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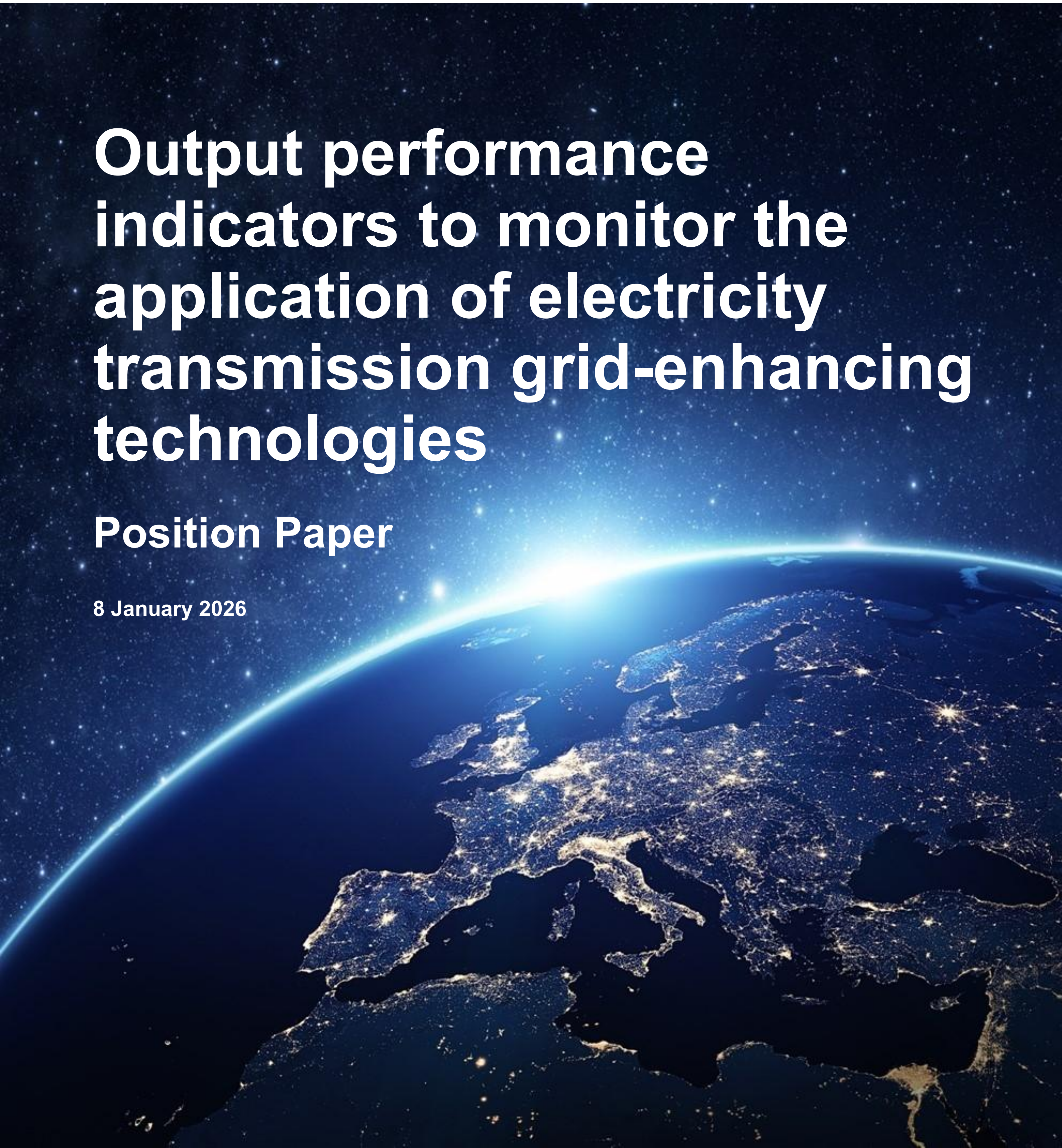

Output performance indicators to monitor the application of electricity transmission grid-enhancing technologies

Position Paper

8 January 2026

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Executive summary

Europe's energy transition requires not only new grid investments but also smarter use of existing electricity infrastructure. Innovative operational practices, digitalisation and grid enhancing technologies can often deliver additional capacity faster and at lower cost than conventional reinforcements – enhancing both system performance and value for consumers.

To make such improvements measurable, Electricity Directive[1] requires national regulatory authorities (NRAs) to monitor and to assess system operators' performance in relation to the development of a smart grid based on a limited set of indicators. The 2025 Copenhagen Infrastructure Forum further invited ACER, in cooperation with ENTSO-E and other relevant stakeholders, to develop the report on the common smart grid indicators at transmission level.[2]

This paper represents ACER's contribution to that task, proposing three "output" indicators to measure performance of smart grid solutions applied by the TSOs in transmission systems.

These proposed key performance indicators (KPIs) are novel indicators which would require careful implementation and analysis of results, allowing their evolution over time. As such, these indicators should not be immediately connected to incentive schemes, nor were they assessed or discussed by ACER's revenue/incentive workstream.

Why output indicators are needed

Transmission smart grid infrastructure can be assessed using two types of indicators, namely input and output indicators. While input indicators measure the means and functionalities implemented to achieve desired outcomes, the output indicators measure the actual performance that these solutions deliver.

Few countries today report indicators that directly capture how smart grid technologies affect TSOs' operational capacity, system security, or investment in network expansion. The output indicators proposed in this paper fill this gap. They measure tangible performance outcomes, providing NRAs with evidence of whether smart grid measures deliver real performance improvements. They also create a foundation for more consistent and comparable assessments of TSO performance across Europe.

The proposed indicators

ACER proposes three core output indicators to measure infrastructure performance due to smart grid development:

- **KPI_{PET} – Performance of existing transmission assets in real-time system operations**

  This KPI measures how smart grid solutions are performing in real-time system operations. It compares the ampacity applied by transmission system operators (TSOs) in real-time system operation with the corresponding static ampacity on key grid elements such as lines and transformers. A value above 1 indicates that grid enhancing technologies or improved operational practices have increased the usable transmission capacity of existing assets.

- **KPI_{SEC} – Performance of operational security**

  This KPI measures how TSOs perform in maintaining operational security. It compares actual annual costs of remedial actions (e.g. redispatch, countertrading) with the theoretical costs that would have been incurred under a standard baseline (e.g. static ratings, no smart optimisation). A value below 1 shows that smart grid measures reduced operational costs for maintaining operational security.

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[1] Article 59(1)(l) of Directive (EU) 2019/944 of the European Parliament and the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

[2] "The Forum calls upon CEER and ACER in cooperation with ENTSO-E, EU DSO Entity and the relevant stakeholders, to deliver the respective reports, in a coordinated manner, on the common indicators for smart grids at all voltage levels, including both output and input indicators, by the next Forum."

- ***KPI*$_{GEP}$ – Grid expansion performance**

  This KPI measures how smart grids help meet new system needs through grid expenditures. It compares the actual total cost (CAPEX and OPEX) of realised or planned investment with the theoretical total cost of a conventional (“classical”) investment (for example, building a new line) that would achieve the same network benefit. A value below 1 indicates that equivalent outcomes were achieved more cost-effectively through innovative or capital-light solutions, including operational actions.

Each indicator uses a counterfactual comparison – a reference case representing conventional operation or investment – so that performance improvements can be clearly identified and attributed to the use of smart solutions.

The design and implementation of the indicators should also be aligned with key principles to ensure clarity, consistency and practical usability. They should be clearly defined, focus on parameters TSOs can influence and apply only to regulated activities. To the extent possible indicators should also be measurable, data-feasible, technology-neutral and futureproof, allowing for meaningful and consistent tracking of performance trends over time.

Additional monitoring dimensions

Beyond the three proposed output indicators, the paper also highlights complementary areas of monitoring that can enhance regulatory insight. It presents a preliminary mapping between input and output indicators, showing how the deployment of smart grid technologies and digital solutions can translate into measurable performance improvements. In parallel, the paper notes the potential for European-level monitoring of cross zonal capacity efficiency using existing flow-based datasets, such as remaining available margin (RAM), to assess how innovative grid technologies improve cross-border capacity use. Some Member States may also choose to explore related national indicators where relevant to their systems.

A pragmatic path forward

Some NRAs have begun integrating elements of this approach through early output-based monitoring or performance incentives. However, practices remain limited and uneven.

Implementation should therefore follow a phased, learning-oriented approach. The immediate priority is to begin testing and monitoring these indicators nationally, building a shared evidence base. Given their innovative nature, this transition period should also serve as a structured testing phase allowing NRAs and TSOs to validate practical applicability and, where warranted, refine methodologies or adjust the indicator set. Such refinements should be understood as strengthening the framework, rather than questioning its conceptual robustness or strategic direction.

As data and experience accumulate, they can underpin a more systematic assessment of grid performance and innovation across Europe. Whether they eventually support performance-based regulation will depend on national choices and indicator maturity.

ACER recommendations

- **Adopt a common monitoring framework –** NRAs are encouraged to incorporate the three proposed output indicators (*KPI*$_{PET}$, *KPI*$_{SEC}$, *KPI*$_{GEP}$) as a shared framework for monitoring smart grid performance at transmission level. When implementing the framework at national level, NRAs should consult with the relevant stakeholders to ensure technical robustness and practical relevance. A two- to three-year transition period is foreseen to establish data collection, modelling and reporting processes, allowing time for methodological refinement and alignment across Member States.

- **Develop complementary input indicators:** National TSOs should propose to their NRAs complementary input indicators reflecting the accessibility of tools (for example relevant smart grid technologies or operational practices) which impact the output indicators applied. ENTSO-E should support this process by providing guidance or reference mappings to promote consistency across Member States.

Collectively, these steps mark a path toward a shared European framework for assessing outcomes of smart grid deployment in transmission infrastructure. Through cooperation, transparency and mutual learning, NRAs and system operators can ensure that Europe's electricity grids evolve efficiently and in line with the objectives of the energy transition.

1. Introduction

Expanding the capacity of the European electricity system requires not only securing investments but also improving the efficiency and utilization of existing infrastructure. While efficient use of infrastructure can be achieved in many different ways, this paper only focuses on the deployment of smart grid solutions in the transmission system as means to achieve faster and more cost-effective ways to enhance the transmission system performance compared to conventional wire-based investments.

NRAs play an important role in ensuring the deployment of smart grid solutions for infrastructure development and operation by:

- encouraging network operators to evaluate all types of network technologies;
- monitoring and fostering improved network performances;
- promoting cost-effective investments; and
- maximising the value of grid investments for network users.

To this aim, Article 59(1)(l) of the Electricity Directive mandates NRAs to monitor and assess the performance of TSOs and distribution system operators (DSOs) in relation to the development of a smart grid that promotes energy efficiency and the integration of energy from renewable sources, based on a limited set of indicators and publish a national report every two years, including recommendations.

Since the adoption of the Electricity Directive, NRAs have made gradual progress in identifying and reporting smart grid indicators, though practices differ significantly. Experience with output indicators at transmission level remains limited, though some emerging examples, such as indicators on network capacity utilisation, demonstrate growing efforts to measure tangible performance outcomes.

ACER, in its position paper on incentivising smart investments to improve the efficient use of electricity transmission assets[3], recognises the potential contribution of network KPIs in measuring the impacts and the benefits of TSO investments and consequently for supporting the development of KPI-based incentives. The paper explained that efficient use of infrastructure can be considered as one of the measurable effects of (mature) innovative solutions. Conversely, infrastructure efficiency can be considered as one of the main measurable outputs of smart grid investments.

Furthermore, in 2024 ACER and CEER jointly developed a set of guiding principles to evaluate the performance and efficiency of European electricity smart grids (ACER-CEER guidance paper).[4] Published on 21 June 2024 and followed by a public consultation[5] until 28 July 2024, this paper supports the goal of identifying a limited set of output indicators for use in all Member States.

The Copenhagen Infrastructure Forum conclusions from 3 June 2025 call upon “CEER and ACER in cooperation with ENTSO-E, EU DSO Entity and the relevant stakeholders, to deliver the respective reports, in a coordinated manner, on the common indicators for smart grids at all voltage levels, including both output and input indicators, by the next Forum.” The scope of this paper responds to this request and is limited to the assessment of smart grid-related output performance indicators.

This paper represents ACER’s contribution to assist NRAs in monitoring and assessing grid indicators as per Article 1(2) of the ACER Regulation[6]. The paper focuses on developing recommendations for a

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[3] See ACER Position on incentivising smart investments to improve the efficient use of electricity transmission assets, 2021.

[4] See Electricity transmission and distribution “smart-grid” performance indicators - an ACER-CEER guidance paper, 2024.

[5] Feedback from this consultation broadly supported ACER and CEER’s proposed classification of input and output indicators, with respondents emphasising that NRAs should take the lead in defining and validating output indicators, while system operators support by providing data and methodological input. Participants also welcomed the proposed balance between a limited set of common EU indicators and national flexibility, while noting that consistent definitions and calculation methods are essential for comparability.

[6] Article 1(2) of the Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators: “*The purpose of ACER shall be to assist the regulatory*

limited set of output indicators that can support transparency and comparability in relation to the deployment and performance of smart grid functionalities. While NRAs remain free to consider how such indicators may inform their national practices, this paper does not prescribe any specific regulatory use of these indicators.

Importantly, this paper does not aim to assess network efficiency in its broad economic or regulatory sense. In particular, it explicitly excludes:

- any form of general efficiency benchmarking or comparative performance assessment of TSOs for regulatory, financial or revenue-setting purposes, including total expenditure (TOTEX)-based efficiency comparisons;
- market-related infrastructure efficiency topics, including those associated with bidding zone configuration, bidding zone review, congestion management efficiency, or locational (nodal) pricing models; and
- tariff-related efficiency incentives, including smart tariff design, dynamic pricing structures, network charge reforms or other pricing signals intended to influence consumer or system behaviour.

These areas are addressed through separate regulatory and analytical workstreams, which follow distinct objectives, analytical approaches and governance processes.

Furthermore, as KPIs could also be impacted by means outside of the sole control of the national TSO (e.g. via coordinated efforts), the focus is on outputs which can be measurably impacted by actions of the national TSO alone.

Cooperation with ENTSO-E

ACER presented the draft set of electricity smart grid output performance indicators for transmission grids to ENTSO-E at a workshop hosted by the European Commission in June 2023 followed by the informal exchange of an early draft in August 2025 and a formal consultation on the advanced draft in mid-October 2025. ENTSO-E provided an initial round of feedback on 10 November 2025, summarising input collected from several member TSOs. This feedback, outlined in Annex B, focused mainly on the proposed output indicators, their underlying assumptions and the methodological feasibility of counterfactual comparisons. ACER and ENTSO-E agreed to continue the discussion in 2026, with a view to further refining the indicator framework ahead of the next Copenhagen Infrastructure Forum.

authorities referred to in Article 57 of Directive (EU) 2019/944 and Article 39 of Directive 2009/73/EC in exercising, at Union level, the regulatory tasks performed in the Member States […]. ACER shall also contribute to the establishment of high-quality common regulatory and supervisory practices, thus contributing to the consistent, efficient and effective application of Union law in order to achieve the Union's climate and energy goals."

2. Why output indicators are needed

Monitoring transmission infrastructure smart grid performance requires two complementary perspectives:

- **Input indicators**, which measure the means and functionalities that are implemented to achieve a desired outcome, for example the level of readiness and uptake of digital and smart grid solutions by system operators;
- **Output indicators**, which measure the actual benefits and performance outcomes these solutions deliver for network users.

Some existing smart grid monitoring frameworks in Europe rely on input indicators – for example, the number of substations equipped with digital control systems or the length of lines under dynamic thermal rating (DTR). While useful for tracking technological progress, such indicators describe ‘what has been implemented’ rather than ‘what it achieves’.

Output indicators address this gap. They measure the actual performance outcomes of smart grid deployment, for instance, additional network capacity, reduced operational costs, or avoided investment needs. By focusing on measurable results rather than technology inputs, they allow NRAs to assess the delivery of real gains for network users.

This outcome-oriented perspective supports both learning and practices sharing across Member States. It provides a consistent basis for monitoring how deployment of smart grid solutions affects TSOs’ system operation and grid development, regardless of the specific technologies or national contexts involved.

Finally, output indicators lay the groundwork for more evidence-based regulation. Once data and experience accumulate, they could inform performance evaluations or future incentive frameworks that reward proven efficiency outcomes. Developing and applying output indicators therefore represents a key step from descriptive monitoring toward a more analytical and results-oriented approach to regulating Europe’s transmission grids. At the same time, it should be noted that the proposed KPIs in this paper are novel indicators that require careful implementation and analysis of results, allowing their evolution over time. As such, these indicators should not be immediately connected to incentive schemes, nor were they assessed or discussed by ACER’s revenue/incentive workstream.

3. Overview of the proposed key performance indicators

Building on the previously discussed 2024 ACER-CEER guidance paper, ACER has aimed at identifying a limited set of output KPIs for TSOs that:

- measure how efficiently key societal objectives are delivered; and
- are directly linked to the deployment of innovative (smart) grid solutions by comparing their performance with that under a more conventional ('standard') approach through a counterfactual analysis[7].

This scoping exercise identified three TSO output KPIs to measure infrastructure performance due to smart grid deployment that fit the following criteria:

1. **TSO KPI 1 (*KPI_{PET}*): Performance of existing transmission assets in real-time system operation**, which can be monitored via available transmission ampacity versus standardised (static) transmission ampacity.

$$KPI_{\mathrm{PET}} = \frac{\text{available operational transmission ampacity}}{\text{standardised transmission ampacity}}$$

2. **TSO KPI 2 (*KPI_{SEC}*): Performance of operational security**, which can be monitored via actual costs incurred to maintain operational security (e.g. redispatch or other costly remedial actions) versus the same costs with no smart grid solutions applied.

$$KPI_{\mathrm{SEC}} = \frac{\text{actual costs to maintain operational security}}{\text{theoretical costs to maintain operational security}}$$

3. **TSO KPI 3 (*KPI_{GEP}*): Grid expansion performance**, which can be assessed by comparing the actual total costs of investments targeted to meet a specific system need versus the total costs of classical investment of the same objective (e.g. building a new line or transformer), as follows:

$$KPI_{\mathrm{GEP}} = \frac{\text{total actual costs of investments}}{\text{total costs of classical investment}}$$

The three indicators are explained in further detail in the following sections.

To the extent possible the implementation of these KPIs is intended to be aligned with the following key principles for defining KPIs[8]:

- **Clarity:** KPIs should be based on clear and unambiguous definitions to ensure consistent interpretation.
- **Influenceability:** Each KPI should capture parameters that the system operator can influence, either fully or partially, with the degree of influenceability clearly indicated.
- **Regulatory scope:** KPIs should relate solely to regulated activities of the system operator.

[7] As a point of emphasis, use of a counterfactual is considered fundamental to determining whether 'smartness' has actually contributed to the desired outcome measured by the indicator.

[8] Derived from Smart Grid Key Performance Indicators: A DSO perspective, CEDEC, E.DSO, Eurelectric, GEODE, 2021.

- **Practical relevance:** KPIs should be measurable with reasonable effort and sufficiently significant to support effective regulatory oversight.
- **Technology neutrality:** KPIs should focus on the functionality or performance outcome achieved, rather than the specific technology used to deliver it.
- **Data feasibility:** The data required to calculate each KPI must be available or collectable without disproportionate effort.
- **Appropriate granularity:** Where necessary, KPIs may be split into sub-indicators (e.g. 400 kV, 220 kV and 110 kV to reflect different voltage levels) to enhance comparability and interpretation.
- **Futureproof design:** KPIs should be designed to remain relevant over time, allowing for consistent tracking of performance trends and technological developments.

3.1. Performance of existing transmission assets in real-time system operations (KPI_{PET})

Definition

We propose monitoring performance of existing transmission assets due to smart grid deployment by comparing the actual available transmission ampacity used in real-time operation versus standardised (static) transmission ampacity.

$$KPI_{\mathrm{PET}} = \frac{\text{available operational transmission ampacity}}{\text{standardised transmission ampacity}}$$

For the purpose of the indicator, the available operational transmission ampacity or *ATA* (measured in A) is the annual average of the ampacity values applied by the TSO in real-time system operations (e.g. as recorded in SCADA or EMS systems) and should be performed for those transmission assets (lines and transformers) used to set operational security limits.

The standardised transmission ampacity or *STA* (measured in A) is the sum of the standardised[9] transmission ampacities of the same set of transmission assets (e.g. lines and transformers) used to define the *ATA*.

Scope

KPI_{PET} focuses exclusively on real-time system operation, the domain fully under TSO control and directly linked to system security and operational performance. Although higher operational ampacities can in principle increase capacity available to the market, we propose monitoring these effects separately (see section on European-level monitoring opportunities).

Examples

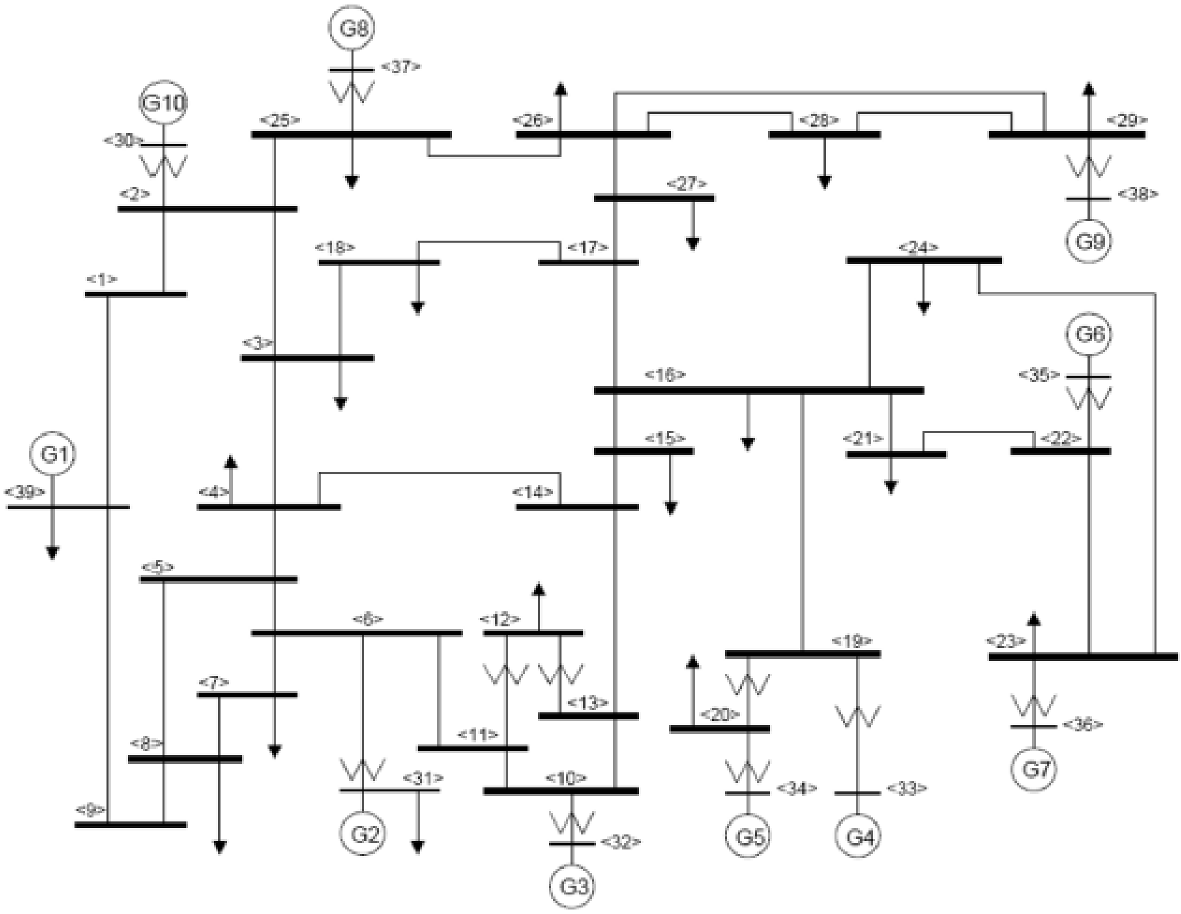
- The TSO identifies elements in need of increasing capacity (e.g. due to frequent N-1 violations, market capacity needs, etc.). The proposal should consist of all network elements affecting the transfer capacity in question (i.e. lines, transformers, etc.).
- Figure 1 shows a 39-node theoretical system and Table 1 provides the elements which, in this example, benefit from increased capacity.

[9] Standardised ampacities are usually determined based on conservative values of the atmospheric conditions (e.g. wind velocity, ambient temperature and solar radiation) and can be seasonally-dependant.

Table 1: List of elements in need of capacity increase and their standardised capacity, based on static operational limits

Element	Average standardised (static) capacity
Line between nodes 1 and 2	1000 A
Line between nodes 17 and 18	1000 A
Line between nodes 6 and 31	600 A
Line between nodes 16 and 19	1000 A
Line between nodes 3 and 18	600 A

Figure 1: IEEE 39-node system



In case there are no smart grid investments into increasing the grid's performance, the actual available capacity would be equal to the standardised one and the resulting KPI_{PET} = 1. If the TSO implements DTR, the individual line's ampacity would be defined by local atmospheric conditions for each quarter hour[10] of that year. Table 2 provides such an example for the line between nodes 1 and 2.

[10] The frequency of DTR calculations can also be different.

Table 2: Calculating the yearly average transfer capacity for the line between nodes 1 and 2

	Standardised (static) capacity	Hourly capacity with DLR
Hour 1	1000 A	1300 A
Hour 2	1000 A	1260 A
Hour 3	1000 A	1310 A
…	…	…
Hour 8759	1000 A	1192 A
Hour 8760	1000 A	1130 A
AVERAGE	***1000 A***	***1200 A***

Table 3: Full DTR implementation on all elements in need of capacity increase

Element	Average standardised (static limits) capacity	Average hourly capacity with DTR
Line between node 1 and 2	1000 A	1200 A
Line between node 17 and 18	1000 A	1160 A
Line between node 6 and 31	600 A	710 A
Line between node 16 and 19	1000 A	1192 A
Line between node 3 and 18	600 A	685 A
SUM	***4200 A***	***4947 A***

In the example of Table 3, the TSO implements DTR on all monitored lines. Table 3 shows average hourly capacity limits after DTR was implemented, versus standardised hourly capacities. The DTR capacity is a measured/calculated one, provided by the DTR algorithm for each hour of the year *Y*. The average DTR of all hours of year *Y* is calculated at the beginning of year *Y+1*. In this example, the sum of the average capacity increased the KPI_{PET}:

$$KPI_{\mathrm{PET}} = \frac{ATA}{STA} = \frac{4947\ A}{4200\ A} = 1.178$$

Implementation

TSOs can implement this indicator using data already available in their operational and asset management systems. The process focuses on a limited number of grid elements that are recurrently constraining transfer capacity.

To ensure consistent and comparable results, the following steps outline a practical approach to developing and reporting the KPI:

4. **Define the monitored scope:** Identify the lines and transformers that most often limit transfer capacity or have smart grid solutions applied. Only these assets should be included to ensure the KPI focuses on areas where performance improvements are most relevant.
5. **Establish the standardised ampacity (*STA*):** Establish the static thermal rating of each monitored asset determined based on the reference parameter values (for example, 25°C ambient

temperature, 0.5 m/s wind velocity and 60°C conductor temperature). These values are already available in each TSO's asset database and capacity calculation models. ENTSO-E could coordinate a common reference framework to harmonise baseline assumptions such as ambient temperature and conductor ratings across TSOs.

6. **Determine the available ampacity (*ATA*):** Extract the actual available ampacity applied operationally from SCADA or asset management systems. Most TSOs already record both static and dynamic ratings as part of operational and capacity-calculation processes. Where DTR is used, the minute, quarter-hourly, hourly or daily values can be averaged annually to determine the available transmission ampacity.
7. **Calculate and interpret the KPI:** Compare the aggregated average available ampacity of the monitored assets to their standardised ampacity. A value above one indicates that grid enhancing technologies or improved operational practices have increased the usable capacity of existing grid assets.
8. **Validate and report:** Document the list of monitored assets and the measurement methods used. The KPI could be reported annually using a standardised template coordinated by ENTSO-E to ensure comparability across TSOs.

Relevant existing practices

Several Member States are already moving beyond descriptive input metrics toward throughput or output-oriented measurement of infrastructure performance linked to the use of innovative grid technologies.

- **Finland** will begin collecting *ATA*/*STA* (actual vs. static thermal ampacity) data from 2025 (to be reported in 2026), providing the building blocks to compute KPI_{PET} directly.
- **Portugal** has legally adopted an output metric (dynamic vs. static annual average capacity), with the regulator signaling potential use for incentives from 2030.
- **Slovenia** applies a **throughput indicator** that evaluates how increased transmission capacity enabled by DTR was utilised in N-state. The evaluation examines the time-periods when the actual loading exceeded the static limits. The indicator is already embedded in the national incentive framework (no penalties before 2028).

See Annex A for country-specific details.

3.2. Performance of operational security (KPI_{SEC})

Definition

We propose measuring the performance of operational security by monitoring actual costs incurred to maintain system security (e.g. redispatch or other costly remedial measures) versus same costs with no smart grid solutions considered. Recognising that operational security issues are often cross-border and are in such cases treated in coordination with all involved TSOs, ACER proposes to focus this assessment only on operational limits of elements which are not cross-border relevant and as such do not require coordinating efforts (i.e. excluding cross-border relevant network elements or 'XNEs').

$$KPI_{\text{SEC}} = \frac{\text{actual costs to maintain operational security}}{\text{theoretical costs to maintain operational security}}$$

The **actual costs to maintain operational security** [EUR] are the sum of annual operational costs incurred to ensure N-1 secure operation of the transmission system, for example redispatch, countertrading, or other costly remedial measures required to resolve operational-security violations (e.g. thermal or voltage limit exceedances).

The **theoretical costs to maintain operational security** [EUR] represent the annual redispatch or remedial-action costs that would have occurred if the TSO had operated under standardised static operational limits, without applying smart grid measures such as DTR, modular FACTS, adaptive topology optimisation, advanced voltage control solutions, or other digital and operational technologies enhancing transmission system flexibility and security[11]. These costs are obtained by re-simulating representative operational events under the standardised baseline network. In cases where actual costs are zero (i.e. smart grid measures prevented redispatch), the theoretical costs can still be estimated counterfactually to quantify the avoided expenditure.

Example

- TSO notes events requiring redispatch (or other costly remedial measure). For each of these events, the TSO in parallel to the real-time calculation of redispatch volume, calculates the amount of redispatch needed without smart grid infrastructure investments. The KPI compares the situations with improved grid performance (thus higher operational limits) versus the situation with standard grid performance (Table 4).

Table 4: Redispatch cost comparison between a system with standard operational limits and a system with better performance

N-1 simulation		Yearly redispatch costs	
Critical outage	**Critical element**	**Standard grid performance**	**Improved grid performance**
Line between node 3 and 18	Line between node 17 and 18	3.450.000€	1.950.000€
Line between node 5 and 8	Line between node 6 and 7	1.430.000€	1.150.000€
Line between node 23 and 24	Line between node 21 and 22	850.000€	450.000€
SUM		5.730.000€	3.550.000€

$$KPI_{SEC} = \frac{\text{actual costs to maintain operational security}}{\text{theoretical costs to maintain operational security}} = \frac{3.550.000€}{5.730.000€} = 0.620$$

In the above example, as the TSO implemented smart gris solutions, the actual costs to maintain security of supply went down and a comparison with the situation with no performance improvements provides a KPI_{SEC} below 1. The lower the KPI_{SEC} the better. KPI_{SEC} equals 1 if there is no performance improvements.

Implementation

KPI_{Sec} can be implemented using existing operational data and simulation tools, requiring a structured re-analysis of selected redispatch events under standardised assumptions. This approach allows TSOs to quantify, in a consistent and comparable manner, how smart grid technologies improve the performance of secure and stable system operation.

TSOs can calculate the indicator by re-simulating a representative set of operational events on a standardised baseline network model and comparing the resulting redispatch costs to the actual observed costs. The following steps outline a practical approach for implementation:

[11] While some smart grid technologies primarily affect thermal capacity and others primarily affect voltage stability or reactive power control, this KPI intentionally captures their combined effect on reducing overall redispatch and remedial action costs. The technology examples provided are illustrative and non-exhaustive.

1. **Define the standard grid performance baseline:** Establish a reference network model representing the system without smart grid measures such as DTR, modular FACTS, or adaptive topology optimisation. This baseline can build directly on ENTSO-E's existing capacity calculation assumptions, which already define static line ratings, fixed topologies, standard contingency lists and neutral phase-shifting transformer (PST) or FACTS settings. While ENTSO-E could coordinate a harmonised reference framework through the common grid model to ensure consistent boundary conditions across borders, national TSOs would need to apply their own, more detailed grid models to simulate redispatch scenarios and cost differences. These national models contain the granularity required to assess the performance of smart-grid technologies at operational level.
2. **Select key operational events:** Using annual SCADA and redispatch data, identify representative operational hours or events where system security actions (such as redispatch or countertrading) were required. The selection should include not only high-cost events but also representative hours with low or zero redispatch costs, since these often demonstrate where smart grid measures have successfully reduced or avoided remedial actions. A balanced sampling approach – covering both cost-intensive and low-cost situations – will provide a more complete picture of performance improvements across operating conditions.
3. **Quantify actual costs:** For each selected event, determine the actual costs incurred to maintain security of supply, including redispatch, countertrading and other costly remedial measures. These values can be taken directly from operational cost logs and market data already collected for system operation reporting.
4. **Simulate the counterfactual baseline:** Re-run the same operational events on the standard baseline model, keeping demand, generation and outages constant while applying static ratings and/or standard remedial actions only. The simulation should reproduce redispatch needs and costs as they would have occurred without smart grid measures. This can be done using existing TSO planning and simulation tools for detailed network analysis or, where appropriate, open-source frameworks to enhance transparency and reproducibility. The chosen toolset should reflect national practices and ensure sufficient granularity to capture the physical network behaviour underlying redispatch outcomes.
5. **Calculate and aggregate results:** Compare the actual costs of maintaining secure operations with the theoretical costs under the baseline scenario. Both cost-intensive and avoided-cost (zero-cost) cases should be included to capture the full range of operational performance improvements. A value below one indicates that smart grid measures have reduced operational costs.
6. **Validate and report:** TSOs document the selected events, modelling assumptions and data sources to ensure representativeness and transparency. The KPI could be reported annually using a harmonised ENTSO-E template defining baseline parameters, reference conditions and minimum event coverage.

Relevant existing practices

Several Member States monitor redispatch and congestion management costs that are conceptually linked to KPI_{SEC}. Germany provides the most detailed public reporting in Europe through the SMARD and Netzausbau.de platforms, which track redispatch volumes, costs and curtailment in detail. Comparable data are also collected in several other countries, though mostly for transparency rather than regulatory performance assessment. The Italian NRA applies output-based incentives that reward the TSO for reducing dispatching costs relative to pre-set targets, aligning with the spirit of KPI_{SEC}. However, in both Germany and Italy, the explicit link between cost outcomes and infrastructure efficiency or smart grid technologies remains indirect, as redispatch savings are not yet attributed specifically to measures such as DTR or advanced grid management tools. See Annex A for details.

3.3. Grid expansion performance (KPI_{GEP})

Definition

We propose measuring the grid expansion performance by comparing the actual total costs of investment targeted to meet a specific system need versus the total costs of classical investment of the same objective (e.g. building a new line or transformer), as follows:

$$KPI_{\mathrm{GEP}} = \frac{\text{total actual costs of investments}}{\text{total costs of classical investment}}$$

The total actual costs of investments [EUR] are costs (CAPEX and OPEX[12]) of all planned and realised investments to meet a specific need (e.g. increasing or maintaining cross-border or internal capacity).

The total costs of classical investments [EUR] are costs (CAPEX and OPEX) of theoretical 'classical' infrastructure solutions to meet the same specific need as mentioned above. The costs of these theoretical classical investments could be based on 'unit investment costs' and standard OPEX of similar investments – for example, using the ACER unit investment cost indicators developed under the TEN-E Regulation.

Impacts on network losses are generally excluded, as the indicator focuses on investment rather than operational performance; however, where a project explicitly targets loss reduction and quantifiable benefits are available, these may be incorporated for completeness.

Example

- At the end of the year, TSO lists the investments made and their costs as well as the benefits estimated in the latest network development plan.
- For each infrastructure smart grid investments, the TSO provides the cost estimate of a 'classical' infrastructure investment, which provides a similar benefit.

Table 5: Comparing actual investment costs with theoretical costs

Investment	Real (actual) investment cost	Comparable classical investment cost
New 400kV line	500 million EUR	Same (=500 million EUR)
New PST	80 million EUR	Same (=80 million EUR)
Smart probabilistic N-1 algorithm	500.000 EUR	5 million EUR[13]
Upgrading some lines with DLR	500.000 EUR	20 million EUR[14]
SUM	581 million EUR	605 million EUR

$$\mathrm{KPI}_{\mathrm{GEP}} = \frac{\text{total actual costs of investments}}{\text{total costs of classical investment}} = \frac{581 \text{ million EUR}}{605 \text{ million EUR}} = 0.960$$

[12] OPEX value can be estimated, if the estimate is substantiated by similar existing investments.

[13] This estimate is based on upgrades of 2 substations which would bring a similar benefit to the smart investment.

[14] This estimate is based on the costs of a 110 kV interconnector, bringing a similar increase of capacity.

In the above example, as the TSO implemented smart grid infrastructure investments, the comparison with the situation with only classical infrastructure investments provides a KPI_{GEP} below 1. The lower the KPI_{GEP} the better, while KPI_{GPE} equals 1 if no performance improvements are made.

Implementation

KPI_{GEP} can be implemented using cost and capacity data already collected by TSOs for network development plans and investment monitoring. It measures how TSOs perform in meeting network needs by comparing the actual cost of realised or planned investments with the theoretical cost of a 'classical' grid investment delivering the same functional outcome. Using existing project and reference cost data, the indicator provides a consistent, transparent way to assess whether smart grid solutions achieve equivalent capacity at lower cost.

The indicator can be developed using the following practical steps:

1. **Define the investment scope:** Identify investments completed or committed within the reporting year that address a defined network need, such as relieving congestion, increasing cross-border capacity, or improving system stability. Each investment should be linked to a quantifiable system benefit, such as increased transfer capacity or reduced curtailment.
2. **Determine actual investment costs and estimated OPEX:** Record the total costs (CAPEX and OPEX) of the selected investments as reported in TSO project or accounting systems. Costs should cover all measures implemented to meet the targeted need, including conventional components and innovative technologies such as DTR, power flow control, or digital upgrades. If impacts on network losses are material and directly linked to the investment choice, these can be reflected as avoided-cost adjustments, provided the methodology is applied consistently across projects.
3. **Estimate the classical investment reference:** For each project, estimate the cost of achieving the same benefit using a conventional grid expansion measure (e.g. new line, new transformer). This reference cost could draw on ACER's unit investment cost indicators under the TEN-E Regulation wherever applicable. Reference values should, where possible, be expressed in consistent units such as EUR/km or EUR/MVA of new capacity.
4. **Calculate and interpret the KPI:** For all projects addressing the same network need, compare total actual investment costs with total reference costs based on the equivalent classical solutions. A value below one indicates that the TSO achieved the same functional benefit at lower total cost, reflecting better grid expansion performance. Each project entry should include both actual costs and the associated reference capacity increase for transparency.
5. **Validate and report:** Document the equivalence between actual and reference investments, the cost data used and the corresponding capacity or system benefits. TSOs can report results annually in a harmonised template coordinated by ENTSO-E and ACER, using common definitions of cost categories, reference conditions and minimum data documentation standards.

Relevant existing practices

Italy provides an example of performance-based regulation focused on the efficiency of grid expansion. Under the framework established by ARERA (and currently applicable until 2025), the transmission system operator Terna is rewarded when it delivers equivalent system benefits at lower total CAPEX than a conventional investment – for example through capital-light or innovative solutions such as DTR. The regulator sets a reference expenditure for each cross-zonal boundary and evaluates actual CAPEX outcomes against them, sharing a small part of the CAPEX savings to the TSO and thus creating a direct financial incentive for efficient network development.

Except the CAPEX vs. TOTEX implementation, this approach mirrors the logic of KPI_{GEP}, benchmarking realised investment outcomes against a reference 'classical' solution to assess whether the same functional benefit can be achieved more efficiently. Another main difference is that Italy's model works through periodic, target-based and technology-neutral incentives rather than a continuous monitoring framework explicitly linked to the performance of smart grid technologies. Nonetheless, the results (capacity increases and costs) achieved in 2020-2024 demonstrate how benefit-based regulation can successfully reward infrastructure efficiency and innovation in practice.

The same principles are formalised in the benefit-based remuneration framework developed by the Florence School of Regulation for ACER in 2024. That study extends the Italian logic into a general regulatory model in which TSOs are rewarded not for the volume of capital invested but for the net system benefits delivered relative to a reference investment representing the standard way of addressing a network need. Operators may propose a more efficient alternative – for instance through digitalisation, network optimisation, new technology solutions or dynamic rating – and share the resulting cost savings with network users. This approach explicitly links remuneration to demonstrated efficiency outcomes, offering a transparent and scalable mechanism to align innovation with consumer welfare.

3.4. Additional opportunity: Efficient use of infrastructure to increase market capacity

In developing the proposed indicators for adoption at national level, another potential area for future work was identified – capturing the benefits or efficiency gains from using innovative grid technologies to increase capacity offered to the market.

While this paper focuses primarily on real-time operational performance and infrastructure utilisation, the ability of smart grid technologies to expand RAM or network transfer capacity (NTC) between bidding zones represents a complementary dimension of efficiency, directly linked to market integration and welfare benefits.

Several Member States already monitor such effects. Belgium applies the RAM indicator to assess how operational improvements increase cross-zonal capacity, while Italy and Croatia have explicit indicators tracking NTC between bidding zones.

Further exploration of such market-oriented indicators at national level is recommended, as they could complement the operational focus of KPI_{PET} by capturing the market efficiency benefits of innovative grid technologies. These national experiences could also inform future European-level monitoring work on cross-zonal capacity and market efficiency, which is discussed later in this paper.

4. Possible input indicators for smart grid KPIs

Once the relevant output indicators have been identified, it may be necessary to identify complementary input indicators that directly relate to these output indicators.

Based on the reflections on possible output KPIs for TSOs, it seems evident that the key element that should be addressed in the relevant input indicators is the extent to which relevant solutions of direct relevance to each indicator are being applied in the relevant transmission network. This would enable NRAs to track the adoption of smart solutions of relevance and thus the readiness of the grid to influence the performance tracked by the output indicator. For example, the ACER-CEER guidance paper proposed the following possible input indicators for dynamic line rating (DLR):

- Number (as an absolute value or in percent of the total amount of transmission lines) of transmission lines under DLR;
- Length (as an absolute value or in percent of the total length of transmission lines) of transmission lines under DLR; and
- Percentage of capacity-limiting transmission lines under DLR (meaning the percentage of lines which constrain the capacity across bidding zones, for which DLR is in use).

In this context, the asset categories identified in the ENTSO-E Technopedia and the smart grid and network efficiency reporting categories for the ACER unit investment cost survey serve as two relevant reference points for the definition of input indicators relevant to the proposed output indicators (See Table 6).

Table 6: Indicative input metrics for key smart grid technologies

Technology / Input indicator category	Typical technical metrics
Advanced conductors	• Length of upgraded line (km) • Number of circuits covered • Average capacity increase (MVA)
Advanced power flow control	• Installed controllable capacity (MVA) • Number of devices installed • Voltage level (kV)
Capacitive transfer system	• Installed transfer capacity (Mvar) • Number of installations
Dynamic line rating	• Length of lines under DLR (km) • Share of total line length (%)
Static synchronous series compensators	• Installed controllable capacity (Mvar) • Number of installations
Storage as a transmission asset	• Installed capacity (MW/MWh) • Hours of operation for congestion relief
Superconductor Circuits	• Circuit length (km) • Voltage level (kV)
Topology Optimisation Software	• Number of substations or regions covered • Hours or events using optimisation

These input indicators could track a range of different smart solutions but should likely be restricted to a limited number to focus on those smart technologies of greatest relevance to the output indicators.

Numerous NRAs are already monitoring input indicators of relevance to the proposed output indicators, providing a valuable empirical foundation for aligning input–output relationships. Most prominently, several countries monitor the application of DTR, as detailed below.

- **Finland – Number of line kilometers with dynamic load capacity in use**: Measures the total length of transmission lines equipped with DLR. Two complementary metrics record the average annual static and average annual dynamic ampacity (A) for the same lines. Calculations cover all hours of the year and all voltage levels.
- **France – Lines equipped with DLR:** Measures both the number and total length (km) of lines equipped with DLR systems. The indicator is based on data from TSOs and DSOs and applies to overhead lines selected through cost-benefit and topographical analysis.
- **Germany – Lines under weather-dependent operation (DLR):** Records the number and total length (km) of overhead transmission circuits operated with weather-dependent dynamic ratings by TSO. Lines are classified into static and dynamic operation modes, with data reported by implementation phase (in operation, planned by 2025, or post-2025).
- **Portugal – Ratio of overhead lines operated with dynamic parameters:** Defined as the sum of the lengths of overhead lines operated with DLR divided by the total length of all overhead lines, calculated separately for very-high-voltage (VHV), high-voltage (HV) and medium-voltage (MV) levels.
- **Slovenia – Share of network elements operating under DTR:** Measures the proportion of transmission elements (lines and transformers) equipped by DTR by voltage level (400 kV, 220 kV and 110 kV) and asset type. Slovenia is unique in monitoring transformers in addition to lines.
- **Sweden – Number and length of lines equipped with DLR**: For both the transmission system operator and regional DSOs, Sweden records the number of lines equipped with automatic DLR as well as their total aggregated length.

This overview demonstrates that there are notable differences in how countries define and calculate these input indicators. Some, such as Portugal, use relative ratios (e.g. share of total line length), while others like Finland, Germany and Sweden rely on absolute measures in kilometres. Portugal and Slovenia differentiate results by voltage level, whereas others, such as Finland, France, Germany and Sweden, report a single aggregate figure. Slovenia stands out for also including transformers in its monitoring, unlike most others which focus solely on transmission lines. Germany is distinctive in also reporting the anticipated future implementation status of DLR systems, distinguishing between lines already in operation, planned by 2025, or scheduled beyond that date.

In countries that collect output indicators on DTR or DLR, the input indicators are of direct relevance for determining the scope of the output indicators, as they define which network elements are included in subsequent efficiency or utilisation assessments.

Indicative mapping between input and output indicators

To support a more structured understanding of how investments in digitalisation and smart technologies translate into measurable performance outcomes, the table below provides an indicative mapping between technology categories (input indicators) and the proposed output indicators (KPI_{PET}, KPI_{SEC}, KPI_{GEP}).

The mapping illustrates where technological deployments are most directly expected to influence the respective output indicators. It does not represent a final or exhaustive list of input indicators but rather a conceptual linkage showing ‘many-to-many’ relationships between technologies and performance outcomes.

Table 7: Simplified mapping between technology-based input and output KPIs

Technology / Input indicator category	Most directly linked output KPI(s)	Primary impact channel
Dynamic Line/Thermal Rating (DLR/DTR)	KPI_{PET}, KPI_{SEC}, KPI_{GEP}	Increases rated ampacity in real-time operation and reduces redispatch needs.
Advanced power-flow control (FACTS, PSTs)	KPI_{PET}, KPI_{SEC}, KPI_{GEP}	Enables active management of power flows and congestion.
Topology optimisation	KPI_{SEC}, KPI_{GEP}	Relieves congestion operationally and defers reinforcement needs.
Storage as a transmission asset	KPI_{SEC}, KPI_{GEP}	Provides flexibility that lowers redispatch and postpones expansion.
Advanced conductors	KPI_{PET}, KPI_{SEC}, KPI_{GEP}	Raises asset capacity and substitutes for new lines.
Voltage and reactive-power control (e.g. synchronous condensers)	KPI_{SEC}	Supports secure voltage and contingency management.

This mapping highlights that several technologies contribute simultaneously to multiple KPIs. For example, DTR or advanced conductors can simultaneously enhance asset utilisation (KPI_{PET}), improve operational-security performance (KPI_{SEC}) and delay the need for new investments (KPI_{GEP}).

Going forward, ENTSO-E could build on such mappings to develop voluntary guidance encouraging the use of a harmonised set of input indicators across Europe. These indicators could then be used by national TSOs to propose consistent input-indicator frameworks to their respective NRAs, supporting alignment between technology deployment and the performance outcomes captured by the output KPIs.

5. European-level monitoring opportunities

Strengthening the performance of existing transmission infrastructure is a central objective of this paper. While national KPIs (KPI_{PET}, KPI_{SEC}, KPI_{GEP}) focus on measurable improvements in grid-operation performance and innovation at Member-State level, complementary opportunities exist at European level. One of the most promising is to build on ACER's ongoing monitoring of RAM in flow-based capacity-calculation regions. Although initially introduced as an available amount of transmission capacity for each critical network element with contingency to be allocated at flow-based market coupling, RAM data also provide a direct lens on how effectively the existing grid is used and, indirectly, on how innovative grid management contributes to overall system efficiency.

A practical example of RAM-based efficiency incentives (Belgium)

Belgium provides a concrete illustration of how RAM-based monitoring can be turned into a regulatory incentive for efficient grid use. The Commission for Electricity and Gas Regulation (CREG) first analysed differences in thermal line ratings across TSOs in its 2018 monitoring report for 2017, showing that some operators already applied seasonal or dynamic ratings, while others relied on fixed static limits. These differences could be observed directly through flow-based market-coupling data, revealing how innovative operational practices influence the capacity made available to the market.

Building on this analysis, CREG introduced in 2019 a RAM incentive for the 2020–2023 tariff period[15]. The incentive is technology-neutral: it rewards Elia, the Belgian TSO, for achieving higher available capacity efficiently, irrespective of the specific measures applied – be it dynamic line rating, topology optimisation, or improved forecasting.

- 80 % of the incentive is based on Elia's own RAM performance and 20% on that of neighboring TSOs, to encourage cross-border coordination.
- A redispatch-cost filter ensures that capacity increases result from genuine efficiency improvements, not from costly remedial actions.
- Elia reports monthly RAM data to CREG, which uses them for annual assessment.

Related to the baseline, the tuning of the parameters for the remuneration is based on the average performance over the last three years.

This model demonstrates how flow-based monitoring can underpin output-oriented, cost-efficient regulation. It also illustrates the type of data and methodology that could support an EU-level RAM-based infrastructure-efficiency indicator under ACER's monitoring framework.

Existing ACER monitoring activities

ACER already analyses RAM and related capacity-calculation parameters in its annual Market monitoring report and dedicated assessments of margin available for cross zonal trade (MACZT)[16]. According to Article 16(8) of the Electricity Regulation[17], MACZT should be at least 70% of the maximum flow for critical network elements respecting operational security limits for all critical network elements with a contingency (CNEC). MACZT is thus a real measure of how much of the available capacity is allocated for cross-zonal exchanges (as opposed to loop flows, internal flows and reliability margin, which should jointly fit into the remaining 30%)[18].

[15] For the tariff period 2024-2027, output KPIs for cross-zonal capacity in the intraday timeframe was introduced. For the intraday timeframe, ATC values are used instead of RAM values.

[16] See ACER's Monitoring Report Transmission capacities for cross-zonal trade of electricity and congestion management in the EU, 2025.

[17] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity.

[18] In this context, MACZT is equal to $RAM+F_{uaf}$ in the CCRs applying flow-based approach (Core and Nordic), where F_{uaf} is a portion of flow allocated in outside CCRs. For more information, see ACER Recommendation 01/2019.

Using data from TSOs and the Joint Allocation Office, ACER tracks the average RAM offered on critical network elements (CNEs), the distribution of limiting elements and the operational factors explaining variations in available capacity. These analyses effectively measure the degree of infrastructure and system efficiency achieved under real network and market conditions.

Logic of RAM-based indicators

In the flow-based capacity-calculation methodology, RAM represents the margin available for the flows by the cross-zonal exchanges within the observed flow-based region. It is given as a portion of maximum flow after accounting for reliability margin and zero-exchange flow within a region. Zero exchange flow accounts for loop flows, internal flows and flows by the cross-zonal exchanges outside the region:

$$\text{RAM} = F_{\max} - F_{0,\text{ccr}} - FRM + AMR - (IVA + CVA)$$

where

- F_{max} is the maximum admissible power flow on a network element (MW);
- $F_{0,cc}$ is the flow with no exchanges with the observed flow-based capacity calculation region (CCR); it includes loop flows, internal flows and flows by cross-zonal exchanges outside the CCR (unscheduled allocated flow F_{uaf});
- *FRM* is the flow-reliability margin reflecting uncertainty;
- *AMR* is adjustment of minimum RAM, ensuring that RAM+F_{uaf} complies with minimum capacity target of 70% of F_{max}, pursuant to Article 16(8) of the Electricity Regulation; and
- *CVA* and *IVA* are coordinated and individual validation adjustments, respectively.

Each term of the equation can thus be influenced by innovative or digital operational measures as explained in Table 8.

Table 8: Influence of innovative or digital operational measures on RAM

Symbol	Meaning	How it can change
I_{max}	Maximum permissible current on a line (ampacity)	Raised by DLR, reconductoring, or seasonal ratings
F_{max}	Maximum admissible power flow (MW) as function of I_{max}× voltage	Raised when I_{max} increases or conservative limits are relaxed
FRM	Flow reliability margin (uncertainty buffer)	Lowered with better forecasting and modelling
$F_{0,ccr}$	Zero-exchange flow within a region (loop flow + internal flow + unscheduled allocated flow)	Bidding zone reconfiguration changes loop flow and internal flow. Extension of FB region (and/or introduction of advanced hybrid coupling at its perimeters decreases F_{uaf} (to the benefit of RAM).

Hence, DLR and similar technologies raise RAM indirectly by increasing F_{max}, improved forecasting lowers *FRM*, while other operational measures, such as PSTs, raise RAM by lowering validation adjustments.

Toward a RAM-innovation

While ACER's current monitoring focuses on regulatory compliance with minimum capacity target, the same dataset could support a broader infrastructure-efficiency and innovation-monitoring framework.

A RAM-innovation indicator would quantify the additional system capacity attributable to innovative grid technologies or operational ‘smartness’. This requires establishing a counterfactual – a simulated static network case representing operations without such innovations. In practice, this could be implemented using existing capacity-calculation and market-coupling simulation tools, including the Euphemia algorithm or national common grid models, as follows:

1. **Baseline simulation (‘static’ case):** run the capacity-calculation algorithm using standard F_{max} values (seasonal or conservative ratings) and reference network configurations, excluding dynamic or innovative measures.
2. **Actual case:** use observed data incorporating DLR, topology optimisation, advanced forecasting and remedial actions.
3. **Compute differential:**

$$KPI_{\mathrm{RAM}} = \frac{\mathrm{RAM}_{\mathrm{actual}}}{\mathrm{RAM}_{\mathrm{static}}}$$

The resulting ratio represents the incremental network margin achieved through innovation-enabled operation, expressed either per CNE, per CCR, or aggregated EU-wide.

Because all data components already exist within the flow-based methodology and ACER’s monitoring databases, such an indicator could be produced with limited additional reporting burden. It would translate ACER’s current compliance-oriented monitoring into a broader assessment of how innovative grid management improves system and infrastructure efficiency.

Complementarity with national KPIs

National KPIs and ACER’s potential RAM-based indicator would provide mutually reinforcing perspectives. National indicators apply to all Member States, including those outside flow-based market coupling and capture innovation in grid operation, planning and technology deployment. A European-level RAM indicator, in contrast, would quantify aggregate efficiency gains visible in flow-based regions, using consistent market data. Together they would create a multi-layered monitoring framework: national KPIs demonstrating innovation uptake and operational progress across systems and ACER’s indicator capturing the resulting efficiency at interconnection and regional level.

Applicability of RAM and NTC metrics

The **RAM** is only defined in regions applying flow-based market coupling, where capacity for cross-zonal exchanges is calculated at the level of CNEs. In these regions, RAM-based analysis allows ACER to assess how efficiently existing transmission capacity is used and how innovative grid technologies contribute to increasing available capacity.

In **NTC-based regions**, capacity is calculated per border rather than per network element. While a simple border-level utilisation ratio (offered NTC relative to maximum feasible NTC) could provide a high-level proxy for available capacity, this approach lacks the granularity needed to attribute improvements to specific technologies or operational practices. Moreover, the data and modelling inputs required for counterfactual analyses are available to a limited extent under the NTC methodology. The flow-based-like values are reported for the NTC-limiting CNEC, for the sake of monitoring the minimum capacity target[19].

Given ACER’s access to detailed flow-based data (F_{max}, F_0, FRM…) and simulation tools, ACER’s monitoring should therefore focus on RAM-based indicators in flow-based regions, as well as the cNTC CCRs, to the extent possible. This monitoring could be progressively extended as market coupling evolves under CACM 2.0. This provides a coherent, data-supported and future-proof framework for assessing infrastructure efficiency at European level.

[19] See ACER Recommendation 01/2019 on the implementation of the minimum margin available for cross-zonal trade, 2019.

6. Conclusion and recommendations

The development of smart-grid infrastructure performance indicators marks an important step toward more transparent, outcome-based regulation of Europe's transmission grids. Building on existing NRA monitoring of grid digitalisation, reliability and flexibility, future regulatory frameworks should increasingly incorporate indicators that measure how TSOs perform in operating and expanding their networks.

The work undertaken by ACER builds on these existing efforts and demonstrates that meaningful output indicators can be developed by comparing actual outcomes with a defined counterfactual, thereby quantifying the performance improvements achieved through innovative or smart grid measures. However, establishing robust data, definitions and analytical consistency will take time.

For this reason, ACER recommends a phased and learning-oriented approach. The immediate goal should be to begin applying and refining a consistent set of output indicators across Member States to build a common evidence base. Over time, as data quality and comparability improve, these indicators can support broader assessments of grid performance and innovation and, where appropriate, provide the analytical foundation for performance-based elements within regulatory frameworks.

To guide this process, ACER makes the following recommendations:

Recommendation 1: Common monitoring framework – NRAs are encouraged to incorporate the three proposed output indicators (KPI_{PET}, KPI_{SEC}, KPI_{GEP}) as a shared framework for monitoring smart grid performance at transmission level. When implementing the framework at national level, NRAs should consult with the relevant stakeholders to ensure technical robustness and practical relevance. A two- to three-year transition period is foreseen to establish data collection, modelling and reporting processes, allowing time for methodological refinement and alignment across Member States.

Recommendation 2: Complementary input indicators – National TSOs should propose to their NRAs complementary input indicators that reflect the accessibility of tools (for example relevant smart grid technologies or operational practices) which impact the output indicators applied. ENTSO-E should support this process by providing guidance or reference mappings to promote consistency across Member States.

ACER will support this process by facilitating knowledge sharing, methodological consistency and best practice exchange. This gradual approach will allow NRAs and system operators to build confidence and comparability in measuring infrastructure performance while maintaining flexibility for national adaptation.

Annex A – Overview of relevant NRA practices

Belgium

Belgium offers an illustrative case of how regulatory incentives can promote the efficient use of existing transmission infrastructure and indirectly encourage the deployment of grid-enhancing technologies such as DLR, topology optimisation and PSTs.

Background

The Commission for Electricity and Gas Regulation (CREG) began analysing the use of innovative grid management in its 2018 monitoring report for 2017. Using flow-based market coupling data, CREG compared the maximum and minimum thermal limits applied to critical network elements in Belgium, France, Germany and the Netherlands.

It observed that some TSOs already applied seasonal or dynamic line ratings and adjusted limits under outage conditions, while others still relied on fixed static ratings. This revealed that the degree to which network operators use of dynamic or context-sensitive ratings can be detected through differences in the maximum admissible flow (F_{max}) in flow-based data and that these practices directly affect the capacity made available to the market.

How innovative grid technologies influence RAM

In flow-based capacity calculation, the RAM represents the margin left on a critical network element for cross-zonal exchanges after internal flows and reliability margins are deducted. In simplified form, it reflects how much of the physical network capacity (F_{max}) is made available to the market after accounting for internal network use (F_{ref}) and security margins (*FRM*, *FAV*). Innovative grid technologies such as DLR, improved forecasting, or topology optimisation can therefore increase RAM either by raising the usable physical limit or by reducing conservative margins.

A detailed explanation of this framework, including definitions of F_{max}, F_{ref}, *FRM*, *FAV* and their link to innovative technologies, is provided in the section European-level monitoring opportunities.

The 'RAM incentive'

In its 2019 tariff decision for 2020–2023[20], CREG introduced a RAM incentive to encourage higher available capacity and efficient congestion management.

- The incentive considers both Elia's performance (80%) and the average performance of neighbouring TSOs (20%) to foster cross-border cooperation.
- It includes a penalty for disproportionate redispatch costs, ensuring that RAM increases are achieved through efficient operation rather than excessive redispatch.
- The calibration aimed to avoid mis-incentives, such as providing more market capacity only to buy it back later via redispatch.

For the tariff period 2024-2027, output KPIs for cross-zonal capacity in the intraday timeframe was introduced. For the intraday timeframe, ATC values are used instead of RAM values.

Elia reports relevant data monthly, though CREG currently applies the indicator only for annual assessment. Related to the baseline, the tuning of the parameters for the renumeration is based on the average performance over the last three years.

DLR is explicitly recognised as one possible means to improve RAM. Elia uses sensors to derive dynamic ratings and is free to cap the usable capacity below the theoretical maximum when safety margins require it. However, there is currently no monitoring of how much of the high-certainty DLR potential is actually utilised or offered to the market, which could be an area for future transparency improvement.

[20] https://www.creg.be/sites/default/files/assets/Publications/Decisions/B658E55NL.pdf

Related innovation and forecasting incentives

Separately, CREG introduced in 2019 a 'Quality of forecasting inputs' KPI, aiming to improve data quality and reduce redispatch volumes. In 2021, it added a one-off innovation incentive for a study to identify the main causes of forecasting errors affecting redispatch costs. These measures are loosely connected to the redispatch cost KPI (KPI_{SEC}) in this report and are distinct from the RAM incentive, which primarily supports KPI_{GET} 1 on efficient provision of transmission capacity rather than on redispatch cost reduction directly.

Relevance for this report

The Belgian case demonstrates how flow-based monitoring data can underpin output-oriented, cost-efficient regulation. It also shows that RAM-based incentives can remain technology-neutral, encouraging system-level efficiency improvements regardless of which innovative tools are applied.

France

France was the first Member State to publish a stand-alone national report under Article 59(1)(l) of the Electricity Directive. The French Energy Regulatory Commission (CRE) released its first such report in 2023, assessing progress toward smarter and more efficient electricity networks[21]. The report is structured around three themes: grid connections, flexibility and grid management tools and user services and focuses mainly on indicators that describe the deployment of enabling technologies rather than direct performance outcomes.

The indicators were developed through an extensive consultation with TSO and DSOs and a stakeholder workshop in 2022. This process aimed to define a limited set of indicators that are both meaningful and practical to monitor.

Monitoring of DLR

Within the 'grid management' theme, DLR is included as a key input indicator. The indicator records the number and total length of transmission lines equipped with DLR, as reported by the TSO (RTE). The selection of lines for DLR installation is guided by cost–benefit analyses and detailed topographical surveys assessing the physical geometry and sag behaviour of conductors under varying environmental conditions. This ensures that DLR deployment is prioritised where the expected operational benefits, such as improved utilisation or congestion relief, are highest.

CRE presents the extent of DLR deployment in its smart grid report and tracks its evolution over time. However, the monitoring focuses on the scale and targeting of deployment rather than on quantified performance impacts, such as additional ampacity achieved or reduction in redispatch costs.

Broader Indicator Framework and Assessment

Other monitored indicators under the 'grid management' theme include the participation of new assets (e.g. storage, demand response, EV charging) in flexibility markets and grid observability, expressed as the share of data available in near-real time. These indicators are accompanied by qualitative analysis, reflecting differences in operator practices and digital maturity.

Overall, the French framework remains input-focused, measuring the implementation of smart technologies and digitalisation measures rather than their direct efficiency outcomes. Nevertheless, it stands out as one of the most structured and transparent national monitoring systems in Europe and provides a solid foundation for gradually moving toward output-oriented indicators that capture the real performance benefits of smart grid deployment.

Finland

The Finnish Energy Authority is responsible for monitoring and assessing the development of smart grids and how grid investments and operational measures improve energy efficiency and the integration

[21] https://www.cre.fr/fileadmin/Documents/Rapports_et_etudes/2023/2024-02_Rapport_indicateurs_eng.pdf

of renewable energy sources. Historically, this has focused mainly on DSO-level developments such as smart metering, demand flexibility and storage, but recent regulatory updates have extended this framework to the transmission level.

In December 2024, the Energy Authority issued an updated regulatory order introducing new key performance indicators for the TSO, Fingrid Oyj, including a specific indicator on DLR. The data will be collected for the first time in 2026, covering the 2025 reporting year.

The indicator on dynamic load capacity of cables includes three components:

- a) total kilometers of lines with DLR in use, reported in absolute terms;
- b) total average static thermal load capacity (A) of those same DLR-equipped lines; and
- c) total average dynamic thermal load capacity (A) of those lines under DLR operation.

The values for (b) and (c) are calculated as averages over all hours of the year, not just when dynamic limits exceed static ones. Together, they correspond closely to the numerator and denominator of the efficiency ratio proposed by ACER for assessing the efficient use of existing transmission assets. No differentiation by voltage level is applied at this stage and the indicators will initially be used for monitoring rather than incentive purposes.

Finland is therefore among the first Member States to have a legal basis and clear methodology for collecting data that can underpin a future output-oriented indicator on infrastructure efficiency. While the current focus is on data gathering rather than performance assessment, the new reporting framework already provides the essential inputs needed to calculate an output-based measure of how DLR improves transmission asset utilisation.

Germany

Germany has one of the most comprehensive systems in Europe for monitoring transmission grid operation and optimisation. The Federal Network Agency (BNetzA) publishes detailed data through the SMARD platform (for operational indicators)[22] and Netzausbau.de (for network optimisation and development)[23].

Congestion management, redispatch and curtailment

Under Redispatch 2.0, TSOs and DSOs report detailed congestion-management and renewable-curtailment indicators. The SMARD platform publishes quarterly and annual data on redispatch and countertrading volumes (MWh), total and disaggregated costs (EUR) for redispatch, countertrading and compensation of curtailed renewables, feed-in adjustments by energy source (renewables and conventional generation), the share of renewable generation curtailed (as a percentage of total output) and quarterly and annual trends in congestion and cost development. These data provide a detailed picture of how grid congestion is managed and at what cost, but they do not yet attribute changes to the deployment of specific smart technologies such as DLR.

Network optimisation and DLR

In parallel, BNetzA's quarterly grid development monitoring on Netzausbau.de tracks a wide range of network-optimisation and reinforcement measures implemented under the NOVA principle (optimisation before reinforcement before expansion). These include PSTs, reactive power compensation, topology optimisation and other technologies that can defer or reduce the need for conventional grid expansion.

Among these, DLR, referred to in Germany as Freileitungsmonitoring, is particularly notable for its detailed and structured monitoring approach. The monitoring distinguishes three categories of operation: 'Bestandsoptimierend' (legacy circuits operated with sub-80 °C design temperatures, often with seasonal limits), 'Statische Grenzwerte' (circuits operated at fixed static ratings according to DIN

[22] https://www.smard.de/en/energy-data-compact/electricity

[23] https://www.netzausbau.de/Vorhaben/uebersicht/report/de.html

EN 50341) and ‘Potentialoptimierend’ (circuits operated dynamically above static ratings based on ambient conditions).

TSOs report the share of total circuit length falling under each category and its implementation stage (already in operation, planned by 2025, or target after 2025). For example, Amprion currently applies DLR on over 40 % of its network, with an expected increase to around 70 % by 2025. DLR is fully integrated into Germany’s target grid planning (Zielnetzplanung) under the Netzentwicklungsplan and is assumed to be widely deployed to minimise the need for new grid expansion. However, it is not implemented on all circuits – exclusions apply for interconnectors, generation-connection lines, mixed overhead/underground cables and circuits with limited regional transport functions.

Assessment

Germany’s framework combines comprehensive operational monitoring (via SMARD) with systematic tracking of network-optimisation measures, particularly DLR. While this provides a strong evidence base on network efficiency and utilisation, the indicators remain largely descriptive and input-oriented, reporting deployment levels and costs rather than output performance metrics such as ampacity gains or redispatch-cost savings.

Recently, BNetzA has also begun to explore output-based performance metrics for digitalisation and smart grids at DSO level. Recently, an external study commissioned by the regulator proposed a combined system of output indicators and a digitalisation index for energy transition competence[24]. The output indicators focus on: (1) additional installed renewable capacity, (2) newly connected energy transition technologies on the consumption side and (3) time between connection request and commissioning. These aim to measure DSO performance in enabling the energy transition, complemented by a proposed incentive mechanism linking financial rewards or penalties to the speed and reliability of grid connections. However, these developments apply to distribution networks only. At TSO level, output-based incentives directly linked to infrastructure efficiency are not yet being discussed in the German regulatory framework.

Italy

Italy provides one of the clearest examples in Europe of output-based and benefit-oriented regulation already applied to its TSO, Terna. The Italian regulator ARERA has progressively introduced incentive mechanisms that directly reward measurable efficiency gains in both grid operation and investment – concepts that closely mirror the KPI_{SEC} and KPI_{GEP} indicators proposed in this paper.

Under ARERA’s framework, innovation incentives have been awarded where Terna achieved quantifiable cost savings relative to predefined targets[25]:

- **Efficient grid expansion (KPI_{GEP}):** In 2020, Terna implemented several ‘capital-light’ solutions, including DTR, which increased cross-zonal transmission capacity by 1,450 MW. The regulator recognised savings of over 1 billion EUR compared to traditional grid expansion and awarded Terna a 143 million EUR bonus, partly linked to lower-than-expected CAPEX. This incentive structure directly parallels the KPI_{GEP} logic – comparing actual investment costs to a reference ‘classical’ solution.
- **Efficient management of operational security (KPI_{SEC}):** In 2021, ARERA introduced a similar scheme for dispatching costs, setting target expenditure levels based on historical data. Terna reduced these costs significantly in 2022 through operational and technological improvements, including smarter congestion management and received a 800 million EUR reward against estimated savings of 2.2 billion EUR. This mechanism aligns with the KPI_{Sec} approach, where

[24] https://www.bundesnetzagentur.de/DE/Beschlusskammern/1_GZ/GBK-GZ/2024/GBK-24-02-1x4_Q-Reg/Downloads/Gutachten_E-Bridge_Consulting_FGH.pdf

[25] For more details see Bovera, F., L. Schiavo and R. Vailati (2024): Combining Forward-Looking Expenditure Targets and Fixed OPEX-CAPEX Shares for a Future-Proof Infrastructure Regulation: the ROSS Approach in Italy.

performance is measured through reduced costs of maintaining secure and stable operation compared to a theoretical baseline.

Together, these examples show that Italy's regulatory practice already incorporates the core principles of output-based indicators – benchmarking actual performance against standard cost or efficiency baselines. The proposed KPIs would thus formalise and standardise such comparisons, providing a transparent and replicable framework that could be applied across Member States beyond Italy's national incentive schemes.

Portugal

Portugal adopted a comprehensive framework for monitoring smart grid development through a regulatory directive published on 19 August 2024. The directive establishes 48 indicators covering electricity transmission and distribution, to be reported for the first time in 2025 based on 2024 data. The indicator set was developed through a process that included internal research on EU practices, public consultation and input from the national TSO (REN) and DSO (E-Redes).

Among the indicators, two directly address the efficient use of existing transmission infrastructure and the operation of overhead lines with dynamic parameters:

- **Input indicator:** Representativeness of the length of overhead lines with dynamic parameters – defined as the ratio between the total length of overhead lines operated with dynamic parameters and the total length of all existing overhead lines, calculated separately for each voltage level (VHV, HV, MV).
- **Output indicator:** Overhead lines operating performance with dynamic parameters – defined as the ratio between the annual average dynamic transmission capacity of the lines operated with dynamic parameters and their corresponding annual average static transmission capacity, again by voltage level.

This approach closely mirrors the ACER-proposed indicator for efficient use of transmission assets, combining both an input (extent of deployment) and an output (operational performance) dimension. Although the methodology is still being refined and initial data indicate that no lines currently operate under DLR, the legal framework and indicator definitions are already in place.

For now, Portugal's Energy Services Regulatory Authority (ERSE) is collecting data to gain experience with the indicators. While there are no performance incentives linked yet, ERSE envisages that the indicators could form the basis for output-based incentives in future regulatory periods – potentially starting from 2030. Network operators can submit proposals for regulatory sandboxes using dynamic network management tools to maximize capacity availability. The application horizon for the projects must be within the regulatory period of 2026-2029. Given Portugal's single TSO and DSO, international benchmarking is considered important for future calibration and assessment.

Slovenia

Slovenia's framework for tracking the efficiency of smart grid operation combines project-level and system-level output and throughput monitoring as the basis for providing additional financial incentives to the system operator. System-level monitoring also depends on measuring preparedness levels.

In the domain of **efficient use of existing transmission assets**, the following applies:

- Project-level approach based on the TSO's application: throughput indicators measuring increase of transmission capacity,
- System-level approach: input and throughput indicators directly related to DTR. The framework was introduced by the NRA in 2022 and refined in 2025.

Double rewarding is avoided by excluding system-level incentives whenever a project-level reward has been granted for the relevant scope.

Project-level monitoring

Project-level monitoring is performed based on a successful qualification of the project by the NRA. The approach is based on technology agnostic throughput-based KPI (various measures can apply such as DTR, DLR or others) that can be monitored either across the entire transmission system (treated as a system-level KPI) or more granularly at the level of individual assets (for example overhead lines, transformers etc.). The monitoring is based on measuring the impact according to the study the NRA published in 2016[26].

System-level monitoring

A certain level of input indicators is a prerequisite for measuring efficiency based on throughput indicators. Input indicators measure the level of preparedness which provides the basis for meaningful measurement of efficiency at the system level.

Input indicator – Share of network elements operating under DTR

The input indicator measures the share of transmission assets operated with DTR. The overall indicator is calculated as weighed average of input sub-indicators for each voltage level (400 kV, 220 kV and 110 kV), considering both transmission lines and transformers. Monitoring DTR deployment for both transformers and lines reflects an advanced level of technological implementation.

Throughput indicator – Utilisation of increased transmission capacity

This KPI evaluates the extent to which the additional transmission capacity made available through DTR is actually utilised under N-state operation conditions. The overall indicator is calculated as a weighed sum of two sub-indicators calculated separately for transmission lines and transformers. Each sub-indicator assesses the average realised relative loading of network elements operating in DTR regime during periods when the actual loading exceeded the static (non-DTR) transmission capacity of the respective element. The results for sub-indicators are averaged across all transformers and lines of which loading exceeded the static capacity, respectively.

The Slovenian indicator captures utilisation of DTR-enabled capacity. Opposite to the proposed KPI_{PET}, which is based on the available operational capacity applied in real-time operation and the static capacity, the Slovenian indicator focuses specifically on periods when realised loads exceed static limits. It therefore provides a throughput-based perspective on how often and to what extent DTR capacity is used under N-state operation condition.

This design has inherent limitations for use as an output indicator. For example, it depends on system loading and dispatch patterns that TSO has limited control over and is sensitive to variations in demand and transits, leading to year-to-year volatility. Moreover, because the indicator reflects realised flow conditions rather than operational practice, its cross-country comparability is limited. The Slovenian indicator can be considered a throughput indicator, providing an insight into grid usage rather than controllable efficiency.

Data to calculate the indicator are drawn from SCADA systems, aggregated by the TSO and reported annually to the NRA which currently receives only top-level indicators, while detailed reporting of the underlying data for each transmission element is envisaged to be implemented in near future. The indicator already forms part of Slovenia’s regulatory framework, though no penalties will apply before 2028.

ACER notes that Slovenia stands out for having a comprehensive input–throughput monitoring system for DTR that includes both lines and transformers. While the utilisation indicator captures real operational behaviour, it should be interpreted as complementary to, rather than equivalent with, KPIs based on rated ampacity applied in real-time operations.

[26] https://www.agen-rs.si/documents/10926/37376/Reguliranje-na-podro%C4%8Dju-pametnih-omre%C5%BEij---analiza-stanja-in-priprava-izhodi%C5%A1%C4%8D/4ecca0fc-c236-4c58-a1f2-a2ba3900ffce

Sweden

Sweden plans to publish its first stand-alone smart grid monitoring report by the end of 2025, in line with the requirements of the Electricity Directive. The Swedish Energy Markets Inspectorate (Ei) has introduced a new indicator on DLR, to be reported annually starting in 2024 based on data from the previous year (e.g. the 2024 report is based on data from 2023).

The indicator applies to the TSO and regional DSOs and records the number of lines equipped with automatic DLR as well as their total aggregated length. This indicator is primarily input-based, focusing on the scale of DLR deployment rather than its operational effects.

While Sweden’s monitoring framework is still at an early stage, the inclusion of DLR represents a concrete step toward systematically tracking the use of smart grid technologies that enhance the efficiency of existing transmission infrastructure.

Annex B – Summary of initial ENTSO-E feedback

Context

ENTSO-E provided initial, non-exhaustive feedback on ACER's draft set of electricity output smart grid performance indicators for transmission grids framework on 10 November 2025.

The feedback received from ENTSO-E members represents initial views collected from several TSOs and does not reflect ACER's position. It provides useful input for further dialogue on the refinement and practical implementation of the proposed indicators. Key themes raised included:

- **Output indicator design:** Some members questioned whether the three proposed output indicators (KPI_{PET}, KPI_{SEC}, KPI_{GEP}) fully capture system operators' performance objectives, suggesting that aspects such as security of supply, balancing quality and voltage control may require further reflection. Respondents emphasised that the metrics should also recognise elements of operational quality and resilience.
- **Counterfactual approach:** Concerns were raised about the feasibility of constructing reliable 'non-smart' counterfactuals, particularly where these require modelling market-based outcomes (e.g. redispatch costs or investment alternatives). Several members cautioned that hypothetical monetary counterfactuals could be complex to maintain and may risk over-interpretation.
- **Redispatch and controllability:** Some respondents underlined that redispatch volumes are influenced by external factors beyond TSO control and therefore questioned the appropriateness of using redispatch costs as direct indicators of efficiency.
- **Heterogeneity and interpretation:** Feedback highlighted that significant differences in network design, price levels and asset life-cycles across TSOs may limit direct comparability. It was suggested that any future use of indicators in comparative or incentive contexts should take such heterogeneity into account.
- **Time horizon:** A number of respondents sought clarification on whether the indicators are intended to capture short-term operational performance, multi-year trends, or long-term structural improvements.