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Energiewende

IMPULSE

Making the most of green electricity

Key principles for identifying flexibility gaps in the power system

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Key principles for identifying gaps in the power system.

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Preface

Dear reader,
Europe is making strides in decarbonising its power system, with the rapidly expanding share of renewable energy increasingly displacing coal and gas – in the power mix, in setting market prices and in end-use sectors. Yet alongside this successful expansion, increasing unused renewable electricity and periods with negative power market prices point to the deeper structural challenge of integrating renewables into the power system. To safeguard the successful clean energy transition driven by wind and solar, unlocking power system flexibility must now become a central focus.

Recognising this, the European Electricity Market Design reform has introduced Flexibility Needs Assessments (FNAs) as a strategic reporting obligation for member states. FNAs aim to help define the right amount and type of flexibility required to integrate renewables efficiently while maintaining system stability and reducing fossil dependency. The EU Agency for the Cooperation of Energy Regulators (ACER) has until 16 July to finalise an assessment methodology.

This report, prepared by Consentec GmbH on behalf of Agora Energiewende, offers recommendations for such a methodology aimed at maximising the use of available decarbonised electricity – provided it remains cost-efficient. If well-designed, FNAs can form the basis for policy measures that address market barriers and unlock investment in flexibility solutions – accelerating decoupling from fossil fuels and lowering power system costs.

I wish you a pleasant read!

Émeline Spire
Director Europe, Agora Energiewende

Key findings at a glance

1 **As Europe integrates more renewable energy each year, growing volumes of decarbonised electricity are going unused due to mismatches between supply and demand in time and location.** In 2024, Germany had to cut back one-fifth of its offshore electricity generation, while Finland saw over 700 hours of negative electricity prices, during which electricity producers were compelled to pay to offload power that could have been used to meet demand in other hours of the day. Shifting electricity demand over time will be key to better integrating renewable energy.

2 **Growing renewable surpluses and more frequent negative prices signal the need for greater flexibility in a largely decarbonised power system, creating opportunities for storage and demand response.** Flexibility Needs Assessments (FNAs), required under the EU Electricity Market Design reform, can play a key role in unlocking the potential of these solutions. If designed well, the flexibility assessments help identify the cost-efficient level of flexibility needed to shift surplus renewable electricity to periods of deficit.

3 **FNAs should take an integrated approach to system and network needs, including transmission and distribution constraints, to accurately estimate flexibility needs.** Results should directly inform Resource Adequacy Assessments, fully leveraging decarbonised flexibility before resorting to conventional plants. An open-source methodology backed by harmonised data collection would enable comparability across member states and usability for research and market actors.

4 **FNAs can help uncover flexibility gaps and support tailored policy action.** Core design principles – such as cost-efficiency optimisation, transparency, recognition of network needs and that they feed into Resource Adequacy Assessments – should be consistent across member states, but policy responses can vary. These may include capital support for storage and demand-side flexibility, adjustments to market rules or network tariffs, or a combination of measures tailored to the specific system context.

Contents

1 The role of flexibility needs assessments (FNAs) in Europe's power system transformation

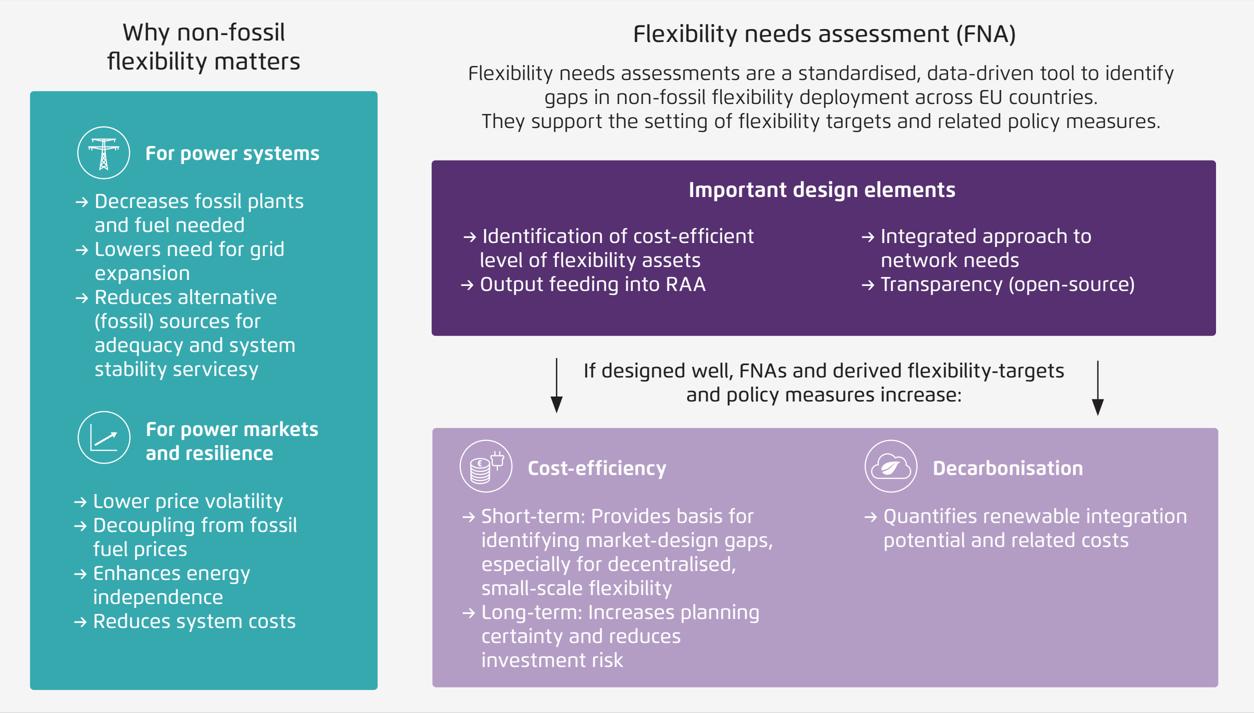
1.1 Why non-fossil flexibility matters for power systems

Aligning demand with decarbonised power supply is key to making the most of Europe's growing renewable power fleet. It enables clean electricity to be used efficiently by ensuring that wind and solar power can be integrated into the system, reducing the need for fossil generation capacity. Greater demand-side flexibility and storage decreases renewables curtailment, improves market efficiency and minimises not only the need for investment in thermal backup generation capacity but also the fuel costs of scarce and expensive decarbonised energy carriers.

A flexible power system also maximises the use of existing grid infrastructure, helping to balance peaks in demand from electrification (such as electric vehicles, heat pumps, electrolysers). By shifting consumption, demand-side flexibility and storage can reduce the need for costly and time-consuming grid expansions, making the energy transition more efficient and affordable.

Finally, as power systems move towards less dispatchable power generation, other flexibility sources are needed to address adequacy and system stability requirements such as covering peak demand, providing balancing reserves and (synthetic) inertia and managing ramping constraints and further system stability needs.

Important design elements and benefits of flexibility needs assessment methods → Fig. 1



Why non-fossil flexibility matters

For power systems

- → Decreases fossil plants and fuel needed
- → Lowers need for grid expansion
- → Reduces alternative (fossil) sources for adequacy and system stability servicesy

For power markets and resilience

- → Lower price volatility
- → Decoupling from fossil fuel prices
- → Enhances energy independence
- → Reduces system costs

Flexibility needs assessment (FNA)

Flexibility needs assessments are a standardised, data-driven tool to identify gaps in non-fossil flexibility deployment across EU countries.
They support the setting of flexibility targets and related policy measures.

Important design elements

- → Identification of cost-efficient level of flexibility assets
- → Output feeding into RAA
- → Integrated approach to network needs
- → Transparency (open-source)

If designed well, FNAs and derived flexibility-targets and policy measures increase:

Cost-efficiency

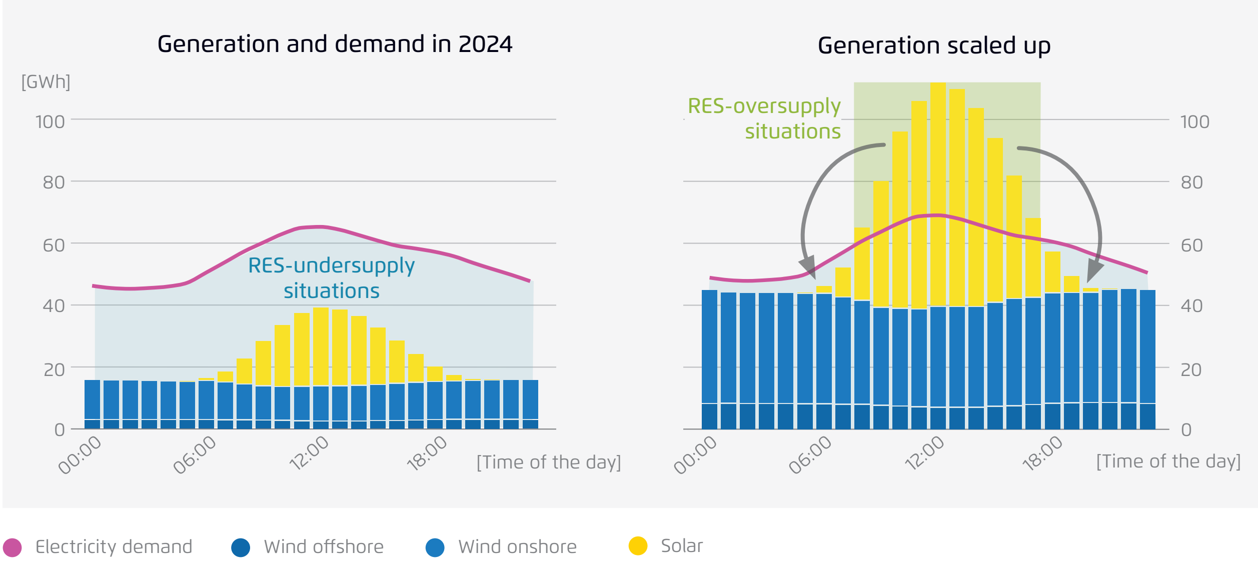
- → Short-term: Provides basis for identifying market-design gaps, especially for decentralised, small-scale flexibility
- → Long-term: Increases planning certainty and reduces investment risk

Decarbonisation

- → Quantifies renewable integration potential and related costs

Agora Energiewende (2025). RAA = Resource Adequacy Assessment

Hourly average generation and demand in Germany → Fig. 2

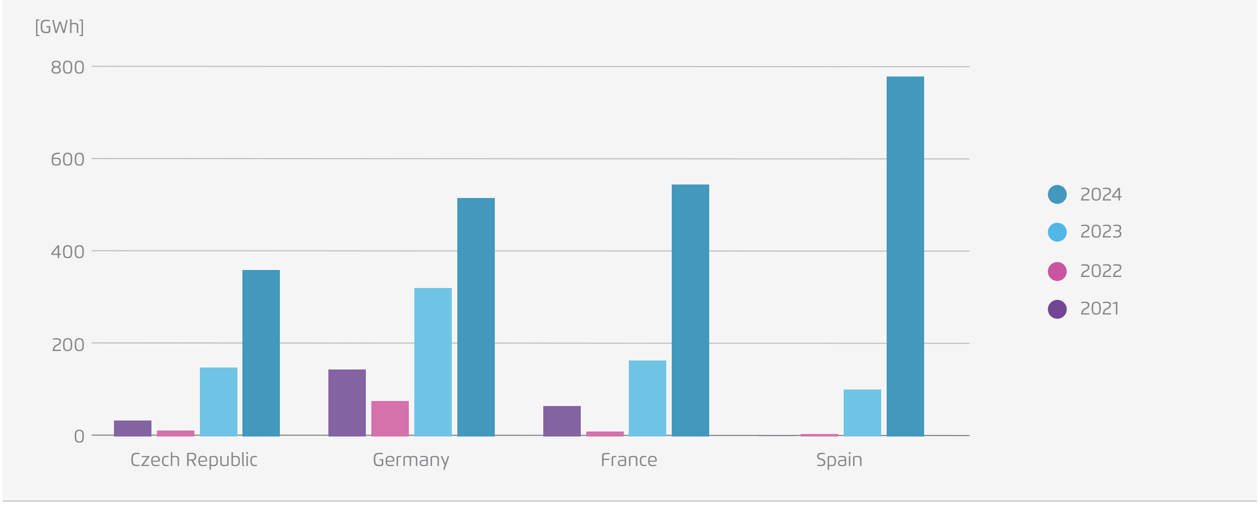


Agora Energiewende based on Agorameter (2025)

1.2 Why non-fossil flexibility matters for power markets and resilience

Europe has a rapidly growing fleet of renewable energy plants that provided almost 50 percent of electricity generation in 2024. By enabling the efficient integration of increasing amounts of renewables into the power system, flexibility enhances energy independence and reduces exposure to volatile global energy markets. As a result, electricity prices become increasingly decoupled from the price of fossil gas. Flexibility also stabilises electricity prices by mitigating extreme price spikes during periods of low renewable generation and preventing negative prices when renewable supply is high.

Number of zero or negative hourly day-ahead power prices, 2021–2024 → Fig. 3



Agora Energiewende based on ENTSO-E Transparency Platform (2025)

1.3 Introducing flexibility needs assessments as a tool for enhancing non-fossil flexibility deployment

Following the 2022 fossil energy price crisis, the European Union adopted the Electricity Market Design (EMD) reform (2024) to enhance energy market resilience and reduce dependence on short-term electricity price fluctuations. One instrument within the new framework is the flexibility needs assessment (FNA), which aims to set up a standardised method of assessing flexibility needs across EU Member States to foster investment in and integration of non-fossil flexibility. Based on national flexibility needs reports, each Member State is required to define an indicative national objective for non-fossil flexibility, which is then reflected in integrated national energy and climate plans (NECPs).[1]

In the FNA definition process, ENTSO-E (European Network of Transmission System Operators for Electricity) and the EU DSO Entity are responsible for developing the methodology, which must be approved or amended by ACER (Agency for the Cooperation of Energy Regulators).

Ultimately, the national regulatory authorities (or another authority or entity designated by a Member State) are to adopt a report on the estimated flexibility needs every two years, covering a five- to ten-year period. These reports must evaluate seasonal, daily and hourly flexibility needs and assess the potential of **non-fossil flexibility resources such as demand response and energy storage.**

1.3.1 The benefit of a well-designed FNA

A well-designed FNA should provide critical insights into the amount of flexibility required for an efficient and decarbonised system.

→ FNAs as a tool for cost-efficiency:
  - a well-designed FNA identifies the cost-efficient balance between maximising the use of available renewable electricity supply and expanding non-fossil flexibility options – that also come at a cost. By comparing this system-optimal level of flexibility with actual deployment, FNAs can reveal whether markets are delivering it. While market prices should in theory trigger the cost-optimal solution, short-term market price signals do not in practice always provide sufficient certainty that upfront investment costs will be covered. Furthermore, market players consider not only price signals but also real-world barriers such as bureaucracy or grid connection constraints. These factors can result in a gap between actual and optimal flexibility deployment. Decentralised demand-side flexibility and storage solutions are particularly vulnerable to barriers outside the market, as units are often small and owned by stakeholders unfamiliar with the way power markets function (such as in the case of residential batteries, heat-pumps, electric vehicles). By identifying these gaps, FNAs can help reveal whether existing policies and regulations facilitate or hinder cost-optimal flexibility deployment and henceforth support the alignment of market incentives and policy with system needs
  - in the long term, FNAs and the associated national objective can contribute to enhancing planning security for grid operators and reducing the investment risk for market players, thereby lowering the cost of capital – a benefit that has a particular impact on demand-side flexibility technologies, given their often CapEx-intensive nature. Increased transparency also enables smaller players with limited analytical resources to participate in flexibility deployment.

→ FNAs as a tool for decarbonisation: making the most of the available renewable energy requires sufficient system flexibility. FNAs quantify how much more renewable power could be utilised and the extent to which emissions could be avoided respectively, and at what cost. These insights enable

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[1] These assessments will also feed into a European Union strategy on flexibility, potentially leading to new legislative measures.

policymakers to design effective market structures, incentives and regulatory measures that unlock the full potential of decarbonised power supply.

1.3.2 Why location matters: paying attention to distribution grids

When assessing flexibility needs in power systems, giving consideration to locational aspects is essential to accurately identify the physical constraints of the grid, particularly at the distribution level. Traditionally, power grids were designed for one-way electricity flows from large, centralised generation plants to consumers. However, with the rapid integration of decentralised renewables and increasing demand from the electrification of industry, transport and heating, distribution grids are more frequently reaching their capacity limits. Flexibilities could mitigate this development – if deployed in the right locations with the right timing.

Considering distribution grids in FNAs offers two key advantages:

→ **flexibility needs are neither over- nor underestimated:** ignoring distribution grid constraints may lead to flexibility needs being underestimated, while conducting separate distribution-level assessments could result in double counting. Integrating distribution-level constraints into FNAs is therefore essential for an accurate estimation of flexibility requirements

→ **data availability and monitoring are improved:** given that a lack of data on the distribution level is currently a major barrier to efficient grid management, improved monitoring and harmonised data collection are necessary steps towards a more flexible and resilient power system. When the distribution level is included in FNAs, DSOs will need to collect and share new data on distribution grid operation and bottlenecks. This presents an opportunity to introduce standardised data collection and reporting across EU member states.

By systematically and accurately assessing flexibility needs, FNAs ensure that policy actions optimise cost efficiency and decarbonisation, allowing the appropriate amount of flexibility to be deployed in power systems.

2 Definition of flexibility in the context of the FNAs

2.1 What is the purpose of a flexibility needs assessment?

A flexibility needs assessment (FNA) is a novel instrument laid down in the European Electricity Market Regulation that requires a new standardised methodology framework to be developed. To be able to do so, the purpose and scope of an FNA, and the concept of flexibility upon which it is based, need to be clearly defined.

The objective of an FNA in the European power system can be viewed from two different perspectives:

- → **to maximise the use of decarbonised electricity**: the idea here is to minimise the use of fossil electricity by efficiently deploying the existing decarbonised supply (particularly insofar as decarbonised electricity remains in short supply in the short to medium term). One key priority is therefore to use load shifting in order to meet demand in situations of renewables undersupply (positive residual load), thereby avoiding renewables curtailment. Viewed from this perspective, an FNA aims to determine the amount of flexibility required to efficiently integrate renewable electricity into the system and match supply with demand
- → **to complement the resource adequacy assessments**[2] **(RAAs)**: this perspective is based on the assumption that current RAA methodologies

System needs for flexibility → Table 1

	Decarbonisation needs	Grid needs	Additional system needs	Adequacy needs
Description	Using flexibility to optimally integrate the available decarbonised power supply and thus avoid the need for additional alternative power supply[3] (system-level perspective).	Using flexibility to avoid or solve grid congestion (and potentially avoid inefficient grid expansion).	Using flexibility to cover additional system needs in order to guarantee system stability with respect to prediction errors (balancing reserves), residual load gradients (ramping), spinning reserves / inertia.	Using flexibility to meet demand at any given point in time by providing sufficient generation and demand response capacity.
Timeframe	Hourly, daily, weekly, seasonal, inter-annual	Quarter-hourly to hourly	(Sub-)seconds to hourly	
Geographical scope	TSO level	TSO level DSO level	Mostly TSO level	TSO level
Scope of the FNA	**Part of the FNA and focus of this report:** both types of needs interact and may overlap → the FNA methodology needs to take this into account and should ideally assess both needs in an integrated way (may require appropriate simplification for practicality).		**Part of the FNA**: addressed in several sub-assessments	**Not in the scope of the FNA**: part of the RAA

Agora Energiewende based on Consentec (2024)

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[2] As laid down in Art. 20 ff of EU Regulation 2019/943.

[3] This additional alternative power supply can be delivered either by non-decarbonised sources and hence entail emissions and related system and possibly societal costs, or by additional decarbonised sources (incurring related costs and possibly pushing these sources closer to their resource limits).

do not give sufficient consideration to flexibility resources as a means of ensuring security of supply. An FNA could address this shortcoming by answering two core questions: (i) Which flexibility options are currently underrepresented in RAAs? (ii) How could these gaps be addressed by a dedicated flexibility assessment?

Both perspectives are valid, as they stem from different assumptions. Nonetheless, they pursue distinct objectives and thus require the FNA to be tailored to their respective goals. For the purposes of this study, the first perspective – where the aim is to maximise the use of decarbonised electricity (while avoiding/efficiently managing grid congestions) – has been adopted as the primary focus. This implies a particular emphasis on energy shifting, which is why the report concentrates on demand-side flexibility and storage.

The table 1 provides a comprehensive overview of the different system needs for flexibility and how these are addressed by the FNA. Though decarbonisation and grid needs are the focus of this report, additional system needs should also be addressed within the scope of the FNA. However, these can be covered in separate, largely independent "sub-assessments".

Adequacy needs and flexibility are closely related, and flexibility helps cover adequacy needs. However, the FNA and the RAA should be regarded as separate assessment approaches with clearly distinct purposes. While the FNA, as explained above, is based on an assumed available amount of decarbonised electricity, its objective is to determine how much flexibility is required to use this electricity production potential efficiently over time. In contrast, the RAA primarily assesses whether a sufficient level of capacity (that is, power) is available to meet demand in situations of potential scarcity.

Consequently, the two assessments involve a degree of direct dependency: flexibility directly reduces the demand for dispatchable generation capacity by mitigating situations of undersupply (some of which are situations of potential scarcity that are of interest in the RAA). However, the availability of dispatchable capacity does not directly influence the outcome of an FNA, as it changes neither the amount of decarbonised electricity available nor the underlying demand curve. A general methodological recommendation can therefore be given regarding the time order of FNAs and RAAs: results from the FNA should inform the RAA. Proceeding in this order ensures that the RAA can incorporate the results of the FNA – particularly regarding the most efficient level of flexibility. In practice, this could mean that a flexibility-informed scenario could be considered within the RAA; much like CRM (capacity remuneration mechanism) scenarios are treated today.

2.2 Definition of flexibility and its operationalisation in the FNA

For this study, and in line with the role of the FNA outlined above, the following definition of flexibility is used:

> *"Flexibility is the ability of the electricity system to optimise the use of the available decarbonised power supply in different temporal and spatial resolutions while ensuring system balance and stable grid operation."*

This definition, while comprehensive, requires further clarification for practical application in an FNA. We propose the following approach:

The FNA should determine the most cost-efficient level of flexibility so that the available decarbonised power supply in cases of oversupply is optimally used to meet demand in cases of undersupply (and hence avoid the need for fossil or additional decarbonised power supply and/or grid expansion). It answers the following question: How much flexibility is needed to meet a given demand curve using a specific amount/mix of decarbonised power supply without exceeding a defined threshold that would require additional power supply?

The following aspects (based on the question above) provide a more precise explanation of the suggested purpose and specific task of the FNA, adding to the definition contained in the Electricity Market Regulation (EU Regulation 2019/943):

- **the FNA determines how much flexibility is needed →** flexibility needs will be determined according to different types of flexibility. The FNA is not about determining a single flexibility need; rather, different flexibility needs (such as decarbonisation needs, grid needs, additional system needs) and different types of flexibility (such as daily- or seasonal-scale flexibility) should be specified. A variety of incentives – first and foremost market incentives – can be used to meet these needs, with no inherent requirement for explicit capacity procurement
- **the FNA relates flexibility needs to meeting a demand (curve) →** the FNA assesses flexibility needs in relation to demand patterns. Ideally, this considers **the natural demand curve**, namely the demand for electricity before any impact from externally incentivised demand-side flexibility measures. Although approximating the natural demand curve is inherently complex, especially as new flexible loads emerge whose "natural" consumption behaviour is not empirically observable, deliberate and transparent approximations are nonetheless essential to ensure that demand-side flexibility is explicitly represented in the model rather than inadvertently included in an inflexible baseline
- **the FNA does not determine the amount of flexibility required to reach the absolute minimum amount of additional (non-decarbonised) power supply needed →** the FNA does not necessarily determine the amount of flexibility that will result in the absolute minimum amount of additional power supply needed. Instead, the FNA should identify an efficient amount of flexibility, considering the costs of additional flexibility and the value of avoiding extra amounts of additional power supply. This additional power supply might come from non-decarbonised or decarbonised sources (entailing costs for emission certificates, fuels, additional capacity etc.).

3 Cost-benefit considerations and the concept of cycles as "flexibility needs standard"

As previously outlined, the primary objective of an FNA is to determine the level of flexibility required to ensure the cost-optimal integration of the decarbonised power supply. This level is determined on the basis of cost-benefit considerations, balancing the costs of additional flexibility measures against the (socio-)economic impacts of the need for additional non-decarbonised power supply.

The following figures illustrate the underlying concept of a cost-benefit analysis in the context of an FNA. The starting point is a stylised situation in which the natural demand curve and the available decarbonised power supply do not match. This gives rise to situations of over- and undersupply of electricity produced from renewable energy sources (RES). Without further measures, this would lead to curtailment in oversupply situations and the need for additional power supply in undersupply situations.

In the absence of demand-shifting flexibility measures, all undersupply situations will need to be compensated entirely by additional power supply[4]. Demand-shifting flexibility allows surplus electricity from oversupply periods to be reallocated to cover demand during undersupply periods, thereby reducing reliance on additional power supply. Flexibility therefore allows demand to be met during undersupply situations without having to increase the amount of electricity produced over a longer time period[5] (such as the amount of electricity produced during a day, a week or a year). Increasing production in this way would be necessary if dispatchable power plants

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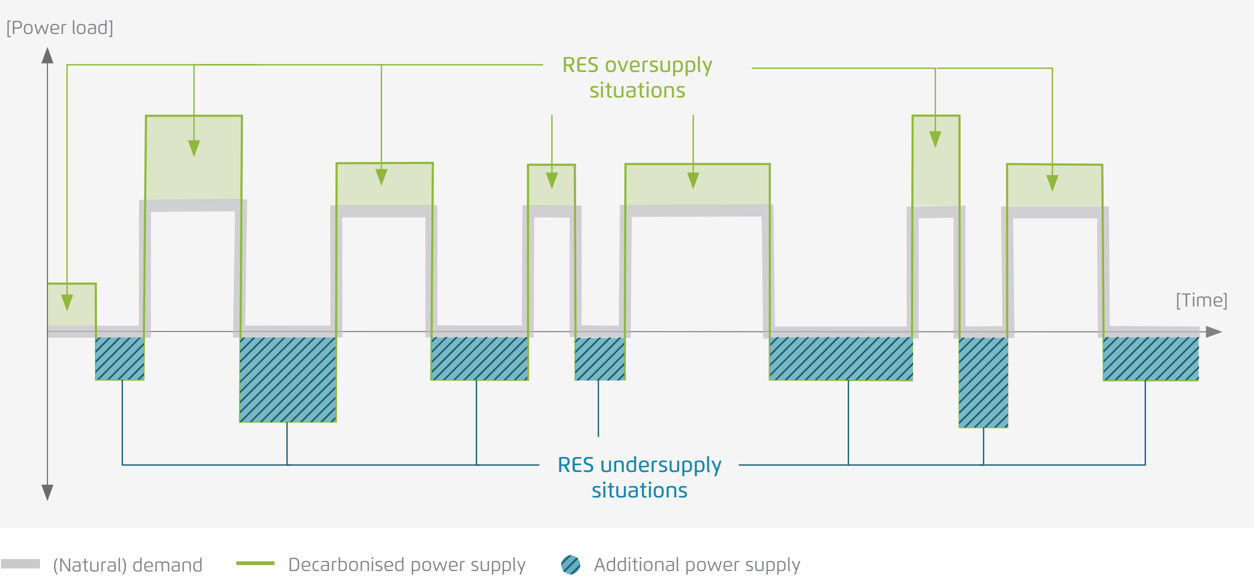
[4] Whether sufficient reliable generation capacity is available to provide this additional power supply has to be determined by the RAA (as distinct from the FNA).

[5] This also involves reducing the amount of electricity consumption over a longer time period by load shedding.

Stylised example with RES over- and RES undersupply situations → Fig. 4



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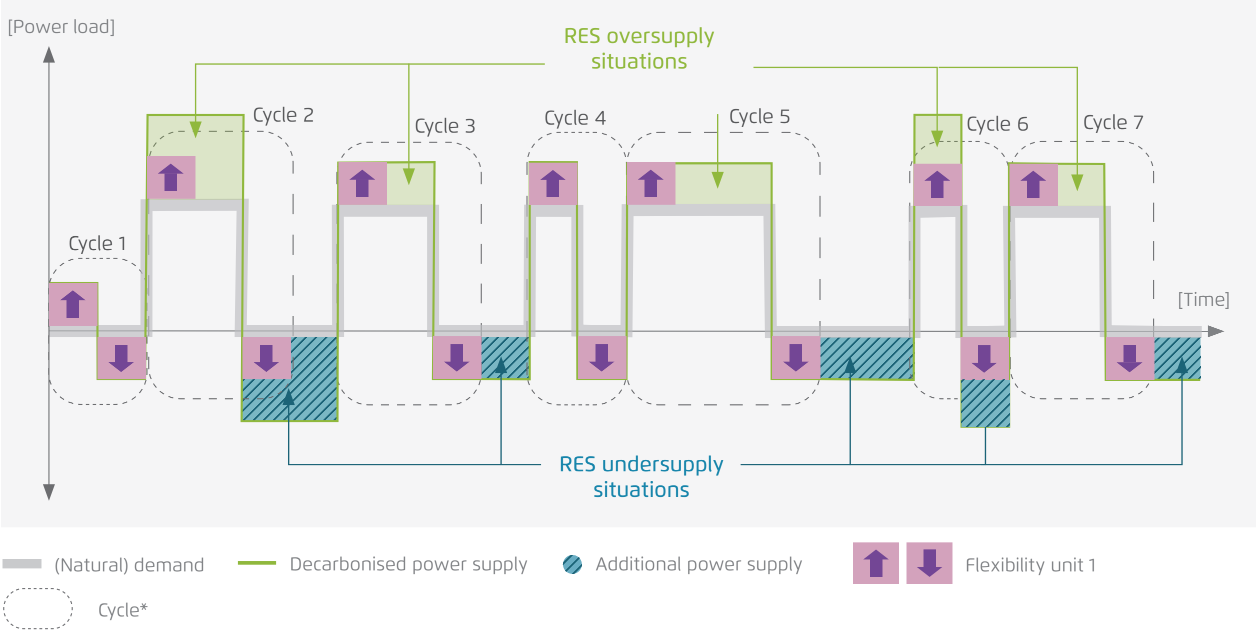
Stylised example with one flexibility unit

→ Fig. 5



Agora Energiewende based on Consentec GmbH (2025); * Cycle: One sequence of "charging" in oversupply situation and "discharging" in undersupply situation and, hence, thereby covering demand

were used to cover undersupply situations. This would require not only technical flexibility on the part of the dispatchable plants (in the sense of being able to control their electrical output) but also the additional use of fuels.

In the context of the FNA, flexibility can thus be considered as an energy-shifting unit (ESU), and the flexibility of a unit can be described as its capability to shift energy.

Flexibility units can help match oversupply with undersupply situations multiple times in the considered timeframe of the FNA, depending on the profile of the residual demand. This is depicted in Figure 5. In this stylised example, flexibility unit 1 runs seven times (= seven cycles) in a given period of time. In other words, it matches oversupply and undersupply seven times. The following paragraph explains the concept of cycles in more detail.

The above example is extended by adding further flexibility units (cf. Figure 6). This extended example also shows that the marginal benefit of additional flexibility decreases as more flexibility units are added: while flexibility unit 2 still runs five cycles, unit 3 only achieves two cycles.

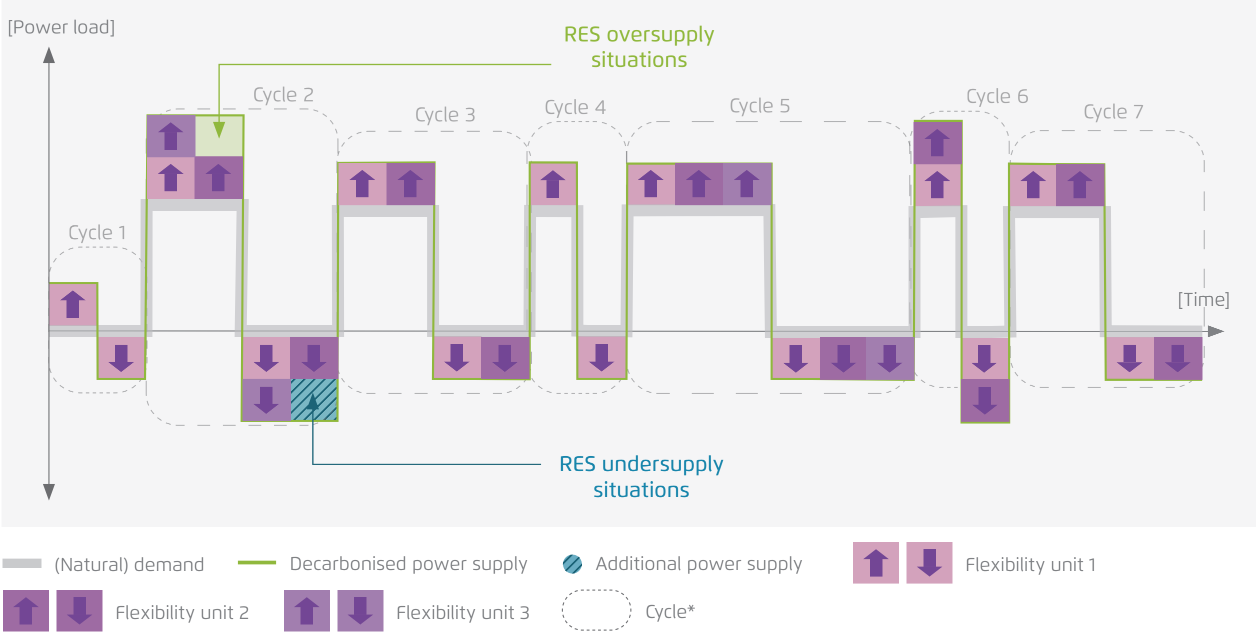
This example illustrates that the cycle serves as a metric for the utilisation of a flexibility unit (analogous to full-load hours). The number of cycles a unit completes within a given timeframe and scenario quantifies its contribution to reducing the need for additional power generation relative to its capacity (in terms of "energy content", or the megawatt hours (MWh) that can be directly or indirectly stored using the flexibility unit).

The concept of "cycles" is also a valuable metric in cost-benefit considerations related to flexibility. With regards to flexibility, cost-benefit considerations include:

- → costs: the investment required to integrate a flexibility unit into the system (cost of flexibility), primarily reflected in capital expenditures (CapEx)
- → benefits: the economic value generated by reducing the need for additional power supply (cf. Section 4)

Stylised example with further flexibility units added

→ Fig. 6



Agora Energiewende based on Consentec GmbH (2025); * Cycle: One sequence of "charging" in oversupply situation and "discharging" in undersupply situation and, hence, thereby covering demand

As a first approximation, the benefits of flexibility are directly proportional to the number of cycles (additional power supply is assumed to be OpEx-intensive), while the costs are often fixed in nature (flexibility is assumed to be CapEx-intensive), meaning they remain unchanged regardless of the number of cycles completed.

Consequently, the minimum number of cycles required to achieve cost efficiency can be determined for a given flexibility technology with known cost parameters. This threshold is calculated by dividing the total cost of flexibility (in euros per unit per year) by the value of additional power generation avoided per cycle (in euros per cycle per unit):

Deriving the unit "cycle"

→ Fig. 7

$$\frac{\text{Cost of flexibility} \quad \left(\frac{\cancel{\text{EUR}}}{\cancel{\text{unit}}}\right)}{\begin{array}{c}\text{Value of avoided}\\ \text{add. power supply}\\ \text{per cycle of}\\ \text{flex unit}\end{array} \quad \left(\frac{\cancel{\text{EUR}}}{\text{cycle}} \; \frac{1}{\cancel{\text{unit}}}\right)} = \frac{1}{\frac{1}{\text{cycle}}} = \text{cycle}$$

Agora Energiewende based on Consentec GmbH (2025)

If the flexibility unit is standardised to an output of 1 MWh, the value of additional power supply avoided per cycle is equivalent to the cost of generating one additional MWh to cover demand in RES undersupply situations.

3.1 Flexibility standard: analogous to the reliability standard in RAAs

In this sense, the "cycle" metric is closely analogous to the loss of load expectation (LOLE), a widely used reliability standard in RAAs, as defined in European regulations. This standard, derived from a cost-benefit analysis, determines the minimum number of hours per year that a marginal capacity unit must operate to be considered cost efficient. Specifically, cost efficiency is achieved when the cost of new entry (CONE) for a marginal unit is lower than the benefits gained from avoiding the value of lost load (VOLL), which represents the economic impact of unmet demand. The target value for LOLE – the reliability standard – is calculated as[6]:

$$\text{LOLE} = \frac{\text{CONE}}{\text{VOLL}}$$

In practical applications, a RAA evaluates the expected number of hours with lost load in a given scenario. If this number exceeds the predefined LOLE standard, it indicates a need for additional capacity investment. Conversely, if the expected lost load hours remain on or below the threshold, the system is considered to have reached a sufficient level of resource adequacy.

Analogous to the reliability standard, the flexibility standard defines the minimum amount of additional power supply a flexibility unit must avoid in order to be considered cost efficient – in other words, its cost must be lower than the economic benefit of displacing additional supply. The amount of avoided power supply can be expressed as a number of cycles, allowing the flexibility standard to be expressed as a number of cycles a flexibility unit must run to be cost efficient.

To calculate a flexibility standard, a benchmark technology must be defined – similar to the way in which the CONE is used to derive reliability standards. The benchmark flexibility technology provides the cost reference required to calculate the flexibility standard. The benchmark technology is the technology that can provide the type of flexibility under consideration cost efficiently (e.g. daily- or seasonal-scale flexibility). This is in analogy to the RAA, where the

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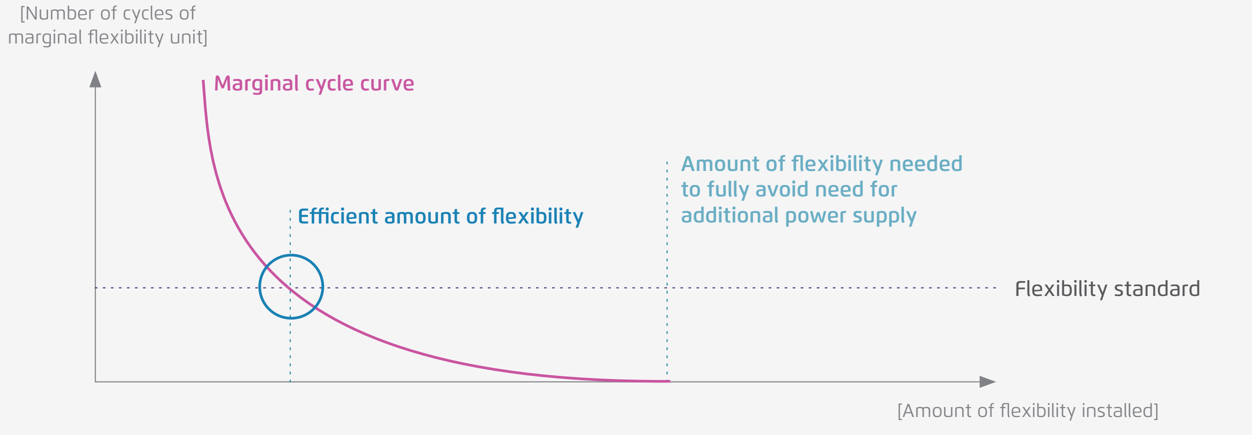
[6] Formula simplified. In a more detailed form it also includes the variable costs (such as fuel costs) of the "new entry unit" when avoiding lost load situations.

Marginal cycle curve (MCC)

→ Fig. 8



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CONE is based on the technology that can provide additional resource adequacy cost efficiently (such as the costs of a newly built open-cycle gas turbine). Batteries or demand-side response solutions might serve as a benchmark for daily-scale flexibility, while the benchmark for seasonal-scale flexibility could be hydrogen storage or seasonal thermal (heat) storage.

The flexibility standard can be applied within an FNA by deriving a marginal cycle curve (MCC) – a representation of how the utilisation of flexibility units (measured in cycles) evolves as additional capacity is integrated into the system. The MCC can be derived by incrementally adding flexibility units (additional units of the defined benchmark technology as discussed above) to the analysed power system and thereby determining the number of cycles that the marginal flexibility unit is running. With each added unit, the number of cycles it completes is calculated (how often it shifts energy from oversupply to undersupply periods). As more units are introduced, the marginal value of each additional unit tends to decline (compare Figure 7), resulting in a decreasing marginal cycle curve.

Comparing this curve to the flexibility standard – which defines the minimum number of cycles required for cost efficiency – allows the threshold to be identified at which an additional flexibility unit is no longer economically justified (compare grey dashed line in Figure 8).

Infobox: Example for how to derive the flexibility standard

We assume that a large-scale battery can serve as a benchmark for daily-scale flexibility. To calculate the flexibility standard – the minimum number of cycles a marginal battery has to run in order for it to be considered cost efficien – the minimum further assumptions have to be made about the costs of the battery systems and the value of the avoided additional power supply.

Regarding the techno-economic characteristics of the battery system, we assume the following:

- investment costs and average yearly fixed costs: EUR 250/kWh, EUR 5/kWh/a
- interest rate: 6%, lifetime: 15 years
- round-trip efficiency: 90%
    - annualised CapEx: per $\mathrm{kWh}_{\mathrm{discharged}}$: EUR 32.36/$\mathrm{kWh}_{\mathrm{discharged}}$ /a

Regarding the value of avoided additional power supply, we assume that the additional power supply would be provided by electricity generated by a gas turbine fired using green hydrogen. The costs of green hydrogen are assumed to be EUR 180/$\mathrm{MWh}_{\mathrm{thermal}}$, while the efficiency of the gas turbine is assumed to be 40%. Hence, the value of avoiding additional power supply amounts to EUR 450/$\mathrm{MWh}_{\mathrm{electricity}}$.

This results in a flexibility standard for daily-scale flexibility of

$$\mathrm{cycle}_{\mathrm{daily—scale}} = \frac{32.36 \times \frac{10^3\,\mathrm{EUR}}{\mathrm{kWh/a}}}{450\,\frac{\mathrm{EUR}}{\mathrm{MWh}}} = 71.9\,\frac{1}{\mathrm{a}}$$

Hence, a marginal battery system needs to run at least 72 cycles to be cost efficient.

This approach is conceptually analogous to RAAs, where the objective is to determine the optimal amount of reliable capacity needed to maintain system adequacy. In both cases, the intersection of marginal benefit and cost thresholds reveals the efficient deployment level.

3.2 Role of round-trip efficiency

One question that might arise is how round-trip efficiency (or losses of the flex unit per cycle) influences the described concept of a flexibility standard. Round-trip efficiency has two implications:

- → it impacts the calculation of the standard because the parameters "cost of flexibility" and "value created per cycle" depend on the round-trip efficiency of the benchmark technology (the technology that is likely to be the most cost efficient at the margin): the higher its round-trip efficiency, the more value per cycle can be created as losses are lower (the costs of this type of flexibility are likely to be higher, however)
- → it also impacts the MCC, as the lower the efficiency is the lower the achievable cycles of the unit will be (a unit with lower efficiency can cover less undersupply with the same amount of oversupply)

3.3 Integration of grid needs

The proposed FNA methodology is fully capable of identifying grid-related flexibility needs, provided that residual load curves and flexibility potentials are spatially disaggregated into network regions that are assumed to have no internal grid constraints. Such regionalisation enables the flexibility requirements arising from transmission congestion to be identified. In principle, the same approach can be extended to include distribution-level constraints. However, incorporating detailed distribution-level modelling may exceed computational feasibility. Therefore, it is recommended to apply simplified approaches that approximate distribution-level needs on the basis for example of representative distribution grid models or typical congestion scenarios and then integrate them into the TSO-level FNA in an aggregated form.

4 How to determine the value (benefit) of avoiding the use of additional power supply

One important factor when weighing up the costs and benefits of flexibility as described above is the value of avoiding the use of any additional power supply. This value will depend on which alternative power source would be used to meet demand in RES undersupply situations. Two possible scenarios can be distinguished:

- → fossil / non-decarbonised sources: in this scenario, the value of avoiding power supplied by such a source consists of two main components:
  - the cost of the energy carrier (for example, coal, gas or oil)
  - the cost associated with additional greenhouse gas (GHG) emissions. This would be the cost of emission certificates or even the social cost of carbon (SCC), which quantifies the long-term environmental, health and economic damage caused by increased emissions. Though SCC estimates vary widely due to uncertainties in climate modelling and economic projections, established sources provide reference values for possible integration into the FNA framework (UBA 2024, Wissenschaftliche Dienste des Deutschen Bundestages 2024, Rennert et al. 2022)
- → decarbonised sources: if additional power supply originates from decarbonised sources, the value of avoiding the need for power supply from such sources consists of two main components:
  - technology costs: note that figures such as the levelised cost of electricity (LCOE) are not as suitable in this case because they do not reflect the cost per kilowatt hour (kWh) specifically provided during undersupply situations. Instead, an adjusted cost framework would need to be developed and applied
  - social acceptance costs: expansion of additional decarbonised electricity production is often constrained by land use conflicts, regulatory challenges and, possibly, public opposition. While academic research on this topic exists, it is not as extensively quantified as SCC (Fraunhofer ISI 2024, Fraunhofer ISI et al. 2024, Hydrogen Europe 2024).

Estimates of the costs of power produced using green hydrogen could serve as an initial proxy for the value of avoiding additional power supply. Though the costs of green hydrogen are likewise highly uncertain, renowned modelling studies are available, which could serve as a source for making the necessary assumptions.

5 Appendix: Remarks on the technology neutrality of the proposed approach

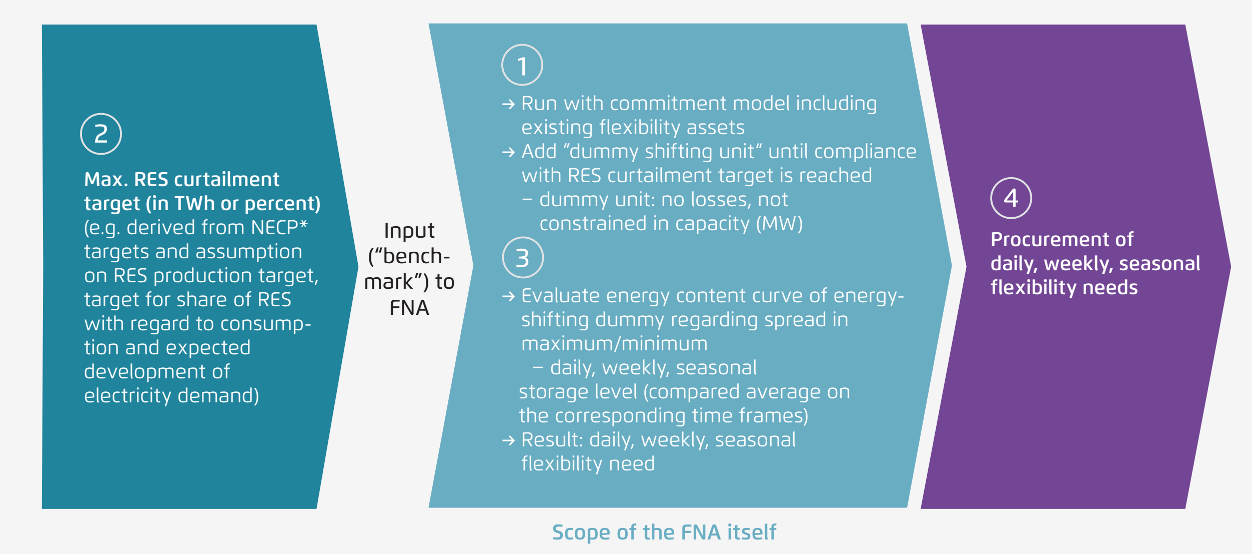
The FNA approach proposed in this report, particularly the concept of deriving marginal cycle curves (MCCs) and comparing them to a flexibility standard based on a benchmark technology, may raise concerns regarding its technology neutrality. European regulations generally aim for technology-neutral approaches. The following section therefore discusses the degree of technology neutrality in the proposed FNA approach and evaluates this issue by comparing our methodology to the FNA approach developed by the Joint Research Centre (JRC) of the European Commission, which can serve as a reference with regard to technology neutrality (Thomassen and Ladeka, 2024).

The following figure describes the JRC approach, especially in terms of how it is framed by the preceding step (setting maximum RES curtailment targets) and subsequent flexibility procurement step.

The JRC defines the core of an FNA as being the process highlighted in the middle section of Figure 9 ("Scope of the FNA itself"). This process includes the following key steps:

- → a cost-optimizing unit commitment model is run based on specific scenario assumptions, such as the residual load curve and available flexibility assets. It runs iteratively, varying the dispatch of available flexibility units.
- → the resulting degree of curtailment of a mode run is compared to a curtailment target (provided as an input to the FNA). If curtailment remains above the target, a dummy energy-shifting unit is added to the model. This dummy unit can shift energy from times of surplus to times of deficit. It is assumed to have no losses and not be constrained in its power rating, but to be constrained by its energy content (the total amount of energy (MWh) it can shift). The model is then re-run.

JRC approach for an FNA → Fig. 9



Agora Energiewende based on Consentec GmbH (2025); *NECP: National energy and climate plans

- → the model is run repeatedly with increasing dummy flexibility until the curtailment target is met. The final model run (where the curtailment target is met) is used to derive daily, weekly and seasonal flexibility needs. This is done by evaluating the spread between maximum and minimum storage levels, compared to the average, across the three timeframes.

The iterative unit commitment approach developed in this report is conceptually similar to the JRC method. Our approach aims to minimise the need for additional power supply during undersupply periods by shifting excess energy from oversupply periods using flexibility units. Assuming that this flexibility unit is one hundred percent efficient (that is, no losses), minimising additional supply will be equivalent to minimising curtailment.

However, our approach uses benchmark technologies as flexibility units in each iteration. Being modelled on the basis of real-world flexibility options, such units have losses. When losses are included, minimising curtailment could incentivise the inefficient use of energy merely to reduce curtailment figures. We therefore propose that the optimisation objective should be to minimise additional power supply.

While the JRC method appears technology neutral in isolation (as seen in the middle section of the referenced figure), it nonetheless relies on implicit technology assumptions when viewed in a broader context. Our approach makes these assumptions more transparent. **That said, both approaches remain compatible with the principle of technology neutrality in the subsequent flexibility procurement process.** Referring to the numbered elements in the figure above, the following section explains how the JRC approach also requires various technology-driven assumptions.

1. **The "core" of the JRC approach appears technology neutral:** the JRC approach appears technology neutral at its core because it uses a generic, non-specific "dummy unit" in its iterations. In contrast, our method incorporates real-world benchmark technologies with specific techno-economic characteristics.
2. **Efficient RES curtailment targets should be based on cost-benefit considerations, taking into account the costs and technical specificities of different types of flexibility:** the JRC method uses fixed RES curtailment targets as its input. However, setting efficient targets requires a cost-benefit analysis, which depends on the costs and characteristics of different flexibility technologies (such as losses, efficiency). Therefore, even in the JRC approach, technology assumptions – whether explicit or not – are necessary to define meaningful curtailment targets.
3. **Differentiating between temporal levels of flexibility acknowledges that different technologies will be cost efficient at different times:** both approaches recognise different temporal scales for flexibility (daily, weekly, seasonal), as embedded in the EU regulatory framework. This differentiation reflects the fact that different technologies are cost efficient at different time scales – an idea we emphasise by using "marginal cycle curves" for benchmark technologies.
4. **Procuring different flexibility products requires temporal and technological differentiation:** although procurement is a separate step, the FNA determines the required granularity (for example, daily versus seasonal flexibility). Differentiated FNA outputs are essential to enable such procurement. Moreover, techno-economic characteristics – such as cycle efficiency – play a key role in procurement design

Hence, we conclude that – even though not obvious at first glance – both approaches are very similar when cost efficiency is a target. Our approach makes the necessity of technology assumption more explicit, whereas this is part of the preceding and subsequent steps in the JRC approach.

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