Maximising the power of wind through grid flexibility

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1.

Executive summary

Clean energy transitions are gaining momentum in Europe and the power sector is at the forefront of these transitions. Electricity is only one quarter of the energy we consume in Europe today. The EU wants to change that, aiming to increase the share of electricity in the energy mix to 75% by 2050: with 57% of energy consumption being powered directly by electricity; and another 18% coming from green hydrogen and its derivatives[1]. Electricity will be the backbone of Europe's future energy system with other clean energy sources supplementing the energy transition effort.

This means that by 2050 we will need around four times the power generation capacity and we will need to transfer up to three times as much electrical energy compared to 2020. A large amount of this power generation capacity will come from variable renewables, such as wind.

Wind, like bulk solar, is a cost-effective resource for decarbonizing Europe's energy system. However, there are inherent limitations to the controllability of wind power, making life difficult for system operators who are trying to continuously balance supply and demand. To continue the wind revolution which we have seen transform our power systems over the past 10-15 years, we must deliver a power system able to cope with high levels of variable renewables, powered by power electronics and monitored and controlled by digital systems. This will require a focus on flexibility.

While power systems have always needed some degree of flexibility to balance supply and demand, flexibility requirements will grow in the coming years. According to a study by the European Commission's Joint Research Centre (JRC)[2], the flexibility requirements for power systems in the European Union are projected to increase significantly. In 2021, flexibility requirements were 11% of the total electricity demand in the EU. This figure is expected to grow to 24% in 2030 and to 30% in 2050.

This report explores what levers can be utilized to meet the flexibility needs of our future power systems, from supply and demand side options to battery storage and active grids and interconnectors. The report also considers the two fundamental technology enablers supporting the provision of flexibility: digital technologies and power electronics, as well as the role of policy, regulation, and business models.

Finally, recommendations which will enable the power system to utilize any available flexibility levers are identified:

Today's power systems are facing two major challenges: the need for more capacity and the need to address the increasing complexity. The build-out of renewable generation and grid capacity is a priority for governments, regulators, asset operators and other energy sector stakeholders. However, as the power system becomes increasingly dependent on variable and often distributed renewables, coupled with electrification of transport, heating and industrial processes, including growing demand from loads such as data centres, the complexity also increases. Addressing this increasing complexity requires more focus. Flexibility, which enables the power system to cost-effectively manage the uncertainty and variability of supply and demand across all timeframes, must be prioritized.

There is no one-size-fits-all solution when it comes to flexibility. Every market has different legacy-based characteristics that influence the choice of technology. However, the clean energy technologies are available today to deliver on flexibility needs as large volumes of variable renewables are integrated into power systems in Europe. And while technology research and innovation will continue, stakeholders must now focus on the rapid deployment and scaling of available clean energy technologies, as relevant to each market. New policy and regulatory approaches enabling innovative business models will be important for this accelerated deployment.

Cross border interconnectors contribute to Europe's energy security, supporting the integration of renewables while increasing power system flexibility across all timeframes. To integrate large volumes of renewables, hence delivering on onshore and offshore renewables targets across the EU, more cross border interconnectors combined with enhanced power flow controllability across power systems will be crucial. The European Commission plans to double cross-border transmission infrastructure to approximately 180 GW by 2030 and has also set an interconnection target of at least 15% by 2030 to encourage countries to interconnect their installed electricity production capacity. Given the essential role of cross border interconnectors in both contributing to Europe's energy security and increasing power system flexibility across short-, medium- and long-term timeframes, both targets must evolve based on actual data and long-term planning forecasts as we look out to 2050. In addition, to achieve the accelerated delivery of this long gestation infrastructure, policy makers must simplify access to financing and ensure societal acceptance; regulators must ensure faster permitting; and new business models are needed to accelerate project delivery.

Power electronics can play an important role in both integrating more renewables and addressing the complexity associated with operating a power system with large volumes of variable renewables. With increasing supply and demand complexities, innovative technologies which address these complexities must play a greater role in the functioning of our grids. Power electronics devices such as inverters are playing an increasing role in supporting the integration of renewables, while also providing grid support such as flexibility. As an example, grid-forming technologies can offer system services to address lower levels of system inertia due to variable renewables displacing synchronous fossil generation. Such technologies will be essential to provide much needed grid flexibility and strengthen energy security. The deployment of these technologies must be accelerated and scaled across Europe.

A step increase in how we leverage digital technologies and power electronics is required if we are to achieve our energy and climate goals. The complexity across our power system is increasing exponentially. It is vital for power system stakeholders to invest in the innovative digital tools and technologies that maximize the efficiency of all available flexibility solutions. As the digitalisation of our energy system advances, digital technologies combined with power electronics will make the system more connected, intelligent, efficient, sustainable, resilient, and flexible over the coming decades. However, accelerated digitalisation needs an infrastructure fit for the future, based on interoperability and common standards, gigabit networks and secure clouds. We must plan now for a future proofed digital infrastructure.

The next level of cross stakeholder, cross sector and cross geography collaboration is required to develop the forward-looking, coordinated, and holistic power system planning required to achieve our climate and energy goals. A more coordinated approach to increase the complementarity of national assessments of flexibility needs and common policies across borders can bring extended benefits. The development of integrated, forward-looking power grid plans (including offshore and onshore systems) must be a holistic European wide coordinated activity, rather than a coordinated planning of different national grids. Policy makers must regularly assess the flexibility needs of the power system at the European level and deepen coordination on different national approaches via individual countries' National Energy and Climate Plans (NECPs) and national greenhouse gas projections. There is scope for NECPs and projections to develop based on regional cooperation to ensure Member States can better meet their flexibility needs.

Develop a healthy supply chain for skills. The skills needed to accelerate energy transition are changing, along with demographics and employee expectations. Across Europe there is drastic skills shortage, especially in the field of power electronics. Power sector companies will also need a workforce with suitable digital skills. The urgency is increasing as countries and companies throughout Europe invest heavily in semiconductor manufacturing and in renewable energy. Addressing the skills gap is vital for achieving the EU's clean energy goals. Efforts to increase diversity (and particularly the participation of women) in STEM subjects will be an important contributor to building up a more resilient skills supply chain. In addition to 'skills partnerships' across the sector, policy makers could also consider the inclusion of energy transition modules in the curricula for secondary schools.

The investments required to build out a future flexible power system will require a careful balancing. Regulators will need to enable forward looking expenditure while managing the impact of these investments on electricity bills. Innovative regulatory approaches will be required to balance the need for forward looking grid build-out with potential increases in tariffs for consumers. According to the EU Action Plan for Grids, the socio-economic welfare losses of delaying the network upgrades necessary to connect renewables and flexible demand will normally outweigh the additional initial cost of anticipatory investments. Regulators will need to cooperate closely with regulated entities to find solutions enabling investments which go beyond current system needs but which have significant potential to reap savings in the future. Regulators will also need to consider how to leverage network tariffs to account for operational expenditure (e.g. digital and cyber resilience investments). This process will need to be guided and monitored by the European Commission to ensure a coordinated and effective implementation.

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2.

Setting the Scene

Coping with the integration of high volumes of variable renewables combined with new electrified demand in our power systems requires focus on both capacity and complexity. For now, the emphasis is on capacity build-out at speed and scale, including the development of power grids to connect the queues of stand-by and upcoming renewable power projects. However, as the power system becomes increasingly dependent on variable renewables, coupled with electrification of transport, heating and industrial processes, and new demand loads such as data centers, the complexity also increases.

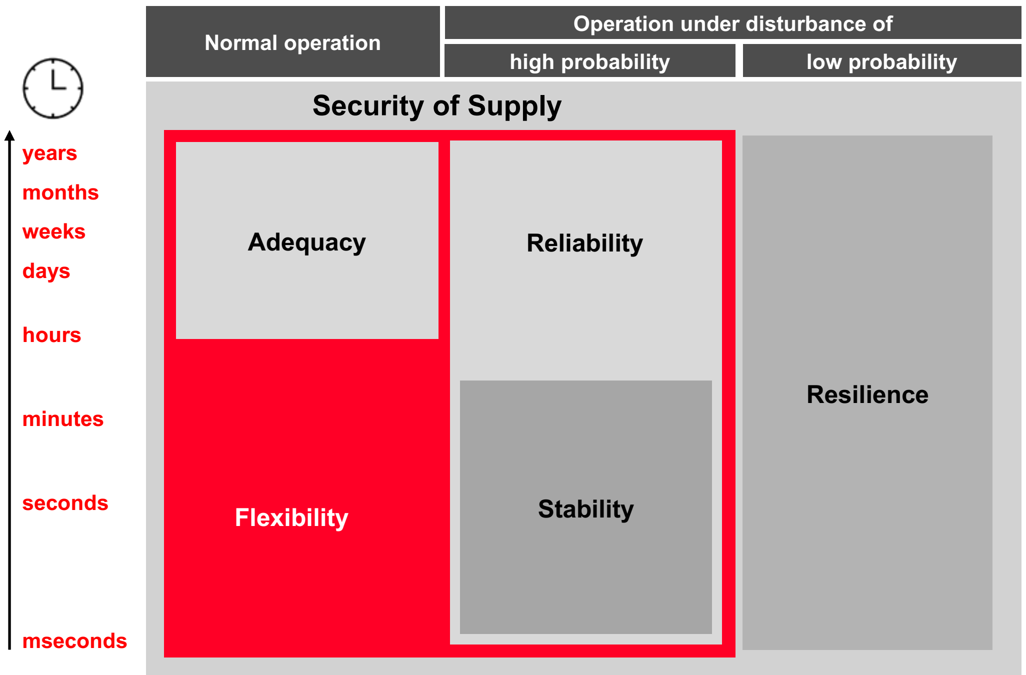
System operators are finding it more challenging to balance supply and demand. Fortunately, digital technologies and advanced power electronics are now positively impacting grids around the world, offering grid operators increased visibility into and control over both power flows and demand variability. In addition, system operators can rely more on power system characteristics which can support both normal operation and operation under disturbances, such as resilience, reliability, stability, adequacy, and of course, flexibility.

The traditional paradigm which focused more so on reliability and stability is now expanding towards prioritizing flexibility and resilience. According to the proposed EU Electricity Market Design Reform regulation, "flexibility means the ability of an electricity system to adjust to the variability of generation and consumption patterns and grid availability, across relevant market timeframes.'' Power systems have always needed flexibility to balance varying demand and to deal with unexpected failures.

As illustrated in Figure 1 below, flexibility plays an important role in supporting power system operations across all time frames from milliseconds to years. Flexibility is also utilized during both normal operation and during high probability operational disturbances.

Depending on the timeframe, different flexibility levers, as outlined in Chapter 3, can be called upon by the system operators. Chapter 4 outlines the fundamental technologies enabling flexibility and Chapter 5 focuses on the role of innovative policy, regulation, and business models.

FIGURE 1. Flexibility and other operational and planning requirements of modern power systems.



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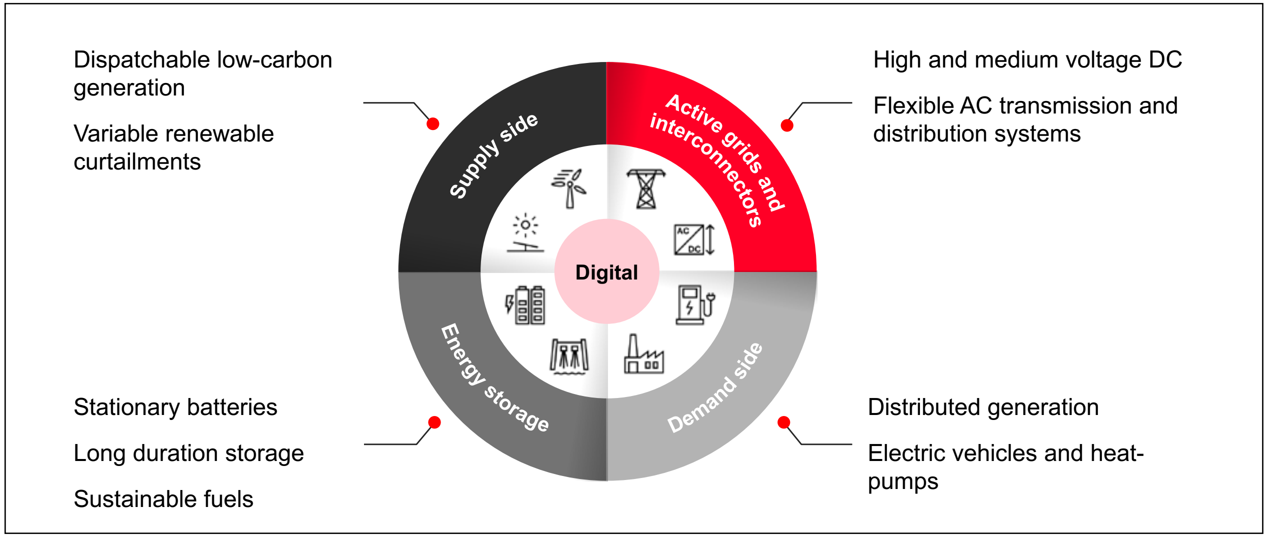
3.

Four Flexibility Levers...

Addressing power system flexibility is a complex task. However, there are 4 main options available ranging from leveraging the supply side, the demand side, energy storage and / or active grids and interconnectors, as illustrated in Figure 2 and described below. Together, these four options offer an alternative to the controllable capacity offered by conventional power stations. Digital technologies and power electronics are essential for unlocking the full potential and complementarity of these four levers for an optimal and coordinated response.

Power system flexibility needs and solutions will look different across the globe and will be determined by regional geography, natural resources, and power system specifications. In Europe, efforts are intensifying to enhance power system flexibility, while bolstering energy security, optimizing the efficiency of power system assets and ensuring that solutions are aligned with the EU climate targets. This trend is anticipated to gain momentum globally.

FIGURE 2. Four dimensions of flexibility with digital technology at the core



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Recommendation 1

Today's power systems are facing two major challenges: the need for more capacity and the need to address the increasing complexity. The build-out of renewable generation and grid capacity is a priority for governments, regulators, asset operators and other energy sector stakeholders. However, as the power system becomes increasingly dependent on variable and often distributed renewables, coupled with electrification of transport, heating and industrial processes, including growing demand from loads such as data centres, the complexity also increases. Addressing this increasing complexity requires more focus. Flexibility, which enables the power system to cost-effectively manage the uncertainty and variability of supply and demand across all timeframes, must be prioritized.

Recommendation 2

There is no one-size-fits-all solution when it comes to flexibility. Every market has different legacy-based characteristics that influence the choice of technology. However, the clean energy technologies are available today to deliver on flexibility needs as large volumes of variable renewables are integrated into power systems in Europe. And while technology research and innovation will continue, stakeholders must now focus on the rapid deployment and scaling of available clean energy technologies, as relevant to each market. New policy and regulatory approaches enabling innovative business models will be important for this accelerated deployment.

3.1 Supply Side Flexibility

In the past, and even still today, flexibility is primarily provided by large, centralised and dispatchable power plants that can add or remove electricity supply simply by adjusting the input of primary energy. Even in a very large power system, like continental Europe, these amount to only several hundred power generators whose flexibility services are relatively straightforward for system operators to call upon amid predictable and stable electricity demand patterns. In this system, flexibility was more a byproduct of a centralized, highly dispatchable power production machine.

Driven by targeted policy support combined with innovation in manufacturing, equipment performance and business models, as well as by economies of scale and more competitive access to financing, the years from 2010 – 2020 represented a remarkable period of cost reduction for solar and wind power technologies.

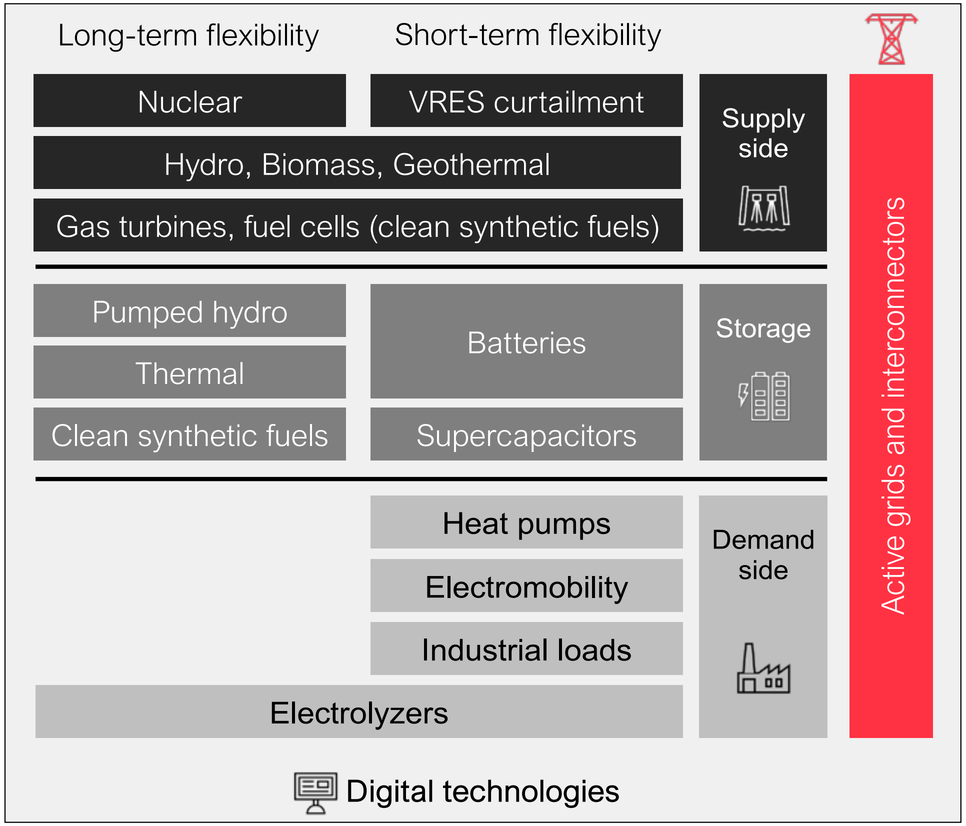
Taking wind power as an example, for onshore wind projects, the global weighted-average cost of electricity between 2010 and 2020 fell by 56% and for offshore wind projects it fell by 48%[3]. As a result, in the space of 10 years, renewable electricity from solar and wind power went from being an expensive niche, to being a serious contender with fossil fuels for new capacity additions.

With this shift, comes an end to the highly controllable and dispatchable power generation system of the past. Where electricity supply was previously decided by power plant managers and dispatch centers, it will be increasingly influenced by weather conditions.

This can be quite challenging for system operators across Europe, whose major role is to balance supply (coming from power generation) and demand (coming from consumers) at every moment of the day. The variability of renewable power generation combined with the increasing fluctuation of demand brought on by new electrified loads and increasing electrification makes the tasking of balancing the system increasingly complex.

There are several low-carbon supply side solutions available however, as outlined in Figure 3, mostly garnered from a diverse power system offering options such as small modular nuclear reactors (SMRs) which can respond to balancing requirements, as well as run of river hydro generation, geothermal generation, and biomass and gas power generation. While curtailment of renewables can also be considered for the provision of short-term flexibility, it should be avoided where possible. An evolution of the way we treat demand, thanks to digital technologies, could see a shift from the traditional supply following demand, to scenarios where demand can be optimized to follow supply, thus minimizing the curtailment of renewables.

FIGURE 3. Advanced landscape of future power systems



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3.2 Demand Side Flexibility

According to the IEA[4], global electricity demand is expected to grow by an average of 3.4% annually through 2026. The growth in electricity demand in advanced economies such as Europe is expected to come from increasing electrification of transport, heating for buildings and industrial processes. In parallel, we are increasingly seeing electricity consumption from growing loads such as data centers, artificial intelligence, and cryptocurrency mining. Demand from these additional loads could double by 2026 to more than 1000 TWh (roughly equivalent to the annual electricity consumption of Japan)[5].

With the fluctuation of these electrified loads, come challenges but also opportunities.

Firstly, the growing distributed renewable energy capacity – much of which is solar PV placed on household rooftops – has the possibility to simultaneously supply some of new types of load, such as electric vehicle charging and heat pumps. However, this can only happen when the electric vehicle is being charged or the heat pump is consuming during the solar PV production hours, unless a storage solution is installed in tandem. Equally, in some remote locations, wind farms are being built next to data centers or large industrial sites.

On the other hand, flexibility is inherent in electric vehicles and heat pumps, thanks to their ability to store energy in batteries and insulated water tanks for subsequent use. Electric vehicles are not only capable of flexible charging but can also accommodate flexible discharging. During peak demand or emergencies, electric vehicle owners can be incentivized to supply power back to the grid through their batteries, including at specific locations where system operators are experiencing specific challenges. Key to harnessing this potential are bidirectional chargers, either onboard or integrated into the grid, and digital connectivity for efficient data exchange and optimal control, as well as appropriate incentives, such as, for instance, dynamic pricing.

Industrial demand response is also an important resource for providing grid flexibility, particularly as more industrial processes become electrified. Industrial processes can provide grid flexibility by ramping up or down their load and production intensity based on grid instructions or electricity prices. Historically, industry may not typically participate in demand response because of operational, financial, regulatory, and knowledge barriers. However, this may be changing, as system operators include large industry in demand response programs and industry stakeholders start exploring the opportunities associated with market trading i.e. assessing the monetary value of down time where financial incentives are offered.

Most of the hydrogen produced today is for industrial processes and most of that hydrogen is produced from fossil hydrocarbon fuels. Increasingly, water electrolysers are becoming a critical technology to produce low-emission hydrogen from renewable or nuclear electricity. While the primary uses of hydrogen will likely continue to be industrial processes as well as aviation or shipping fuels in the future, the production of hydrogen via electrolysers can be ramped up and down quickly, offering a flexible load that provides valuable grid-balancing services to system operators. In addition, according to the European Network of Transmission System Operators – Electricity (ENTSO-E)[6], electrolysers could also be leveraged to accommodate otherwise curtailed surplus variable renewable generation.

Demand-side flexibility, especially at residential level, will increasingly be managed by aggregators. These market participants group the electricity generation and consumption of large numbers of small prosumers into flexibility services which can be commercialized by offering demand-side response into the balancing market, as well as into the day-ahead and intraday electricity markets.

Nowadays, aggregators already offer demand-side response services into reserve capacity markets to act as standby levers in unexpected situations.

3.3 Energy Storage

Energy storage plays a vital role in providing flexibility ranging from short (seconds to hours) to long-term (days to weeks) intervals. But it will also help manage the load and electricity supply from prosumers. Energy storage's ability to shift demand as well as generation is key to a well-working, flexible future power system. In some markets, storage needs are even supplied by local solutions such as networks of electric vehicle batteries or hot water tanks.

3.3.1 Hydro Power Plants

In Europe's electricity market, energy storage capacity is largely provided by pumped hydro power plants. These large reservoirs use electricity to power water pumps that shift large amounts of water from a lower mountain reservoir to higher at times of oversupply (usually during the night), only to release them again to drive electric turbines and generate electricity at times when more power is needed (for example during the morning peak). Pumped storage is an important source of flexibility for Europe's power system.

In addition, hydropower systems can have a large storage capacity in existing water reservoirs. Norway's natural water feed hydro reservoirs, for example, are already acting as a flexibility tool to balance out variable wind power production in neighboring countries that are connected via submarine cables. The NordLink interconnector, for example, linking the German and Norwegian power markets by enabling the integration and cross-country exchange of renewable solar, wind and hydro power underlines the importance of interconnections in sharing flexibility resources across geographic areas.

3.3.2 Battery Energy Storage Systems

The more imminent focus for the provision of electricity storage solutions lies on battery energy storage systems (BESS). The flexibility provided by BESS will enable it to support activities such as peak shaving, self-consumption optimization, and backup power in the event of outages. BESS can be installed in front of the meter (i.e. utility scale), and also behind the meter for industrial, commercial and residential needs. Lithium-ion is the main electric battery storage technology that is being deployed currently. This may change given the scarcity of lithium and other options are being explored such as sodium-ion (Na-ion), sodium-sulfur (Na-S), and metal-air batteries. Today, economics dictate that battery applications provide up to four to six hours of capacity replacement, although based on cost reductions, twelve hours of discharge capacity is foreseen by 2050[7].

Leveraging BESS to Solve Future Grid Challenges

Introducing large amounts of variable renewables on to power systems will have an impact on grid inertia, making it more difficult to manage the frequency stability of the system. BESS (Battery Energy Storage Systems) connect with power systems through power converters, which can be controlled as either grid-forming or grid-following units. While most installations currently use grid-following mode, innovative approaches which tackle future low-inertia grid challenges focus on grid-forming control strategies, which can further leverage BESS as a flexibility resource, to provide support to both frequency/voltage regulation and system stability.

3.3.3 Long Term or Seasonal Storage

For now, there is no accepted solution for how a low-carbon electricity system will address longer periods of low wind speeds and solar irradiation, often coupled with high demand during cold winter spells. Addressing these long-term energy deficits would require technologies capable of storing substantial amount of energy at considerably low cost. Some examples that are being explored include liquid air, underground compressed air, stacked blocks, and flow batteries. With that in mind, it is also worth noting, that in general, weather events like Dunkelflaute[8] affect limited geographic areas. For example, some studies have observed that when wind and solar generation is low in Germany, it could be high in UK or Sweden or Spain or Balkans. This means that if variable renewables are strategically placed and distributed between different weather zones (and slightly oversized in certain cases) then Europe can benefit from the spatial and temporal complementarity of resources, thus significantly reducing the need for long duration storage.

3.4 Active Grids and Interconnectors

The expansion, upgrade and modernization of transmission and distribution grids will be pivotal to developing a decentralized, digitalized, integrated and flexible system. The European Commission has already proposed an ambitious plan to overhaul the region's power grids, allocating a staggering €584 billion to be spent by 2030[9].

The Commission also recognizes the need to address the increased complexity, while building out the additional capacity and plans to invest in a more digitalized, decentralized, and flexible system with millions of rooftop solar panels, heat pumps and local energy communities sharing their resources, more offshore renewables coming online, more electric vehicles to charge, and growing hydrogen production needs.

In addition, by 2030, according to the EU Action Plan for Grids[10], the EU plans to double cross-border transmission infrastructure to approximately 180 GW, with the aim of leveraging cross-border energy infrastructure to decrease generation costs by €9 billion annually until 2040[11]. The EU has even set an interconnection target of at least 15% of each member state's installed electricity production capacity by 2030 to ensure that there is sufficient transmission capacity to handle growing power exchanges and energy trading across Europe.[12] Furthermore, by the end of 2025, EU grid operators are required to allocate at least 70% of their cross-border capacities for daily energy trading.[13]

It is important to note that Europe's electricity system is the world's largest interconnected grid, with more than 400 interconnectors linking nearly 600 million citizens, representing approximately 93 GW of cross-border transmission capacity, with a further 23 GW in construction/advanced permitting to be installed by 2025. This impressive transmission grid is planned, developed and operated by Europe's Transmission System Operators (TSOs). ENTSO-E brings together Europe's 40 TSOs across 36 countries, to coordinate the functioning and development of the interconnected power system.

Grids which are both more interconnected and controllable play a crucial role in the provision of flexibility. Enhancing the interconnection of electricity markets has emerged as the most cost-effective strategy to increase power system flexibility. Interconnected power systems excel in sharing flexibility resources, surpassing the capabilities of more isolated markets. In fact, a well-interconnected network in large part addresses the need for flexibility by more effectively distributing the variability of renewable energy over a wider area. Integrating storage capacity with a robustly interconnected grid forms a key pillar in the future architecture of the low-carbon, flexible electricity system because it enables the balancing of supply and demand over the widest possible area. As described above, the greater the variety of climatic, geographic, and temporal locations linked, the more flexible the power system becomes.

In highly interconnected regions, power system flexibility will utilize all four flexibility levers: demand-side flexibility, supply-side flexibility, energy storage, and interconnected controllable grids.

Recommendation 3

Cross border interconnectors contribute to Europe's energy security, supporting the integration of renewables while increasing power system flexibility across all timeframes. To integrate large volumes of renewables, hence delivering on onshore and offshore renewables targets across the EU, more cross border interconnectors combined with enhanced power flow controllability across power systems will be crucial. The European Commission plans to double cross-border transmission infrastructure to approximately 180 GW by 2030 and has also set an interconnection target of at least 15% by 2030 to encourage countries to interconnect their installed electricity production capacity. Given the essential role of cross border interconnectors in both contributing to Europe's energy security and increasing power system flexibility across short-, medium- and long-term timeframes, both targets must evolve based on actual data and long-term planning forecasts as we look out to 2050. In addition, to achieve the accelerated delivery of this long gestation infrastructure, policy makers must simplify access to financing and ensure societal acceptance; regulators must ensure faster permitting; and new business models are needed to accelerate project delivery.

While cross-border interconnectors can be built as alternating current (AC) or direct current (DC) assets, in the evolving energy landscape, dynamic and flexible power flow control through technologies based on advanced power electronics will become increasingly essential. HVDC technology plays a crucial role in modernizing power grids, efficiently controlling and routing the flow of electrons where needed, thereby optimizing electricity transmission, and minimizing the curtailment of renewable energy.

Within Europe, important HVDC interconnector projects are underway which will substantially improve the continent's flexibility. Notable examples include the interconnection between England and France, which aims to strengthen power networks in both countries and accelerate the integration of renewable energy. Similarly, a new submarine HVDC interconnector between Spain and France facilitates economic exchange of electricity between Spain and central and northern Europe. It is also worth mentioning the ongoing work to develop multi-vendor interoperability for future offshore HVDC grids.

4.

...Supported by two fundamental technology enablers

Chapter 4 considers the underlying and fundamental role of digital technologies and power electronics in the provision of grid flexibility.

Digitalisation and digital technologies: These are key enablers of a flexible low-carbon power system. Digitalisation is also the glue that fuses all flexibility technologies that the future low-carbon power system needs. It helps orchestrate each piece of the puzzle, such as battery storage, interconnectors, or demand-side response tools, which all add their own value within the coordinated power system.

However, to fully leverage the opportunities offered by digitalisation, there is a need to first focus on the availability of, access to, and sharing of energy-related data based on seamless and secure data transfers among trusted parties. Often, where sufficient data exists it is in different formats, not labelled appropriately, stored on-site, and not available to share with third parties. ENTSO-E's transparency platform[14] is a great start, and now it is time to go further. Under the EU action plan for digitalising the energy system from 2022, a common European energy data space will be deployed no later than 2024[15]. According to the EU, and subject to the necessary protections such as intellectual property, the deployment of an appropriate data sharing framework for energy could help facilitate the participation on the wholesale markets of more than 580 GW of flexible energy resources making full use of digital solutions by 2050[16].

Power electronics: The modern solid-state electronics revolution began with the invention of transistors in 1948 by a group of researchers from Bell Laboratories. The transistor is a semiconductor device used to amplify or switch electric signals and power and is a building block of modern electronics. Today, there are few components more crucial than semiconductors, also sometimes referred to as microchips or integrated circuits. They are the foundation of modern computing and are ubiquitous in our daily lives with devices such as smartphones and laptops relying on them.

While electronics is the field of engineering which deals with devices that operate on low voltages and currents, power electronics deals with devices that operate on high voltages and currents. Power electronics is a multidisciplinary technology covering a multitude of fields such as power semiconductor devices, converter circuits, advanced control techniques, as well as digital signal processors and artificial intelligence techniques.

Power electronics already have a crucial role in applications such as high voltage direct current (HVDC) systems, flexible alternating current transmission systems (FACTS), fast electric vehicle charging systems and green hydrogen production via water electrolysis and will be essential as countries work to achieve their climate and energy goals.

4.1 Digitalisation and Digital Technologies

Digital technologies already automate complex processes, facilitate information sharing in the power sector, and generally play a significant role in managing our power systems. These tools facilitate performance improvements and cost savings through a combination of automation, optimization, and the enabling of new business and operational models across the traditional energy value chain i.e., generation, transmission, distribution, markets, consumption. This computing and communications infrastructure complements and enables the electric equipment in the grid, and its availability and performance are key to moving forward with the energy transition.

The applications enabled by digital technologies deliver flexibility at various stages of a low-carbon electricity system. This section explores the role of digital technologies across the power grid planning, forecasting, trading, monitoring, and operations phases, as illustrated in Figure 4.

4.1.1 Planning for an Efficient Power System

We are now past the days of predictable power flows on power grids thanks to more variable renewables, fewer conventional generators, and more complex load patterns. System Operators are finding the planning of grid upgrades and maintenance outages more challenging.

Nonetheless, holistic, forward looking, and integrated planning is required for clean energy infrastructure development. Longer term strategic plans up to 20 - 25 years are required which consider cross sectoral demand growth, as well as cross border needs. Long term coordinated infrastructure planning ensures maximum integration of variable renewables, system adequacy and the optimal mix of controllable generation, dispatchable demand, and energy storage.

In addition, short- and medium-term planning is also becoming more complex, involving selecting the generators, storage, grid topology and renewable energy sources which will be required to meet the 'optimized' demand, considering security constraints for a given time period.

Model-based simulation tools, advanced analytics and simulation-ready data are all key to ensuring the accuracy of such short, medium, and long-term planning, as well as the ability to process more data to assess more options. Optimization tools for long-term grid planning can now capture the operational benefits of flexibility sufficiently accurately for planning purposes[17]. Probabilistic Monte Carlo simulations allow operators to understand how the power system will react under many possible scenarios enabling them to calculate the risk of certain loads not being served. Advances in high performance computing and the incorporation of machine learning (ML) techniques such as reinforced learning make possible more detailed, more accurate, and faster simulation, assisting system planners in their need to keep pace clearing the backlog of system interconnect studies resulting from the addition of renewables to the grid.

4.1.2 Forecasting Power System Needs

To maximize the integration of variable renewables such as wind into the grid, accurate production forecasting is crucial. A power generation forecast combines a forecast of plant availability with weather forecasts for a particular location or a region more broadly. High accuracy power generation forecasts – short term, long term, centralized and decentralized – are all invaluable to both system operators and market participants.

Steady advances in machine learning data analysis have resulted in significantly improved renewable production forecasts than were previously available. These advances yield many benefits including enabling companies like Google to increase the financial value of its wind power by 20% by selling it in advance rather than in real-time, thanks to forecasting accuracy[18]. By combining power generation forecasts with demand forecasts incorporating demand side market sensitivity, system operators get necessary insight into evolving and imminent mismatches between supply and demand, needed to be able to take corrective action. Similar forecasting techniques are also extending to the key grid stability parameters, including both system inertia and thermal ratings of transformers and transmission lines. Having improved short term forecasts of evolving grid conditions improves the ability of system operators to make proactive dispatch and grid reconfiguration adjustments.

4.1.3 Facilitating Trading

Efficient electricity markets play a pivotal role in ensuring flexibility. When markets operate efficiently in the short term, economic low-carbon generation assets run with minimal curtailment as grid interconnections address interregional capacity constraints, and local flexibility assets such as storage and demand response relieve capacity and congestion constraints motivated by clear price signals. In the longer term, efficient capacity markets motivate investment to ensure flexibility assets are added to the grid at the right time and in the right locations.

Implementation of efficient electricity markets is achieved by IT systems that match bids and offers for generation and demand across large regions while observing the operational constraints of the underlying electricity grid. These markets are essential for enabling flexibility across the power system. One of the main responsibilities of the TSOs is maintaining short-term operational security, and the capacity calculation and allocation processes carried out by the day-ahead and intraday markets are essential for supporting the TSOs in that task. The outcomes of the market processes provide the system operators with an understanding of what remedial actions might be required to balance the system in each timeframe.

Wholesale electricity markets have evolved to directly incorporate flexibility from larger variable renewables. To complement, flexibility markets are emerging to offer to smaller and more distributed flexibility assets the ability to participate as well. Requiring their own market clearing software with robust and secure communications and control capabilities, flexibility markets are a good solution to incorporate much more demand side participation in ensuring flexibility across grid operations.

Meanwhile, market participants rely on their own set of digital applications to trade in these electricity markets. Energy trading and risk management (ETRM) software programs allow generation asset owners and demand serving entities to coordinate short-term market participation with bilateral trading to manage long term positions and better manage financial risk. These applications often leverage AI, ML techniques combined with optimization algorithms to coordinate generation, storage, and demand bids and offers across multiple markets, relying on data-based decision making.

4.1.4 Real-time Monitoring

Maintaining visibility of what is happening on the power network, identifying threats to system stability and security quickly, and taking fast proactive and corrective actions consistently are also considered priorities for system operators.

For system operators, the ability to monitor the power system in real time so as to best react to system disturbances is essential, particularly for short term operational security. Sensors and communication networks are essential for monitoring and estimating the actual state of the power system. In the event of a forced outage of a transmission line for example, the operator can quickly establish where the outage occurred, what equipment was affected, but also what network topology modification options or other remedial actions are available to ensure that the system stays stable. Such real-time monitoring is also essential in the case of an unexpected drop in wind power production. Even the remedial actions taken in these situations are more often automated, and able to react close to instantaneously.

In practice, the realization of the monitoring and control needed for assuring flexibility is achieved today by a combination of SCADA (supervisory control and data acquisition) and solutions for transmission control (energy management system (EMS)), distribution network control (advanced distribution management system (ADMS)) and generation (generation management system (GMS)). From a data acquisition perspective, modern SCADA systems incorporate diverse sensor networks and secure IoT connections, greatly increasing information synthesis over previous generations of similar systems.

For market participants such as suppliers and generators, monitoring the state of 'charge' or the available energy storage on a continuous basis, monitoring the real-time output from a wind farm, monitoring asset ratings to optimize their usage and monitoring the flexibility of demand for aggregators all require sensors and communication networks.

In the field at the edge of the grid, digital technologies in the form of communicating control systems are the real-time and coordinating complement to control actions taken in the control room. In particular, digital control algorithms ensure that power conversion solutions such as energy storage, solar inverters, HVDC links and grid devices such as STATCOMs can respond immediately to dispatch signals and provide valuable services to the grid such as dynamic voltage and frequency support.

Finally, as both transmission and distribution grids become more digitalized, regulators can leverage the additional information available on the current state of the grid, as well as future preparedness, in order to reflect the active contribution of grids to a successful energy transition.

This information can also be used to justify investments in specific areas which are not meeting benchmark conditions.

4.1.5 Efficient Power Delivery

Without digital technologies, it would become increasingly difficult to ensure the efficient delivery power to where it is needed at every moment of the day. Manual dispatch of the power grid becomes far more complex as the percentage of renewables increases on a power grid.

A key to controlling power systems is high performance model-based simulation. System operators must perform extensive 'what-if' contingency analyses to ensure that redispatch options (or remedial actions) are ready for unexpected events, particularly as uncertainty increases. As a starting point these models must accurately represent the current state of the grid, based on up-to-date data. AI and ML can play a role here to improve the model-based analysis, as well as the parameters of the analysis, based on self-tuning models. In fact, this is an active area of research, and such models represent the pre-cursor to next generation digital twins of power systems.

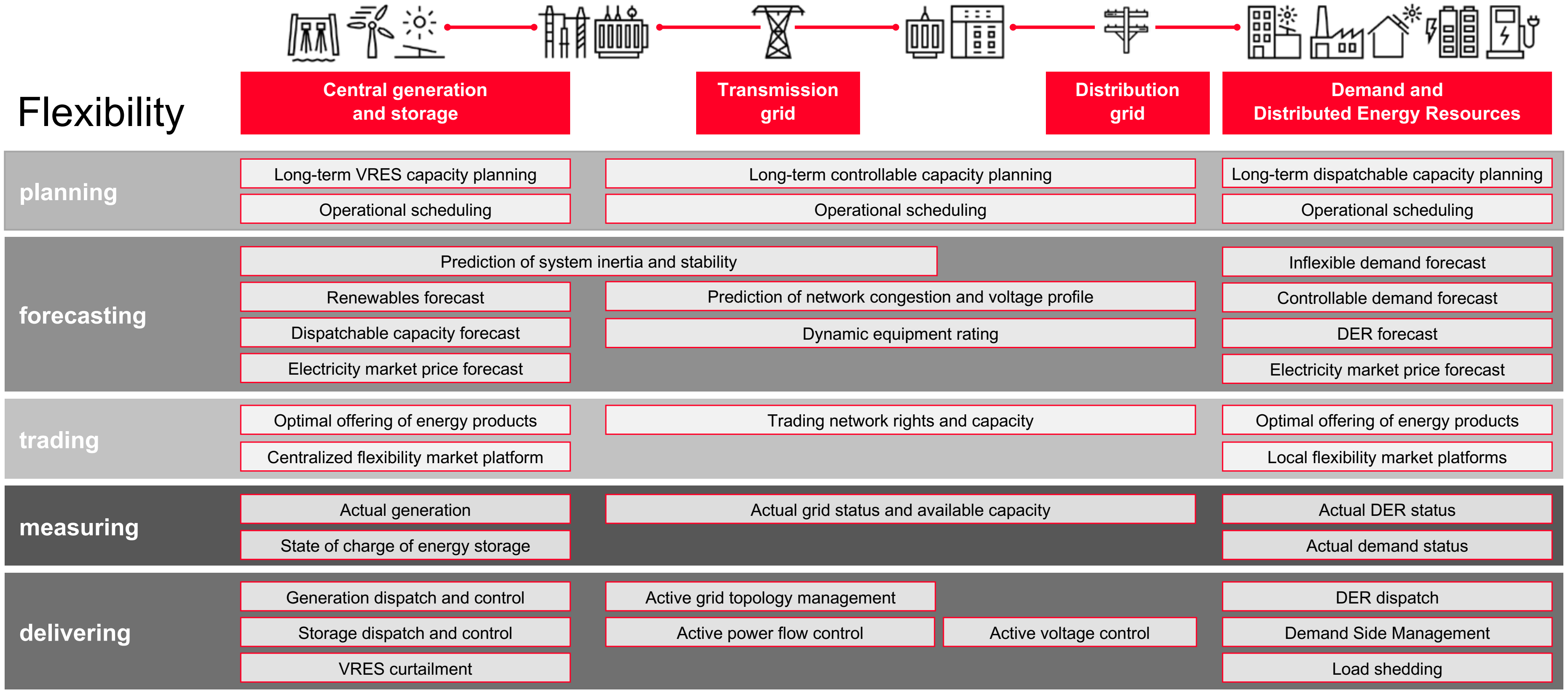
High performance simulation is embedded within scheduling and control algorithms that are capable of coordinating dispatch of generation, dispatch of distributed energy resources, and changes in grid topology for both transmission and distribution networks. The combination of operations research, model-based simulation and forecasting with AI and ML ensure system operators can maintain grid economy, grid security and stability.

Within the grid and at the grid edge, communications and computing technologies are essential for dispatch and control of distributed energy resources, including and especially storage, schedulable demand, and curtailable renewables. Within distribution grids, in addition to the digital infrastructure needed for grid control, metering will play a key role as a digital technology.

Technology Innovation to Address Increasing Complexity

System operators must balance power supply and demand continuously. This becomes more complex as we transition from fossil-fuel synchronous generation to inverter-based resources like wind and solar and experience a resulting decrease in rotational inertia, which is crucial for counteracting sudden imbalances in active power. If supply and demand are not balanced, the system can quickly fall outside its frequency stability limits e.g. veering at a high rate away from 50 Hz. In parallel, operators must also ensure dynamic voltage stability which can be impacted by factors such as forced outages of transmission lines. A STATCOM (Static Synchronous Compensator) is a power electronics device which can control the reactive power flow through a power network and thereby increase the stability of the power network. When integrated with an energy storage system, it becomes an E-STATCOM which can be an important flexibility resource for operators, enabling them to simultaneously improve the frequency and voltage stability of a renewable energy dominated grid thanks to its active and reactive power support, as well as power quality services.

FIGURE 4. Flexibility through digital technologies across power system processes



Credit: Hitachi Energy

4.2 Flexible Grids through Power Electronics

When it comes to our power systems, three examples of the importance of power electronics for flexibility are laid out below:

4.2.1 Generation: Inverter Based Resources (IBRs)

Inverter based resources include devices such as variable renewable energy generators (i.e. wind turbines, solar panels) and pumped hydro storage plants, but also batteries[19]. The inverter is a power electronics device which converts the DC electricity generated from sources such as solar panels, batteries, or fuel cells to AC electricity.

In contrast to conventional generators, such as gas turbines, the characteristics of today's IBRs are almost entirely defined by control algorithms. High dependance on control algorithms can present challenges to system stability, particularly as their penetration increases. While IBRs present challenges, it is now being recognized that they can also provide support to the grid and respond to abnormal grid conditions. Inverter technology is evolving from what is known as grid-following (designed to operate on an existing grid that is generally dominated by synchronous machines e.g. gas turbines) to grid-forming (designed to operate on a new type of grid which is mostly powered by variable renewables). When appropriately programmed, IBRs can provide operational flexibility and control and the ability of IBRs to perform with precision, speed and control can mitigate disturbances across the power system frequently outperforming synchronous machines.

Recommendation 4

Power Electronics can play an important role in both integrating more renewables and addressing the complexity associated with operating a power system with large volumes of variable renewables. With increasing supply and demand complexities, innovative technologies which address these complexities must play a greater role in the functioning of our grids. Power electronics devices such as inverters are playing an increasing role in supporting the integration of renewables, while also providing grid support such as flexibility. As an example, grid-forming technologies can offer system services to address lower levels of system inertia due to variable renewables displacing synchronous fossil generation. Such technologies will be essential to provide much needed grid flexibility and strengthen energy security. The deployment of these technologies must be accelerated and scaled across Europe.

4.2.2 Active Grids and Interconnectors

In addition to enabling large scale renewables integration, power electronics plays a key role in the technologies supporting Active Grids and Interconnectors. It can manage the variability and predictability of new power sources to maintain stability in an ever more complex grid, where inertia is limited due to the replacement of traditional synchronous generation, more new energy generators are present, and more demanding grid codes need to be complied with.

AC Grid Flexibility

Power electronics-based systems, such as Flexible AC Transmission Systems (FACTS) have become instrumental in solving new power quality issues associated with more variable renewables combined with increased demand side electrification. FACTS technologies include synchronous condensers, and STATCOMs. An E-STATCOM, which combines energy storage (i.e. supercapacitors or batteries) and a STATCOM, is a tool used to improve both the voltage and frequency stability of a variable renewable energy dominated grid by providing active and reactive power support together with power quality services. FACTS technologies, such as phase shifting transformers (PST) and thyristor-controlled series compensation, can help provide existing grid infrastructure with the flexibility to cope with new dynamic power flow even when the grid strength is reduced. However, there is no one size fits all and the power electronic solutions must be adapted to the application they are used in.

High Voltage Direct Current (HVDC) Technology

HVDC technology was first installed in Sweden in 1954, interconnecting the island of Gotland to Sweden's mainland. The mercury arc valve was the technology used to convert AC to DC and vice versa in HVDC schemes until the thyristor, a controllable semiconductor, was applied to a commercial HVDC project in 1970.

There are two main categories of converters for HVDC:

- Current-sourced converters are made with electronic switches that can only be turned on. As an example, Line-commutated converters (LCC) used thyristors from the 1970s to the present day.

- Voltage-sourced converters are made with switching devices that can be turned both on and off. Voltage-source converters (VSC), which first appeared in HVDC in 1997, use transistors, usually the insulated-gate bipolar transistor (IGBT), which can perform power conversion at very high speeds and with minimum losses.

Power electronics has enabled the evolution of HVDC technology which can now offer greater controllability, including frequent reversal, of power flows and can make smaller HVDC systems economically viable. HVDC technology is also shown to enhance the AC grid, increase grid resilience and can be used to address grid stability and flexibility challenges. Large amounts of power can now be transmitted underground, underwater and on overhead lines making this new technology ideal for applications like offshore wind connections, city center in-feeds, as well as cross border interconnectors. There is now more than 300 GW of HVDC transmission capacity installed globally[20].

4.2.3 Demand: Electrification across Sectors

Transportation: The rapid development of power electronics in the transportation sector is enabling faster and more reliable charging of electrical vehicles, which greatly contributes to the adoption of e-mobility across the world. As an example, flash charging of electric buses at bus stops allows for an improved design of the electric bus, reducing the need for a large battery and making room for more passengers to be carried instead. Meanwhile, a sophisticated digital algorithm enables the stationary battery to cooperate with the fast chargers to smoothen charging power surges, providing essential relief to the grid.

Power Electronics is also playing a crucial role in the electrification of rail, helping remove the use of polluting diesel trains. Static frequency converter solutions help electrify rail networks by decoupling the voltage and frequency of the rail network from that of the national transmission grid.

Industrial: Through the applications of devices such as STATCOMs and active power quality filters, power electronics ensures a reliable and resilient power supply for industry, stabilizing current and voltage fluctuations and therefore increasing the productivity of industrial facilities. As an example, the use of electric arc furnaces for steel-making has grown dramatically in the last decade. They are used for melting and refining metals, mainly iron, in the production of steel. AC and DC arc furnaces represent one of the most intensive disturbing loads in the power system and are responsible for hazardous frequency perturbations and voltage fluctuations. Power electronic devices, such as STATCOMs, play an important role in mitigating the impact of these industrial processes on the power system and simultaneously ensuring that the power system has the flexibility to manage these loads.

4.3 Combining Power Electronics and Digital Technologies

The combination of PE and digital technologies offers significant benefits to the future electrical power grid. Power Electronics systems are supervised and controlled by digital controllers, as performance is important in obtaining the optimal system operation. The controllers perform millions of calculations per second using many inputs that are measured thousands of times per second.

The evolution of digital technologies facilitates even higher controllability and flexibility of the overall system and improves visibility by gathering and analyzing data thus improving decision making and control outcomes. Edge and cloud solutions help to increase controllability of grid assets, fleets, and the interaction of power electronics solutions with the power grid. Artificial intelligence, machine learning and advanced analytics bring the next level of customer experience when it comes to tasks such as planning, forecasting, trading, monitoring, and operations.

Technological advances are still required. When it comes to semi-conductors, increasing integration at component-, converter-, and system-level demands new power electronics concepts to address challenges in thermal management, insulation, testing, manufacturing, and cost reduction. Life cycle analysis, including recycling to ensure the sustainability of power electronic products, is of increasing importance.

The increased use of Power Electronic converters, at grid level, as well as at generation and consumption points, will challenge the power system stability over a wide frequency range. Methods to analyze, assess and mitigate such problems are needed, including being able to analyze an interaction between thousands of power converters at the same time in real-time simulation systems. Advances in high performance computing will play a role here.

Recommendation 5

A step increase in how we leverage digital technologies and power electronics is required if we are to achieve our energy and climate goals. The complexity across our power system is increasing exponentially. It is vital for power system stakeholders to invest in the innovative digital tools and technologies that maximize the efficiency of all available flexibility solutions. As the digitalisation of our energy system advances, digital technologies combined with power elec-tronics will make the system more connected, intelligent, efficient, sustainable, resilient, and flexible over the coming decades. However, accelerated digitalisation needs an infrastructure fit for the future, based on interoperability and common standards, gigabit networks and secure clouds. We must plan now for a future proofed digital infrastructure.

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5.

...and the key Role of Policy, Regulation & Business Models

In February 2024, ENTSO-E released its Strategic Roadmap[21] providing a framework to address the ambition and the challenges of the European electricity system. A key element of this roadmap is the focus on developing significant energy system flexibilities to balance the increased weather-dependency and complexity of the energy system. An accurate assessment of short, medium, and long-term flexibility needs and potential at both European and national level is vital for a cost-effective and reliable power system. A comprehensive "system of systems" approach combined with next generation levels of collaboration between TSOs, DSOs, technology providers and other stakeholders is necessary to coordinate the development and deployment of the most efficient flexibility resources.

For this to become a reality, the role of new business models which innovatively valorize the provision of flexibility services will be important. Policy makers and regulators also have a key role to play. The first step on this journey is take a more coordinated approach to developing complementary national assessments of flexibility needs and common policies across borders. In addition, flexibility needs of the power system at the European level must be regularly assessed (not only at the national level) and these needs should be linked to countries' National Energy and Climate Plans (NECPs), as well as national greenhouse gas projections. Regional cooperation is becoming essential to ensure that European countries can meet their flexibility needs in the most efficient and economic manner.

Recommendation 6

The next level of cross stakeholder, cross sector and cross geography collaboration is required to develop the forward-looking, coordinated, and holistic power system planning required to achieve our climate and energy goals. A more coordinated approach to increase the complementarity of national assessments of flexibility needs and common policies across borders can bring extended benefits. The development of integrated, forward-looking power grid plans (including offshore and onshore systems) must be a holistic European wide coordinated activity, rather than a coordinated planning of different national grids. Policy makers must regularly assess the flexibility needs of the power system at the European level and deepen coordination on different national approaches via individual countries' National Energy and Climate Plans (NECPs) and national greenhouse gas projections. There is scope for NECPs and projections to develop based on regional cooperation to ensure Member States can better meet their flexibility needs.

5.1 The Role of Innovative Policy

New policies can play an important role in addressing the need for more flexibility, from creating new roles for market participants to creating the conditions for a marketplace to sell services. An interesting example is the formal introduction of the role of aggregators in the Clean Energy for All Europeans package in 2019.

The 'Clean Energy for All Europeans' package was adopted to decarbonize the EU's energy system in line with the European Green Deal objectives. The Electricity Directive (EU) 2019/944[22] on common rules for the internal market for electricity, published as part of the Package, provides for the introduction of independent aggregators into European electricity markets for the first time. An aggregator is defined in Directive 2019/944 as an entity that combines multiple customer loads or generated electricity for sale, purchase, or auction in any electricity market. Based on the Clean Energy for All Europeans Package, member states are required to recognize and enable this type of market participant.

As households and businesses become more electrified, adding more electric vehicles, and becoming even more active as prosumers, often with dedicated storage systems, their ability to provide flexibility will increase. By combining the flexibility from multiple prosumers, aggregators can theoretically increase or decrease load or generation from their customers based on the needs of the power system, leveraging data and digital technologies such as smart meters and home management systems. Aggregators can sell this system service to relevant power markets.

5.1.1 Maintaining a Healthy Skills Supply Chain

While the energy transition is creating massive new opportunities for job creation, there are also growing concerns around hiring the skilled people to work on increasing complex areas from power system planning to power electronics. European governments and businesses are already developing skills training programmes to facilitate the upskilling and reskilling needs of a workforce in transition. New programmes are also being introduced in education systems which focus on building the relevant skills to deliver on energy transition.

Recommendation 7

Develop a healthy supply chain for skills. The skills needed to accelerate energy transition are changing, along with demographics and employee expectations. Across Europe there is drastic skills shortage, especially in the field of power electronics. Power sector companies will also need a workforce with suitable digital skills. The urgency is increasing as countries and companies throughout Europe invest heavily in semiconductor manufacturing and in renewable energy. Addressing the skills gap is vital for achieving the EU's clean energy goals. Efforts to increase diversity (and particularly the participation of women) in STEM subjects will be an important contributor to building up a more resilient skills supply chain. In addition to 'skills partnerships' across the sector, policy makers could also consider the inclusion of energy transition modules in the curricula for schools.

5.2 The Role of Innovative Regulatory Approaches

Network codes are a set of rules or regulations, so far drafted by ENTSO-E, with guidance from the Agency for the Cooperation of Energy Regulators (ACER). They are designed to facilitate the harmonization, integration, and efficiency of the European electricity market. ENTSO-E is also cooperating with the new EU DSO Entity on the drafting of new Network Codes, notably on cybersecurity and demand side flexibility, which must provide the harmonized rules for these topics to power system stakeholders.

Through the Capacity Allocation and Congestion Management (CACM) Network Code, as well as the Electricity Balancing Network Code, Europe is moving closer to a fully integrated internal European energy market. Flexibility services can now be offered by market participants, including aggregators, through the continuous intraday, day-ahead, or balancing-power markets. The Network Codes, considered to be an innovative approach to European regulation, have provided European market participants with the certainty required to develop business models around the provision of flexibility to the day-ahead, intraday, and balancing markets.

In addition to supply and demand side flexibility and energy storage, the improved operation of interconnected markets, thanks to the Network Codes, enables us to unlock a key lever of flexibility, interconnectors, or cross border capacities.

On a separate note, according to the proposed Regulation to improve the Union's Electricity Market Design, network tariffs should be designed so as to take into account the operational and capital expenditures of system operators or an efficient combination of both so that they can operate the electricity system cost-efficiently. This could represent a significant shift from the previous system depending on how regulators decide how to balance the need for forward looking grid build-out (including physical infrastructure as well as digitalisation and cyber resilience needs) with the likely increases in tariffs for customers.

Recommendation 8

The investments required to build out a future flexible power system will require a careful balancing. Regulators will need to enable forward looking expenditure while managing the impact of these investments on electricity bills. Innovative regulatory approaches will be required to balance the need for forward looking grid build-out with potential increases in tariffs for consumers. According to the EU Action Plan for Grids, the socio-economic welfare losses of delaying the network upgrades necessary to connect renewables and flexible demand will normally outweigh the additional initial cost of anticipatory investments. Regulators will need to cooperate closely with regulated enti-ties to find solutions enabling investments which go beyond current system needs but which have significant potential to reap savings in the future. Regulators will also need to consider how to lever-age network tariffs to account for operational expenditure (e.g. digital and cyber resilience invest-ments). This process will need to be guided and monitored by the European Commission to ensure a coordinated and effective implementation.

5.3 The Role of New Business Models

The shift to more electrification, digitalisation, and the increasing deployment of renewable energy resources at both transmission and distribution level is encouraging market participants to develop new business models comprised of technological solutions and coordinated market processes focused on the optimal operation of the whole electricity system. Both local and regional flexibility platforms are emerging to facilitate or co-ordinate the trade, dispatch and/or settlement of energy or system services between TSOs, DSOs, generators, and other market participants. This includes platforms that are self-contained marketplaces, as well as platforms that act as intermediaries to established wholesale and balancing markets. Moreover, these platforms pertain to both 'local' flexibility, where the primary focus is to resolve constraints on the distribution networks, as well as flexibility that can help with national (or cross-border) balancing of the electricity system.

These balancing and flexibility markets will provide clear opportunities for market participants to be compensated for the provision of system services related to flexibility. In fact, the future challenge for market participants will be to develop strategies and business models to optimize compensation for a flexibility offering through advanced algorithms, ML and AI, across a range of different markets.


Credit: Hitachi Energy

End notes

1. https://windeurope.org/newsroom/press-releases/wind-will-be-half-of-electricity-in-a-climate-neutral-europe/
2. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/future-eu-power-systems-renewables-integration-require-7-times-larger-flexibility-2023-06-26_en
3. https://www.irena.org/Energy-Transition/Technology/Wind-energy
4. https://www.iea.org/reports/electricity-2024
5. https://ourworldindata.org/energy/country/japan#how-much-electricity-does-the-country-consume-each-year
6. https://www.entsoe.eu/2022/06/28/entso-e-publishes-a-study-on-flexibility-from-power-to-hydrogen-p2h2/
7. https://environment-review.yale.edu/power-127-hours-economics-long-duration-energy-storage
8. Dunkelflaute is a period of time where there is neither wind or sunlight, meaning that little or no energy can be generated via wind and solar power. https://qz.com/can-europe-survive-the-dreaded-dunkelflaute-1849886529
9. Commission sets out actions to accelerate the roll-out of electricity grids - https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_6044/IP_23_6044_EN.pdf
10. Grids, The Missing Link – An EU Action Plan for Grids - https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0757
11. European Commission, Directorate-General for Communication, EU action plan for grids, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2775/919160
12. https://energy.ec.europa.eu/topics/infrastructure/electricity-interconnection-targets_en
13. Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R0943-20220623
14. https://transparency.entsoe.eu/
15. Digitalising the energy system - EU action plan - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0552&qid=1666369684560
16. European Commission, Directorate-General for Energy, Antretter, M., Klobasa, M., Kühnbach, M. et al., Digitalisation of energy flexibility, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/113770
17. Bødal, E.F., Lakshmanan, V., Sperstad, I.B., Degefa, M.Z., Hanot, M., Ergun, H., Rossi, M.: Demand flexibility modelling for long term optimal distribution grid planning. IET Gener. Transm. Distrib. 16, 5002–5014 (2022). https://doi.org/10.1049/gtd2.12651
18. Why AI and energy are the new power couple - IEA - https://www.iea.org/commentaries/why-ai-and-energy-are-the-new-power-couple
19. https://www.hitachienergy.com/news/features/2023/02/hitachi-energy-innovates-pioneering-solution-for-pumped-hydro-storage-plant-in-europe
20. https://acore.org/wp-content/uploads/2023/09/The-Operational-and-Market-Benefits-of-HVDC-to-System-Operators.pdf
21. ENTSO-E Strategic Roadmap 2023 – 2025: https://www.entsoe.eu/news/2024/02/15/entso-e-outlines-challenges-and-ambitions-for-european-electricity-system-in-its-newly-published-strategic-roadmap-2023-2025/
22. Note that the EU Council and Parliament reached a provisional political agreement on the Electricity Market Design Reform in December 2023, which will lead to an update of Regulation 2019/944 in the short term. https://www.consilium.europa.eu/en/press/press-releases/2023/12/14/reform-of-electricity-market-design-council-and-parliament-reach-deal/

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