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ORIGINAL ARTICLE

Applying the Energy Efficiency First principle based on a decision-tree framework

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Abstract Energy Efficiency First (EEF) is an established principle for European Union (EU) energy policy design. It highlights the exploitation of demand-side resources and prioritizes cost-effective options from the demand-side over other options from a societal cost-benefit perspective. However, the involvement of multiple decision-makers makes it difficult to implement. Therefore, we propose a flexible decision-tree framework for applying the EEF principle based on a review of relevant areas and examples. In summary, this paper contributes to applying the EEF principle by defining and distinguishing different types of cases — (1) policy-making, and (2) system planning and investment — identifying the most common elements, and proposing a decision-tree framework that can be flexibly constructed based on the elements for different cases. Finally, we exemplify the application of this framework with two example cases: (1) planning for demand-response in the power sector, and (2) planning for a district heating system.

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Introduction

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

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

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

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

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

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

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

Literature review

In general, EEF is understood as a guiding principle for EU policy design in the energy sector. In essence, the principle states that so-called demand-side resources should be considered and prioritized whenever they are more or as cost-efficient in meeting stated objectives as alternative supply-side resources (ENEFIRST, 2020a).[1] The underlying rationale is that consumers in households and firms do not demand electricity and other energy carriers as such, but the energy services derived from them (Bhattacharyya, 2019; Kalt et al., 2019). This means that for a given energy service, e.g., thermal comfort, there are multiple resources, from the supply or demand-side as well as a combination of them, that can serve these needs.

On the one hand, supply-side resources refer to all technologies that convert energy to deliver energy services. This includes utility-scale assets, including renewable and non-renewable power plants, networks for power, gas and heat, as well as storage facilities. In a broader sense, supply-side resources may also comprise onsite energy conversion technologies like heat pumps and photovoltaic installations (ENEFIRST, 2020b). On the other hand, demand-side resources can be conceptualized as technologies and actions that reduce or shift final and useful energy demand. In essence, this includes end-use energy efficiency measures (e.g., thermal renovations in buildings) and demand-response (e.g., shifting appliance usage in response to hourly electricity tariffs) (ENEFIRST, 2020b; Rosenow & Cowart, 2017). Energy service sufficiency (e.g., reduction of living space) is also being discussed as a dedicated demand-side resource (ENEFIRST, 2020b). At its core, the definition of EEF principle suggests that the trade-off between demand- and supply-side resources for meeting demand of energy services is to be solved on a cost basis. The most adequate operationalization here is not the private cost incurred by individuals and firms, but the cost to society (ENEFIRST, 2020b; European Commission, 2021). In other words, EEF as a principle of public policy is meant to prioritize demand- over supply-side resources to the extent that they minimize the net cost or maximize social welfare (cost-benefit analysis, CBA) from a societal perspective. This implies that the EEF principle considers energy efficiency not as an end itself, but as a means of delivering energy services at the lowest possible cost to consumers. It also implies that costs borne by society are not solely composed of capital expenditures and operating expenses, but also a variety of social, economic, and environmental effects — referred to as multiple impacts or multiple benefits (IEA, 2015; Ürge-Vorsatz et al., 2016).[2] For example, Thema et al. (2018) identified and quantified a variety of multiple impacts associated with end-use energy efficiency measures in the EU, including reduced air pollution, job creation, increased labor productivity, and more.

The rationale behind the EEF principle is thus inherently economic. As the EU aims to transform to a climate-neutral or net-zero economy by the year 2050, the EEF principle can be viewed as a means to achieve a socially optimal or welfare-optimal deployment of end-use energy efficiency measures and other demand-side resources. As per the European Commission guidelines on EEF (European Commission, 2020), the principle should "ensure [...] that only the energy needed is produced and that investments in stranded assets are avoided in the pathway to achieve the climate goals".

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

[1] Formally, the EU Governance Regulation (European Commission 2018) defines EEF as follows: "'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand-response initiatives and more efficient conversion, transmission and distribution of energy, while still achieving the objectives of those decisions".

[2] Ürge-Vorsatz et al. (2016) defines multiple impacts as "all benefits and costs related to the implementation of low-carbon energy measures which are not direct private benefits or costs involving a financial transaction and accruing to those participating in this transaction."

Furthermore, in conceptual terms, Mandel et al. (2022) propose a distinction between two different planning approaches for implementing the EEF principle in the EU.

- The first approach is decentralized/market-based, addressing consumers and producers in various competitive energy markets by resolving market and behavioral failures. To illustrate, average cost pricing is a commonly known market failure in economic theory because it hides the marginal cost of supply in the price signal conveyed to consumers. If the average cost are lower than the marginal cost at a point in time, this leads to overuse of generation and network capacities relative to the economic optimum (Gillingham et al., 2009). The deployment of dynamic tariffs can be an effective policy response to address this market failure.
- The second approach is centralized planning. Its key rationale is to address regulatory failures, that is, situations where governments or state agencies take regulatory measures that do not, at reasonable cost, produce desired outcomes for society (Baldwin et al., 2011). This covers the process of policy formulation, addressing misleading assumptions and methodologies in impact assessments (e.g., on discount rates). More narrowly, it also covers the design of regulatory price control regimes for regulated electricity, gas and district heating (network) companies. For example, incentive structures transitionally imposed on regulated companies by regulators have been associated with adverse effects on the cost of energy supply. Novel incentive designs, subsumed under the term performance-based regulation (Pató et al., 2019), can create effective incentives for regulated companies to procure cost-effective demand-side resources as counterparts to supply-side capacity expansion and operation.

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

Decision-tree framework

Methodology

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

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

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

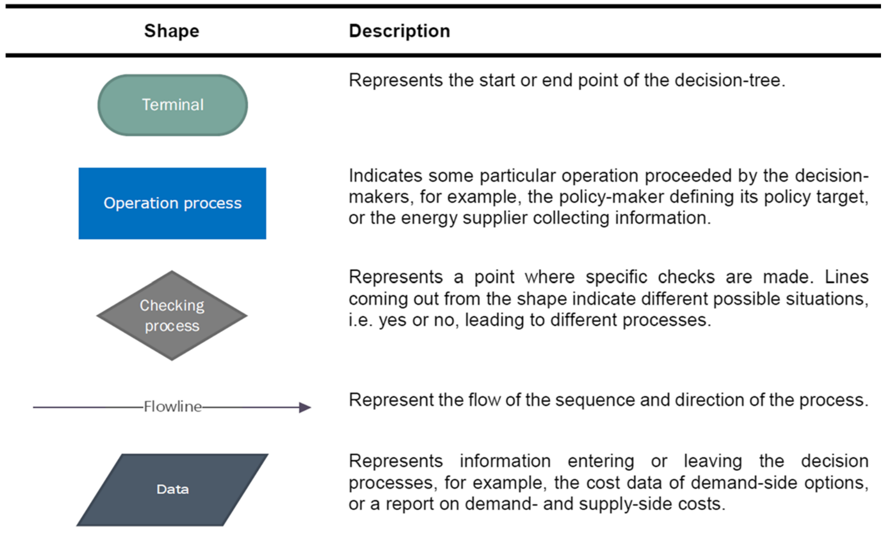

Fig. 1 Shapes for information display in the decision-tree

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

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

Using the Microsoft Visio software, decision-trees are composed of shapes and flow-lines, with different shapes having different meanings. These mostly correspond to established standards defined by the International Organization for Standardization (ISO 5807/1985) and are outlined in Fig. 1.

Building elements of the decision-tree framework

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

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

- Policy-makers: (1) major institutions involved in the EU's standard legislative procedure, i.e.,

European Commission, European Parliament, Council of the European Union; (2) parliaments and administrative departments whose competencies extend over the whole territory (NUTS 0) of a Member State; (3) parliaments and administrative departments whose competencies extend over the regions (NUTS 1), provinces (NUTS 2) and municipalities (NUTS 3) of a Member State, respectively.
- Regulators: the public regulatory authorities or agencies designated at the national or regional level to set rules and ensure compliance, oversee the functioning of markets, and control tariffs in regulated market segments;
- Energy suppliers: the commercial producers of electricity, heat, and other commodities, as well as the legal entities that sell energy (electricity, heat, natural gas) to consumers;
- Network operators: entities responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution and transmission system in a given area for ensuring the long-term ability of the system to meet demands for electricity, heat, and natural gas;
- Service providers: the entities that provide management service (supporting consumers for both improved energy efficiency and DR), for example, the aggregators in the power system or dedicated energy service companies (ESCOs) who can increase the responding flexibility of consumers;
- Consumers: the customers in the industry, transport, residential, tertiary and agriculture sectors who purchase energy carriers for final use and invest in energy-using assets of a certain energy efficiency level.

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

- Inception: the phase when the policy-makers define the policy targets and the regulatory framework, based on which relevant decision-makers define the goals of their business. For system planning and investment cases, the regulators will check if the business goals comply with the targets defined by the policy-makers;
- Preparation: the phase when the market or planning entities, including the energy suppliers, network operators, consumers, DR service providers, and other relevant decision-makers collect necessary information and systematically evaluate their options within a cost-benefit framework, which is defined by the regulatory authorities;
- Validation: the phase when the market actors propose their investment plan after the assessment and the regulatory authorities check the plan. However, such a phase only exists in the vertically integrated sectors. In the market-based sectors, the entities do not need permits from the regulatory authorities when making investment decisions;
- Implementation: the phase when market entities implement the plans.

Third, the common actions of the decision-makers in the phases are identified, as shown in Table 1. The detailed introduction of each action is provided in Appendix A, where we list the most important questions to consider when applying the EEF principle for each action.

In the next subsections, we follow the four project phases to explain the actions of the decision-makers, their meaning and their interlinkage. In "4", we further exemplify how to construct decision-trees for specific cases by providing two examples.

Project phases and actions of decision-makers

Project inception

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

Given the policy targets and the regulatory framework, the regulators will take local conditions and constraints into account and interact with relevant market actors. First, the regulators will define

Table 1 General structure of the decision-tree for applying the EEF principle

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

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

On the other hand, according to the policy targets and regulatory framework, the company market actors will define their business or project goal based on their situations and decisions to make (Bhattacharyya, 2019; Mulder, 2021). In some cases, public entities or state agencies may also be involved in an EEF principle application case, directly participating in the system operation and are responsible for implementing the efficiency or DR programs, e.g., as DR service providers in the power system. Finally, under specific cases, companies from non-energy sectors may also be involved, for example, the industrial companies that provide waste heat to the district heating system.

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

Project preparation

In the project preparation phase, the regulators should consider local conditions and constraints to define the cost-benefit-analysis (CBA) framework from a societal perspective. Apart from the energy savings, they should also look at wider costs and benefits which may not be easy to quantify or monetize (Atkinson et al., 2018; IEA, 2015; Thema et al., 2018; Ürge-Vorsatz et al., 2016), i.e., try to cover and meet all sustainable development goals (SDGs) with lower cost. Furthermore, the regulators should also define the policy and regulatory details,[3] so that the market actors can systematically assess their investment options accordingly.

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

Project validation

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

Project implementation

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

Examples of applying the decision-tree framework

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

Planning for demand-response in the power sector

Based on the development of information and communication technologies (ICTs) and smart measuring and planning devices, demand-response is playing a promising role for the future energy system. It improves the grid flexibility, increases the share of renewable electricity that can be integrated in the grid cost-effectively, decreases the generation cost for peak hours, and avoids over-investment for generation capacity and grid and storage infrastructure (Pallonetto et al., 2020). In the liberalized EU energy

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

market, no vertically integrated utilities exist anymore, and it is the responsibility of the policy-makers and regulators to evaluate the cost and benefit of DR measures from a societal perspective, and adopt them in their infrastructure investment plans.[4] For the electricity system planning, this evaluation includes an assessment of (1) whether future generation capacities will meet demand forecasts, and (2) how the grid expansion should be planned by the energy regulators and transmission and distribution system operators (TSOs and DSOs). Then, the policy-makers and regulators ideally design policies which enable the market access for DR service providers and which motivate consumers to adopt relevant technologies.

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

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

In this example, we focus on the first situation, with DR service providers referring specifically to the aggregators, who provide DR services to the end-consumers (excluding large consumers). The other decision-makers identified in this real-life example include policy-makers, regulators, and consumers. For such a market-based planning (i.e., policy-making) case, the policy-makers and regulators can only design policies to incentivize the DR service providers to enter the market and the consumers to adopt relevant technologies. Therefore, to support the policy-makers and regulators to visualize and analyze potential actions and processes for policy-making decisions, the decision-tree is designed as shown in Fig. 2.

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

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

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

Then, the regulator will define the CBA method from the societal perspective, based on which they define the policy and regulation details. This information will be provided to the DR service providers, based on which they will further define their own CBA method to systematically assess their investment options and services under the given regulatory and

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

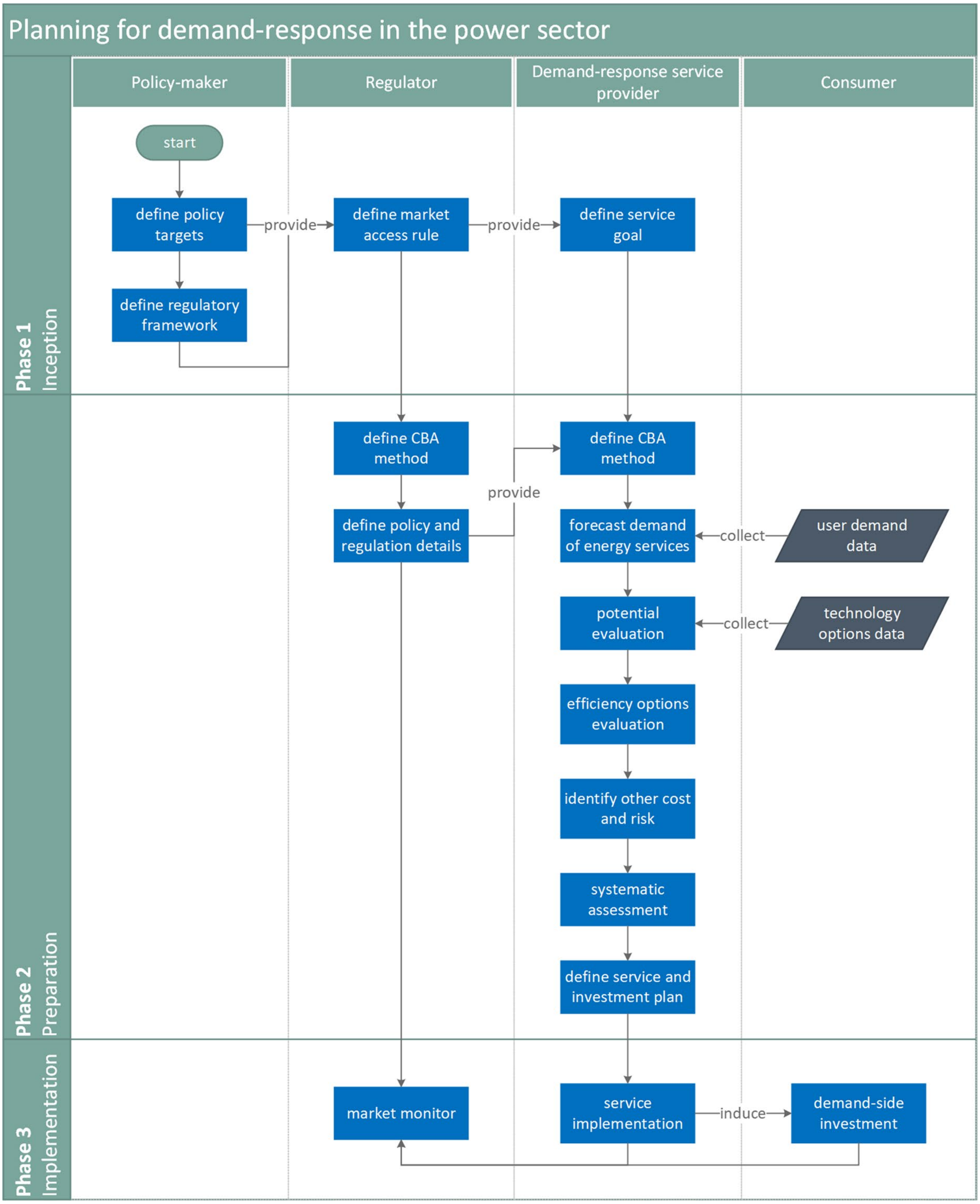

Fig. 2 Decision-tree of planning for DR in the power sector

policy conditions, followed by a series of actions in the preparation phase. At last, based on a close review and assessment, the DR service providers will define their service plan and implement it, which further induces the investment by the consumers on energy storage, smart devices, etc. At the same time, the regulator will keep monitoring the market and respond to the violations.

Planning for a district heating system

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

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

Traditionally, district heating systems are vertically integrated systems, i.e. the system operator is responsible for both heat production and network operation and heat supply, as well as relevant investment decision-making.[5] Additionally, the industrial sectors can also be connected because they can collect waste heat and sell it to the network. In summary, district heating system planning is a good example for the second type of the EEF principle application cases, i.e. system planning and investment. The policy-makers and regulators are more deeply involved in checking and approving relevant planning and investment decisions. Correspondingly, the decision-tree for district heating system planning is provided as shown in Fig. 3.

As shown in Fig. 3, the project starts with policy-makers defining policy targets. These may include reducing energy imports and dependency, cutting costs for households and businesses, and delivering greenhouse gas emission reductions. Then the district heating system operator will define its planning goal, which will be checked and approved by the regulator. This planning goal may differ according to the ownership arrangements of the DH system operator. Publicly owned companies may prioritize societal concerns over profit maximization, and vice versa for privately owned companies. The policy-makers will also define the regulatory framework, based on which the regulator will define the CBA method and the policy and regulation details. While publicly owned companies can more easily adopt criteria favoring investments in demand-side resources, privately owned companies require regulatory oversight to control their performance in considering such resources in their investment and operation decision-making. Possible instruments for this purpose include the following: general regulatory oversight (closely

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

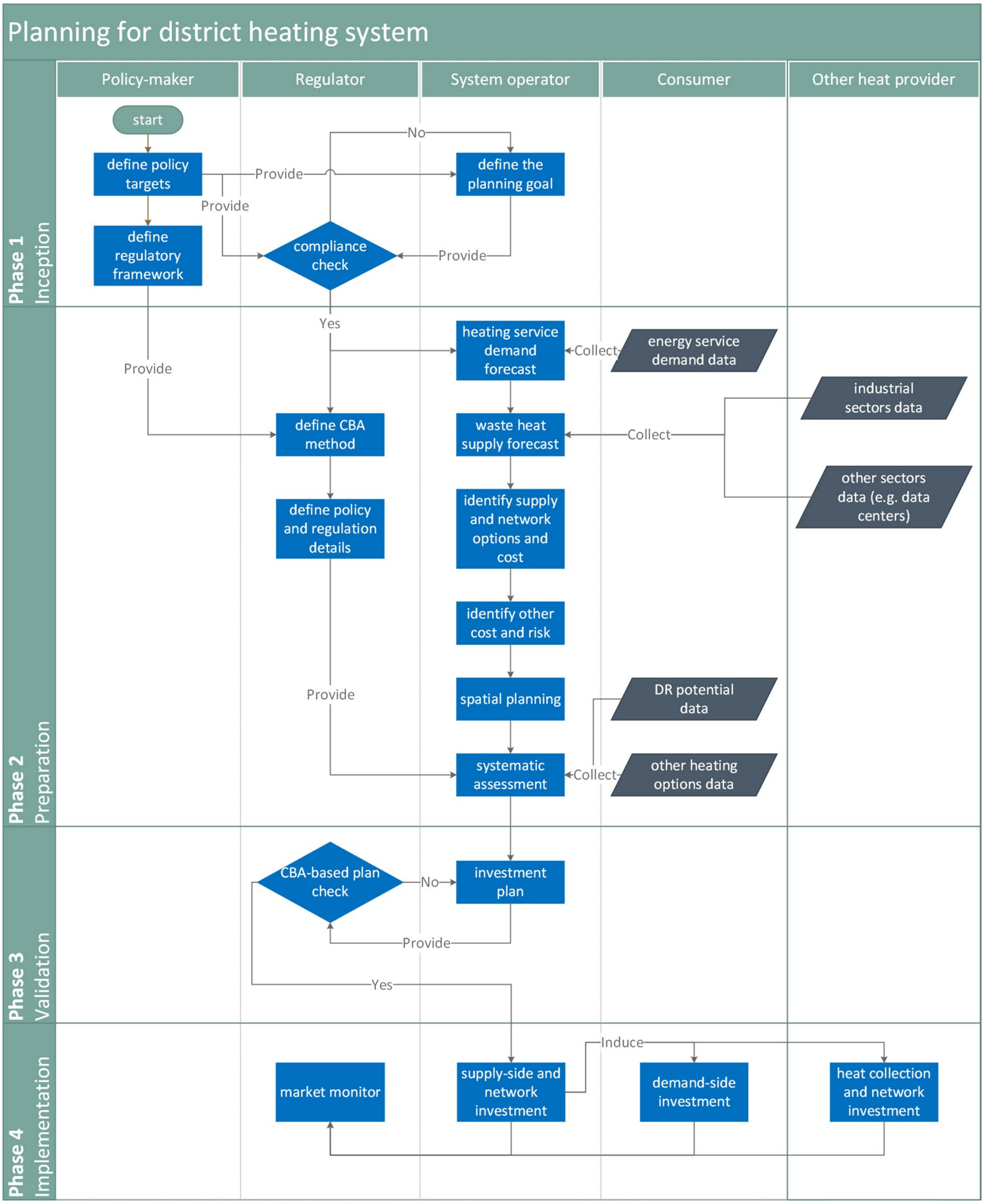

Fig. 3 Decision-tree of planning for district heating system

supervise all costs and make all investment items subject to regulatory approval); price or revenue caps (set a ceiling that the operator is allowed to pass on to consumers relative to the opportunity costs of alternative demand-side investments); and performance-based regulation (reward the consideration of demand-side resources through financial incentives) (Ecorys et al., 2021).

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

Discussion

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

- First, clearly define the application case, that is to define (1) the aim of the case, e.g., policy-making, or system planning and investment, and (2) which solutions, from both demand- and supply-sides, are involved in this case.
- Second, based on a clear definition, we identify which decision-makers are involved in the case, e.g., policy-makers, regulators, or market actors. Then, given the focused solutions in this case, we select from the pre-identified actions, and construct the decision-tree.
- Third, following the decision-tree, we go through the actions and the key questions for each of them (see Appendix A for a detailed list), review relevant studies to find answers and existing experiences, organize meetings and workshops for discussion, and finally form the project plan.

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

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

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

Conclusions

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

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

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

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

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Declarations

Conflict of interest The authors declare no competing interests.

Appendix A. Further explanation for the actions of decision-makers

In this section, we provide further explanation for the common actions of the decision-makers that are listed in Table 1, including a short introduction and the most important questions to consider when applying the EEF principle for each action. As shown in Table 1, four market actors are merged into one group, including energy suppliers, network operators, consumers, and DR service providers, because several actions are shared among them.

A.1. Policy-makers

(P1) Define policy targets

For a specific application case, the policy-maker should define the policy targets following the EEF principle and consider the interactions among them. Then, the policy-makers should provide the targets to the regulatory authorities and other relevant decision-makers for further steps.

For this process, the following questions are involved: (a) What policy targets are usually applied under the specific case? (b) How can these targets be measured? (c) What are the potential trade-offs among these targets?

(P2) Define regulatory framework

Based on the targets defined in the first step, the policy-maker should also define the regulatory framework to support the application of EFF principle, i.e., to provide incentives to procure demand-side resources by integrating necessary policy instruments. Specifically, incentives need to be provided for the system operator in the vertical integrated systems, or energy suppliers and energy service providers in the market-based systems, to promote the use of demand-side resources.

Relevant questions include the following: (a) What policy instruments can be applied to achieve the policy targets listed in the first step? Are there interactions among these policy instruments? (b) What are the existing experiences with these policy instruments? What are the barriers for implementation? (c) For the specific case under consideration, what are the advantages and disadvantages of the policy instruments?

A.2. Regulators

Following the policy targets and regulatory framework defined by the policy-makers, the regulators take local conditions and constraints into account and interact with relevant decision-makers at a micro-level, by checking their business goals and implementation plan, and by defining more detailed cost-benefit-analysis (CBA) method and necessary rules. Four relevant actions of regulators are identified as follows.

(R1) Define market access rules for efficiency or DR solutions

Under the current regulatory framework, some energy efficiency or DR improvement solutions may not be provided by the existing decision-makers. To implement the EEF principle, new players who provide efficiency or DR solutions should be introduced to the relevant markets by defining access rules for them. For example, in the case of a district heating system, additional to the system operator new players such as potential waste heat providers have to be able to access the market. For the DR solutions, it could be the DR service provider (e.g., an aggregator), who improves the flexibility of demand-side, reduces the peak demand, and further reduces the investment for the supply-side or network in the electricity system.

For such cases, the regulatory authority should provide the rules that make this possible. Relevant questions include the following: (a) Concerning the case under consideration, are there any other players that can enhance the energy efficiency or DR flexibility of consumers, or provide energy from waste collection, etc? (b) If there are these kind of players, what are the current barriers for them to implement a more energy efficiency solution or access the market? (c) How can the potential contribution from these decision-makers be evaluated, and are there any costs for letting them in the system? (d) How should the responsibilities be shared for the achievement of the main objectives of the project? (e) What are the existing experiences of the application of energy efficiency solution in a specific area?

(R2) Compliance check

Based on the policy targets provided by the policy-maker, the regulatory authority should check the business/project goals proposed by the market entities. The aim of this process is to ensure that the business/project goals do not conflict with the policy targets defined by the policy-makers and the market access rules, and besides, to ensure that there is space for the application of energy efficiency solutions on the demand-side.

This should be an iterative process at an early stage of the decision-making process that should lead to consideration of increasing energy efficiency in the business goals and ensuring that energy-efficient solutions could be eligible for a given initiative. In particular, potential demand-side options, should be specifically considered if they could contribute to achieving the business goals.

For this process, the regulatory authorities need to answer the following: (a) Are there potential conflicts between the business/project goals and the targets defined by the policy-makers? (b) Given the scope and goals of the business/project, is it possible to incorporate efficiency or DR solutions?

(R3) Define CBA method

The CBA method for applying the EEF principle should be defined from a societal perspective. Apart from the energy savings, it should also look at wider benefits which may not be easy to quantify or monetize, and the benefit should be evaluated from a societal cost and benefit perspective, beyond the market entity perspective.

Relevant questions include the following: (a) What are the available investment options for the market entities on the supply-side and the network for the specific initiative? (b) What are the options on the demand-side that can improve the energy efficiency or DR flexibility, and reduce the investment on the supply-side or the network? (c) For these options, how can their costs and benefits be evaluated? (d) How can the contribution of cost-effective investments to the policy targets be assessed?

For some cases in non-energy areas (e.g., construction of a data center) the evaluation of investment options should also consider their impact on the energy consumption, and see if the more energy-efficient options can be integrated. Relevant questions include the following: (a) Given the policy targets or business goals, what are the available options, especially the energy efficiency options? What are the impacts on energy consumption of various investment options? (b) How can the cost and benefit of these options be evaluated from the societal perspective? (c) If and where can data be obtained and compared?

(R4) Define policy and regulation details

Based on the policy targets and regulatory framework defined by the policy-maker, the regulators should take local conditions and constraints into account to develop the CBA method from a societal perspective, and then define the policy and regulation details to motivate the behavior of market actors and to monitor the market in the implementation phase.

(R5) Implementation plan check

Following the CBA method provided in the earlier step, for system planning and investment cases, the regulatory authorities should check the plans proposed by the decision-makers following the EEF principle. They should evaluate if full advantage of the available energy efficiency options is taken, and the investment on the supply-side and networks are necessary to achieve the overall target. This is an iterative process and will lead to improvement until the EEF principle is fully applied in the planning. Relevant questions are the same as for the action "(R3) Define the CBA method".

(R6) Market monitor

Based on the policy and regulation details defined previously, the regulator should monitor the market and deal with the violations.

A.3. Market actors

The "Market actors" here include energy suppliers, network operators, consumers, and DR service providers. Additionally, in some cases, it also includes public entities or state agencies, which directly participate in the system operation and are responsible for implementing the EE or DR programs, for example, as DR service providers in the power system. At last, under specific cases, some decision-makers from non-energy sectors may also be included, for example, the industrial companies that provide waste heat to the district heating system. Here we put all these decision-makers together because they share several similar actions. The union set of their actions is introduced as follows.

(M1) Define business/project goal

Under a specific EEF principle case, some market actors need to define their business or project goals based on the policy targets defined by the policy-maker. For different market actors in different cases, the emphasis of the goal can be different. For the generation companies in the electricity market, the goal is more about maximizing the profit, while for the operator of a district heating system, the goal may be more about the improvement of energy efficiency, and the cost and benefit is evaluated more from a societal perspective.

In system planning and investment cases, the goals defined by the market actors will be checked by the regulatory authorities, to see if they are consistent with the policy targets, and if necessary efficiency options can be included in the following stages. For the action "define business/project goal", relevant questions include the following: (a) What are the implications of targets defined by the policy-makers on the business or project? Are there any conflicts? (b) Is it possible to incorporate efficiency or DR options within the business or project?

(M2) Define CBA method

When applying the EEF principle in the market-based systems, the societal CBA method will be specified by the regulators. The market entities will also define their own CBA method based on the given regulatory framework and policy instruments, to systematically assess the investment options. The impact of policy instruments will be taken into consideration, and the investment on the supply-side or network may be reduced.

Relevant questions include the following: (a) How will the regulatory framework and policy instruments influence the cost and benefit of the business or project? How will they influence the decisions of other relevant decision-makers? How will they influence the final equilibrium among all decision-makers? (b) Are there any demand-side options that can be applied to reduce the investment on the supply-side or network? How are they influenced by the policy instruments?

(M3) Information collection

For further steps, the market actors need to collect the necessary information. For example, the operator of a district heating system may collect information about the population or number of the dwellings in this area, as well as their location, to forecast the demand of district heating. Additionally, he may also collect the information about potential heat providers from other sectors, e.g., industrial companies or data centers. At last, the system operator also needs to collect information about the cost of heat sources and pipelines, thermal insulation of buildings, social benefit of the district heating system (energy saving, pollution reduction, etc.), to systematically evaluate the cost and benefit of the system and to fully apply the EEF principle.

Relevant questions of this action include the following: (a) What are the factors that influence the demand of the business or project under discussion? (b) What is the cost of potential investment options in the supply capacity or network? (c) Are there any other decision-makers that can be involved for a higher overall efficiency? (d) How can we collect such information with enough details and reliability?

(M4) Energy service demand forecast

To apply the EEF principle in the energy field, all the relevant market actors, especially the ones active on the supply-side and network operation, will forecast the energy service demand. Additionally, for the vertically integrated systems, the task of forecasting could also be upon the regulatory authority. Based on this forecast of energy service, in the following steps they will evaluate the available options based on the CBA method defined before. The forecast should also look at possible further reductions in energy demand levels that could affect the viability and cost-benefit assessment of options.

Relevant aspects to consider include the following: (a) What is the energy service demand for the business or project under discussion? What is the amount of energy service? What does its load-profile look like? (b) Will there be demand reduction led by efficiency improvements or DR options in the future? What is the implication on the system planning or investment decision today?

(M5) Identify other cost and risk

To evaluate the costs and benefits of system planning, investment decision, or a policy design, one also needs to identify other potential costs and risks and consider them. For example, when designing the contract for the consumers, the operator for a district heating system needs to consider the variation of fuel price, environmental cost, etc.

Relevant questions include te following: (a) Are there any other factors that will influence the cost-benefit analysis of the business or project under discussion? For example, the variation of fuel price, environment cost, etc. (b) What are the influencing sensitivities of these factors?

(M6) Systematic assessment

Based on all the information collected, including costs of various available options, the forecast of energy service demand, and identified uncertainties and risks, the decision-makers will systematically assess all the available options based on the CBA method. Following the EEF principle, the demand-side options are included and all the options are treated equally. Relevant questions at this phase include the following: (a) What are the systematic costs and benefits of the system plan or investment decision? (b) What is the final investment decision on supply-side capacity, networks, and demand-side options?

(M7) Propose the implementation plan

In the system planning and investment cases, based on the systematic assessment of all options, the market actors will propose their plans to the regulators for a check. The plan should indicate how energy efficiency and DR options are assessed, whether they have been discarded or selected and under what conditions they could be implemented. This is an iterative process and will lead to improvement until the plan is justified. This action does not indicate other specific questions.

(M8) Implementation

At last, after all the actions above and receiving approval from the regulatory authorities (if necessary), the market actors will implement their plans at last, including adopting energy-efficiency technologies, providing the designed service, making investment decisions, etc. This action does not indicate other specific questions.

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