Making the most of green electricity

Key principles for identifying flexibility gaps in the power system

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5 May 2025

Key findings

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

What is flexibility and why does it matter?

Sufficient flexibility is crucial for the efficient transformation of our power system. Different flexibility needs arise from different system challenges.

Flexibility allows for **optimal use of decarbonised power supply**

A lack of flexibility leads to curtailment of available decarbonised power, resulting in the need for additional power supply to cover demand, e.g., from existing fossil units or additional decarbonised power supply (entailing further investments).

As the share of non-dispatchable renewable energy sources (RES) increases, inefficiencies can occur, such as high curtailment due to oversupply or local grid congestion (at TSO or DSO level), especially when flexibility is lacking. The rising frequency of negative price hours shows this lack of flexibility.

Flexibility allows for more **efficient utilisation of scarce grid capacities**

Sufficient flexibility can reduce grid expansion needs for peaks in the grid load resulting from new consumers (e.g., electrolysers, electric vehicles, heat pumps) or RES units.

This can reduce costs. Activating flexibility is also potentially less time-consuming in implementation than expanding the grid.

Flexibility supports **system stability and adequacy** in a changing power mix

The generation mix is shifting towards more variable and less dispatchable units. To guarantee system stability other (flexibility) sources are required to cover peak demand, balancing reserves, inertia needs, increasing ramping constraints and further system requirements.

Identifying flexibility needs with the flexibility needs assessment (FNA)

The FNA should be an instrument to systematically identify needs for and potential shortfalls of flexibility.
This requires:

→ an unambiguous definition of flexibility (types of flexibility needs)

→ a clear scope of the FNA (including a precise distinction from RAAs)

→ a well-defined method for quantification

Striking the right flexibility balance: Insufficient flexibility is a threat to system transformation (see previous slide). At the same time, flexibility also comes at a cost. Thus, an inefficient level of flexibility can similarly jeopardise the transformation in terms of cost-efficiency.

The FNA should consider cost-efficiency as boundary condition when determining flexibility needs.

→ Art. 19(e) of EU Regulation 2019/943 (as amended) outlines the general principles for an FNA, including the aim of achieving decarbonisation, ensuring stable system operation and reaching cost-efficiency. These principles now need to be translated into a specific method suited for practical application both on the European and national levels.

Closing in on a definition by categorising types of flexibility needs

Types of flexibility needs	Decarbonisation needs	Grid needs	Further system needs	Adequacy needs
Description	Use flexibility to optimally integrate available decarbonized power supply and thus avoid the need for additional alternative power supply[1] (system level perspective).	Use flexibility to avoid or solve grid congestion (and potentially avoid inefficient grid expansion).	Use flexibility for further system needs to guarantee system stability with respect to prediction errors (balancing reserves), residual load gradients (ramping), spinning reserves / inertia.	Use flexibility to balance supply and demand at any given point in time by providing sufficient generation and demand response capacity (to a cost-efficient extent).
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

[1] This additional alternative power supply can be delivered either from non-decarbonized sources and hence emissions and related system and societal costs or from additionally needed decarbonized sources (incurring related costs and possibly pushing these sources closer to their resource limits).

Closing in on a definition by categorising types of flexibility needs

Types of flexibility needs	Decarbonisation needs	Grid needs	Further system needs	Adequacy needs
Description	**Part of the FNA + focus of this presentation**; depending on the extent to which the system level perspective of decarbonisation needs already incorporates TSO- or even DSO-level grid constraints, both needs may potentially overlap		**Part of the FNA**; addressed in several "sub-assessments" (not in the scope of this presentation)	***Not in scope of the FNA****; rather part of the RAA*
Timeframe				
Geographical scope				

Note: consideration here and in the following apply to both a European and national FNA

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Definition of flexibility in the context of the FNA, emphasising decarbonisation and grid needs

Defining flexibility
(in the context of the FNA)

Flexibility is the ability of the power 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.[1]

Operationalising the definition in the FNA
(on decarbonisation and grid needs)

Determine the cost-efficient level of flexibility so that the available decarbonised power supply from oversupply situations is optimally used to serve demand in undersupply situations (and hence avoid the need for fossil or additional decarbonised power supply and/or grid expansion).

 [1] The latter part of the definition refers to the "further system needs" (see slide 8)

How to quantify flexibility needs in the FNA?

The key to flexibility needs quantification: energy shifting capability and energy shifting cycles

Energy shifting capability

→ According to the definition above, flexibility is needed to shift decarbonised power supply from oversupply situations to undersupply situations (or alternatively: shift demand from undersupply to oversupply situations)

→ A flexibility unit is an energy shifting unit (ESU), and the flexibility of a unit can by described as its capability to shift energy

- it can be understood as a storage system
- its capacity is (initially) expressed in MWh_{output}

Cycles

→ For an ESU understood as a simple storage, a cycle describes a sequence of fully "charging" and then fully "discharging" the unit. This concept considers that charging always needs to be followed by an opportunity for discharging before charging again.

→ The ESU uses otherwise curtailed electricity for charging and discharges to meet demand during situations of RES undersupply.

→ Hence, the concept of cycles describes how much demand in undersupply situations can be served by utilizing electricity from RES oversupply situations.

- (number of cycles an ESU is running) x (capacity of ESU)
  = avoided additional power supply by ESU
  = avoided curtailment of decarbonised power supply

The concept of cycles delivers the basis for cost-benefit considerations (1/2)

Cost-benefit considerations

→ The FNA should include cost-benefit considerations to contribute to an overall cost-efficient transformation

→ With regards to flexibility, cost-benefit-considerations include:

- costs = cost of adding a certain amount of energy shifting capability to the system → cost of flexibility
- benefits = the value of avoiding additional power supply

Role of cycles

→ The **more cycles** an ESU runs in a given period…

- … the more power supply is shifted and
- … the less need for additional power supply and
- … the **more benefit** is created (directly proportional to the number of cycles) while …
- … there are (practically) **no additional costs per cycle**

Interaction of renewable integration targets and cost-benefit optimization

→ Renewable integration targets in the form of curtailment limits could be implicitly derived from NECPs* and indicate how much curtailment is acceptable

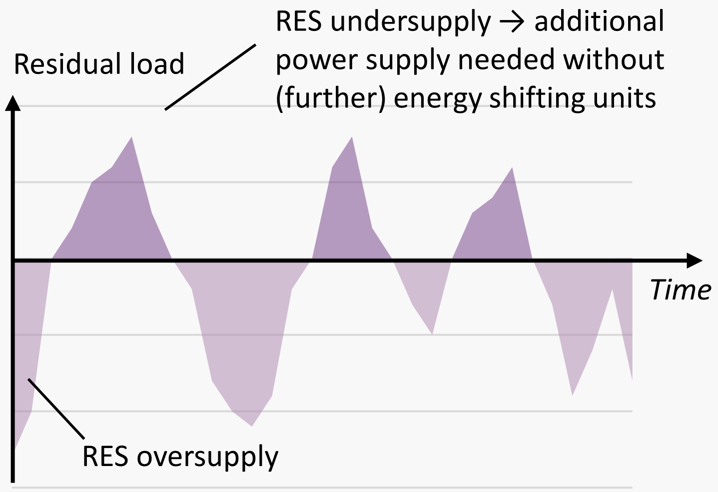
→ For a given scenario (residual load curve and thus level of curtailment without additional flexibility) and a given number of cycles of additional flexibility remaining, curtailment can be derived

→ Currently, renewable integration targets are often not based on cost-benefit optimizations, meaning that the level of curtailment and flexibility could be suboptimal from a system cost perspective

 * NECP: National Energy and Climate Plan

The concept of cycles delivers the basis for cost-benefit considerations (2/2)

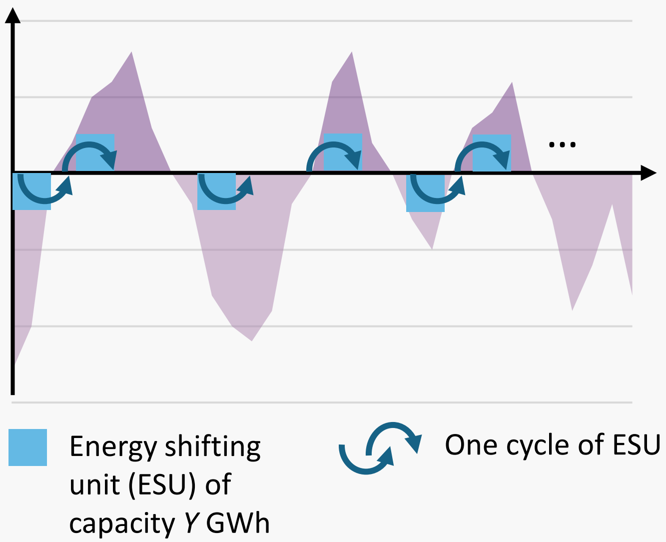
Stylised situation of RES over- and undersupply situations



The residual load should be derived from the "natural demand curve"[1]

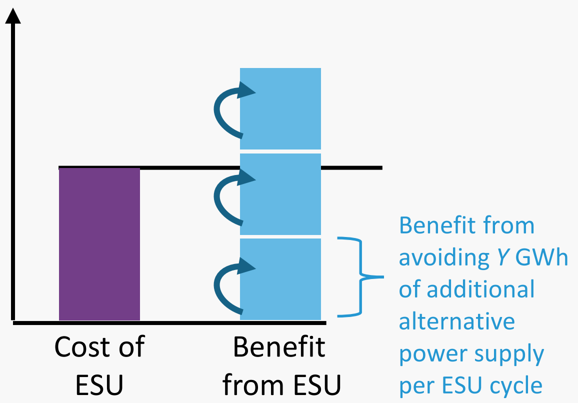
Although approximating the natural demand is inherently complex, deliberate approximations are essential to ensure that demand-side flexibility is explicitly represented in the model rather than inadvertently included in an inflexible baseline.

Concept of energy shifting units and their cycles



ESU runs 3 cycles
→ avoids 3 x *Y* GWh of additional alternative power supply
→ avoids 3 x *Y* GWh of RES-curtailment[2]

Result of cost-benefit considerations



Y GWh of additional ESU capacity is cost-efficient for the given scenario as costs lower than (marginal) benefit

[1] Natural demand curve = the electricity demand before the impact of externally incentivised demand-side flexibility measures. [2] The result regarding avoided RES-curtailment is simplified, as is neglects potential efficiency losses from real flexibilities; these losses must be appropriately accounted for in practical implementation.

How to determine cycles?

Input

Scenario:

→ residual load curve[1] (e.g., covering one year in hourly or-quarter-hourly resolution)

→ existing flexibility[1]

→ grid constraints → residual load curve needs to be geographically split into regions without congestions within the region

Optimisation model

Model:

→ objective function: minimise undersupply

→ degrees of freedom: dispatch of existing flexibility and added ESU

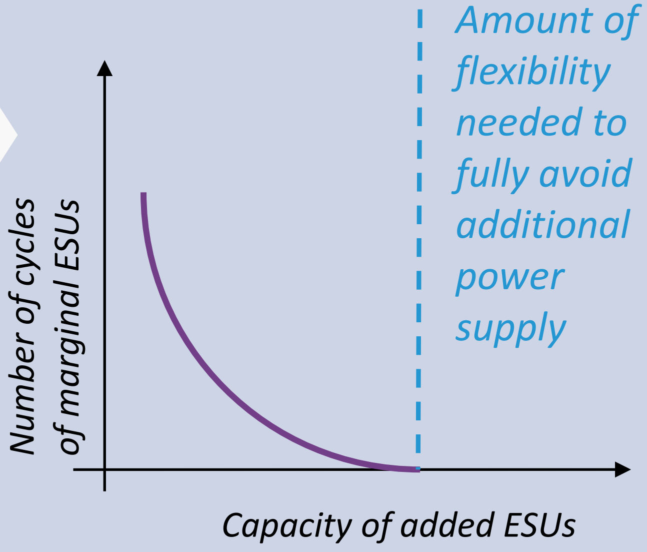
→ restrictions: capacity limits and time-coupling constraints of existing flexibility and added ESU

→ use e.g., state-of-the-art unit commitment model

→ iteratively add further ESU

Result

Marginal cycle curve (MCC)*:



* Simplified illustration. [1] The residual load curve should be based on the net demand pattern, i.e., demand including already installed and activated flexibility, but excluding additionally incentivised dispatch of demand-side flexibility

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The marginal cycle curve and the concept of a flexibility standard (1/2)

What is the flexibility standard?

→ Similar to the reliability standard in the RAA, the flexibility standard specifies the minimum number of cycles a marginal ESU must achieve to be cost-efficient.

→ Following the cost-benefit-considerations above, the flex-standard can be calculated as:

$$flex\ standard = \frac{cost\ of\ additional\ flexibility}{value\ created\ per\ cycle^{1}}$$

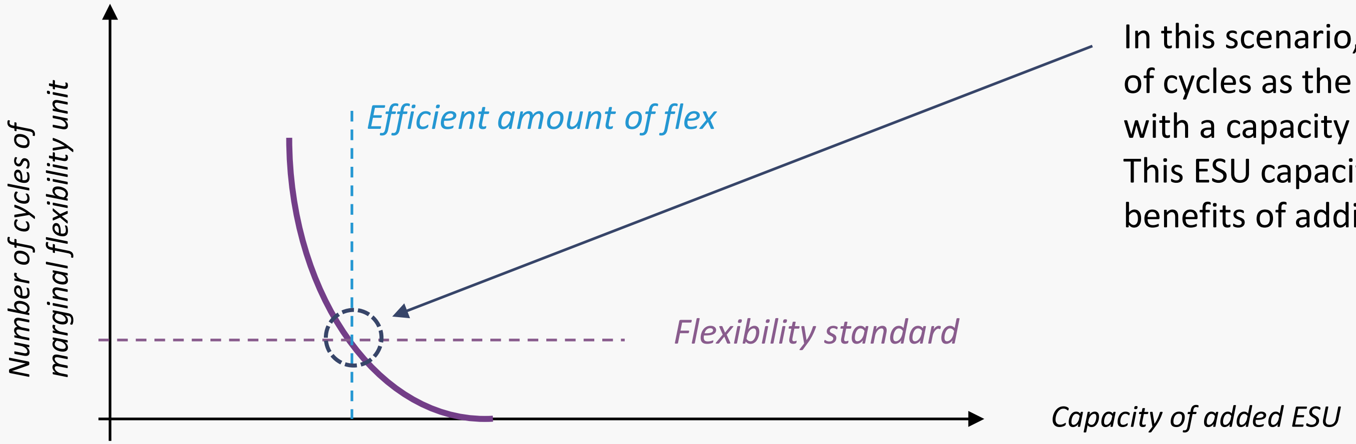
→ Analogy to reliability standard:

$$reliability\ standard = \frac{cost\ of\ new\ entry}{value\ of\ lost\ load}$$

 [1]This could be derived based on the costs for additional decarbonised power supply otherwise needed to cover demand in situations when decarbonised power supply is not sufficient

The marginal cycle curve and the concept of a flexibility standard (2/2)

Matching the MCC and the flexibility standard



In this scenario, a marginal ESU would run the exact number of cycles as the flex standard (blue dashed line) when ESUs with a capacity equal to the purple dashed line are installed. This ESU capacity is cost-efficient, as the marginal costs and benefits of adding another ESU are equal.

→ comparing the calculated MCC to the (scenario independent) flexibility standard allows to derive the cost-efficient amount of flexibility (= flexibility need)[1]

→ as explained above, a given number of cycles of ESU of certain capacity can (for a given scenario) be translated into the amount of remaining curtailment → thus a "remaining curtailment curve" can also be derived and compared to a renewable integration target (and this way a flexibility need could also be derived)

 [1] as existing / assumed-available flexibility is considered in the modelling, this way a net flexibility need is derived.

The need to differentiate time frames and flexibility asset types (1/2)

→ **For the FNA, differentiating time frames and asset types is important** since flexibility assets have varied techno-economic characteristics. Such a differentiation is thus already defined by the Electricity Market Regulation

→ **Techno-economic characteristics of flexibility assets differ in** particular with respect to:

1. **Round-trip-efficiency**
   - High efficiencies (e.g., batteries, demand-side response)
   - Lower efficiencies (e.g., hydrogen storage including electrolysis and hydrogen-gas-turbines)
   - Higher efficiency is advantageous for frequent cycling, reducing “wasted” oversupply
2. **Capacity-dependent costs vs. capacity-independent costs** (fixed costs, power-dependent costs)
   - Primarily capacity-dependent costs (average costs per capacity rather constant independent of unit size) (e.g., batteries)
   - High fixed costs and comparably low capacity-dependent costs or relevant economies of scale (average costs per capacity decreasing with unit size) (e.g., hydrogen storage)
   - Smaller capacities are suitable for hourly/daily/weekly energy shifting, while large capacities are needed for seasonal/multi-annual shifting → the larger the capacity demand, the less relevant the fixed costs

The need to differentiate time frames and flexibility asset types (2/2)

→ Differentiating flexibility asset types is crucial, if the FNA is intended to determine a cost-efficient level of flexibility needs → given the variety of assets, flexibility needs should generally address as a mix of asset types (e.g., x GWh of daily storage, y TWh of seasonal storage)

→ For the proposed FNA approach, this is more specifically considered for:

- determining the MCC → as the MCC depends for a given scenario on the efficiency of the modelled ESU and the capacity-to-power-ratio, MCCs need to be determined for a set of benchmark technologies
- determining the flexibility standard → as the flexibility standard depends on the costs of flexibility it must be determined for each benchmark technology separately

Determining one "benchmark" technology for each time-frame (e.g., batteries on daily and hydrogen storage on seasonal level)

→ **The necessary selection of a benchmark technology does not constitute a prior decision to the technologies that will ultimately meet the flexibility demand** → this is a result of markets / competition (technology-neutral) competition

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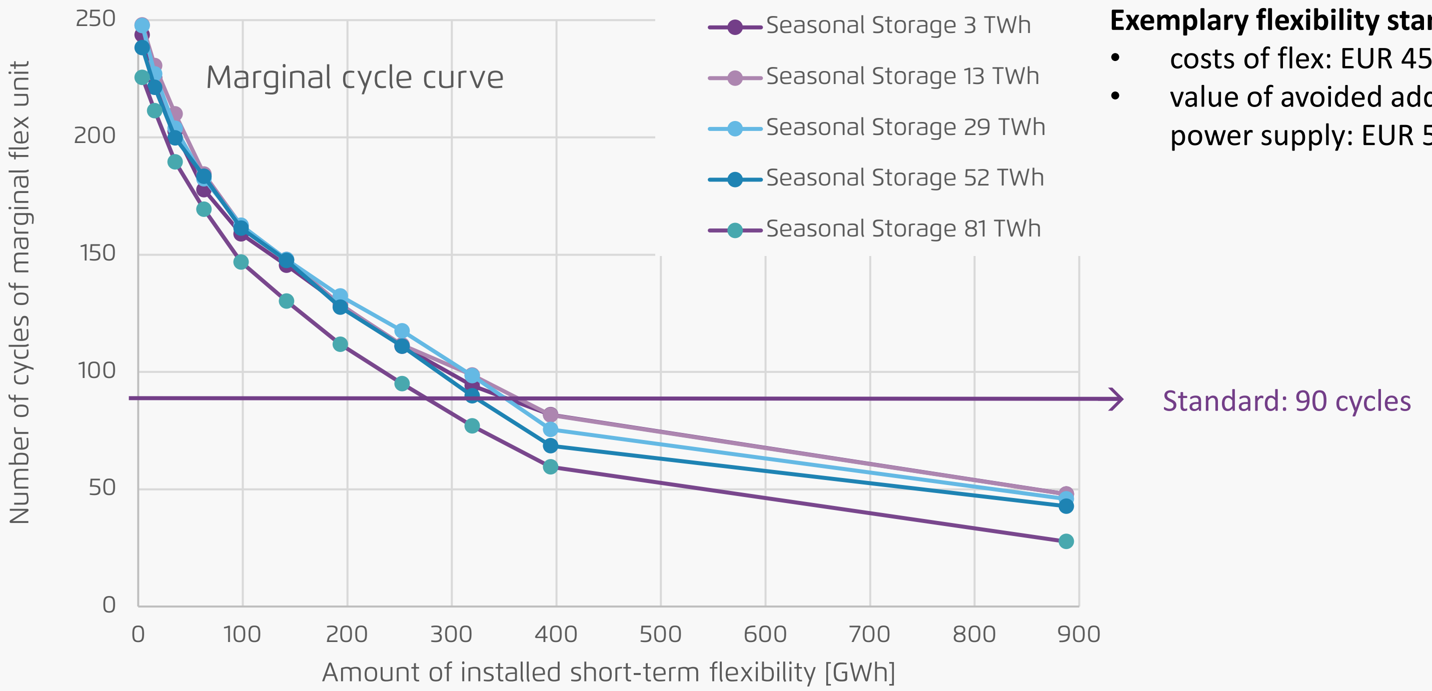
Exemplary results (1)

MCC of ESU for short-term flexibility needs (daily) calculated for a 2045 scenario for Germany



Exemplary flexibility standard
- costs of flex: EUR 45/kWh/a
- value of avoided additional power supply: EUR 500/MWh

Input

→ Scenario from "*Langfristszenarien*" (scenario T45-Strom)

→ European modelling

→ Daily level ESU modelled as four-hour battery (90% round-trip efficiency)

Results

→ Interaction between daily and seasonal level flexibility → MCC for short-term flexibility depends on assumption for seasonal flexibility

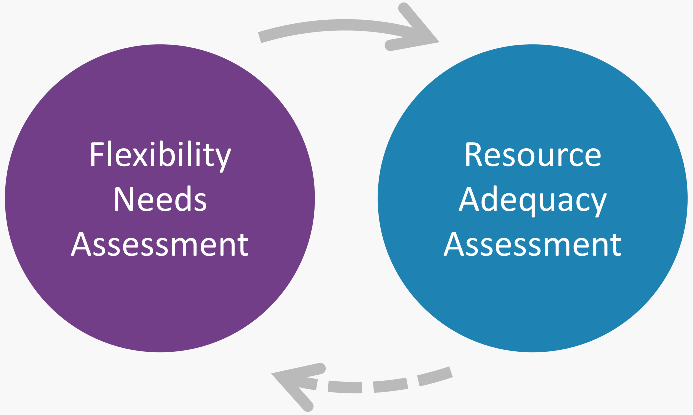
→ For this simplified example: optimal level of short-term flexibility ranges between roughly 250 and 350 GWh of short-term flex

Practical elements of implementation on European and national levels

What is the relationship between the FNA[1] and the resource adequacy assessment (RAA)?

Interaction between FNA and RAA

Direct influence of available flexibility on resource adequacy demand



No direct influence of available dispatchable capacity on FNA

The number of flexible units influences the demand for dispatchable capacity – but not the other way around:

→ Increasing flexibility reduces undersupply situations and thus (potentially) the remaining demand for reliable capacity needed to reach a certain reliability.

→ Increasing reliable capacity does (in general) as such neither influence the amount of available decarbonised power supply nor the demand curve[2] → no influence on FNA[3]

→ **Hence, general recommendation on sequence: Results of FNA should inform RAA**

→ Ideally, both assessments are based on the same general scenario assumptions (regarding load, RES* development, existing / assumed available flexibility)

→ Input from FNA for RAA

- Results of FNA delivers information on efficient amount of flexibility
  → this does not answer to what extent and when this flexibility will actually be available
- Comparable to considering a CRM*-scenario in the RAA, **a FNA-scenario could be considered in the RAA**

[1] Considerations apply to both a European and a national FNA; [2] Demand including already installed and activated flexibility, but excluding additionally incentivised dispatch of demand-side flexibility; [3] Note: this holds true as long as it is referred to a technology-neutral, i.e., not yet technology-specified, interpretation of reliable capacity;
*RES: Renewable Energy Sources, CRM = Capacity Remuneration Mechanism

Integrated approach to network needs

→ **TSO*-level:** The proposed modelling approach can be adapted to cover grid constraints by splitting the residual load curve into multiple regions, each free of congestions (see slide 14). TSO-level grid constraints should ideally be included in the initial applications of the FNA.

→ **DSO**-level:** Including DSO-level grid constraints in the FNA is essential for accurately assessing flexibility needs. Ignoring these may lead to an underestimation of needs, while a separate DSO assessment could result in double counting.

- DSO-level constraints can be integrated using the same general approach as for TSO-level constraints.
- To maintain a manageable assessment, it is recommended to approximate DSO needs (e.g., by analysing typical network models or representative congestion scenarios) first and then incorporate them in a simplified form into the TSO-level FNA.
- DSO-level needs could be examined in greater detail within national FNAs and subsequently be considered in the European FNA using appropriate simplifications.

 *TSO: transmission system operator; **DSO: distribution system operator

Practical application of FNA results

→ … **for member states:**

- Once available, European FNAs should be used to feed back into the national FNAs to account for cross-border contributions of the different flexibility types.
- For the net additional demand for flexibility identified in the national FNAs, member states should assess whether market-based incentives are already expected to address it or if regulatory barriers (e.g., government-induced levies and tariffs) exist, and how these could be reduced. If a flexibility gap remains, explicit support schemes can be considered. Various incentives, primarily market-based, can be used to meet these needs without the need for explicit capacity procurement.

→ … **for market stakeholders and researchers:**

- The methodology should ensure that all input data, assumptions, and outputs are publicly accessible in a user-friendly format. Open-access modeling frameworks and results of the FNAs should be provided aligning with the EU's commitment to data transparency and best practices in energy system planning.

Imprint

On behalf of Agora Energiewende

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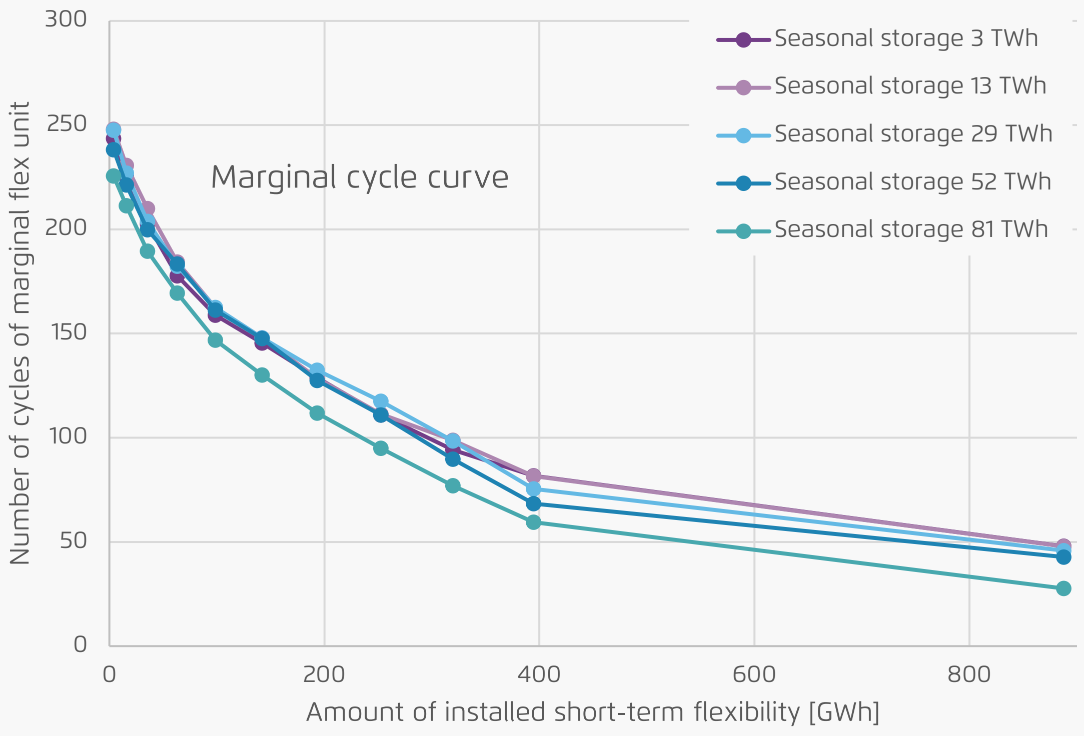
Acknowledgements
Special thanks to: Émeline Spire, Maia Haru Hall, Lena Tropschug

Title picture: akinbostanci

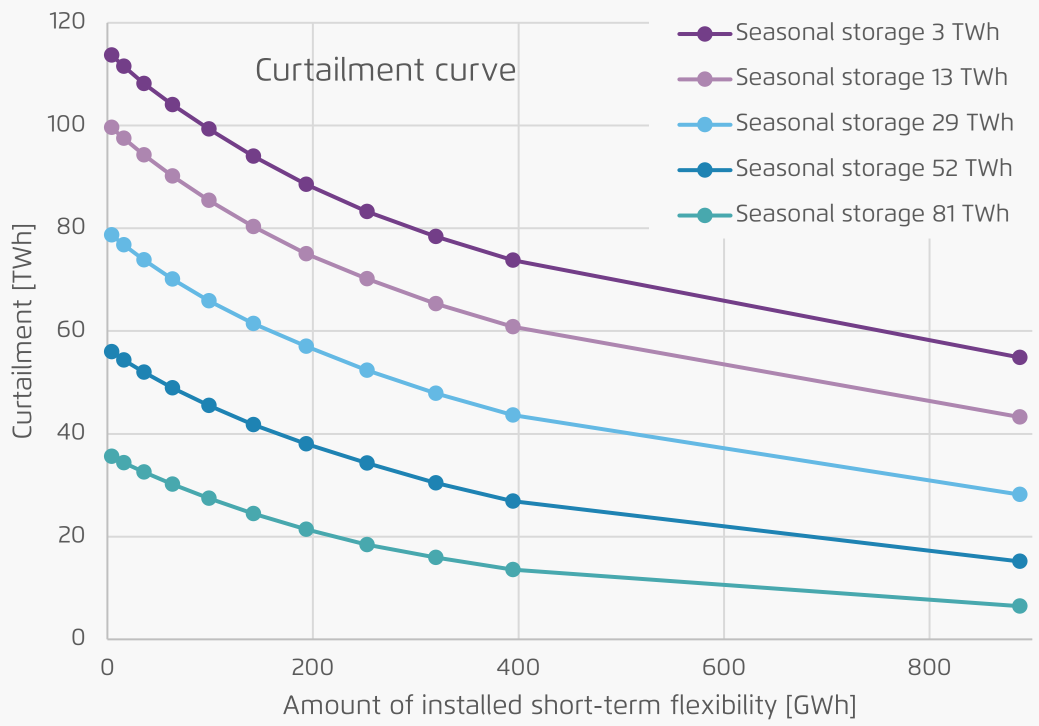
Appendix

Exemplary results (2)*

From marginal cycle curve…



… to remaining curtailment curve



 | * Derived from the same model runs

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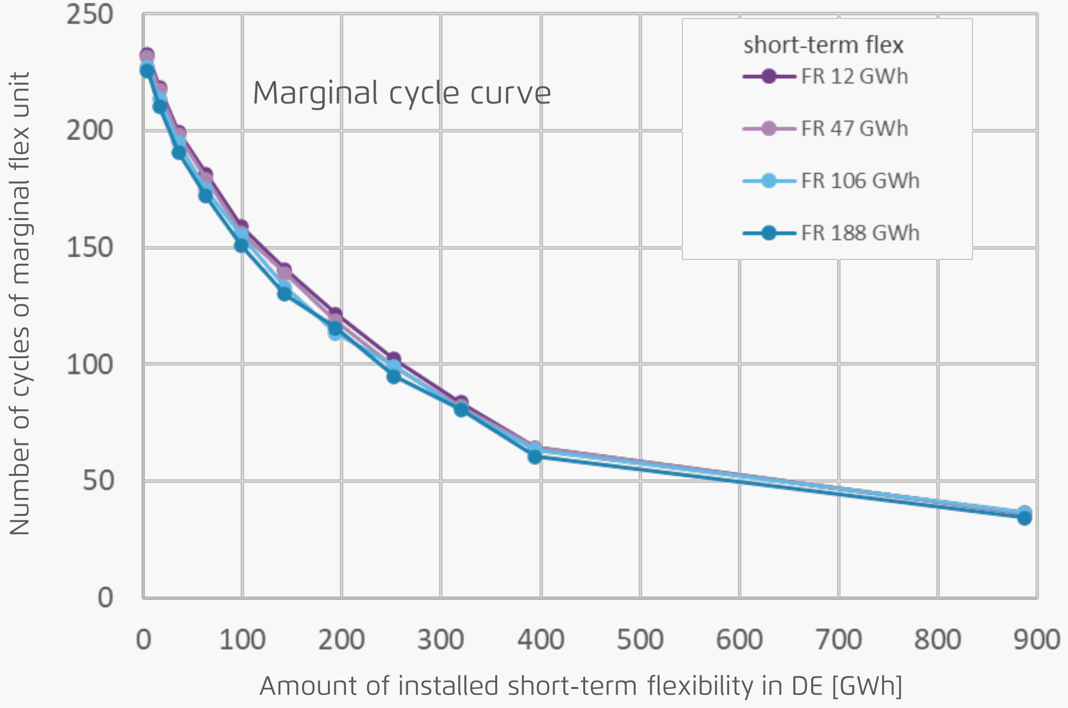
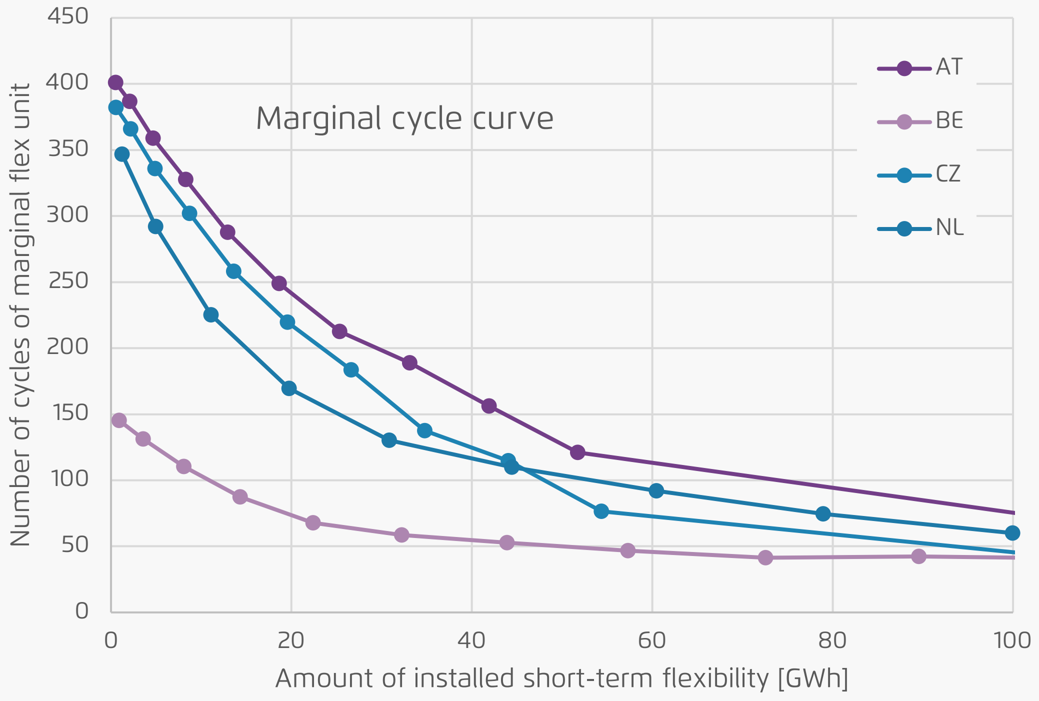
Exemplary results (3)

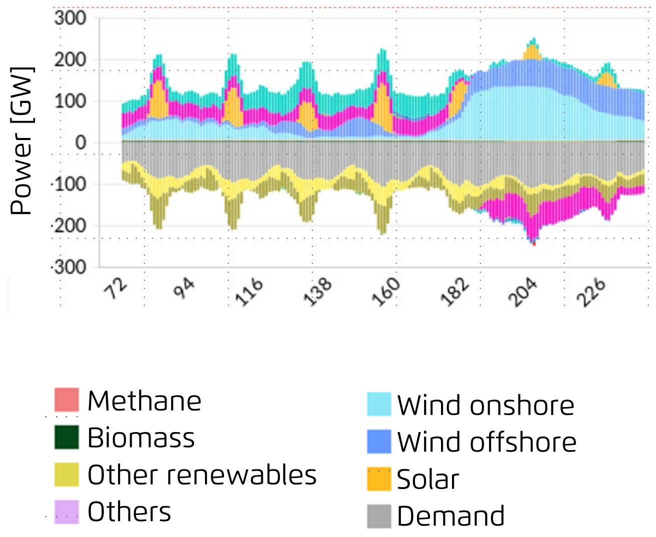
MCC also depends on assumption in other regions of the interconnected European power system



MCC calculated for other regions (derived from the same model runs as for Germany)



Note on the exemplary results



Visualisation/source: *www.langfristszenarien.de*

→ Exemplary results are based on data from "Longterm-Scenarios" (LFS) (study on behalf of the German Federal Ministry for Economic Affairs and Climate Action)

- Pan-European dataset including high resolution RES-E production and load time-series
- Scenario: T45-Strom, scenario year: 2045

→ Flexible loads (such as heat pumps (decentralised and heat grids), electric vehicles, electrolysis) considered static (simplification only for the exemplary results) with dispatch based on LFS optimisation results

→ Interconnectors are considered with limited capacities (according to scenario results)

→ Exemplary benchmark technologies

- Short-term: battery storage system (round-trip efficiency: 90%, energy-to-power-ratio: 4 hours)
- Long-term: hydrogen storage system (electrolysis → hydrogen storage → H_2-OCGT*) (round-trip efficiency: 40%, energy-to-power-ratio: 2,000 hours)

 * H2-OCGT = hydrogen open cycle gas turbine