ENTSO-E Vision

A Power System for a Carbon Neutral Europe

10 October 2022

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The 39 member TSOs, representing 35 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E **brings together the unique expertise of TSOs for the benefit of European citizens** by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the **security of the interconnected power system in all time frames at pan-European level** and the **optimal functioning and development of the European interconnected electricity markets**, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first **climate-neutral continent by 2050** by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires **sector integration** and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources.

ENTSO-E acts to ensure that this energy system **keeps consumers at its centre** and is operated and developed with **climate objectives** and **social welfare** in mind.

ENTSO-E is committed to use its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in **solidarity** as a community of TSOs united by a shared **responsibility.**

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by **optimising social welfare** in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and **innovative responses to prepare for the future** and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with **transparency** and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its legally mandated tasks, ENTSO-E's key responsibilities include the following:

- Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;
- Assessment of the adequacy of the system in different timeframes;
- Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);
- Coordination of research, development and innovation activities of TSOs;
- Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the **implementation and monitoring** of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

Executive Summary

This document presents a comprehensive Vision, developed by ENTSO-E, of what is necessary to achieve a power system fit for a Carbon Neutral Europe. It builds on our previous ENTSO-E Vision 2030, on the long term Ten-Year Network Development Plan (TYNDP) scenarios, and on our Research, Development and Innovation (R&D&I) Roadmap. It also includes the shared knowledge amongst Transmission System Operators (TSOs) on trends, scenarios, challenges, technology and innovation.

In a fully carbon-neutral economy, electricity will be the main and most efficient energy carrier, and it will need to be coupled with other energy sectors. The power system of the future will be based on three key elements, all essential for a sustainable, resilient and affordable power system:

- **Carbon neutral energy sources**, providing the bulk of the power generation, which for the most part will be weather-dependent.
- **System flexibility resources**, to efficiently complement the variability of generation and consumption, and to address the increase in overall system complexity.
- The **power grid**, connecting generators, consumers and flexibility resources across Europe, and enabling a fully integrated European Energy Market.

This future power system in Europe will be:

- A **System of Systems**, which will need strong cooperation between transmission and distribution, and amongst different energy systems. All operators will be key enablers and facilitators to make this future energy system work.
- At the same time more **European** and more **Local**, with TSOs providing a critical interface between both dimensions.

In this Vision we show that a power system for a Carbon Neutral Europe is within our reach, but four key elements will need to change to make this reality possible:

- The development of significant system **flexibilities**, both short and long duration, that will need to be timed with the future system needs and the gradual phase-out of fossil fuel generation.
- An **operation** of the system that will rise up to the challenge of this much more dynamic System of Systems, including the management of a wide portfolio of flexibilities, through innovation and cooperation.
- A regulatory framework, plus planning and permitting procedures that will facilitate the timely deployment of the necessary **investments**, and encourage efficiency and innovation.
- A **market design** as a key enabler, that must evolve to allocate value where and when it will be most needed for the energy system, while reflecting different consumers' needs and preferences.

The scale of change is such that **we need to act now**. To transform this vision into reality as soon as possible, a strong cooperation across the whole energy industry, and a permanent dialogue with consumers, stakeholders and public authorities at European, national and local level, will be needed.

TSOs, through ENTSO-E, propose this Vision as a basis to start building this future together.

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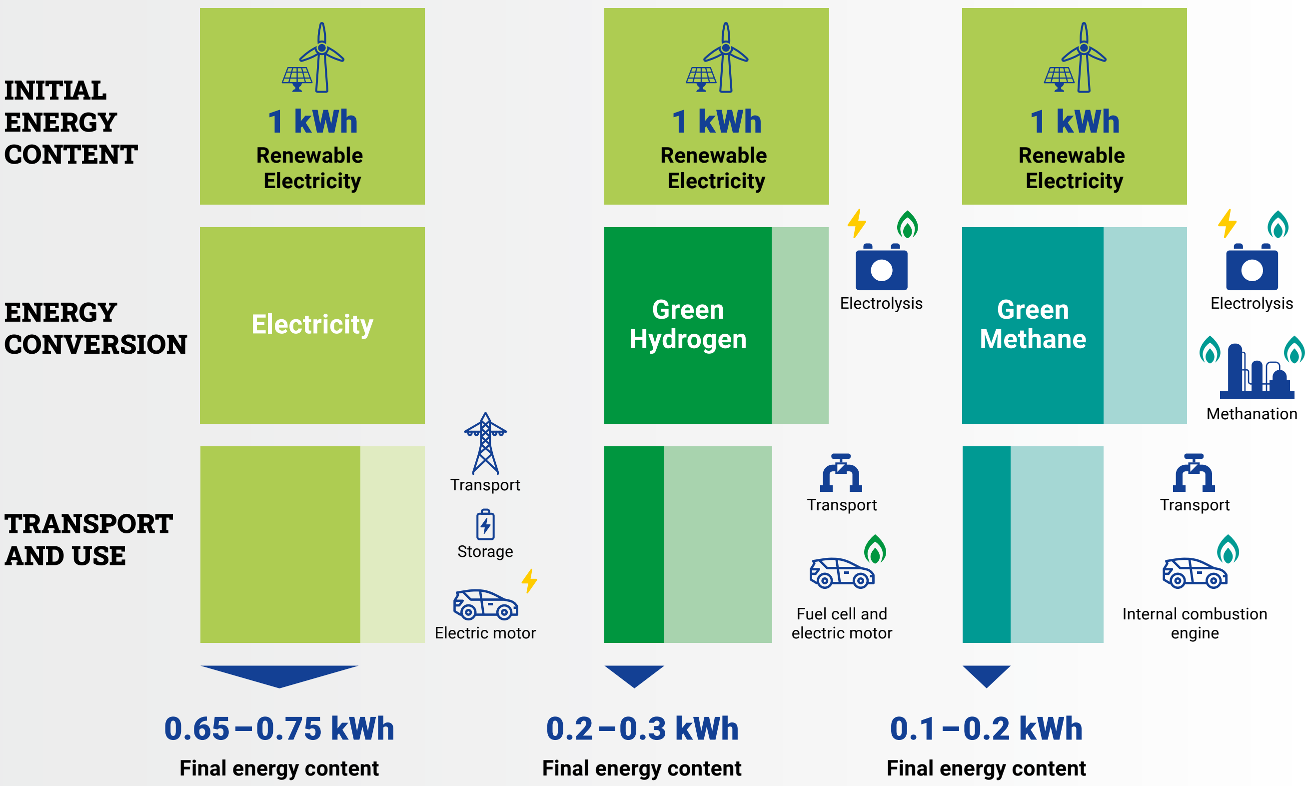
Introduction

The whole of Europe is today clearly committed to lead the global fight against climate change, and this has become the main long term driver for policy and legislation on energy. The EU and European countries today have a clear common objective for a fully carbon-neutral economy, by 2050 at the latest.

This objective implies a unique transformation of the European energy system, underpinned by a challenging geopolitical context. The Russian invasion of Ukraine further highlights the need for Europe to accelerate the energy transition, not only to fight climate change but also to become independent from fossil fuels as soon as possible.

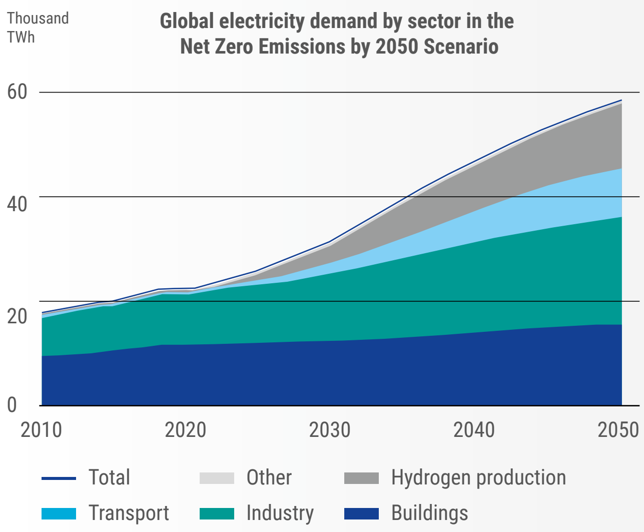
The goal of this document is to present a comprehensive Vision of what would be necessary to achieve a power system for a Carbon Neutral Europe. This Vision builds on the findings of the ENTSO-E Vision 2030, on the Ten-Year Network Development Plan (TYNDP) scenarios and on the ENTSO-E Research, Development and Innovation (R&D&I) Roadmap. It also includes the shared knowledge amongst Transmission System Operators (TSOs) on trends, scenarios, challenges, technology, and innovation.

One of the key assumptions for the future is that in a fully carbon neutral economy, **electricity will become the dominant energy carrier**, as suggested by all European and international long-term future energy scenarios. Electricity will play a central role in the achievement of a carbon neutral energy system, because of the higher efficiency of electrical end uses versus synthetic green fuels, and because of the maturity of renewable electricity generation technologies. Electricity is the most versatile and efficient energy carrier, which can be converted into usable power for an unlimited number of applications.

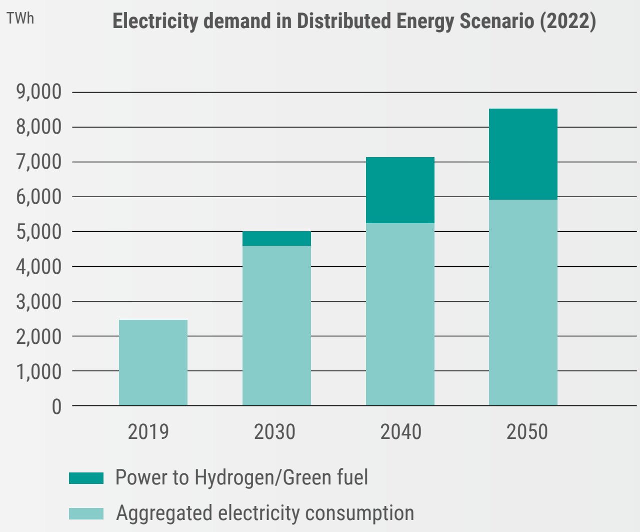


Comparison of efficiency of energy uses – the example of transportation

From this 'efficiency first' principle, it follows that a carbon neutral economy will be a much more electrified economy, and this is clearly shown in all forecasts that have been published recently on the paths to 'net-zero':



International Energy Agency model for Net Zero

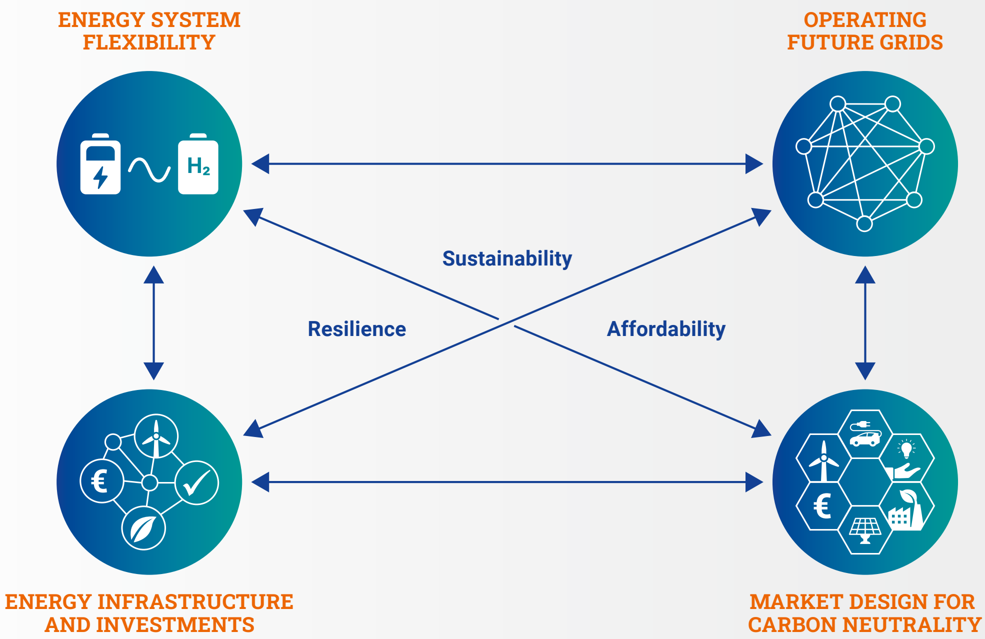


Electricity demand in ENTSO-E countries

This Vision is structured around four main 'building blocks', that are the key components necessary to build a power system fit for a carbon neutral Europe:

- **Energy System Flexibility** – facilitating the development of adequate flexibility resources to handle the increased complexity of the system and to balance what will become a weather-dependent system;
- **Operation of future grids** – preparing and organising the operation of a carbon-neutral energy system that will be very different from today;
- **Energy infrastructure and investments** – accelerating the development and financing of the future system;
- **Market Design** – identifying principles and possible solutions for a new market design fit for a carbon neutral economy.

In addition to these building blocks, this Vision also addresses three fundamental challenges that will be crucial to reach a carbon-neutral energy system: Resilience, Sustainability, and Affordability.



Vision Building Blocks and Transversal Challenges

Energy System Flexibility

A fully carbon neutral energy system, based on electrified consumption and on renewable electricity generation sources (mostly wind and sun), **will become highly weather-dependent**. To manage the resulting complexity and volatility of both generation and demand, while continuing to keep the power system within acceptable levels of adequacy and resilience, a significant amount of flexibility will be required.

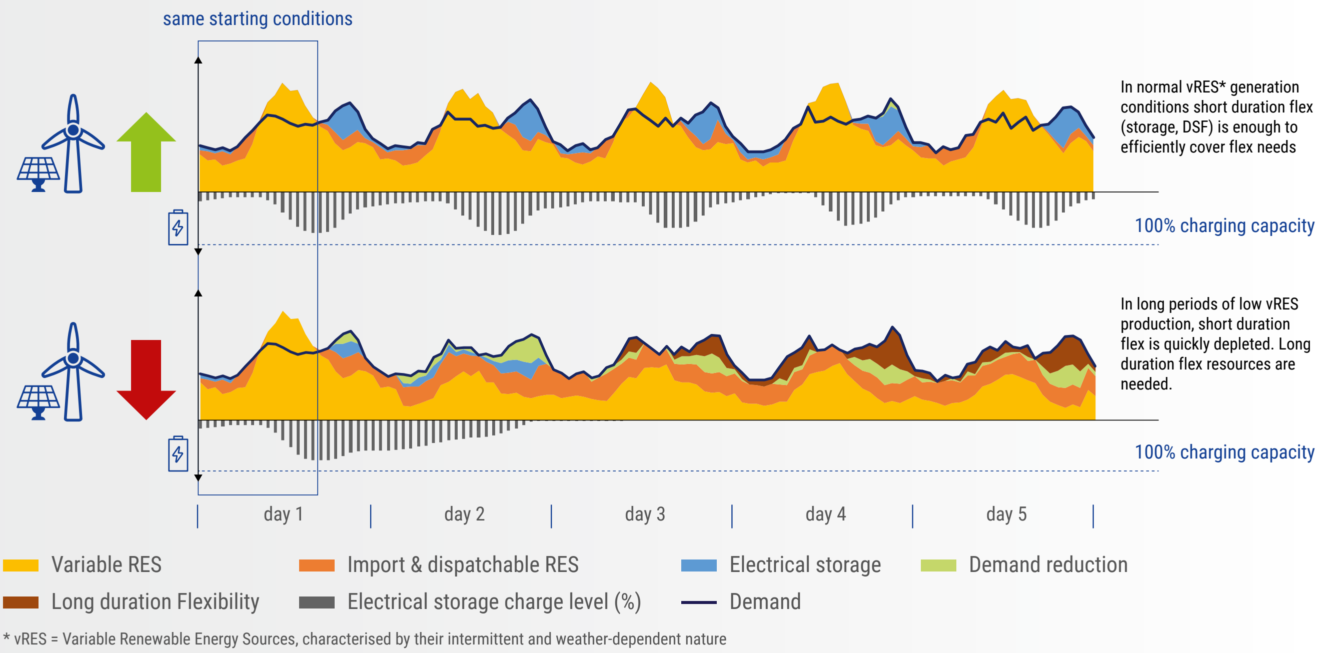
Flexibility refers to the ability of the power system to cope with variability and uncertainty in demand, generation and grid availability.

Going towards carbon neutrality, the nature and volume of flexibility needs and the portfolio of flexibility resources will evolve. The power system will progressively stop relying on the fossil fuel dispatchable generation that provides a significant part of the flexibility and ancillary services today. The timely deployment of multiple resources of carbon neutral flexibility will be needed, including flexible generation, active demand, storage, sector integration and flexible grid use.

From a system point of view, flexibility needs can be structured under two main types, each requiring different flexibility resources:

- **short duration flexibilities** (from milliseconds up to a few hours, to balance the system within the day and ensure system stability),
- **long duration flexibilities** (up to several weeks, to compensate for long periods with shortage of wind, solar and hydro generation).

The need for both kinds of flexibility resources can be explained with the graphic below: short duration flexibility resources are efficient and can provide significant amounts of **power**, but do not have enough **energy** stored to last several days, and will have to be complemented by high energy-density resources.



Use of short-duration and long-duration flexibility resources in different grid conditions

In this context the **electricity network** will play a key role in enabling the exchange of both energy and flexibility resources within the full European "System of Systems", thus reducing the overall amount of flexibility requirements to be covered.

The most suitable flexibility resources to cover a specific need will compete mostly based on market-based mechanisms to provide the related services. The figure below gives a qualitative indication of such suitability, also indicating the current most promising sources for wider diffusion in the coming years and those whose diffusion will be most likely dependent on future technological improvements or only partially contributing to covering a certain need.

- Demand Side resources and electrical storage in particular have good potential to become significant providers of carbon neutral **short duration flexibility**. This include for instance active consumers (where the demand adapts to the generation) and vehicle-to-grid solutions, for which cooperation between TSOs and DSOs will be essential to unlock their potential.
- There are very few potential sources of large-scale carbon-neutral **long duration flexibility**, beyond dispatchable hydro electrical power generation for which further large-scale development would be difficult in most of Europe.

The most promising solution could be hydrogen – produced from carbon neutral generation, stored, and subsequently used for power generation when the system requires it. Other alternatives could emerge assuming that further technological progress is made to decrease their cost and improve their capacity to store energy.

It is likely that the evolution of flexibility resources and needs will differ significantly across Europe, based on geography, local characteristics and policies. In particular, a number of European countries foresee also nuclear power generation as a non-renewable but carbon-free source of energy, and its inclusion in the mix will partially decrease the need for flexibility.

To enable a secure transition towards carbon neutrality **the deployment of both short and long duration flexibility resources will need to be coordinated with the integration of weather-dependent renewable generation sources and the phase-out of fossil-fuel generation**. These resources will be located at transmission and distribution, onshore and offshore, and in other energy sectors. The future energy landscape in Europe will clearly be a **System of** interdependent **Systems**.

	Source \ Need	Periods of vRES shortage	Balancing/ congestion management	Stability/ inertia	Voltage control	Reliability/ restoration
Generation	Fossil thermal generation	↓	↓	↓	↓	↓
Generation	Hydrogen power generation	●				○
Generation	Dispatchable RES (hydro, bio)	●	○	○	○	●
Generation	Variable generation		●	●	●	○
Demand	Smart charging EVs/small DSR	○	●	●	○	○
Demand	Large DSR	○	●	●	○	●
Storage	Chemical batteries/V2G		●	●	●	●
Storage	Supercapacitators			○		
Storage	Hydro pumping storage	○	●	●	●	●
Storage	Flywheels			○		
Storage	LAES/CAES, thermal storage	○	○	○		
Coupling	Power-to-hydrogen		●	○	○	
Coupling	Power-to-heat		○	○		
Grid	Interconnections (incl. HVDC & conversion stations)	●	●	○	●	○
Grid	Grid flexibilities (power flow, voltage control)		●	●	●	●

↓ Phase-out by 2050 ● Most promising ○ Contributing

Qualitative analysis of flexibility sources potential with respect to current use

Operating Future Grids

New approaches are needed to fulfil the overarching goal of a **secure and efficient power system operation** for the whole of Europe, and TSOs will need to change and go beyond the boundaries of today's core activities. The main drivers for this expansion in scope are the ever increasing share of distributed energy resources, weather dependency of both generation and demand, sector integration through flexibilities, transmission and distribution coordination, and changes in the energy market design to cope with these challenges across the future energy System of Systems.

TSOs and DSOs will need to accelerate the uptake of new and emerging technologies available to control the grid in a secure and efficient way, to cope with the characteristics of the future power system.

Significant weather dependency will have a strong impact on the operation of the system. This calls for a more integrated approach where demand will need to become increasingly more capable of adapting to changes in generation to ensure a continuous balance in supply and demand. A variety of flexibility sources will be needed to maintain an acceptable level of security and resilience. The needs identified by TSOs and DSOs will be translated into services and market-based mechanisms, developed to provide the related flexibility services for planning and managing the system.

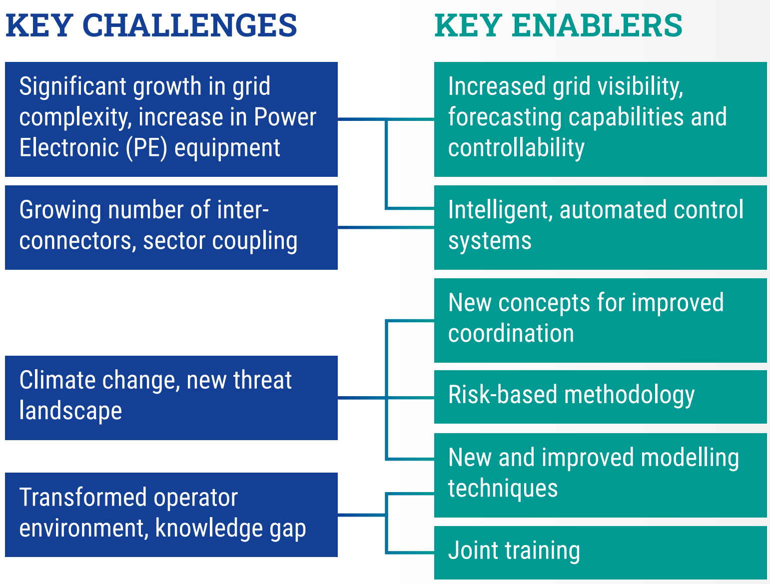
The following key challenges will need to be addressed, and key enablers developed to make this new reality possible:

- For TSOs to operate the **unprecedented growth in grid complexity** and maximise the use of the grid capacity, there is a need to have significantly enhanced granular, real-time visibility on the system state and on flexibility sources, including **enhanced forecasting capabilities and controllability**.
- System characteristics (e.g. the level of inertia and short-circuit current) will have changed dramatically and dynamic stability issues (e.g. voltage and frequency stability and oscillation damping) will become as common and important as congestion management today. This will require a new approach where **automation** will act as the extended arm of human TSO operators to cope with extreme dynamics and grid complexity.
- **Automation and artificial intelligence** will be applied extensively to enhance system resilience by providing a new, protective layer to the grid, serving as an extension of the initial grid response, creating room for decision making for the human TSO operator. The decision-making will be helped by intelligent decision support tools that explore all options available in a particular situation.
- The full potential of Direct Current **(DC) interconnectors and power electronic equipment** will be required to support the integration of Renewable Energy Sources (RES) via grid forming capabilities to fully utilise the advanced controllability of power electronics and load flow.
- The future European energy system will be even more reliant on the power system, and therefore more exposed to its increasing risks and threats. To tackle the new threat landscape, an **improved design for resilience** will require new **risk-based methodologies**, multi-sector awareness, training and higher **cyber security** preparedness, all linked to the increase in automation and digitalisation of the grid.

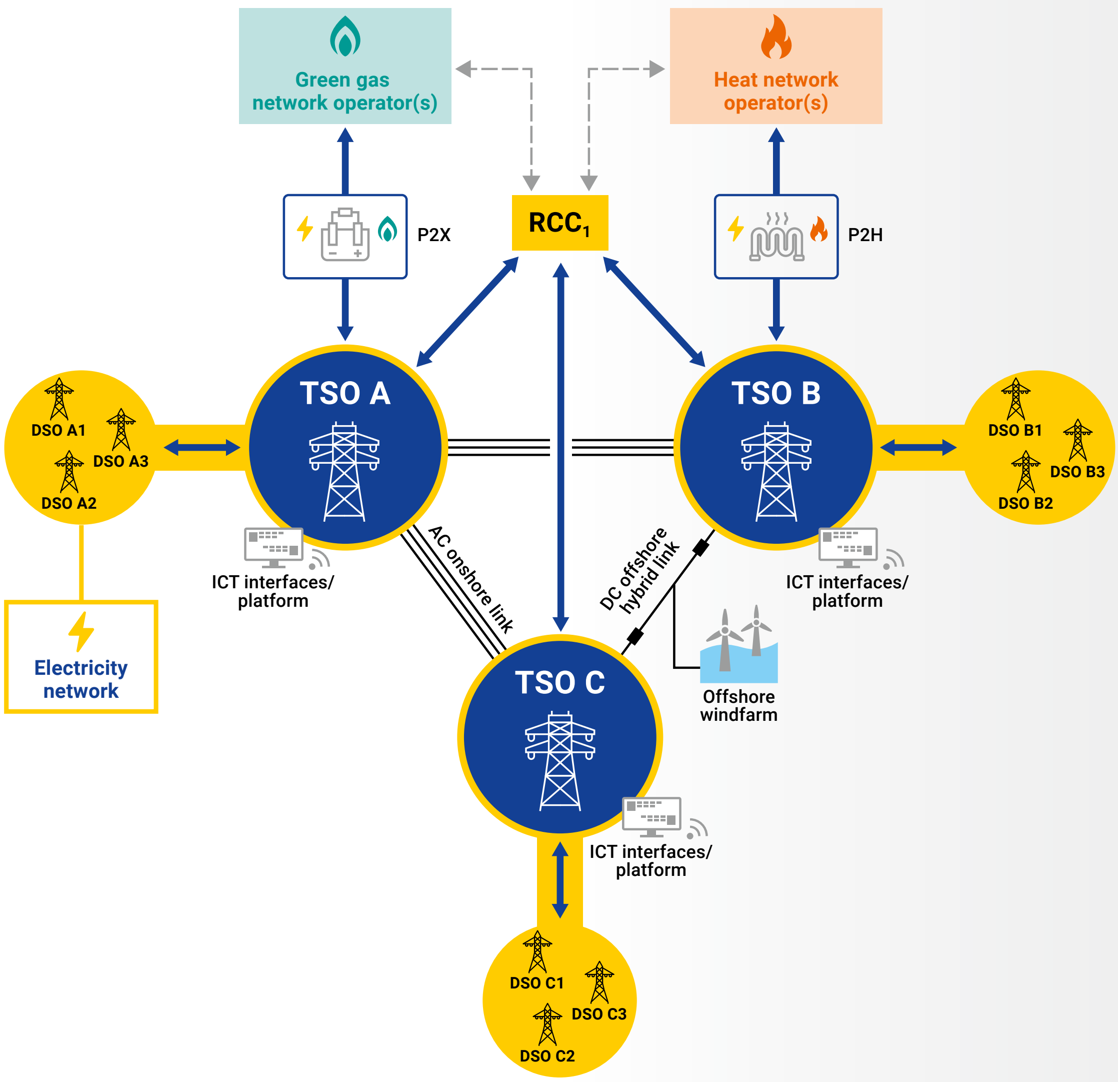
The integration of wide scale flexibilities, coming from transmission (nationally and cross-border), distribution and other energy sectors, will result in a **new concept for coordination** of all operators and actors involved, within a true 'System of Systems'. Resources and networks will need to be operated in compliance with all individual systems needs and aligned with the principles of efficiency and security.

The operation of the future transmission grid will be done in close cooperation:

- amongst TSOs at European and Regional level, assisted by Regional Coordination Centers (RCC);
- with DSOs inside each control zone;
- with other energy sectors integrated with the power system such as Hydrogen.



Key challenges and enablers to operate the future System of Systems



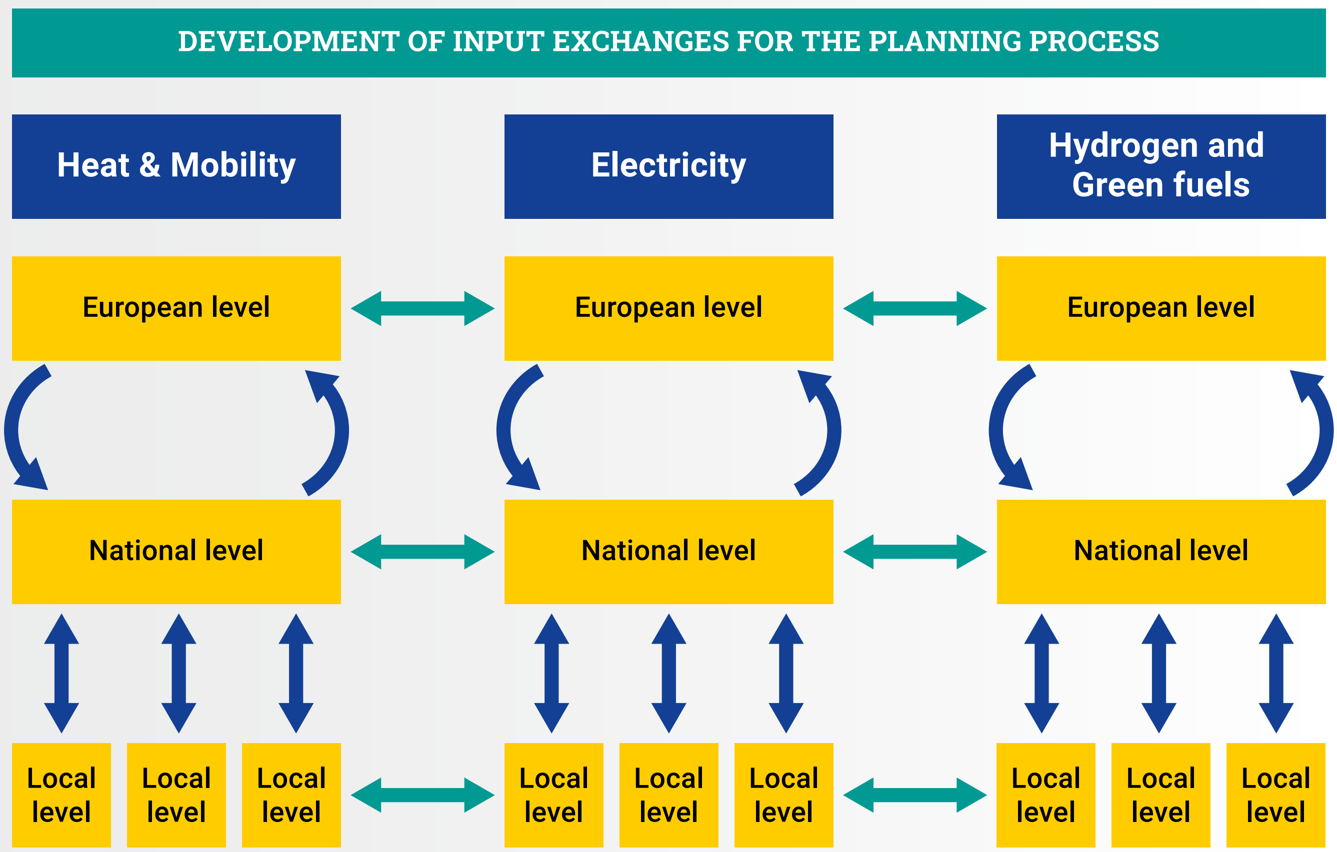
The system of systems across transmission, distribution and other energy sectors

Energy Infrastructure and Investments

The previous section has shown that the future power system will be operated using all technological and organisational advances available, in cooperation with other parts of the System of Systems. But even if used to their utmost limits, the energy transition will still require very significant investments in infrastructure, including generation, flexibility resources, and the grids that will connect them. Investments in **the power grids**, and in particular at transmission level, **will be key to achieve the energy transition** in a timely, secure and reliable way.

Integrated planning processes to achieve a true System of Systems

A decarbonised energy system is a horizontally and vertically integrated system. The **planning processes** for new energy infrastructure will need an **integrated** approach for onshore and offshore, across sectors (horizontal integration) and geographical dimensions (vertical integration). The inputs and outputs of the planning exercises will be increasingly exchanged both horizontally and vertically. **A true System of Systems:**



The transmission system will evolve both onshore and offshore

In a fully carbon neutral Europe, the electricity transmission grid will be the **backbone** of the future energy system. As the European regions will have different characteristics in terms of renewable generation and load patterns, the European transmission system will be necessary to **integrate regional energy systems**. The capability of the transmission grid to add flexibility to level out the differences between these systems across interconnections will facilitate **balance in the face of situations of regional surplus and deficits**.

The development of the **offshore grids**, through a combination of sub-marine transmission infrastructure, radial connections, and multi-purpose solutions, will bring a key contribution to reaching the objectives of the European energy transition to carbon neutrality. To this aim, massive investments must be made to facilitate the integration of offshore wind power generation as well as offshore and onshore transmission infrastructure. In most cases the distance between the demand centres and the RES generation clusters will require a new approach for the planning and design of the European transmission system, with connections evolving from transnational to trans-regional.

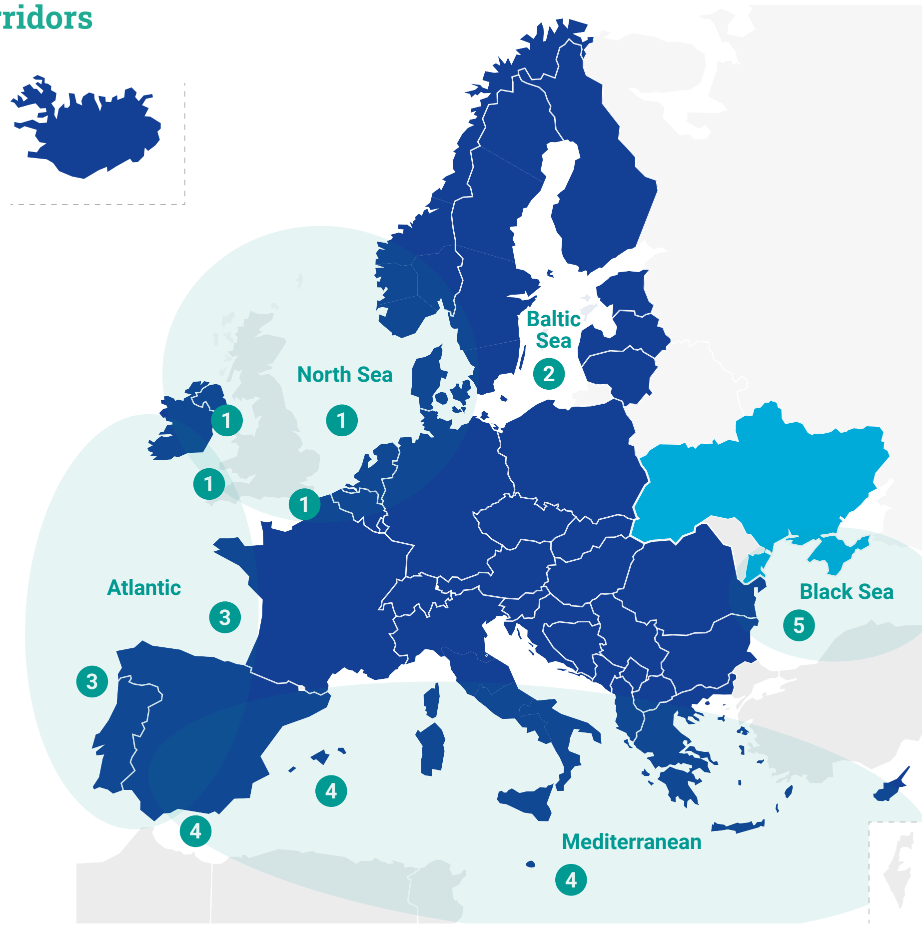
New investments will also be needed to ensure stability management along with new capabilities to be provided by grid users that should be adequately reflected in regulations and technical standards.

Priority Offshore Grid Corridors

1. Northern Sea Offshore Grid (NSOG)
2. Baltic Energy Market Interconnection Plan (BEMIP offshore)
3. Atlantic Offshore Grid
4. South and West Offshore Grid (SW OFFSHORE)
5. South and East Offshore Grid (SE OFFSHORE)

ENTSO-E Member

ENTSO-E Observer Member

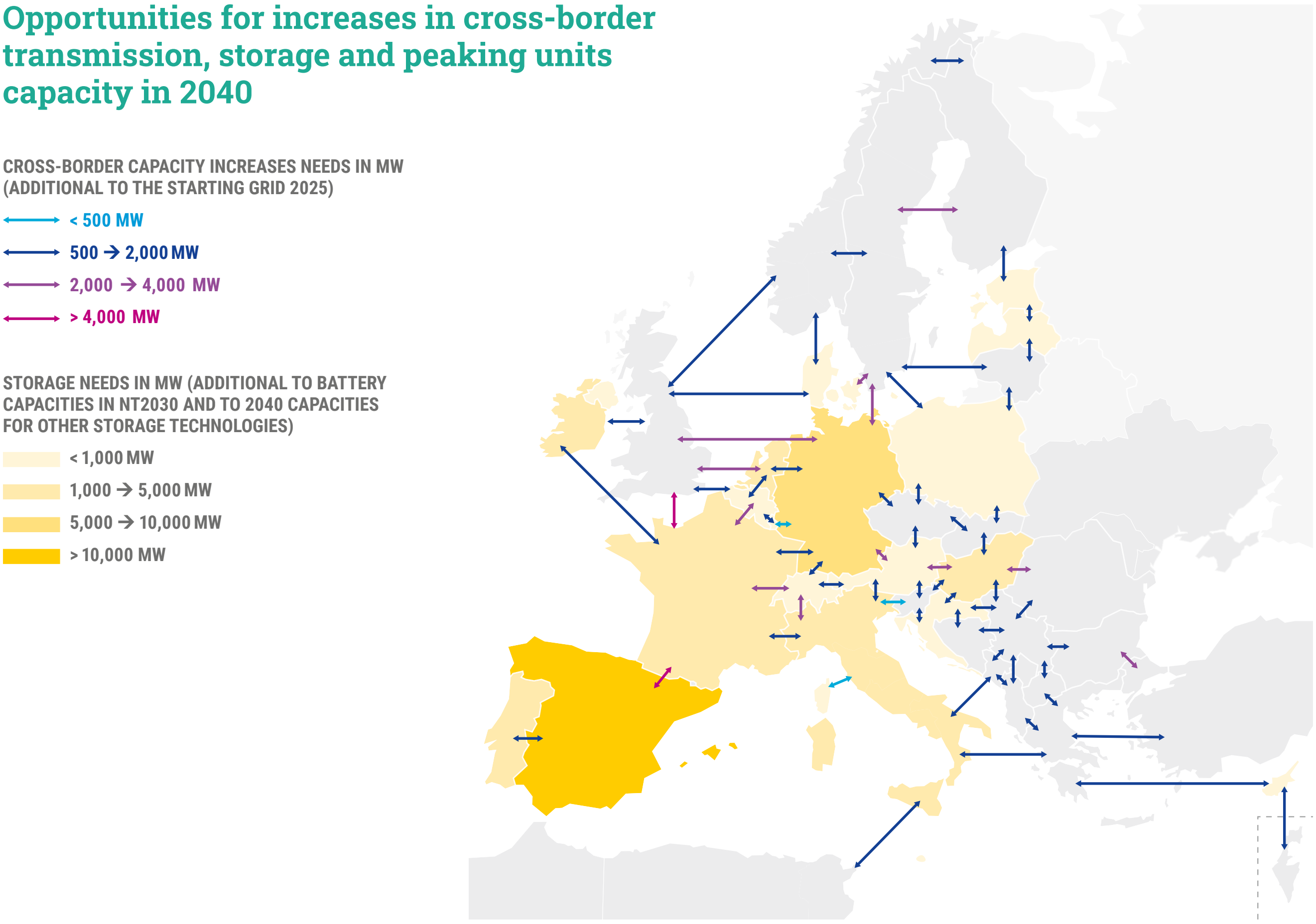


Improve regulatory framework and stakeholder engagement for timely development

The regulatory framework should further promote public acceptance and permitting and incentivise effective and timely infrastructure financing, development, and innovation. Simplifying and speeding up permitting processes will ensure the timely delivery of the right infrastructure, in the right location. The EU regulatory framework can support the concrete delivery of required infrastructure, by favouring a shortening of maximum authorisation times for both RES and grids. However it is also **necessary to have measures in place that guarantee adherence to the planned timelines** through solutions such as

- Introducing **maximum binding timelines** for issuing the authorisation, and instruments for **ensuring the implementation** of these maximum timelines.
- Promoting **the dialogue between the project promoter and the different authorities** involved in the permitting process, and among the authorities themselves, that would allow faster development of the needed infrastructure.
- Introducing the **silent consent provision**, i.e. the implicit approval where the competent authorities involved in the permitting procedure do not raise issues within the given timelines;
- Introducing **simplified environmental assessment procedures** for renewal of projects and modernisation or technological upgrade of pre-existing assets (for instance new kinds of conductors and cables).

Opportunities for increases in cross-border transmission, storage and peaking units capacity in 2040



Additional system needs in 2040 as per TYNDP 2022*

* System needs study: opportunities for a more efficient European power system in 2030 and 2040

Investments in the power system will increase the socio-economic welfare for all European citizens. As shown in the ENTSO-E Ten-Year Network Plan 2022, capacity increases of about 2 billion euros of investment per year by 2030 (64 GW of total cross border reinforcements), would deliver a yearly increase in socio-economic welfare of 5 billion euros. In the 2030-2040 timeframe this trend is confirmed, with a 6 billion euros/year investments (in cross-border capacity, storage and peaking units) producing a 9 billion euros/year increase in socio-economic welfare.

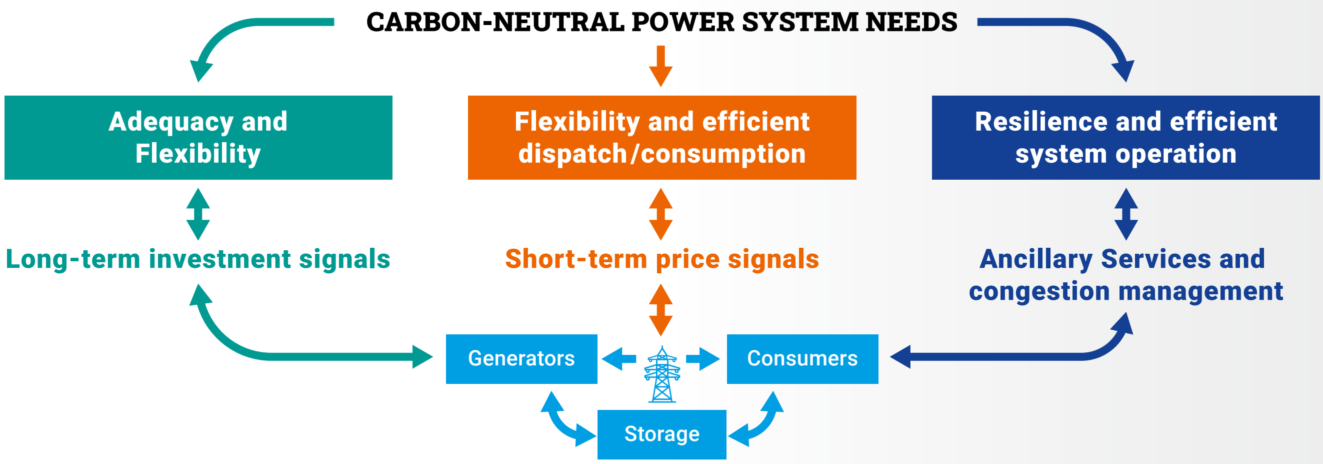
As the final beneficiaries of a timely evolution of the energy transition are the communities hosting the needed infrastructure, their support is critical. TSOs are ready to play their part by continuing enhancing the planning process in the direction of increased transparency and inclusiveness.

Market Design for a Carbon Neutral Power System

To accelerate the transition to carbon neutrality, electricity markets will need to efficiently facilitate the solutions identified in the previous chapters.

In particular, well-designed electricity markets will need to:

1. enable the necessary investments in renewables, flexibility resources, and grid development across the whole value chain via effective long-term signals;
2. incentivise efficient dispatch and consumption of resources, while stimulating flexibility of the whole energy System of Systems across time, space and sectors boundaries;
3. facilitate the operation of stable and reliable electricity grids by ensuring that any incentives for market parties are consistent with the physical network capabilities and overall system security requirements;
4. deliver sustainable and affordable power to consumers as well as a wide range of retail offers and engagement opportunities.



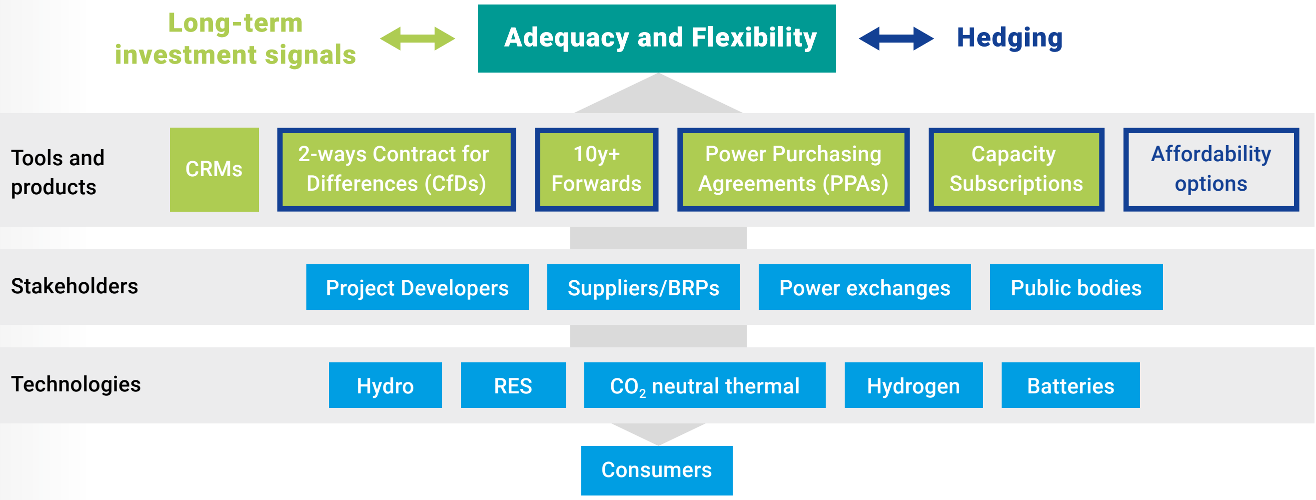
While the present market design has already brought substantial benefits for Europe, the challenges of a carbon free energy system can be met only if significant changes are completed in a timely manner. At the same time, it is also of crucial importance to continue operating in a stable, transparent and forward-looking regulatory framework, so to increase investors' confidence.

Strengthening long-term signals to deliver investments in renewables, adequacy and flexibility

The key challenge for resource adequacy is to stimulate the necessary investments in renewables and complementary flexibility resources. Given the scale of the investment challenge and the need to radically transform the power system in a relatively short period of time, there is a need for stronger long term investment signals. Reduced uncertainty on future revenue streams will reduce capital costs which are essential for capex-intensive investments in flexibility resources and carbon-neutral generation technologies. For this purpose, the regulatory framework should facilitate markets to develop liquid long term hedging products and increase the access to long-term bilateral contracts such as Power Purchase Agreements (PPAs). As these types of contracts are currently not liquid enough or accessible to all parties, introducing market making requirements or forms of public guarantees are potential solutions to be considered to facilitate their use. Hedging instruments are essential not only for generators but also for consumers to limit their risk exposure. Alongside PPAs, Affordability Options – where public authorities enter into long term contracts on behalf of certain groups of consumers – can protect against long-lasting extreme prices while providing revenue stability for generators.

Renewables support mechanisms, where necessary, need to be driven by cost-effectiveness and allow for efficient integration of the supported units in the wholesale and ancillary services markets. Two-way Contract for Differences (CfDs) can also be an effective instrument to limit generator revenues in times of high prices, but need to be carefully designed – for instance by remunerating availability rather than output.

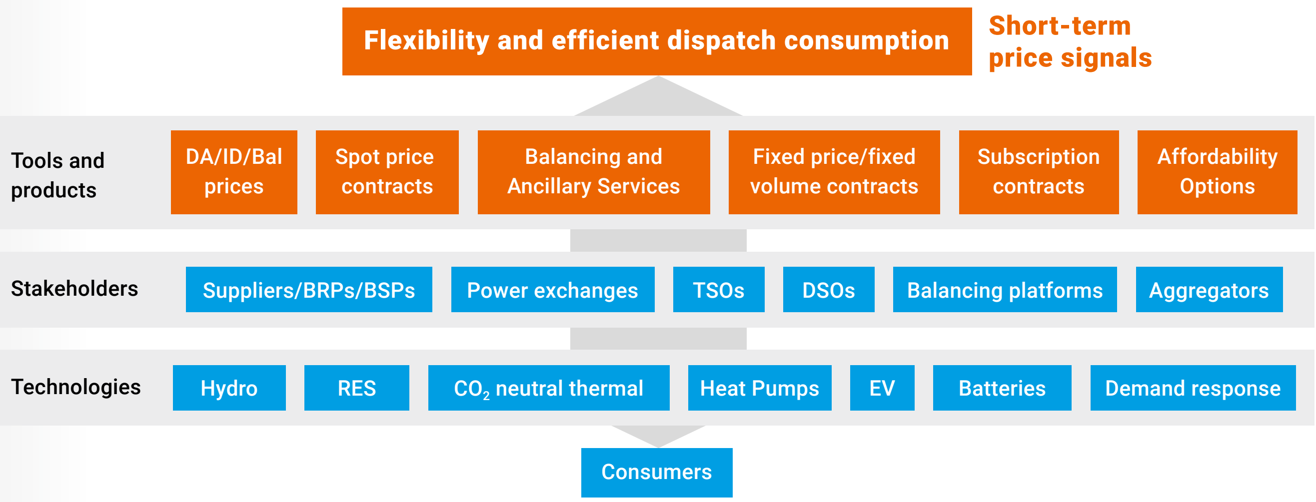
Electricity markets need to **value capacity** – and its contribution to resource adequacy – much more than today. A system dominated by weather dependent generation without large scale long-duration flexibility will inevitably be exposed to periods where these resources are insufficient to cover demand. Therefore, some form of additional **capacity remuneration mechanisms** to ensure timely investments in back-up and/or dispatchable generation are likely to be a key feature of many European markets. Finally, in the future it should become possible to define resource adequacy levels in a more sophisticated and customised manner for more flexible consumers capable and willing to reduce their consumption during scarcity situations, e.g. by introducing Capacity Subscription as further discussed below.



Optimise short-term markets to enhance flexibility in the future System of Systems

To increase short duration flexibility of the energy system, day-ahead, intraday and balancing price signals will be essential to ensure an efficient dispatch of generation and consumption, optimising the integrated energy System of Systems. To match the needs of the future mix of flexibility resources, short-term markets will need to progressively operate closer to real time, adopt shorter settlement periods, remove barriers to market entry and value stacking.

Electricity markets should be designed in close cooperation with all actors of the future energy System of Systems. The goal is to ensure **seamless market interfaces and system optimisation between transmission & distribution and across sectors**. Sector coupling technologies, like electrolysis, heat pumps and electric vehicles, will **foster a more integrated energy system with the electricity sector in the centre**. Efficient price signals will be essential to enable an optimal development of such a system as a whole, optimising the use of all energy resources across space and time. Potential distortions deriving from taxes and levies need to be minimised to ensure a level playing field between energy carriers, taking into account overall energy system costs and environmental externalities. Moreover, the market design should ensure an **efficient access to decentralised energy and flexibility sources** (including demand response) to be used where and when it is most beneficial.

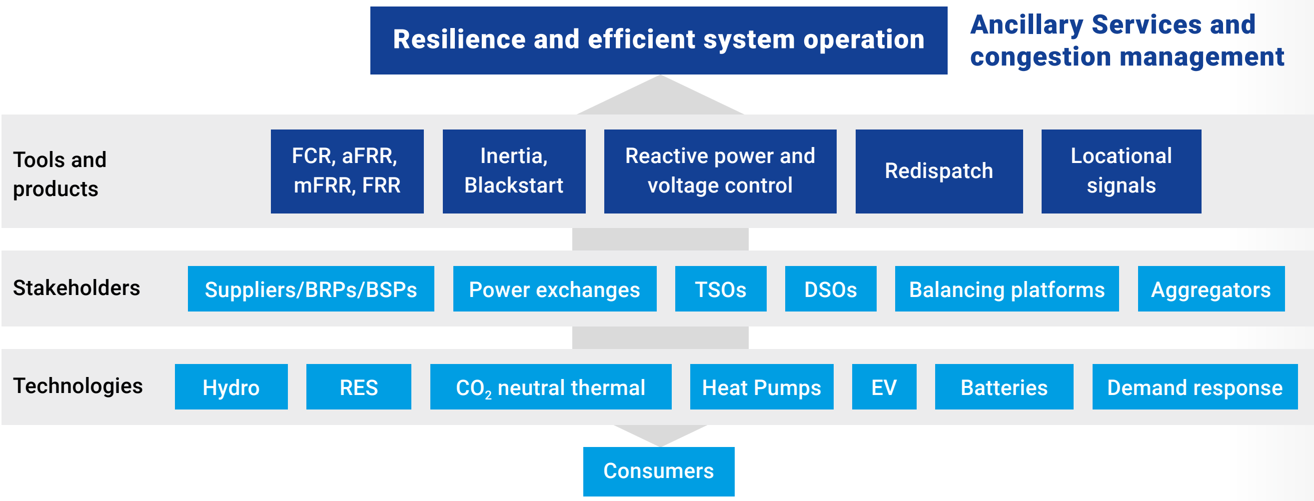


Better reflect operational challenges to facilitate efficient use of infrastructure and secure system operation.

To ensure **system resilience and efficient use of infrastructure**, market design needs to properly reflect grid constraints and operational challenges in a highly complex and heterogeneous System of Systems. This can be achieved via requirements, price signals and products, including new ancillary services, new congestion management approaches coordinated with DSOs, and new grid tariff structures.

Firstly, TSOs need to identify, define, quantify and communicate **long-term system needs** to guide market design evolutions and stimulate technology and business innovation.

Secondly, the electricity market design must be able to **better reflect the physical reality of the grid**. Optimal use of infrastructure limits the costs of RES curtailments and congestion management which are rising in many countries and are ultimately borne by consumers. There are several options of increasing locational price signals within the design of wholesale markets from optimal bidding zones reconfiguration, encompass dispatch hubs [1], or nodal market design (where applicable). The most efficient solution will depend on future scenarios (e.g. pace of grid infrastructure development) and on regional / national specificities. As such, different solutions may be applied across the EU while ensuring the preservation of market integration. To optimise siting of assets, locational signals may also be introduced via specific components in support schemes or capacity mechanisms. The increasing operational challenges and the rapidly changing market actors also require new products for both balancing and non-frequency ancillary services, to support for example, voltage control, inertia and fast frequency response. Close coordination with DSOs will be necessary in order to properly carry out **efficient congestion management mechanisms**. Lastly, it could be useful to assess how **grid tariffs structures** can better reflect individual grid users contributions to system costs and to operational security.



Complement price signals for efficient demand with targeted support to ensure affordability

Any future market design should not only facilitate the achievement of policy goals and support system needs, but also be in line with consumers' needs. The identification of different preferences, promotion of new opportunities and freedom of choice will become even more important in the future. At the same time, affordability, simplicity and transparency must remain top priorities. The design of future markets will need to reflect the different values that consumers associate with their electricity, in terms of reliable capacity, flexibility, carbon footprint, vicinity of production, degree of self-sufficiency, trading possibilities. Energy communities will also become a solution to utilise local resources optimally while enhancing local engagement in the energy transition.

The recent **sharp increase of average wholesale electricity prices**, requires targeted policy measures to ensure energy affordability and consumer protection. Such measures should nevertheless ensure that efficient price signals for flexibility, demand response, and energy savings are not undermined. Direct consumer support measures can be complemented by several retail pricing solutions to mitigate consumers' risks and costs increases such as fixed price contracts with fixed volumes or **affordability options.** Another interesting option is **capacity subscriptions**, which could facilitate smart load modulation during system scarcity, remunerating consumers that prefer this option, reducing overall system costs to ensure adequacy, and establishing a price for capacity based on individual consumers' preferences.

In the longer run, the best way to reduce the impact of high fuel prices on consumers' bills is to accelerate the development towards a power system with **full carbon neutral generation and complementary flexibility**, with significantly higher energy efficiency and optimised price signals.

1 For a detailed description of dispatch hubs see Options for the Design of European Electricity Markets in 2030, ENTSO-E, 2021

Transversal Challenges

The four 'Building Blocks' describe the key components necessary to build a power system fit for a carbon neutral Europe. In addition, there are three main transversal challenges that need to be addressed for this future System of Systems: Resilience, Affordability and Sustainability.

Resilience

Power system resilience is the ability to withstand and mitigate the extent, severity and duration of system degradation following an impactful event. Transitioning from a system based on dispatchable generation towards a system based on mostly weather-dependent generation, should structurally decrease the resilience of the whole system. In addition, ensuring power system resilience will be more challenging due to more frequent and extreme climate events, geopolitical uncertainties, and increased cyber-security risks.

However, a number of solutions can be developed, as previously outlined in our 'Building Blocks', contributing to maintain a high-level of resilience of the system:

1. Resilience through **flexibilities**: all the sources of system flexibility shown in this report will improve the resilience in different time scales and they should be able to compensate for the loss of dispatchable power plants.
2. Resilience through the **operation** of the future grids: the interoperability and increased interconnection with distribution and other energy sectors will allow the sharing and activation of resources through the whole System of Systems. Moreover, increased cross-sector observability and awareness will provide better threat and risk assessments, also taking into account the advances in information technologies and automation.
3. Resilience through **infrastructure and investments**: the evolution of planning methodologies allows for a more accurate resilience assessment and cost-benefit analysis, for all future investments in generation, grid and flexibilities.
4. Resilience through **market design**: when the market rules are designed to allocate value to what and when will be most needed, resilience could be factored in to give incentives to market actors that increase the resilience and robustness of the system.

These combined solutions should be able to provide an adequate level of resilience for the future system.

Affordability

Energy prices for final consumers are of fundamental importance for competitiveness and fairness of the European economy, and a key question for this work is if the future energy system will be more or less expensive for the European society.

It is clear that there are factors of the future system that could increase the costs for society. Mainly the **weather dependency of most generation sources** will require significant infrastructure investments in generation, grids and accompanying flexibility sources.

At the same time, the **ultimate independence from fossil fuels** should be a structural factor driving down the overall cost of the whole system. In addition, the most promising factors to reduce energy costs will be increased **energy efficiency, standardisation, harmonisation** and **coordination**, and of course **innovation**.

The measures and developments proposed in this Vision will pave a cost-efficient way to a carbon-neutral energy system in the Europe. At the same time, we recognise that the transition may be challenging and include periods with prices that are higher than desirable.

Sustainability

Sustainability is one of the fundamental driving forces of the energy system transformation. First and foremost to achieve carbon-neutrality, but also to promote all other environmental dimensions necessary to preserve natural resources for future generations.

Some **intrinsic aspects** of the transition to a carbon neutral economy (such as the increase in use of land and sea, extraction of raw materials) may actually **challenge sustainability** – and thus need to be properly addressed and mitigated. Other aspects can be considered as **risks to sustainability** (development of biofuels, or misaligned development of market design and energy infrastructure); these should be **avoided or at least minimised**.

On the other hand, we believe that in implementing the transition to a carbon neutral economy we have at our disposal many **solutions and tools to improve the sustainability** of the energy system and of our society as a whole. These include accelerating the electrification of the economy, increasing energy efficiency, introducing recycling and circular economy requirements, including nature-inclusive design principles in infrastructure projects, and incorporating environment externalities in market design and procurement strategies.

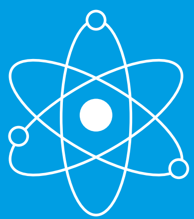
Potential Game Changers

On the way to reach a carbon neutral Europe, some pathways can be predicted and planned, and they are part of this Vision. However some others can only emerge later in time as a result of disruptive and highly impacting factors such as technology breakthroughs, geopolitical changes, environmental or socio-economic events, or natural resources availability. This is what we call “game changers”.

For a more comprehensive perspective of the System of Systems picture, ENTSO-E has analysed some potential technological and socio-economic game changers that could materialise and imply a change in the transition roadmap.

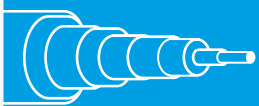
In principle, they can have positive, negative, or mixed consequences on the energy system as a whole. This means they can represent either an opportunity or a challenge for the roadmap. Following a comprehensive screening, eight potential factors have been prioritised and assessed.

Nuclear renaissance



Fusion reaching commercial viability or wide deployment of new generation Fission plants

Superconductivity

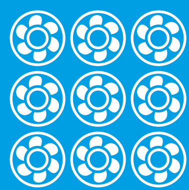


Technology becoming very widely applied for new lines

Hydrogen Uptake

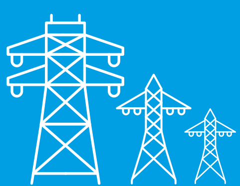
High present expectations materialise only partially

Carbon Capture & Storage



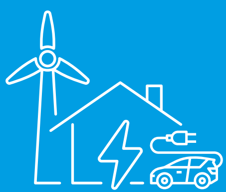
Achieving cheap & wide application to fossil plants

Supergrid



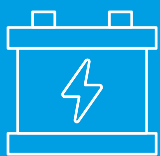
Deploying continental overlaying HVDC grid, including neighboring countries

Prosumers, Microgrids



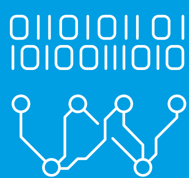
High uptake of local systems, complementing present top-down grid architecture

Cheap short & long storage



Becoming widespread in all use cases as prominent provider of flexibility

Deep digitalisation



Pervasive modifications of most devices, systems and processes

In terms of impact, probability and conditions for them to materialise, the more interesting are

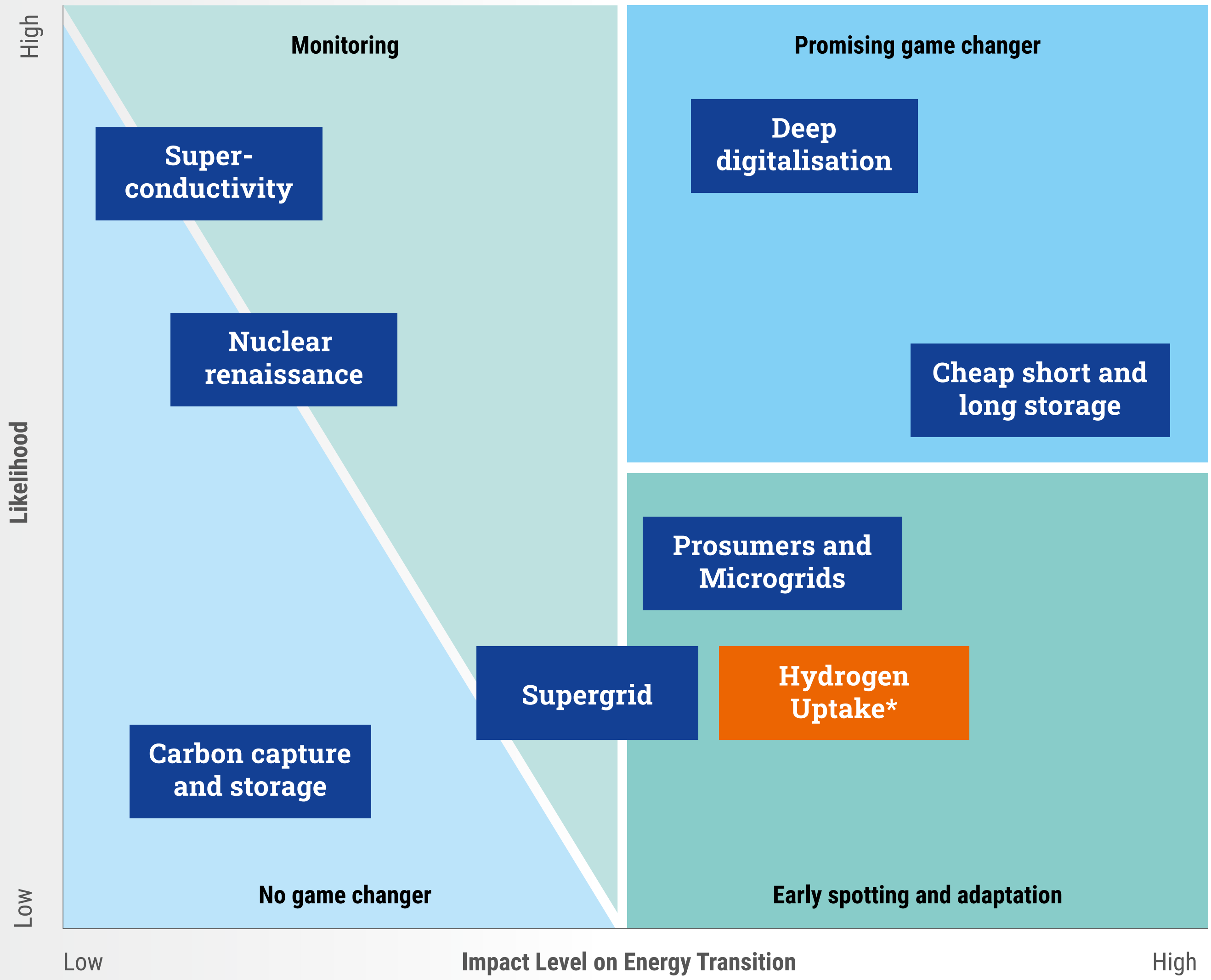
- **Deep Digitalisation**, already underway, but to an extent and impact not fully predictable for the long term.
- **Cheap Storage** applications for all use cases, following significant investments and R&D efforts, if achieved will reduce the relevance of other flexibility forms and speed up the transition.

Possible game changers to follow closely:

- **Prosumers and Microgrids** impacting market patterns, reducing grid flows, supporting grid operation and resilience through multi-level control philosophy.
- **Hydrogen uptake**, that will need to increase in order to provide the required long duration flexibilities.

Other game changers with less probability or impact can be:

- **Superconductivity** is subject to further developments and should find application in specific use cases but not changing fundamentally grid planning and operation.
- **Supergrid & Imports:** the concept could materialise for bulk exchanges with neighbouring countries if geopolitical conditions will allow it.
- **Nuclear fission,** reducing the need for long duration flexibility, will likely remain country-dependent and not a pan-European policy; **nuclear fusion** is still for the very long term.
- **Carbon Capture:** in the short term not mature / cost-effective technologies; in the long term not consistent with the phasing out of fossil industry processes.



* Slower uptake of Hydrogen in comparison with baseline scenario presented in Vision clusters

Recommendations

General recommendations

1. The future will be a **System of Systems**, which means that:
   - **TSOs, DSOs, and other energy sectors** should cooperate to make the most efficient use of all types of flexibility resources and coordinate the planning and operation of the different systems.
   - Energy markets should be designed to ensure seamless **market integration** between transmission and distribution and across sectors.
2. Within this System of Systems, an adequate level of **system resilience** should remain a priority for TSOs, other operators, policy makers and stakeholders.
3. All proposals and actions for the future system should take into consideration their impact on the **affordability** of the system for European consumers, as well as a **sustainability** assessment.
4. Given the scale and urgency of change, we all need to **act now** to make this future possible.

Specific recommendations

1. ENTSO-E will produce with relevant stakeholders a pan-European **assessment of flexibility needs** for the whole timespan of the energy transition, to guide a cost-efficient deployment of flexibility resources.
2. Appropriate market mechanisms should be developed to ensure that both short and long duration flexibility resources are **timely deployed and efficiently procured** where and when needed.
3. The **regulatory framework** should evolve to value innovation, facilitate financing and permit fast and clear authorization processes that are respectful of environmental requirements.
4. TSOs will further enhance the planning processes to increase **transparency** and **inclusiveness** for local communities and stakeholders.
5. TSOs, DSOs, manufacturers and research centres should further develop knowledge and tools to **optimise the operation** of the systems, including advanced modelling and decision support.
6. TSOs and relevant operators of the System of Systems should increase cooperation with standardisation bodies and IT vendors to create standard rules, protocols and digital platforms enabling **interoperability** and **cross sector overview**.
7. Strengthen **investment signals** for carbon-neutral energy and flexibility sources by facilitating the introduction of well-designed two-way Contract for Differences and where necessary capacity remuneration mechanisms.
8. Increase accuracy of **short-term price signals** of day-ahead, intraday and balancing markets in space and time to optimise dispatch, flexibility and grid use.
9. Develop retail pricing solutions that facilitate **consumers engagement** and demand response while ensuring affordability and consumer protection.
10. TSOs will increase cooperation with all other operators, manufacturers, academia and policy makers to accelerate the **innovations** that will be needed to achieve an efficient energy transition:
    - Especially in storage and digitalisation technologies.
    - While monitoring trends for early spotting of new game changers.

Abbreviations

AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
BRP	Balancing Responsible Party
CAES	Compressed Air Energy Storage
CCS	Carbon Capture & Storage
CfD	Contract for Differences
DC	Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operator
DSR	Demand Side Response
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
EU	European Union
EV	Electric Vehicle
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICT	Information and Communications Technology
LAES	Liquid Air Energy Storage
NGO	Non-Governmental Organisation
P2H	Power to Hydrogen
P2G	Power to Gas
P2P	Peer-to-Peer
PE	Power Electronic
PPA	Power Purchasing Agreement
PV	Photovoltaic
RCC	Regional Coordination Centre
RES	Renewable Energy Sources
R&D&I	Research, Development and Innovation
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
V2G	Vehicle to grid

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