For example, building performance certificates have been shown to effectively reduce lack of information and split-incentive barriers, with energy-labelled dwellings achieving higher rents or higher sale prices (Schleich et al. 2016). Hence, model-based assessments should account for household responses to policy measures by lowering the discount rate accordingly.

Determining the exact **effect of different policy measures on the magnitude of the IDR**, however, is a nascent field of research that is complicated by the fact that IDRs vary with household (e.g. income levels, household size, environmental awareness) and technology characteristics (e.g. novelty of technology) (Schleich et al. 2016). As such, the IDRs used in models to simulate households' decision-making may vary substantially (**Figure 7**, right). For instance, the discount rates for the households sector used by two independent impact assessments on the EU's initial 2030 targets – (European Commission 2014) and (Braungardt et al. 2014) – deviate significantly as they make different assumptions on the impact of future policies on perceived risk and external barriers to energy efficiency. Steinbach and Staniaszek (2015) argue that, instead of using highly uncertain IDRs, the effects of risk and external barriers on decision makers' actual technology adoption behaviour should be simulated through dedicated models, e.g. logit approaches or agent-based models. However, parametrizing these models still requires an enhanced empirical evidence base on the impacts of policy measures on the underlying factors of the IDR.

In conclusion, discount rates are a crucial parameter for the quantitative appraisal of demand and supply side resources in light of the E1st principle. To evaluate total costs and benefits of energy systems, a social discount rate should be applied. Based on established methodologies, social discount rates for EU states can be in the range 1% to 7%. To simulate actual investment decision-making and the impact of policy measures, discount rates should be differentiated according to different investors. For industry and commercial firms as well as utilities, the discount rate corresponds to the expected rate of return. Implicit discount rates (IDRs) for household consumers should be empirically derived and vary with the impact of policies, as well as with socio-economic and technology characteristics. As argued by Schleich et al. (2016), failure to account for heterogeneity in the IDR and also for household responses to policy interventions likely biases model-based analyses and, thus, also quantitative assessments of the E1st principle. Additional representative empirical studies, based on households' observed or stated technology adoption behaviour, may provide more realistic IDRs to modellers. Another key recommendation is that quantitative assessments of the E1st principle involving discount rates should be accompanied by sensitivity analyses to determine the impact of the discount rates selected on the quantitative results as well as on the conclusions drawn for system planning and policy design.

3.3.3 Modelling deployment and operation of supply side resources

Spurred by ambitious political commitments and rapid technological progress, the EU increasingly relies on renewable energy to meet its demand for energy and to mitigate greenhouse emissions (IRENA 2017; Collins et al. 2017). In recent years, the EU has undergone a rapid expansion of renewable energy capacities. The share of renewables in gross final energy consumption stood at 18.9 % in the EU in 2018, compared with 9.6% in 2004 (Eurostat 2019). The majority of this new renewable energy generation comes from wind power and photovoltaics (PV). These technologies are frequently referred to as **variable renewable energies** (VRE) because their power generation is intermittent in response to weather conditions, location specific, and only predictable to a limited extent (Collins et al. 2017). VRE are found and expected to have distinct techno-economic impacts on power system operation, including the need for firm generation capacity, flexibility, transmission and distribution capacity upgrades as well as enhanced voltage and frequency control (IRENA 2017; Johnson et al. 2017; Foley et al. 2010; Pietzcker et al. 2017).

Ignoring the unique properties of VRE in quantitative assessments and energy system models for E1st can result in **mistaken signals regarding system costs**, greenhouse gas reduction potentials and the ability of power systems to accommodate VRE. As argued by multiple authors (Collins et al. 2017; Foley et al. 2010; Pietzcker et al. 2017), for high penetrations of VRE, energy system models that feature low levels of temporal, technical, and spatial detail are prone to overestimate the contribution of VRE to baseload, while the value of flexibility resources (e.g. demand response) is underestimated. In turn, by imposing upper limits on VRE shares or by fixing flexibility requirements, low levels of detail can overly restrict the projected deployment of VRE. Ultimately, decision-makers attempting to determine an optimal portfolio of demand and supply side resources in line with the E1st principle require robust quantifications and modelling tools. However, there is an inherent **trade-off** to such models between **sophistication and computational complexity**. Detailed models typically run mixed-linear optimisation methods that are numerically complex, time-intensive, and thus not readily applicable to all relevant planning contexts.[26]

To account for the techno-economic challenges and flexibility need associated with VRE and to address the trade-off between data robustness on the one hand, and computational complexity on the other, research has developed various **methods that make informed simplifications in terms of temporal resolution** (Haydt et al. 2011; Collins et al. 2017; Pfenninger 2017).[27] **Figure 8** provides an overview of major approaches. The least complex approach, referred to as **integral method** (Haydt et al. 2011) and used e.g. in the LEAP model, aggregates demand in a load duration curve, divides this curve into 5 to 10 sections, and matches power demand with available supply options. While the advantage of this method is its simplicity, its major disadvantage is that it does not take account of real-time dynamics demand and supply that are lost due to aggregation. VRE generators thus completely lose their intrinsic power variations to a constant capacity factor and the value of demand response and other flexibility options cannot be assessed (Collins et al. 2017; Johnson et al. 2017; Haydt et al. 2011).

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[26] Assuming a model with a single year of 8760 hourly time steps, 20 technologies, 20 locations and 5 time-dependent constraints (e.g. maximum generation per location), results in more than 17 million constraints. Such models require considerable CPU and memory requirements that can take up to several days or weeks to solve (Pfenninger 2017).

[27] This overview focuses on the temporal resolution as one key lever to the robustness of model data. Of similar importance are the spatial resolution (i.e., the scope of system boundaries and spatial detail of VRE generators) and the technical resolution (i.e., consideration of operational constraints of power generators). See (IRENA 2017) and (Poncelet et al. 2016) for a discussion of these aspects.

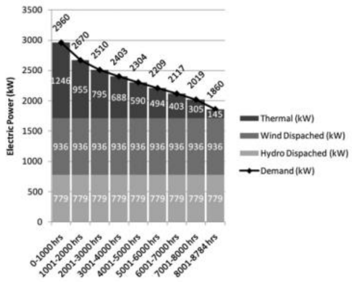
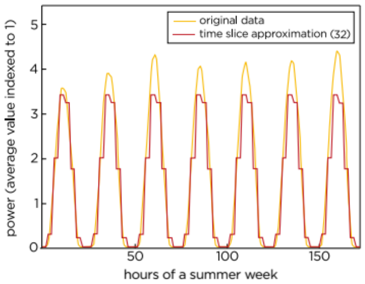
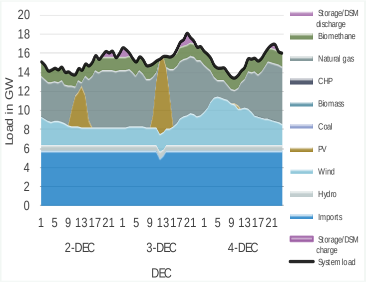
	A) Integral approach	B) Semi-dynamic approach	C) Fully dynamic approach
Illustration			
Level of detail	Time steps: 1-10 Time resolution: Monthly-yearly	Time steps: 10-100 Time resolution: Daily-hourly	Time steps: 10-100 Time resolution: Hourly and better
Model example	LEAP	TIMES	ENERTILE

Figure 8. Approaches to represent operation of VRE in long-term energy system models.

Source: Authors' own, based on (Haydt et al. 2011; IRENA 2017).

A second method, referred to as the **semi-dynamic approach** and used for example in the TIMES model, uses different approaches to create so-called typical days of similar load, wind speed, solar irradiance patterns, etc. Specific approaches range from simple heuristics, to statistical clustering algorithms (including k-medoids, k-means, and fuzzy C-means) and advanced optimisation models (Collins et al. 2017; Pfenninger 2017). While chronology (and thus the possibility to represent demand response and other flexibility options) can be retained in some of these approaches (Collins et al. 2017; Pfenninger 2017) there are well-known disadvantages. Specific algorithms or optimisation models need to be set up, calibrated and validated in terms of their statistical significance, which can be a time-consuming process (Poncelet et al. 2016). In addition, specific approaches for creating typical days are found to vary in performance and strongly depend on the structure of the underlying model (Pfenninger 2017).

Finally, the method with the highest temporal resolution, used for example in the ENERTILE model, consists in using the full extent of load and VRE generation time series under its native resolution (hourly or better), also known as the **dynamic method** (Haydt et al. 2011). In this approach, each hourly demand step needs to be matched with the available supply, according to a predefined dispatch rule. Overall, the main disadvantages of the approach are its large data needs and, compared to the other three approaches, its relatively long computation time. In turn, it offers a high level of detail with regard to supply and demand dynamics occurring throughout the year (Haydt et al. 2011; Pfenninger 2017).

Overall, model detail and resolution is one important lever with respect to the robustness of model-based assessments with high shares of VRE. Disregarding the dynamics of variable supply in energy system models is likely to underestimate the need for firm generation and network capacity, as well as the value of flexibility options (demand response, behind-the-meter storage, etc.). Under such circumstances, quantitative assessments of the E1st principle may suggest sub-optimal levels of demand and supply side resources that do not maximize societal welfare. Practitioners and decision-makers are advised to pay due regard to the limitations of their energy system models used to make investment decisions and to benchmark their results with existing models featuring high levels of temporal, spatial, and technical detail.

In conclusion, this chapter provided a thorough description of existing modelling approaches associated with the concept of E1st. First, it introduced two **paradigms of quantitative assessments** for E1st and associated these with model types. While the **normative paradigm** investigates what demand and supply side resources should be adopted to reach an anticipated vision of the future, the **exploratory paradigm** seeks to project the actual adoption of demand and supply side resources in response to boundary conditions. Second, the chapter presented methodological and conceptual considerations on modelling the E1st principle at the **national, utility, and buildings levels**. It highlights that there is no universal model for representing the E1st principle and that each model-based assessment is nested in a trade-off between data needs and computational complexity versus robustness and credibility of the model outcomes. Finally, this chapter discussed three **key challenges** to modelling the trade-off between demand and supply side resources with respect to the E1st principle. Such assessments are recommended *(1)* to capture a broad array of **multiple impacts** and to monetize them, where possible; *(2)* to apply **social discount rates** unless a model aims to simulate actual technology adoption behaviour; and *(3)* to ensure sufficient **spatiotemporal detail** to represent the true costs of supply-side resources as well as the value of demand-side flexibility options. The following chapter summarizes the overall findings of this report.

4 CONCLUSION

E1st is a compelling principle of energy planning as it seeks to provide a socially optimal deployment and operation of demand and supply side resources. In practice, however, taking explicit account of the E1st in system planning and corresponding policy design is a highly complex planning exercise that is subject to uncertainties. **Energy models** play a vital role in making these complexities and uncertainties tangible and in enabling decision-makers to make informed decisions on future technology investment, system operation and policy design. Existing energy models are diverse in terms of objectives, geographical scopes, technologies and sectors considered, spatiotemporal resolutions and other properties. Given the novelty of the concept of E1st in the political and academic debate, at present there are only few studies that make explicit reference to the E1st principle and to its implications for quantitative modelling.

Against this background, the **objective of this report** was to provide modellers and policymakers with a comprehensive guidance on conceptual implications and existing quantitative approaches for assessing demand and supply side resources in the light of the E1st principle. With respect to the conceptualization of E1st for quantitative modelling (**Chapter 2**), the report recapitulated the definition of the E1st principle adopted in ENEFIRST and highlighted implications of four particular aspects within this definition:

- First, **systematic assessments and comparisons of demand side resources** (e.g. end-use efficiency) **and supply-side resources** (e.g. networks) are the unique feature of the E1st principle, which adds a novel perspective to established modelling practices. Instead of modelling either the deployment of demand or supply side resources, quantitative assessments of E1st call for an integrated appraisal of costs and benefits to determine cost-optimal resource portfolios. A provided taxonomy of resources helps identify relevant technology options to be considered in quantitative assessments.
- Second, quantitative assessments in the context of the E1st principle are shown to require a common functional unit in terms of **planning and policy objectives**. The most fundamental planning objective is to consider what combinations of demand and supply side resources can meet the demand for energy needs and services at lowest cost, e.g. to provide comfortable indoor temperatures in the buildings of an urban area. Policy objectives may complement planning objectives in quantitative assessments, e.g. requiring that each resource configuration meets a given pollution reduction target.
- Third, the E1st principle is closely associated with the economic discipline of cost-benefit analysis (CBA) as it postulates the prioritization of demand side resources whenever these are more **cost effective** (i.e. create greater benefits) than alternative supply side options. A simple mathematical formulation of the E1st principle highlights the need for a common numerical basis in comparing costs and benefits; the discounting of costs and benefits; and the acknowledgement of risk and uncertainty.
- Finally, the E1st principle prescribes a **societal perspective** in evaluating the costs and benefits of various resource options. In distinction from the private perspective, this essentially means to consider social welfare gains or losses instead of the financial profitability for the owners of particular resources. As such, a societal perspective must take explicit account of the multiple impacts of different resource options in order to represent the net social welfare effects of different resources – be it direct benefits for society (e.g. additional employment) or negative externalities (e.g. air pollution). Another implication is that the societal perspective should adopt a social discount rate, which reflects the opportunity cost of capital from an inter-temporal perspective for society as a whole. The disregard of transfer payments (e.g. subsidies and taxes) are another key feature of the societal perspective.

Following this conceptual background, **Chapter 3** of this report set out to describe existing modelling approaches associated with the E1st principle. It introduced two major **paradigms of quantitative assessments for E1st**. One the one hand, such assessments might investigate what demand and supply side resources *should* be adopted over time to reach an anticipated vision of the future, e.g. a given GHG emission reduction target. This is referred to as the **normative paradigm** to E1st. It can help decision-makers identify priorities for policy design and technology investment, along with specific opportunities and risks associated with different pathways. On the other hand, quantitative assessments might investigate what demand and supply side resources *could* or are likely to be adopted over time in response to socio-economic conditions and policy measures. We refer to this as the **exploratory paradigm** to E1st. Its merit lies in identifying the possible future performance and limitations of single resource options and can thus help policymakers in assessing whether their policy instruments and other actions will be sufficient to reach a desired target state. In terms of practical approaches, energy system optimization models (e.g. TIMES) are designed for the normative paradigm, while energy system simulation models (e.g. PRIMES) pertain to the exploratory paradigm. Power system and electricity market models can address both paradigms.

Subsequently, this report provided an in-depth overview of how to provide quantitative assessments of demand and supply side resources at the **national, utility, and buildings levels**. Each of the levels has distinct methodological and practical requirements with respect to the assessment of demand and supply side resources. Given the complexity of the energy system, it is highlighted that there is no universal model or modelling approach for representing the E1st principle. Instead, each model has to make a choice in a trade-off between data needs and computational complexity on the one hand, and robustness and credibility of the model outcomes on the other.

Finally, this report discussed three **methodological challenges** that quantitative assessments of E1st may be confronted with and presented possible avenues and recommendations for addressing them in modelling practice. First, model-based assessments should capture the broad array of **multiple impacts** to provide a comprehensive account of societal costs and benefits. Where possible, multiple impacts should be monetized to integrate them in cost-benefit analyses (CBA). Second, appropriate **discount rates** should be selected to enable a fair comparison of demand versus supply side resources. To evaluate total system costs, a social discount rate is warranted. In turn, to model actors' actual technology adoption behaviour, financial discount rates should be used and varied with the impact of policy interventions as well as with socio-economic characteristics. Finally, models should feature sufficient **detail and resolution** to represent the true costs of supply-side resources as well as the value of demand response.

To conclude, this report informs analysts and policymakers engaged in energy system modelling and policy design about quantitative approaches concerning the trade-off between demand and supply side resources. As such, it advances the nascent field energy modelling in the context of the E1st principle. In addition, it provides the methodological foundation for two upcoming reports in the ENEFIRST project.

- **Energy system analysis for the EU-27**: Model-based assessment of the contribution of energy efficiency and other demand side resources in the buildings sector to achieve European climate targets for the year 2050 at the lowest societal cost;
- **Five local case studies for urban areas:** Model-based assessment of the contribution of energy efficiency and other demand side resources in residential and non-residential buildings to achieve local planning targets in urban districts, commercial areas, and other local scales.

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No.	Expert	Interviewer
1	Andreas Müller (TU Vienna)	Judit Kockat (BPIE)
2	Christopher Andrey (Artelys)	Zsuzsanna Pató (RAP)
3	Dominique Osso (EDF)	Jean-Sébastien Broc (IEECP)
4	Edith Bayer (International Energy Agency, IEA)	Zsuzsanna Pató (RAP)
5	Johannes Thema (Wuppertal Institute)	Tim Mandel (Fraunhofer ISI)
6	Kjell Bettgenhäuser (Guidehouse)	Judit Kockat (BPIE)
7	Martin Patel (University of Geneva)	Vlasis Oikonomou (IEECP)
8	Maurizio Gargiulo (E4SMA)	Judit Kockat (BPIE)
9	Patrick Plötz (Fraunhofer ISI)	Judit Kockat (BPIE)
10	Péter Kotek (REKK)	Zsuzsanna Pató (RAP)
11	Peter Mellwig (ifeu - Institut für Energie- und Umweltforschung Heidelberg)	Heike Brugger (Fraunhofer ISI)
12	Philippe Quirion (CIRED laboratory / Negawatt)	Jean-Sébastien Broc (IEECP)
13	Robert Pietzcker (Potsdam Institute for Climate Impact Research, PIK)	Judit Kockat (BPIE)
14	Robert Schroeder (ENTSO-E)	Zsuzsanna Pató (RAP)
15	Roberto Garay (Tecnalia Research and Innovation)	Judit Kockat (BPIE)
16	Serena Pontoglio (European Commission / DG ENER)	Zsuzsanna Pató (RAP)
17	Silvio De Nigris (Sustainable Energy Department, Piemont Region)	Benigna Boza-Kiss (CEU)
18	Stanicic Damir (Josef Stefan University)	Benigna Boza-Kiss (CEU)

ACRONYMS AND ABBREVIATIONS

ADS	Active distribution systems
CAPEX	Capital expenditure
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CSP	Concentrated solar power
DER	Distributed energy resource
E1st	Efficiency First
ETS	Emission trading system
FDR	Financial discount rate
GHG	Greenhouse gas
IDR	Implicit discount rate
IRP	Integrated Resource Planning
JRC	Joint Research Centre
LCOE	Levelized cost of energy
LCP	Least-Cost Planning
MCA	Multi-criteria analysis
MILP	Mixed-integer linear programming
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operating expenditure
PV	Photovoltaics
SDR	Social discount rate
TOU	Time-of-use
VAT	Value added tax
VRE	Variable renewable energies

ANNEX: INTERVIEW QUESTIONNAIRE

Introduction to the purpose and topic of the interview

"In a nutshell, "Efficiency First" means that investment decisions in the energy system should be based on the best value for the entire society. This essentially requires rethinking decision-making processes and applying cost-benefit-analyses to determine the cost-effectiveness of demand-side resources against alternative supply-side resources. However, in these cost-benefit analyses or comparisons of scenarios, choices need to be made in how to determine costs and benefits of the different alternatives considered. In our interview today, I would like to touch upon some of these aspects in more detail and also talk about your experience with such analyses."

Topic 1: General questions

"We contacted you as we have seen your *study XYZ [or that you are doing research about XYZ, or that you are involved in decision processes about XYZ] therefore possibly using cost-benefit analysis, energy models, scenario analyses or alike*.

(Q1.1) Have you heard about the "Efficiency First" principle and to what extent do you consider it relevant for your work?

(Note: This should not be the major focus of the interview.)

(Q1.2) Is there recent work of yours that you would like to highlight and that deals with "Efficiency First" or comparisons between demand-side and supply-side investments?

(Q1.3) Which methods did you use in these analyses and why?

(e.g. system models, scenarios, cost curves, etc.)

(Q1.4) What temporal and geographical scope did you consider?

(e.g. temporal resolution: hourly/daily/yearly/5-years/...; geographical scope: local/national/EU/world/...)

(Q1.5) What investment options did you analyze? Were there important ones that you had to neglect?

(e.g. energy efficiency actions, demand-response actions, RES actions, network reinforcements or extension)

(Q1.6) Were possible path dependencies or lock-in effects part of your analyses?

(i.e. the fact that today's decisions can have an impact on what can be done or achieved later)

Topic 2: Defining system costs

"In cost-benefit analysis, it is important to consider which costs are accounted for and who bears these costs. In the US for example, there are detailed cost-benefit methodologies that have been developed over time to account for the costs to different actors when assessing investment plans of utilities. For example when assessing energy efficiency programmes, the assessment can include the costs borne by the state/programme administrator, the costs for implementing efficiency measures borne by the consumers, lost revenues to the energy suppliers, environmental costs, and others depending on the cost-benefit test used."

(Q2.1) Which cost elements did you include in the analysis you conducted?

(e.g. equipment costs, installation, fuel, operation & maintenance, administration costs, incentive costs, ...)

(Q2.2) Are there cost elements that you consider important but that you had to ignore in your analysis?

(Note: Environmental costs and other multiple impacts are dealt with in the 'benefits' section.)

*"**Discount rates** play an important role in determining the cost of demand- and supply-side resources over a given period of time. [The discount rate is applied to determine the net present value (NPV) of energy savings that extend into the future. A higher discount rate will result in the value of future energy savings being considerably reduced, while a lower discount rate will indicate a greater valuation of future savings.] Often, there is significant variation in the discount rates applied in model-based analyses. In the end, selecting the appropriate discount rate requires careful balancing of the factors that affect the value of an investment, such as the cost of capital, transaction costs and various risks and barriers."*

(Q2.3) How did you determine the discount rate for different sectors and actors in your analysis?

(Q2.4) Which of these were most controversial to determine and why?

Topic 3: Defining benefits

"Many energy efficiency programmes and other demand-side resources are clearly cost-effective based on an analysis of just a few of the main benefits, such as bill savings to participating end users or the energy resource cost savings to all customers and reduced need for investment in supply. At the same time, many other cost-effective opportunities are overlooked when only a narrow set of benefits is fully accounted for – such as health impacts, air quality, and energy security. This can create a bias in favour of supply-side resources by not providing an accurate comparison between the full costs of supply- versus demand-side resources."

(Q3.1) Besides pure cost effects, did you consider other multiple benefits and impacts in your analysis?

(e.g. air quality, employment, poverty alleviation, energy security, public budgets, ...)

(Q3.2) How did you select the benefits or other impacts to be included in your analysis?

e.g. based on research objectives, requests from policy makers, data availability, ...)

(Q3.3) Are there benefits or other impacts that you consider important but that you had to ignore in your analysis?

(Q3.4) What are the main strength and weaknesses about the assessments or results related to benefits or other impacts?

(Q3.5) Did you apply discount rate(s) to the benefits and other impacts?

(for example, some studies use a 1% discount rate for environmental costs related to greenhouse gas emissions).

(Q3.6) What was your approach for accounting for lifetime savings of demand-side measures?

"Lifetime savings must be properly accounted for to ensure that longer-lived measures with higher upfront costs are not disadvantaged relative to short-lived, low-cost measures. The Energy Efficiency Directive requires Member States to take into account the lifetime savings when calculating energy savings under Article 7. However, the experience to date reflects different approaches to lifetime savings."

Closing comments and completion

(Q4.1) All in all, what were the main added value(s) and limitation(s) of the approach(es) you have used?

(Q4.2) What mistakes do you think modelers and researchers can make when comparing the costs and benefits of demand- and supply-side resources?

(Q4.3) Is there someone else you believe we should speak to? Why?

(Q4.4) Are you available for the modelling workshop (second round of consultations in workshop carried out with 30 key experts of the modelling community organised under WP6 in June 2020)