

From Legacy to Leadership: Europe's Digital Grid Transformation

Why smart regulation is key to ensuring digital grids deliver value to all stakeholders

Final report – Executive Summary

Developed for:

T&D
&europe

Foreword

Europe is facing the challenge of providing Europeans with an affordable, resilient and sustainable energy system. This T&D Europe Digitalisation Study was commissioned to analyse how digital solutions can transform the continent's electricity grid—making it smarter, more flexible, and better equipped to integrate renewable energy and manage new patterns of demand. It explores the regulatory and operational changes needed to unlock the full potential of digitalisation for all stakeholders. The result is a vast amount of expert content that can help policymakers, regulators, network operators, and technology providers to take the right decisions in building the modern electrical system that Europe needs.

This study, conducted by Compass Lexecon, is the result of close collaboration among T&D Europe members, with valuable input and review from experts whose comments and suggestions have helped shape the study's direction and clarity. It is, however, grounded in real world experiences from practitioners, which adds to the richness and strength of the study. The dedication and the efforts of all contributors has ensured a comprehensive and actionable analysis.

Special thanks go to Christiane Mann, chair of the T&D Europe working group Grid Digitalisation, who was the initiator and driving force behind the study, and Hyeonji Hwang and Federica Bottacin, policy advisers in T&D Europe, who have tirelessly supported the project.

We extend our sincere gratitude to the sponsors whose support made this research possible. We are grateful for the financial support from our national associations Afbel, BEAMA, Gimelec, ZVEI, and our corporate members ABB, Eaton, Ganz, GE Vernova, Hitachi Energy, Schneider Electric and Siemens. Their commitment to advancing Europe's energy future is deeply appreciated.

Diederik Peereboom
T&D Europe Secretary General



Today's power grids were not designed to support the energy transition

Power grids are the backbone of the energy transition. The three dimensions of the Energy Trilemma - resilience, affordability, and sustainability – continue to guide every policy decision

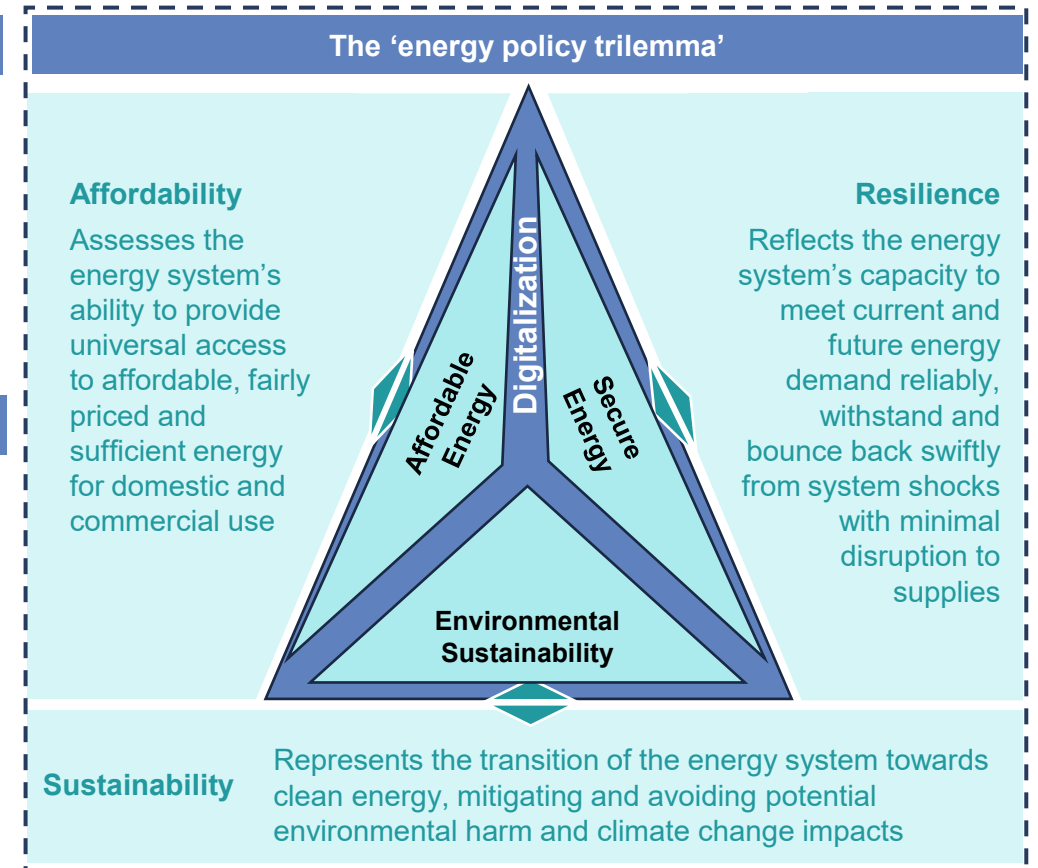
The electricity grid lies at the heart of Europe's decarbonisation

Delivering clean, reliable and affordable energy at scale requires significant investment in a modernized network.

- In 2023, the European Commission launched its *Grid Action Plan*, identifying over €584 billion in investment needs by 2030 to expand and upgrade EU grids. This figure could rise to €1.87 trillion by 2050, according to the European Court of Auditors.^{1,2}
- The *Draghi report* warns that electricity networks must be built 3 to 20 times faster than historical rates to meet Europe's net-zero targets.³

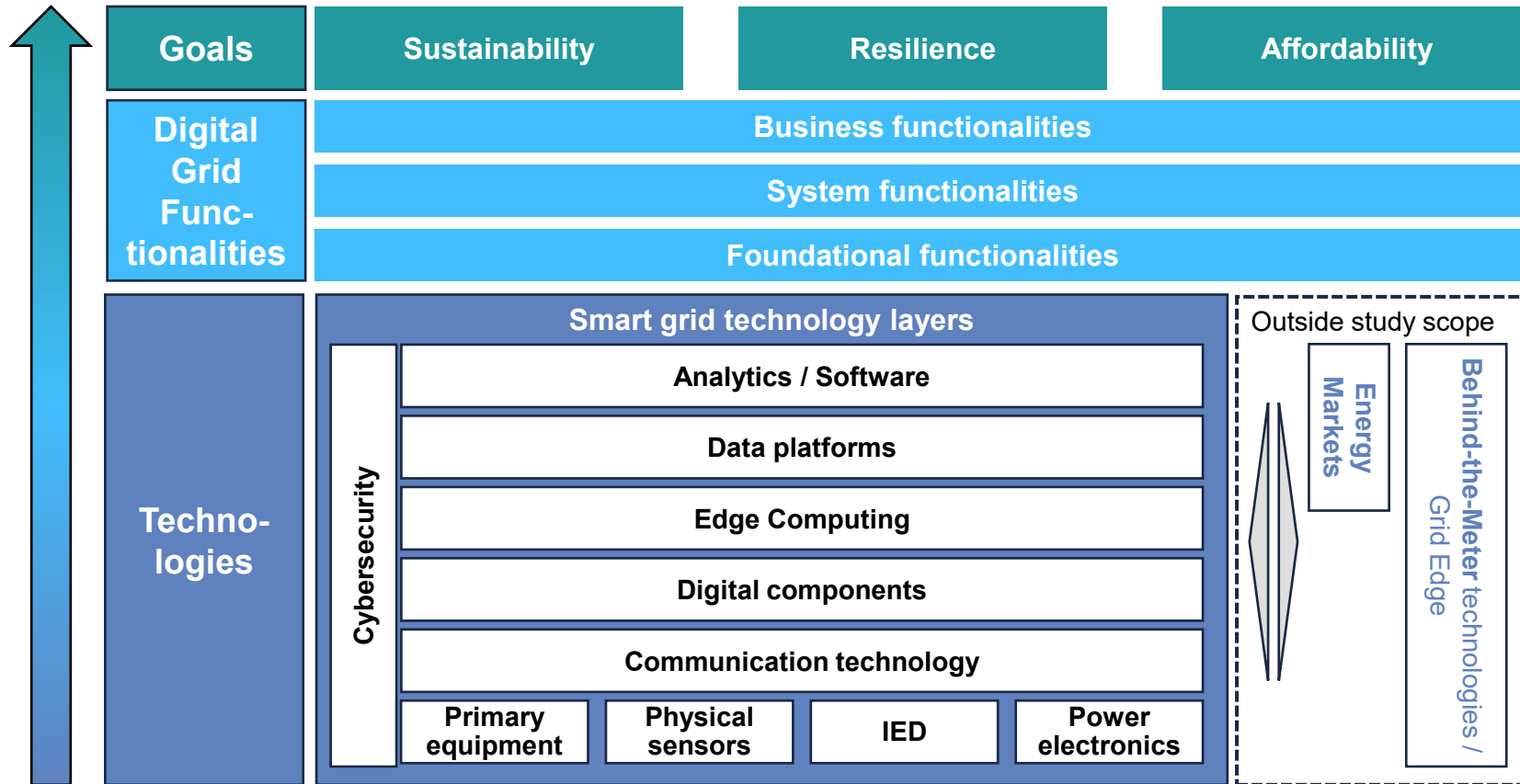
Economic and administrative factors exacerbate the upgrade challenge

- **Supply Chain Impacts:** Grid development depends on critical components, including transformers, cables, and essential raw materials like copper and rare earth elements
- **Permitting Bottlenecks:** Permitting processes for new grid infrastructure are often long and fragmented, many projects taking around seven years to gain approval
- **Skills and Workforce Challenges:** Labor shortage impacts installation capacities
- **Sustainability Requirements:** Grid projects are increasingly subject to strict environmental standards, including requirements for biodiversity protection and climate resilience
- **Financing and Investment Gap:** Achieving Europe's grid modernization goals will require massive investment, particularly DSO often face challenges accessing capital
- **Ecosystem:** New stakeholders are adding to the complexity of the energy business



Grid digitalisation is the key enabler of the energy transition, positively contributing to the dimensions of the Energy Trilemma

Grid digitalisation needs holistic implementation across all layers, phases and respective technologies



- There is **no single “silver bullet”**; grid digitalisation requires a mix of hardware and of software solutions.
- Grid digitalisation begins with establishing a **technology stack that enables foundational functionalities**. These are prerequisites for enabling higher-level system and business functionalities like flexibility utilization and system balancing.
- Digitalisation must be treated as an **integral part of grid evolution**, not an add-on. System approach across the lifecycle is key, it must include permitting and procurement processes.

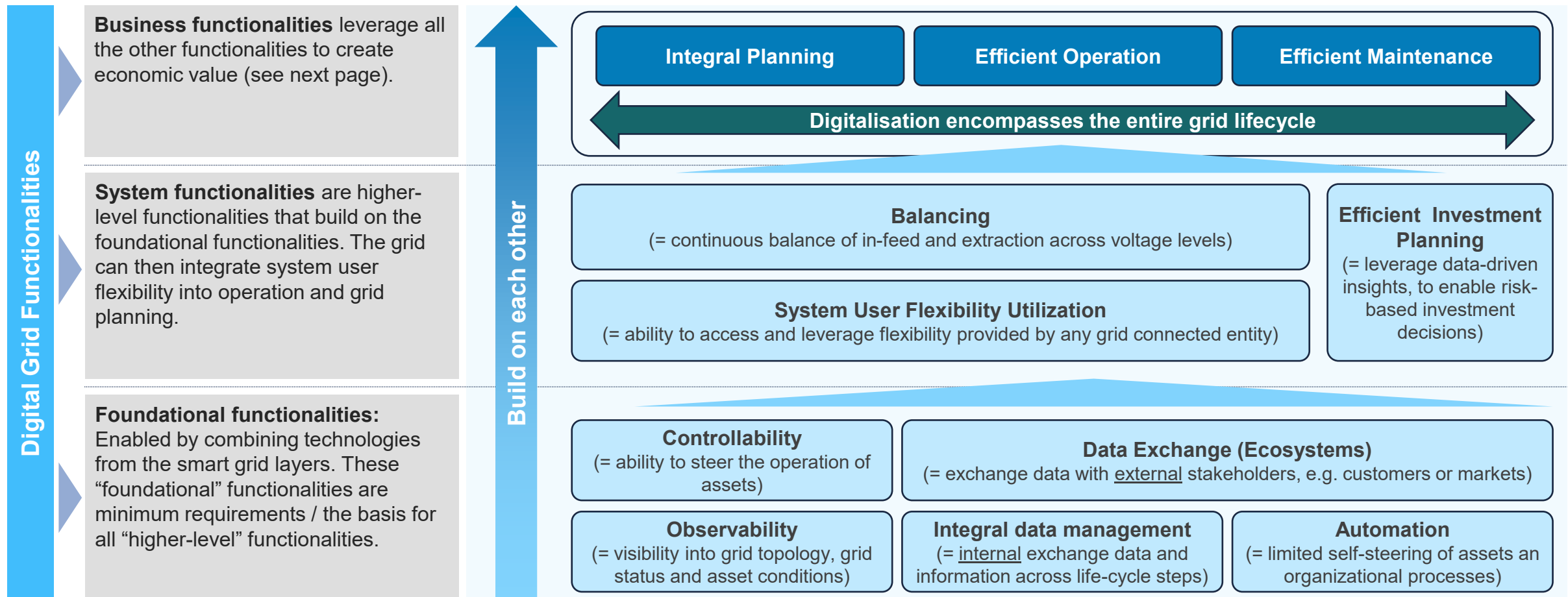
“Digital grid technologies”

- The result of **smart layering of traditional and digital technologies**
- Example:** “passive” transformer/ switchgear + IED + sensor + communication = digitized transformer / switchgear (provides data) + connectivity = monitored transformer + analytics = smart transformer / switchgear

Simplified schematic; will differ per TSO / DSO

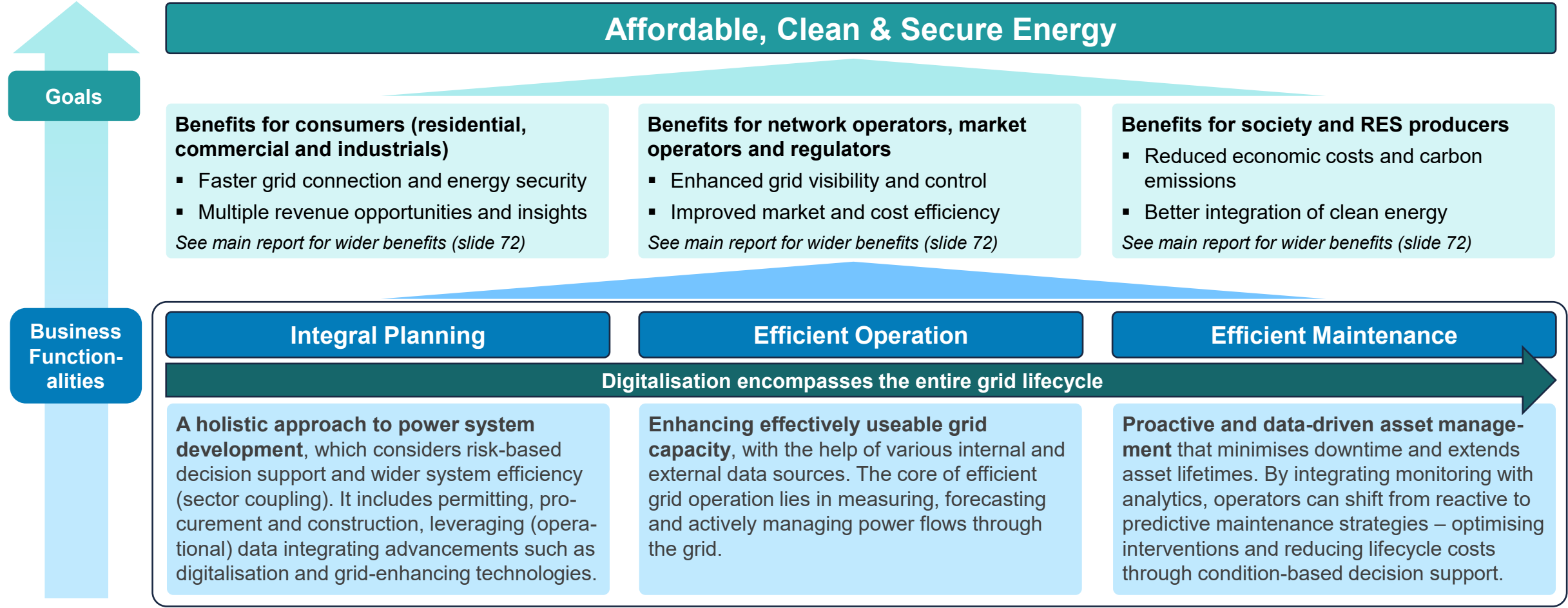
Digital Grid Technologies enable advanced functionalities necessary to plan, build and manage the Grid of the Future

Laying the foundational groundwork is essential before higher-level functionalities can be accessed



Digital grid functionalities uniquely support the energy trilemma dimensions across the grid value chain and across other sectors

Grid digitalisation enables more than smart grids



Regulatory frameworks of grids have evolved over the years, reflecting respective context and policy objectives

Current regulatory frameworks are not always fit-for-purpose and require appropriate adjustments

Time period (roughly)	Pre-2005	2005-2012	2012-today	Context and objectives of regulation
<u>Challenge and policy priority</u>	Investment certainty related to privatisation	Focus on reducing costs	Re-focus on investments and long-term grid expansion	Innovative and efficient investment and operation
<u>Description</u>	With privatisation, investment certainty was introduced through Cost+ regulation and Regulated Asset Base (RAB) to ensure financing of large investments	Focus on cost cutting by using fixed cost benchmarks Introduction of quality regulation to counterbalance incentive to cut quality (which was a first form of output-based regulation)	Energy turnaround introduced need for network expansion, which triggered a re-focus on investments and long-term grid expansion (this often created more CAPEX-bias)	Network expansion is becoming more expensive, putting a focus on grid utilisation. Digitalisation creates opportunities but also unclarity for the regulator and risk for the network operators.
<u>Regulatory solutions and regulatory innovations</u>	Cost + regulation and Regulated Asset Base (RAB)	Revenue cap regulation Quality regulation	Network development plans and investment programs were introduced. These are focused on primary grid components (lines, substations) rather than the development of new functionalities.	Regulatory framework needs to evolve to allow network operators to innovate and incentivise efficient investment and operation with DGTs. It will shape and enforce system transformation.

Regulatory evolutions reflect the evolution of the context and policy objectives. The next challenge is to address current regulatory hurdles for DGTs

Efficient regulation to enable the deployment of digital grid technologies

The Grid of the Future must operate under different circumstances and adequate Smart Grid Indicators can be used to reflect these new conditions

	Holistic planning and investment decision	Efficient operation and maintenance	Risk profile
Future grid = traditional + digital solutions	<p>Optimized total cost & CAPEX-OPEX balanced</p> <p>+ Improved, integrated planning – reduced investment need relative to grid expansion w.o. innovative technologies</p>	<p>Enhanced and more granular / timely monitoring</p> <p>+ Efficient grid operation – improved utilisation, hosting capacity, faster connection</p> <p>+ Efficient maintenance – lower maintenance cost and higher reliability</p>	<p>Better controllability but higher residual risk profile, operating grid closer to its limit</p> <p>Some early-stage technologies may need a supportive framework</p>
Traditional grid	<p>CAPEX-dominated</p>	<p>Often based on limited set of normative indicators (e.g. standard lifetime, asset performance), lack of locational data</p>	<p>Designed to limit risk exposure of network operator but in a system with limited variability</p>

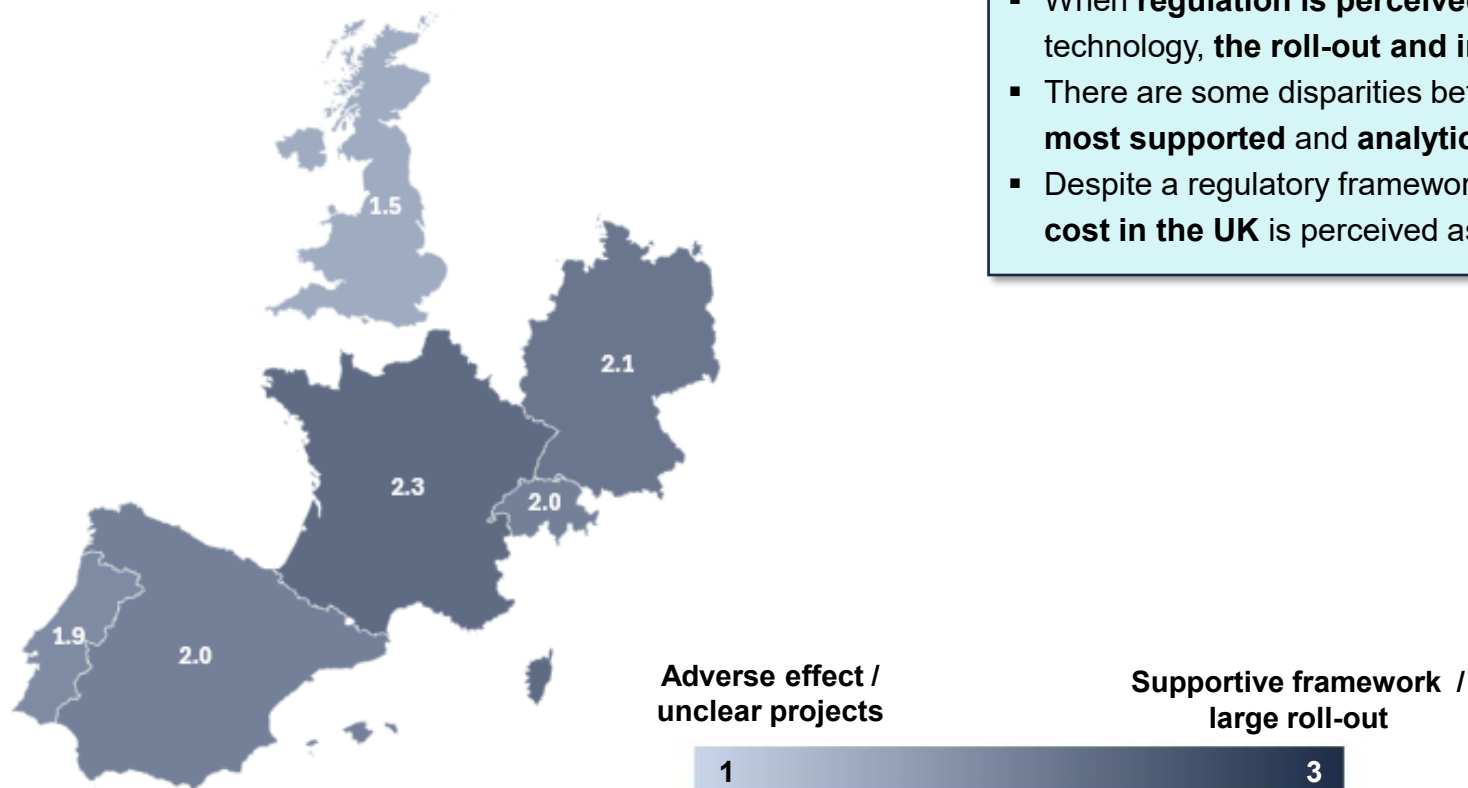
Digital grid technologies typically have a **different cost structure and risk profile** compared to traditional grid technologies. The **regulatory system**, tailored for traditional grid requirements, must be adopted to not disadvantage digital technologies and to **create a level playing field**.

- Level playing field** means a network operator will:
- Have KPI incentives to reward to efficiently address the trade-off between inputs, outputs and risks associated with different technologies
 - Consider all technologies on a level playing field and choose to add digital solutions to an existing grid or substitute some conventional network expansion for digital solutions if that is efficient
 - Engage in holistic network planning and investment decisions that minimise overall costs, accounting for the interplay between all technological options

Survey amongst selected T&D members - Uneven deployment of digital solutions

Grid digitalisation is rolled-out when the regulatory framework is supportive

Development of digital solutions in Western Europe



Country findings:





- When **regulation is perceived as supportive** in the development of a given technology, **the roll-out and inclusion in planning is more straight-forward**
- There are some disparities between technologies, with **smart meters being the most supported** and **analytics the less supported**.
- Despite a regulatory framework with few tipping points, the **incentive to reduce cost in the UK** is perceived as a significant limitation for digital deployment.

Methodology:

- CL addressed surveys to T&D members in the different countries. These regroup grid technology providers for the given country.
- Surveys included 4 categories (sensors, analytics, digital substations, smart meters). CL present the average of the 4 categories.
- Surveys included questions about the perception of (i) technology development and (ii) the supportiveness of regulation.

Regulatory systems in place – Variants of revenue cap approaches

The study reviewed 4 different regulatory frameworks across Europe

	Germany 	Spain 	UK 	France 
General information	<ul style="list-style-type: none"> Regulatory period: 2024-2028 (5 years) 	<ul style="list-style-type: none"> Regulatory period: 2020-2025 (6 years) 	<ul style="list-style-type: none"> TSO: 2021-2026 (6 years) DSO: 2023-2028 (6 years) 	<ul style="list-style-type: none"> Regulatory period: 2025-2028 (4 years)
Regulation approach for OPEX	<ul style="list-style-type: none"> Revenue cap based on non-controllable controllable and volatile costs. Efficiency benchmark between TSOs and DSOs. 	<ul style="list-style-type: none"> Revenue cap based on non-controllable controllable costs. 	<ul style="list-style-type: none"> Revenue cap based on TOTEX approach (fair margin). 	<ul style="list-style-type: none"> Revenue cap based on non-controllable and controllable costs.
Regulation approach for CAPEX	<ul style="list-style-type: none"> Cost +, with RAB model (fair margin). 	<ul style="list-style-type: none"> Cost +, with RAB model (fair margin). 	<ul style="list-style-type: none"> Revenue cap based on TOTEX approach (fair margin). 	<ul style="list-style-type: none"> Cost +, with RAB model (fair margin).
OPEX incentives	<ul style="list-style-type: none"> Controllable costs are incentivized at 100%. Congestion costs (costs incurred by limited transmission capacity) are incentivized. The cost of losses is considered volatile: uncertainty mechanism depending on efficiency according to the NRA. 	<ul style="list-style-type: none"> Controllable costs are incentivized at 100%. Incentives for network availability. Incentives to reduce losses and improve quality. 	<ul style="list-style-type: none"> Uncertainty mechanisms allow for a revisiting of the during the control period. Innovation incentives: Network operators compete against each other for substantial funding of demonstration projects (up to 2.5% of revenue). Output incentives: Rewards and penalties for customer satisfaction, reliability and availability, safety, connection terms, environmental impact, and social performance. 	<ul style="list-style-type: none"> Controllable costs are incentivized at 100%. Tariffs account for increased expenses related to cybersecurity, data management, smart monitoring of the network and R&D spendings. Incentives on service quality Incentives on innovation and on quality of data. Targets for digitalisation.
CAPEX incentives	<ul style="list-style-type: none"> The CAPEX trajectory may be revised during the period in the event of a significant investment approved by the regulator. 	<ul style="list-style-type: none"> Investment cap based to GDP growth. Incentive to keep fully depreciated assets operational. Norm cost approach. 	<ul style="list-style-type: none"> Uncertainty mechanisms allow for a revisiting of the during the control period. 	<ul style="list-style-type: none"> Specific budget for large projects Specific mechanism for IT and telecom expenses (TOTEX like)

Grid of the Future calls for a fundamental rethinking of not only how we regulate but also how we manage the grid

Country deep dives reveal 4 best practice areas for “fit-for-purpose” regulation

Lifecycle phases:



Key findings for digital technologies:

Informed by interviews and research made across multiple European jurisdictions*



Network regulation and network planning best practices:

Wider best practices: (integr. in operations, change management, market design, etc.)

- **Insufficient** transfer of project results to regulators/ insufficient incorporation into market solutions
- **Death by pilot:** adoption can be hindered by long processes or by not accepting pilots from other EU-countries
- **Planning doctrine** insufficiently considers cross-sectorial and/ or flexibility aspects
- Especially on distribution side, **limited anticipation and planning of evolving tasks** due to the energy transition
- **CAPEX-bias:** reasonable remuneration provided through CAPEX, while OPEX often loss-making (either delay or non acceptance by regulator)
- **“Reliability of supply” bias:** focus on avoiding risks resulting in missed opportunities to improve performance and/ or increase efficiency by innovation (e.g. new forms of congestion management; connection request processes)
- **Limited output incentive:** Grid operator revenues are mostly based on costs and not on the utility of network users

1 Improved network planning

Network planning should **make full use of and consider the possibilities** enabled by digital tools, such as digital twins.

Pilots, such as regulatory sandboxes, should reflect legal and regulatory frameworks and include respective expert stakeholders. Jointly develop criteria to define “proven technology” (TLR).

2 Cost recognition and risk sharing

Regulation must consider the new realities of **OPEX-driven technology** and **different risk profiles**. This can be resolved by easier capitalisation of OPEX and more elements of OPEX-friendly regulation.

3 KPI incentives

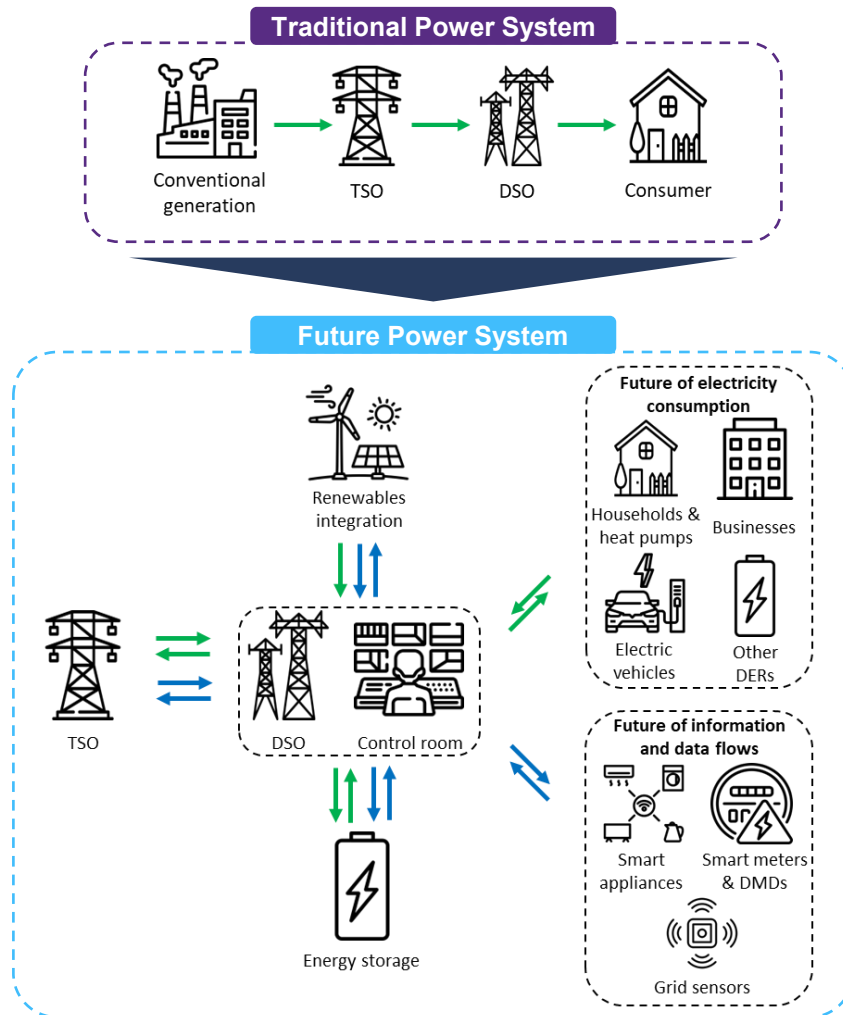
Across the lifecycle, targets need to be implemented, and risks should be assessed and adopted. Reasonable regulation risks should be allowed. Implementation / goals should be **incentivised**.

4 Integrated approach for digitalisation

The full value of digitalisation is unlocked only when technologies, processes and actors are **coordinated across the system**. This requires interoperability, coordination and efficient regulation.

Best practices 1 – Improved network planning

Leverage data to improve planning, support innovation, and enable system transformation



Tipping points found

Investment doctrine focused on conventional technologies

- Digital and innovative solutions are usually not part of DSO grid development plans.
- They require market and technological readiness to get considered in planning.
- There is a lack of transparency and independence in decision making.

R&D and pilots focused on the traditional system operation

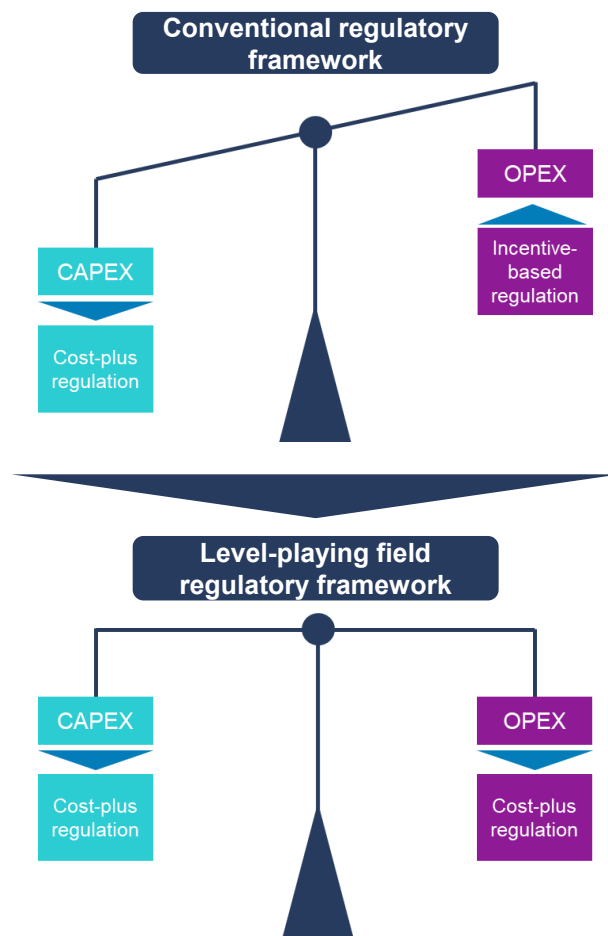
- Traditional R&D and deployment may not be optimal in a system with multiple interfaces
- Long processes for pilots and not accepting pilots from other EU-countries also hinder the potential of new technologies.

Best practices

- **Digital planning:** Digitalise network planning itself and take on board data from all possible sources (digital twins).
- **NOVA principle:** Consider the potential of grids with a higher utilisation in network planning.
- **Rethink R&D and deployment approach:** Consider a system-wide approach, with decentralised benefits (not only for system operation but for other stakeholders) and multiple interfaces (storage, decentralised generation, demand-side flexibility, demand-side data flows).
- **End-To-End approach for digital:** planning should include R&D, studies, permits, and construction work for asset integration.

Best practices 2 - Making the regulation more OPEX-friendly

Foster a level playing field for cost recognition and an efficient management of risks and uncertainties



Tipping points found

CAPEX bias / OPEX disadvantage

- Most European regulatory systems treat capital expenses (CAPEX) more favourably than operating expenses (OPEX).
- This so-called **CAPEX-bias** means that using digital solutions can be less financially attractive than investing in physical assets.
- More specifically, the rules of cost recognition may distort the way in which network operators invest in digital solutions.
- Digitalisation is evolving rapidly. But most regulatory frameworks **lack the possibility to deal with uncertainty** and inaccuracy (for example of cost forecasts).

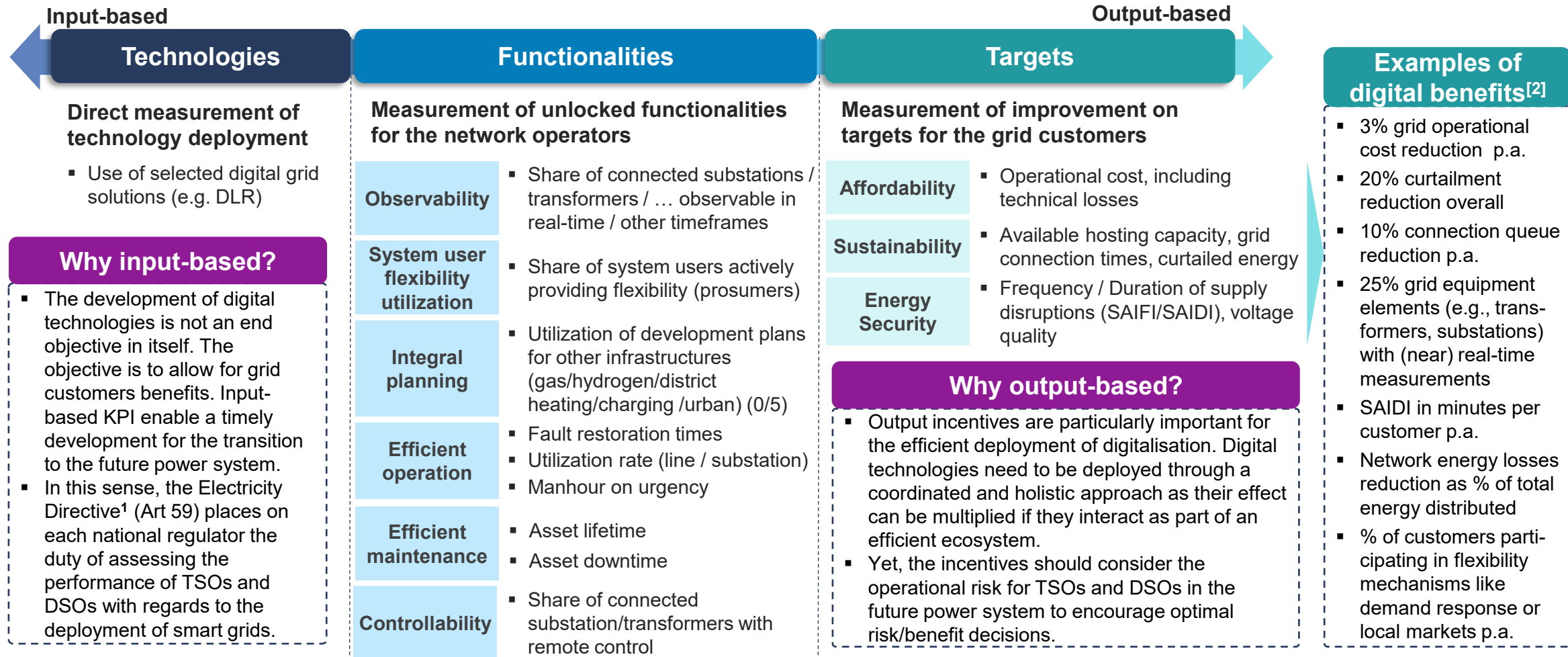
Best practices

Making the regulation more OPEX-friendly

- Cost+ regulation for digitalisation expenses would ensure greater certainty and speed for recognition of costs by implementing a scheme guaranteeing a remuneration of costs plus an adequate return.
- Increased possibility for capitalisation of OPEX.
- This would create a level playing field with other technologies that are more CAPEX-intensive.
- In order to maintain an efficiency incentive, uncertainty mechanisms may be defined based on an adequate sharing of the risks for TSOs.

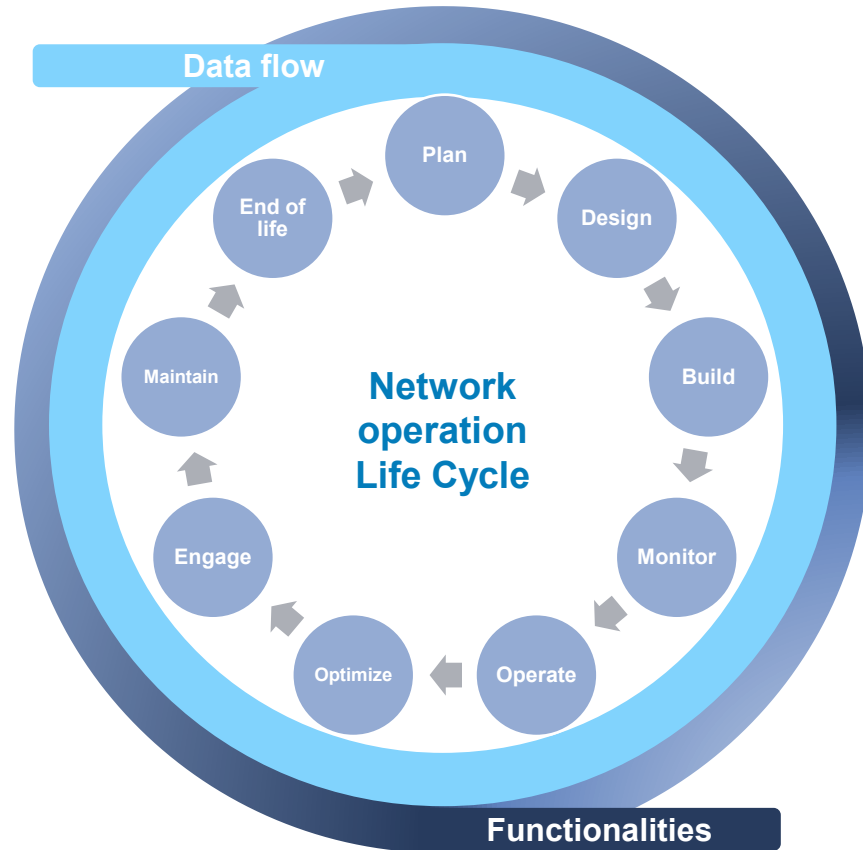
Best practices 3 - Measuring digitalisation and its outputs through KPIs

Incentivize and reward grid operators based on metrics reflecting the benefits of the digital grids



Best practices 4 - Integrated approach for digitalisation

A system wide approach to digital grid technologies is need to maximize value across the network operation life cycle



Tipping points found

Digitalisation is considered as technology roll-out, not as system-wide transformation

- **Lack of interoperability:** isolated solutions increase costs, delay deployment, and require bespoke integration
- **Lack of coordination:** Data exchange between actors – such as between TSOs and DSOs or between grid and adjacent sectors/infrastructures – is progressively standardised, structured and embedded in day-to-day operations
- **No lifecycle integration:** Each stage – planning, investment, operations, and maintenance – generates and depends on data. The different stages are not yet connected.

Best practices

- **Harmonization:** Accelerate the implementation of existing EU regulations and directives in a harmonized way across member states.
- **Data access:** Clearly delineate the rights of usage across network operators and third parties for the data measured in a digitalised grid.
- **Better use of flexibility to support grid stability:** Develop effective mechanisms to access and incentivise the use of reliable flexibilities (incl. flexibility platforms and local flexibility markets) and define the related responsibilities and coordination needs between T/DSOs.

Grid digitalisation creates benefits for various interconnected stakeholders, contributing to a more efficient, sustainable, and resilient energy system

Grid digitalisation is more than infrastructure. Regulation is a key enabler for the energy transition

Energy Trilemma	Sustainability	Resilience	Affordability
Stakeholders	Network Operators & Utilities, Renewable Producers, Regulators	Network Operators & Utilities, Market Operators, Consumers, Regulators	Network Operators & Utilities, Market Operators, Consumers, Regulators
Benefits from grid digitalisation	<ul style="list-style-type: none"> Reduced carbon emissions <ul style="list-style-type: none"> Easier grid integration for RES, better forecasting capabilities Better RES grid connection management Less RES redispatch Reduced environmental impact <ul style="list-style-type: none"> Optimized grid planning Reduced congestions and technical losses 	<ul style="list-style-type: none"> Improved energy security <ul style="list-style-type: none"> Enhanced grid visibility and control Improved asset management and maintenance prediction Better outage management and faster restoration Improved power quality management Increase internal digital maturity of network operators 	<ul style="list-style-type: none"> Reduced economic costs <ul style="list-style-type: none"> Reduced operational costs Reduced technical losses Optimized grid planning and investments Improved market efficiency and in the long run liquidity Enhanced industrial competitiveness Greater choice in energy services

To generate its full potential, grid digitalisation necessitates a fundamental rethinking of how to regulate and manage the grid:

- Failing to adapt and continuing to evaluate tomorrow's grid with yesterday's regulations and performance considerations will inevitably sideline crucial innovations vital for the energy transition.
- Failing to adopt new approaches will deny stakeholders the full benefits of grid digitalisation, including enhanced sustainability, improved resilience, and greater affordability.

Locations

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