Enabling Europe's net zero vision by proactively developing its power grids

Hitachi Energy

WindEurope

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Jochen Kreusel, Adrian Timbus, Alexandre Oudalov

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1. Executive Summary

The European Union has committed to cut greenhouse gas emission by 55% compared to 1990 by 2030, a key milestone in reaching climate neutrality in 2050. It has been widely recognized that electricity will be the backbone of the energy system when it comes to a clean energy transition. In addition to growth of traditional electrical demand, we see a clear trend in terms of growing electrification of transportation, industry and building sectors. Renewables, led by wind and solar, will play a central role in the shift from fossil-based power generation, with evolving energy carriers like hydrogen complementing direct electrification and helping to address harder-to abate sectors. This has been analysed in many reports, among others by ETIP Wind in 2021 [1]. Direct electrification, complemented with the indirect electrification of hard-to-abate sectors, is at the centre of the road to cut energy sector emissions to net-zero by 2050. A broad set of initiatives and programs has been launched to transform the power generation sector as well as demand in order to support this objective. However, all of these measures will only be successful if power grids will be available in due time and with the right capabilities.

There is no point in generating renewables if we cannot deliver them to where they are needed. We therefore need to take a holistic view across the power value chain consisting out of generation, transmission and distribution grids and consumption. We must recognize that power grids, a significantly under-invested sector, are a vital link and highly important facilitator in the chain. Grids will be key as we build resilience, enhance capacity, enable flexibility and strive for greater reliability and efficiency. And added to this are the new supply and demand complexities such as variable and distributed supplies or new demand loads like electric mobility and data centres.

Therefore, the grid needs to evolve considerably, and this is happening even as we speak. But without significant and urgent grid investments we could miss our climate goals. Moreover, we need to understand, what additional functionalities and services we need from future grids and ensure their timely roll-out in parallel to enforcing grids.

The energy transition has become very urgent. When breaking the 2050 targets down to concrete actions it becomes very clear that there is no time to lose anymore – neither for sequential working nor for avoidable delays. Urgency requires a pro-active, highly collaborative and holistic approach, particularly in today’s, unbundled framework of the European single market for electricity:

- **Pro-active:** We need to plan and implement grids and the massive new generation capacities simultaneously. And we need to roll out new infrastructure functionalities long before we recognize that they are missing.
- **Collaborative:** In order to minimise the risk of stranded investments, stakeholder groups need to align from the very beginning. They need to share their plans, discuss and agree on required measures and division of work and responsibilities across the entire power system value chain and commit to actions to be taken.
- **Holistic:** The future power system of Europe will benefit from international exchange and integration across all levels. Hence, it has to be regarded as a truly European system, with European decision and planning processes, with interdependencies and trust between member states and a truly European commitment. Moreover, it also has to be regarded as an integrated system across all of its levels. Planning and deployment have to be aligned from the offshore grids over the onshore transmission grids to the distribution grids.

Beginning with the 3rd Energy Package [2, 3] the European Union is moving in these directions: The introduction of a European planning process for transmission grids, the Ten Year Network Development Plan (TYNDP), and of network codes, both valid for the entire single European market for electricity and subject to public consultations, obviously have enforced a more European perspective and stakeholder engagement. However, with the speed required by the climate goals, further catalysts and enablers for the energy transition need to be unleashed:

- All stakeholders need to be involved and need to engage in a collaborative approach from early planning to deployment. By that, **predictability and certainty of implementation will increase**. Stakeholders includes those affected directly, such as generators, network operators, consumers and technology providers, and those affected indirectly, such as landowners, representatives of nature conservation, owners of other infrastructures, just to give some examples.

- In order to accelerate the transition, **all types of waiting times during planning and permission need to be minimized or even eliminated**. It therefore may even make sense to develop and even permit different grid scenarios in parallel in order to be best prepared when it becomes clear which of the scenarios materialises.
- Legislation and regulation need to focus **not only on collaborative planning but also on accountability in deployment**. As we are talking about the transformation of an entire system in which actors are depending on each other accountability includes financial compensation mechanisms in case parts of the system are deployed too late.
- Developing future grids should not be restricted to adding more wires. Future grids will have to offer new functionalities to accommodate highest possible shares of renewable generation with existing and new assets, to empower consumers, to integrate and coordinate distributed assets, just to give the most obvious examples. **Functional development of the power system is a coordinated effort of all stakeholders and needs to be orchestrated and driven accordingly.**
- Power systems are a technical infrastructure. Hence, **technology is a key enabler**. Technology providers have developed many solutions in the past, many of them also pro-actively and on their own risk. Therefore, the good news is that most technologies required for the achievement of near- and medium-term goals (e.g. till 2030) already exist. Expedited deployment of these technologies and rapid digitalization will be critical to achieve speed and scale required for reaching the net zero target in time.
- Technology providers are ready to support the next steps and at the same time are investing in R&D and production capacity. But without any doubt increased certainty and predictability is an important catalyst to accelerate these activities even further. **And beyond that manufacturers and grid operators need to find new ways to commit on mid-term demand and its coverage in a way allowing ramping up production capacities in time.**

The energy transition is an interdisciplinary challenge with many stakeholders involved or affected. Technology will play a key role as energy infrastructure are complex technical systems. But technology development and deployment will need to be supported by the right policy and regulatory frameworks, appropriate financing, innovative business models and above all collaboration across stakeholders, geographies and sectors.

2. The power grid – the backbone of the energy system

The EU has committed to cut greenhouse gas emissions by at least 55% compared to 1990 by 2030, a key milestone in reaching climate neutrality in 2050. The European Commission’s analysis shows that direct electrification, complemented with the indirect electrification of hard-to-abate sectors, is the most cost-effective and energy efficient way to cut energy sector emissions to net-zero by 2050.

This report shows that deep decarbonisation of the economy is possible. In fact, it will cost no more as a share of GDP than our energy system costs today. And it will dramatically reduce external costs, notably of air pollution, not accounted for today. The technologies that will deliver the bulk of decarbonisation are already available or in development today but need the right market signals to be deployed at scale.

The EU can deliver on climate neutrality by rigorously prioritising the deployment of future-proof technologies, investments in infrastructure and the development of the right business models. And at the same time, it can fully reap the economic and societal benefits of renewables-based electrification.

2.1. Electrification is the most cost-effective path to climate neutrality

The European Commission's scenarios show renewables-based electrification will be central to delivering climate neutrality by 2050. They show that more than three quarters of the final energy demand will be electrified. Electricity will directly cover 57 % of final energy uses while providing another 18 % indirectly through hydrogen and its derivatives as illustrated in fig. 1. According to the Commission's scenarios, this will require the electricity system to grow to 6.800 TWh from less than 3.000 TWh today. And it will require wind to be 50 % of the EU’s electricity mix with renewables representing 81 % of it. Delivering a climate-neutral economy will not lead to higher costs for society. The energy system cost relative to GDP will be similar to 2015 levels, at about 10.6 % of GDP, according to [1].

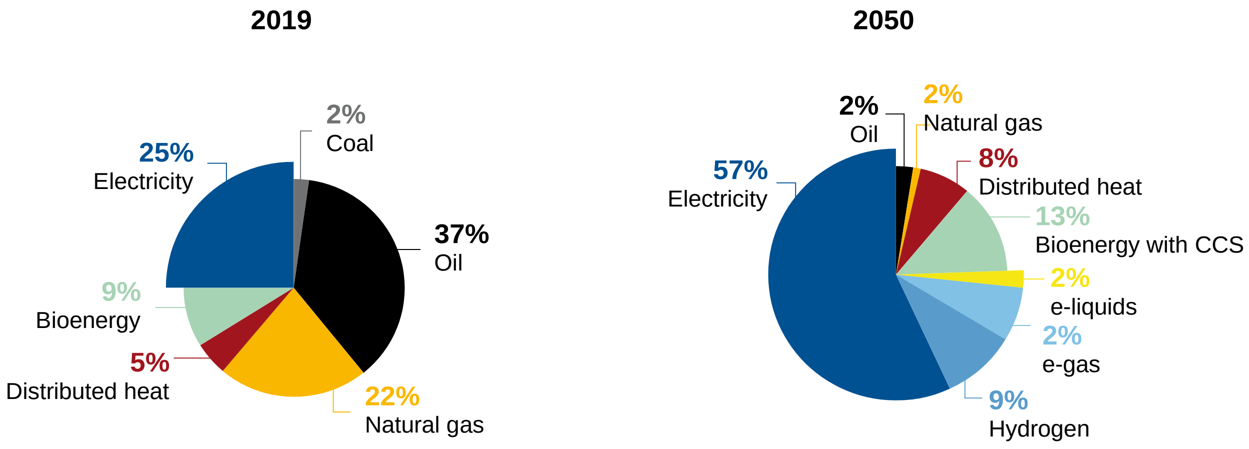

Fig. 1: EU-27 final energy demand by energy carrier. Source: European Commission Impact Assessment, COVID MIX scenario, 2020, from [1]

2.2. Electrification can drive the decarbonisation of industry, buildings and transport

Industry could directly electrify 76 % of its power and heating consumption with technologies that are commercially available. We will need to scale up the supply chain of these technologies, such as electric arc furnaces and infrared heaters to meet growing industry needs. Moreover, industry could electrify even more of its power and heat consumption with the development of emerging technologies including thermal plasma heating, electrolytic reduction of iron ore (electrowinning) and electric steam crackers and reformers. Reaching net-zero emissions in industry will also require the substitution of fossil-fuel feedstocks with renewable hydrogen and derivatives in steel, cement, chemicals, and refineries.

Certainly, the passenger vehicles market will be fully electric by 2050, and most likely a high share of all other road transports, too. Battery electric vehicles are significantly[1] more efficient than conventional cars which will help decrease total sector demand. Battery electric vehicles will soon reach cost parity with internal combustion engine vehicles, but their deployment depends largely on the currently lagging expansion of charging infrastructure.

Short-distance maritime transport can technically be electrified, but investments in ports is still needed to provide robust infrastructure. For deep-sea transport, renewable-based ammonia and methanol appear as the most promising fuels along with renewable hydrogen.

Heat pumps will drive the decarbonisation of heating and cooling in buildings, by almost tripling electrification rates in residential buildings. Overall, this will result in a strong increase of electricity demand, particularly after 2030. Fig. 2 shows two scenarios of the development of generation mix feeding electricity demand in EU27. Graph a) is taken from [1] and shows an estimation without detailing of the geographical distribution of resources and also with only a very rough modelling of system evolution over time. In this report we have added further analysis with particular focus on the geographical distribution of resources in the interconnected European power system[2], electricity cross-border interconnector capacities and evolution of the system in the next two decades. Graph b) therefore shows an updated

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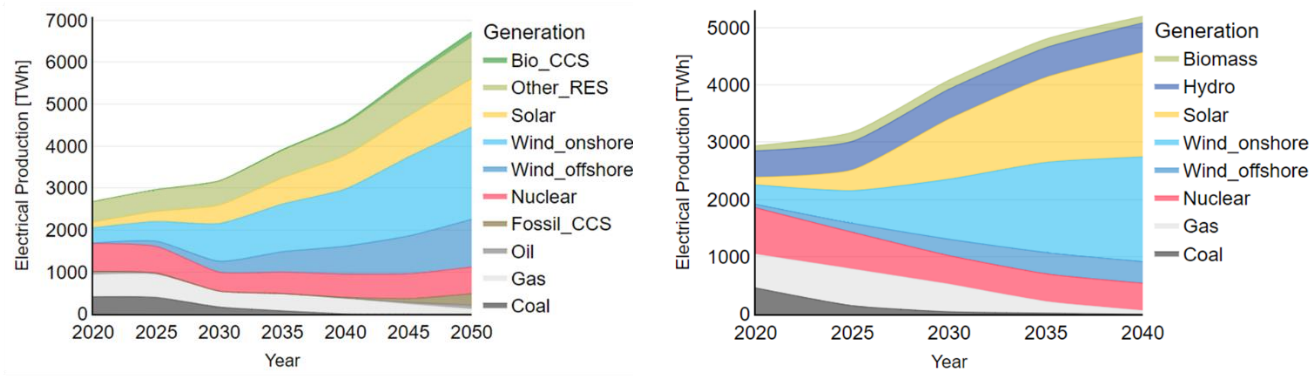
1 According to our own analysis battery electric vehicles are at least 3,5 to 4 times more efficient than conventional cars.

2 EU27 member states, United Kingdom, Norway, Switzerland and non-EU Balkan states synchronised with the European transmission grid

scenario for the time until 2040. In principle it comes to the same conclusions, particularly regarding the high share of variable renewables. The more detailed modelling of system development in space and over time resulted in a more granular forecast of changes in demand. This resulted in a more realistic s-shape evolution of the new load sectors, with a slower starting phase, a strong take-off in the middle of the transition and a saturation at its end.



a) Source: WindEurope based on European Commission Impact Assessment, COVID MIX scenario, 2020 [1]

b) Source: Hitachi Energy analysis

Fig. 2: Expected development of the EU27 electricity production mix

2.3. The power grid will remain the backbone of a climate-neutral energy system

Boosting electricity grids investments is indispensable to delivering climate neutrality, coordinated and proactive system-wide planning will allow Europe to leverage indirect electrification notably via hydrogen valleys.

In 2021 ETIP Wind has pointed out that grid investments need to double from the current €40bn a year by 2025 at the latest. Moreover, as a first estimate, but based on very limited grid modelling, this report indicates a need of additional interconnector capacity of 1,7 times today's capacity by 2030 [1]. In the following chapter grid requirements will be analysed further, based on a more detailed model of the geographical structure of the European power system.

One in three grid infrastructure investments have been delayed or rescheduled. The upcoming Ten-Year Network Development Plan (TYNDP22) must address this by including all the infrastructure investments needed to deliver on Europe's 55 % climate target.

The EU needs to deploy an optimized offshore grid to deliver on its objective of 300 GW of offshore wind by 2050. There are no reasons to expect fundamental technical problems, and from an overall system efficiency point of view connecting this capacity electrically is the obvious approach. However, sea basin planning, speeding up permitting, and new market arrangements ensuring offshore hybrid projects are pre-conditions to having an optimized offshore grid. This needs to be done collaboratively, with the contribution and inputs from all stakeholders.

The investment framework for TSOs and DSOs should reward anticipatory investments and investments that deliver the most TOTEX benefits, rather than focusing exclusively on lowering the CAPEX. The regulatory framework, which traditionally had a primarily reactive approach, focusing on risk minimization, economic efficiency and reliability of supply, needs to be further enhanced to support this anticipatory approach, while maintaining economic efficiency and security and reliability of supply.

3. The energy transition requires a European, holistic, and digital approach

Transition towards a carbon-neutral economy is not possible without a wholistic transformation of the energy system. Long-term scenarios are an important complement to short-term incremental policies, providing orientation and indications for fundamental infrastructure investment decisions. As a leading provider of technologies for electrical networks Hitachi Energy analyses the long-term perspectives of energy demand in a climate-neutral Europe and identifies when, where and what kind of energy infrastructure is needed to achieve full decarbonization targets (see e. g. [4, 5]).

Parameters of scenarios may vary but they all converge towards similar and robust conclusions:

- Electricity from renewable sources will be the main input for the entire energy system (see also [6]). Wind and solar PV together may account for up to 75-80% of total generation.
- Transportation, buildings, and industries shall be directly electrified wherever possible resulting in most efficient and economic use of resources including land and maritime areas. We expect that direct use of electricity may achieve 60% of final energy consumption. For the remaining part complementary, sustainable energy carriers are needed.
- International collaboration and integration are key for a secure, cost-efficient supply. The more interconnected and flexible grid enables an effective use of complementary renewable resources and demand across European geographies and increases a real-time utilization rate of wind and solar generation. In addition, it may facilitate energy exchanges between countries and regions with constrained renewable capacity and ones with a potential over-supply (see also [7, 8]).

> Benefitting from complementary demand and supply patterns is an important source of flexibility. Hence, our approach to the European power system needs to evolve from a system of mutually cooperating national systems to a truly European system, with much stronger interdependencies.

Europe will require a notable expansion of electric transmission grid to accommodate unprecedented shares of variable renewable sources. Fig. 3 demonstrates supply-demand balance at national levels for some selected countries in 2040 during a typical summer day. Countries with different generation and demand patterns support each other by complementing varying resources with clean dispatchable sources and space restricted areas with surplus generation from less densely populated regions.

There are three main sources of flexibility which operate on a continuous base:

1. Cross-border interconnectors are used to exchange power between regions in real time. Some regions do import or export energy 24 hours per day while other regions change a power flow direction several times per day. The most typical diurnal pattern is to import energy during the night-time and export excess energy during the solar hours.
2. Batteries and pumped hydro storage are used to shift energy in time at different scales. Depending on a specific geography some regions possess a remarkable long duration storage capacity and use a strong grid to support supply-demand balance in the regions beyond their own borders. They use remote energy imports to charge a local bulk storage and export energy during periods of local storage discharge.
3. Electrolysers for green hydrogen production at times of significant renewables over-supply usually during the solar hours. Electrolysers are technically capable to vary their production in a wide range. The produced hydrogen can be stored as compressed gas in underground reservoirs or further converted to a variety of none-fossil fuels.

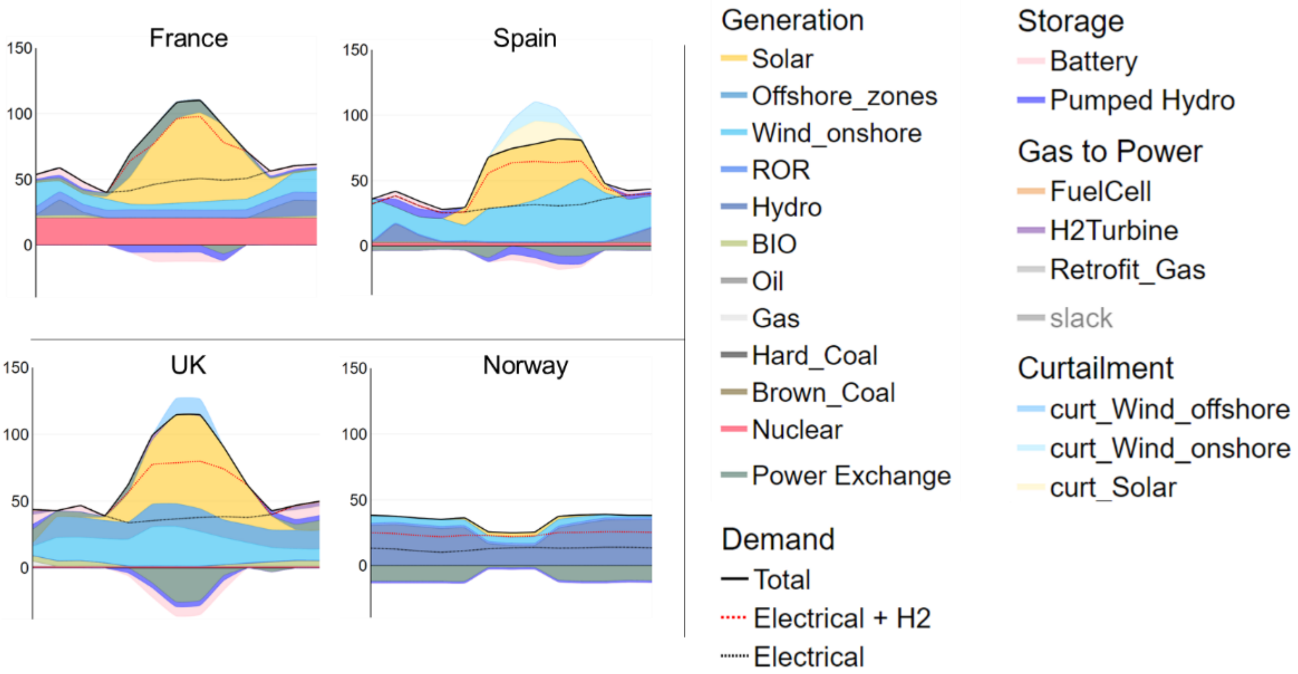


Fig. 3: Demand and supply patterns of four complementary countries during a typical summer day in 2040

Cross-border transmission capacity may increase from 87 GW of installed capacity in 2020 up to almost 150 GW by 2040-2050. A significant capacity increase of European transmission network is mainly foreseen along the north-south axis Spain-France-Benelux-Germany-Nordic countries and the west-east axis UK-Benelux-Germany-Eastern Europe-Baltic countries. This is illustrated in fig. 4.

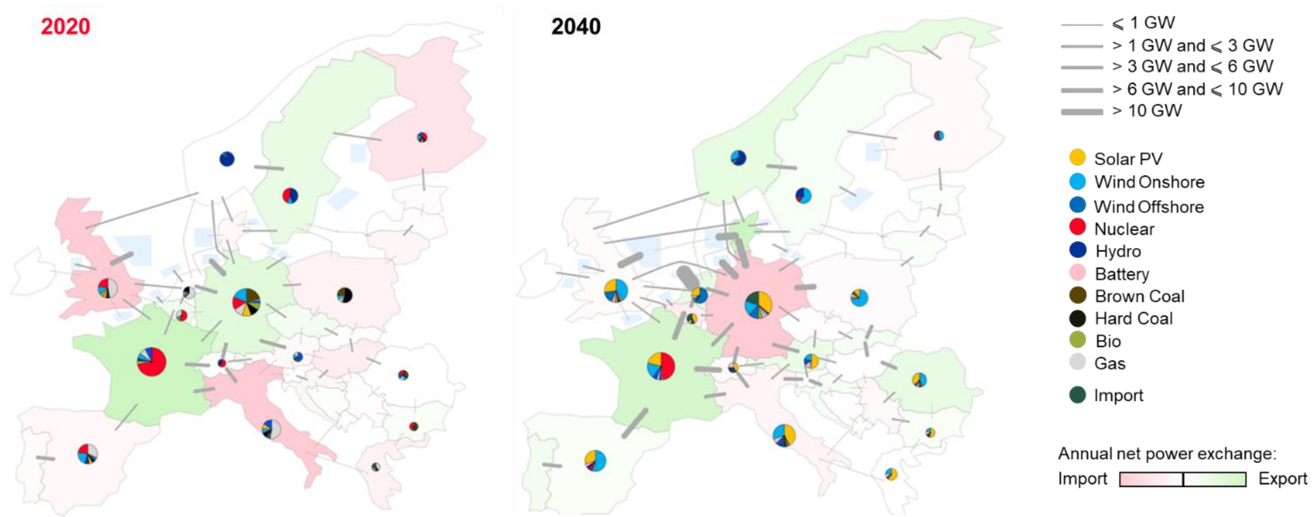


Fig. 4: Possible development of cross-border interconnector capacities from 2020 to 2040[3]

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[3] This analysis has been made prior to the synchronization of the power systems of Ukraine and Moldova to the ENTSO-E system. Future studies will investigate the impact of this system expansion, particularly reflecting the rich potential of renewable energies in Ukraine.

The amount of power exchanges is going to intensify, and their patterns will be less regular which will require a higher degree of coordinated power flow control and flexibility.

Just to highlight an economic advantage a more expanded grid with higher interconnection capacity brings to the society we can mention that in case a future grid expansion is not possible or significantly delayed a total system cost over the next 20-30 years may become 30-40 % higher compared to the case where all required expansions can be realized when needed, provided the net zero objective will still be met. The reason for these higher cost with less or delayed interconnector capacity while still meeting the climate goals are significantly higher installed capacities for renewable generation and storage allowing more local supply.

Analysis discussed so far has highlighted the division of work between European countries with differences in availability of primary energy – primarily hydro, wind and solar power -, space and demand patterns. This division of work and complementarity results in the need of a truly European view on developing the transmission grids. But there are two more important consequences of high shares of variable renewable energies:

Traditionally, distribution grids were relevant only locally. But in future they may have systemwide relevance as they may collect energy from generation clusters or interconnect horizontally with neighboring distribution grids. Hence, they need to be considered in system planning.

Most of the onshore generation capacity, which was historically connected to the transmission level, will now be connected to distribution[4] grids. This will result in massive adaptations in distribution grids which have to be proactively planned and coordinated with the development on transmission level. Up to now there has been much focus on further developing planning processes and permission procedures for transmission grid but much less for distribution grids. But if distribution grids will not be upgraded in time there is a risk that generation clusters will not be able to transfer their production to the transmission level and consequently need to be curtailed. Therefore, a holistic view on grid development does not only need to become more European, but it also needs to integrate the distribution grids.

Last but not least distributed variable resources are exposing power systems to much more fragmentation and variability than in the past. Millions of assets will need to be coordinated and generation output will change fast. Different weather patterns will result in a much broader variety of load flow situations that in the past. Power grids will have to facilitate this, providing faster response and more flexibility. Digitalisation and non-conventional grid components are obvious parts of the solution.

4. A new approach to grid infrastructure is required: Proactive and collaborative

4.1. A need to accelerate

Europe's plans to become climate-neutral are ambitious. In its Communication A Clean Planet for All from 2018 the European Commission has developed eight long-term scenarios with, among many other ambitious targets, offshore wind capacities ranging from 230 GW to 450 GW by 2050 [10]. Assuming just 300 GW to be added by 2050 means that roughly 200 MW of offshore capacity including the necessary grid adaptations have to be added every week from now – or 10 GW every year. In 2021 only 3.4 GW of offshore capacity were installed [11], which illustrates the challenge and the current gap.

Acceleration requires working in parallel, increasing certainty by commitment, starting process as early as possible and maybe even developing alternative paths in parallel in the early phase of the process.

4 including the 110 kV level, also known as sub-transmission or regional distribution

Accelerating deployment is a multi-facetted challenge. All stakeholders will have to contribute in an orchestrated and coordinated effort. Examples for areas of improvement are:

- Planning and permitting of new infrastructure: Early alignment of grid operators, regulators, grid users and stakeholder groups affected by the grids (e.g. defence and fishing sectors for offshore, landowners and general population for onshore) can help providing certainty to all stakeholders. This has been extensively discussed for instance in [9]. Planning is not only about preparing latter implementation but is also a means to show and clear (through different scenarios) the implementation path. It therefore may make sense to develop and even permit different grid scenarios in parallel in order to be best prepared when it becomes clear which of the scenarios materialises. In general, all types of waiting times during planning and permission need to be minimized or even eliminated.
- Standardisation and modularisation can help to accelerate deployment and at the same time reduce cost. Grid operators and technology providers need to cooperate in this area. Various initiatives have been launched in the meantime, for instance on HVDC interoperability, on HVDC as the backbone of future, hybrid AC/DC power system in general and on offshore grid connections.
- Ramping up generation capacity and enforcing and expanding the grids accordingly will also be a challenge for the supply chain. So far, Europe's technology providers have consistently proven that they are willing to invest in time. A very recent example are the long underground cables under construction in Germany. There were many concerns about the production capacity for these when the discussion on going underground started about 15 years ago. But today capacity is available. However, the ramp-up rates we have to anticipate for the future are much higher and the current scarcity across many supply chains gives a first indication that more efforts are required than in the past. Only clear and reliable mid- and long-term boundary conditions for private investors (manufacturers, network operators and power generation investors) will enable the required investment level. Moreover, manufacturers and grid operators need to find new ways to commit on mid-term demand and its coverage.
- A bigger challenge is a shortage of talents. All players are increasingly facing problems in finding people with the right competences already today. In March 2022 a coalition of 18 associations has addressed this issue in an open letter to the European Commission, requesting to ask member states to monitor and disclose the gap between available and required professionals as well as to launch an ambitious EU campaign to change mindsets across Europe and enhance the attractiveness of technical/vocational education and careers in the twin transitions. [12]

4.2. Grids as the critical resource of the power system

Historically grids and generation assets were planned together, taking the needs and structure of demand as input parameter. With liberalization of the generation and supply business and unbundling of grids and energy business this holistic approach has been broken. However, this did not result in immediate problems after the liberalization of European electricity markets in 1998, as neither the geographical distribution of demand nor the sites of power stations were changed by this step.

Problems started to occur when electricity markets began to change dispatch patterns. The first driver for change was the integration of the central European countries into the continental power system, resulting in an increased demand for East-West transmission capacity. In a second period new power plants were built in the second half of the first decade of the century, but not necessarily at the same places as the old ones. The last and most fundamental driver for a mismatch between grids and the generation system was the rapid growth of variable renewable generation with high concentration at attractive sites, most of which are remote from the centres of demand.

With its 3rd Energy Package [2, 3] the European Union acknowledged this consequence of unbundling and introduced a planning process for transmission grids. This process, the Ten Year Network Development Plan (TYNDP), is led by ENTSO-E and its members, who develop scenarios and grid developments as basis for subsequent public consultations and eventually legislative confirmation on European and member state level. This new approach was sufficient as long as changes both in demand and supply were moderate. However, the principal problem of difference in speed between the non-regulated sectors of grid users with an unprecedented speed and innovation across the entire value chain and the regulated grid sector with thorough but also slow planning, approval and deployment processes still remained.

With the energy transition the situation has changed again. Sector integration will result in a dramatic increase of electricity demand. At the same time renewable generation will have to ramp up even faster than in the past two decades. Last but not least by far the majority of onshore generation will feed into distribution grids instead of the transmission level. Changes are fundamental and omnipresent – and they will have to be implemented much faster than in the past. As multiple actors – grid operators, developers of generation assets, consumers building distributed generation assets or heat pumps or buying electric vehicles, just to name same examples – are expected to take action fast and in parallel, a much closer coordination of grid with the development of the generation system and the demand side is required.

> While in the first decade of the unbundled European market for electricity regulation only had to deal with grids serving an unchanged technical structure of power systems, today grid planning and regulation have to deal with a system with is subject to a fundamental and rapid change.

The process of grid planning and permitting therefore needs further development. As interconnection within and beyond Europe becomes more important, a truly European perspective instead of coordinated national ones is needed. Because of the massive shift of generation from transmission to distribution level, turning distribution grids into collection grids, the development of distribution grids, particularly the so-called sub-transmission or regional distribution level (110 kV) needs to be considered in an integrated grid development process.

Finally, grid planning and deployment has to become more pro-active. Starting with the 3rd Energy package from 2009, the European Union, has developed a world leading process for planning transmission grids in an unbundled power system. Much progress has been made already in collaboration among grid stakeholders. Nevertheless, considering the urgency of the energy transition, alignment of stakeholders needs further improvement. Within the existing paradigm of regional monopolies granted to network operators for a certain period of time, today's sequential approach to planning, in which grid operators develop scenarios and propose grid development plans for a latter, retrospective public consultation, should be transformed to a collaborative process. All grid stakeholders, particularly generators and consumers should be actively involved in the process from the very beginning. Implementation of grid development plans needs to become more binding (or mechanisms need to be defined compensating investors in case they cannot use their assets because of delays in grid deployment).

> There is no point in generating renewables if we cannot deliver them to where they are needed. We therefore need to take a holistic view across the power value chain (generation, transmission and distribution, consumption). Closer and earlier alignment of developments within the grids and at grid edge and strong commitment of all stakeholders to deployment are a pre-requisite to achieve the targets of the energy transition and to maintain quality and security of power supply.

Grids are not all, but without grids all is nothing. Today the adaptation and expansion of power grids does not take place timely and in line with the grid edge developments. Hence, achieving the targets of the energy transition is at high risk. Moreover, the existing but insufficient grids may experience severe operational challenges which will impact the quality and security of supply in Europe. Closer and earlier alignment of developments within the grids and at grid edge and strong commitment of all stakeholders to deployment are required.

4.3. Grid development is more than adding wires

Traditionally, the focus of grid development was on expanding the grids by adding new lines or enforcing existing ones. Without any doubt this will remain an important part of the task in future. But it is not sufficient. This structural part of development has to be complemented by functional development. Future power systems will have mainly three new characteristics:

- They will consist of millions of distributed, but active elements. These are distributed generators as well as new types of loads providing flexibility through demand side management. These resources need to be coordinated in order to ensure system stability and reliability of supply.
- Caused by variable renewable resources, primarily wind and solar power, and new types of demand, such as fast - charging facilities for electric vehicles or heat pumps, there will be much faster transitions from one state to another than in the past.

- Local and regional concentration of renewable resources in combination with variations of output of these will result in strongly and rapidly varying load flow situations. Particularly meshed transmission grids will have to deal with these new challenges. Moreover, they will need to be geographically expanded in order to benefit from regional complementarity of primary energy resources.

4.3.1. New functionalities

Grids and their operators will therefore have to provide not only more of the traditional grid capacity, but also new functionalities. Examples for such are:

- Increased transparency and operational flexibility all over the system. Sensors and actors will be required everywhere, particularly in the distribution levels. Information from these will support planning, operation and maintenance and will support higher hosting capacities, particularly for distributed resources, but also more flexibility in utilising existing grids.
- Universal and secure digital connectivity for distributed resources at grid edge. Examples for such resources are distributed generation as well as consumers offering demand side flexibility, for instance industrial facilities, large office buildings or charging infrastructure. The purpose of such digital connectivity is to allow service providers to develop and implement new business models which will help integrating these resources into the electricity market and provide the flexibilities required for stable system operation. With the current rapid take-off of electric vehicles flexible charging is an obvious example for such service, which would help ramping up electric mobility – but unfortunately network operators are not prepared to support it.
- Software systems, together with non-conventional grids assets (as actors) and sensors supporting curative handling of disturbances and by that releasing grid capacity which previously, due to the principle of preventive handling of disturbances, had to be reserved in the interest of system stability.
- Millions of distributed active assets do without doubt increase the complexity of power systems and cause challenges. But at the same time distributed generation also offers a great opportunity to increase resilience. Provided, local distribution networks can operate in stand-alone mode and ensure at least a minimum supply for critical infrastructures, such as water supply, hospitals and telecommunication networks, in emergency situations, the scenario of a system-wide blackout is significantly reduced. Technically such systems can be built already today, but today's legal frameworks and network codes do not only not request such behaviour, they even prevent it.

4.3.2. New regulatory approach

Many of these new functionalities have in common that they require coordinated activities of many players. Hence, the traditional regulatory approach addressing individual players only, cannot ensure their implementation. Another challenge comes from the fact that the purpose of grids is to facilitate benefits across the entire power system. This means that functionalities, which are beneficial for the system as a whole may not be beneficial for the grid operator. In the commonly used regulatory approach of combining an incentive-based element focusing on the economic efficiency of the grid operator as a stand-alone business with a quality element ensuring quality of today's service such facilitating and forward-looking investments cannot take place.

The traditional regulatory approach consists out of two pillars: Efficiency and quality regulation. This assumes the objective of efficient provision of a known and stable service in a stable environment, which was adequate prior to the energy transition. But the energy transition means not only a change in the energy mix, but also a fundamental transformation of the technical system for power generation, transmission and distribution. As a consequence, a third pillar needs to be added to regulation, complementing the proven approach from the past. Eventually, regulation should consist out of three elements:

- Efficiency regulation, ensuring that a given tasks is delivered efficiently.
- Quality regulation, ensuring service provision at a defined quality level.
- A process defining and monitoring the functional development of the grid infrastructure.

The need for an extension of the regulatory principles has been highlighted by various grid stakeholders, e. g. in [13] and [14], and has also been reflected in article 59.1 (I) of the Electricity Directive of the Clean Energy Package [15], asking National Regulatory Authorities for “monitoring and assessing the performance of transmission system operators and distribution system operators in relation to the development of a smart grid that promotes energy efficiency and the integration of energy from renewable sources, based on a limited set of indicators, and publish a national report every two years, including recommendations”.

Fig. 5 illustrates a possible implementation of the proposed third regulatory pillar. Core element is a stakeholder forum representing all relevant stakeholder groups. This forum agrees on functionalities to be provided by the grid infrastructure, monitors their deployment and proposes corrective actions in case deployment does not take place at sufficient speed. Moreover, it regularly reviews assumptions from the past and revises them if necessary. Hence, this process ensures permanent learning and adaptation in an agile manner. This reflects well the reality of a transition which has never been made before and for which no blueprint exists.

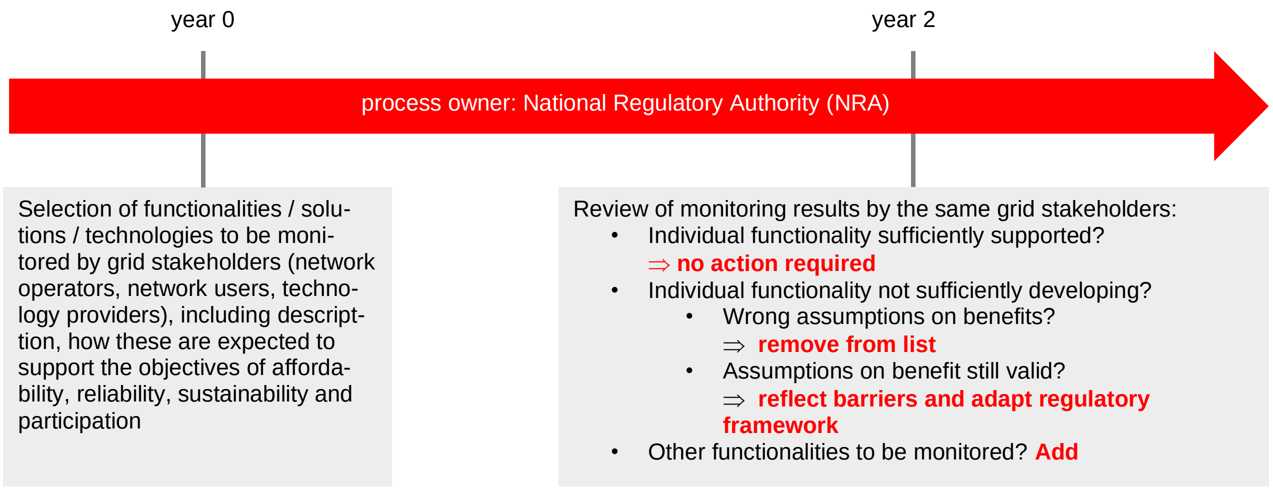

Fig. 5: Concept of a collaborative process defining required grid functionalities and monitoring their deployment (based on [14])

5. Technology is ready to accelerate

The energy transition is a truly holistic challenge. However, in its core it is the transformation of a technical infrastructure, which depends on technological progress and innovation. Europe’s power grids serving the unique European interconnected power system have always been among the most advanced and reliable grids worldwide. Europe has a unique industry cluster of grid operators and grid technology providers. Moreover, it has a leading research and education landscape. The combination of these resulted in countless research, demonstration and implementation projects for new solutions supporting and enabling the energy transition. As a consequence, technologies have always been available in time to do the next steps in the transition and will continue to be available as long as we continue investing in research and innovation in the energy sector in Europe. Technology is not the bottleneck of the energy transition, it offers important opportunities to make the energy transition a success story, but it also requires further evolution. The following chapters summarise the most important building blocks of power grids of the future, highlight recent achievements and outline the next steps.

5.1. Scale up with HVDC

Most technical solutions are available, but some of them require further development. One of the most obvious ones is HVDC (High Voltage Direct Current). Due to its unique features to transmit and control bulk amount of power at high efficiency, HVDC is a key technology to scale up, capture and integrate more offshore wind in Europe. Recently deployed projects used HVDC technology to connect wind farms of 1GW+ to the continental grid, while plans and proposals are discussed for standardization of 2GW+ HVDC grid connection solutions to accelerate the offshore wind development in Europe. But the technology is also a key enabler for concepts like energy hubs or energy islands, where 5GW+ up to 10GW+ grid connections could be realized utilizing HVDC [13], [14]. Further innovation on topics like design of an offshore grid (dominated by generation) and energy islands, its operation and scalability are still necessary to ensure we pave properly the way to a flexible and resilient European grid.

Multi-vendor interoperability is a pre-requisite for broader deployment of a future, hybrid (AC and DC) transmission grid. Similarly, as for the AC systems, where we use a combination of communications standards such as IEC 60870-5-104 [16] and IEC 61850 [17] to obtain vendor interoperability between substations and control centres, we also need to further develop the today proprietary HVDC systems to communicate between themselves and obtain interoperability of the hybrid grid.

Another dimension of the technology which needs to be further elaborated is the multi-terminal setup with multiple vendors. This dimension brings additional interoperability challenges and requires alignment across vendors on system design methods and practices, as well as on control and protection concepts for the overall system. Therefore, modelling and planning tools for HVDC and AC/DC hybrid grids need to be harmonized across the industry, in order to be used more effectively and efficiently. European transmission system operators, manufacturers and universities, supported by the European Commission, have made important steps in the past years in projects like Best Paths, PROMOTioN and currently READY4DC. These shall prepare the ground for the first full-scale, real-life multi-vendor, multi-terminal project. Such a full-scale first-of-its-kind project bears significant innovation risks. The aforementioned projects are aiming to reduce these to a minimum, but there will be a remaining risk nevertheless. As network operators are not entitled to cover such risks, a joint effort, including political and financial support, will be required for this final step of developing European competencies in an area which is critical to enable the acceleration of renewable generation around and across Europe supported by the required grid build-up.

One mid- or longer-term technology with innovation potential for the future grids are superconducting cables or ducts. Superconductivity as a concept and technology promises astonishing efficiency increase, however its cost-effective applicability to the power sector is yet to be proved. The development of superconducting transmission lines for 5 to 20 GW pan-European transmission corridors could be one of the strategic innovation targets of the next decade.

5.2. Reduce costs and risks with digitalization

5.2.1. Energy system automation

Historical, automation helped us increase efficiencies and reduce costs in the value chain. The power grid in Europe has a fairly good degree of transparency and remote controllability, however most of it is at the transmission level. To deal with the integration of the new assets connected at the grid edge and with the complexity of the future system, the automation of the power grid needs to step up. An obvious gap is today the automation of the distribution systems, where more sensors and actuators need to be added for helping the Distribution System Operators (DSO) to properly integrate the distributed generation resources as well as e-mobility charging points and to continue to deliver reliable power to their consumers while providing new network access points to industries. To manage the new load patterns of the distribution systems, the DSO should add not only protection and control solutions based on mission-critical communications, but they need to look at energy management solutions such as ADMS (Advanced Distribution Management Systems) capable to monitor in real time all assets connected to the network and utilize them as power and energy flexibility resources to ensure grid stability. Moreover, whenever the grid architecture requires, the DSO should also employ more advanced actuators such as energy storage, line voltage regulators and even solid-state transformers. These new assets employ power electronics technology to provide a very fast control of active and reactive power, voltages, and power flows in the nodes of the grid. Integrating them into the overall distribution management system not only will support the DSO to manage the complexity of their future grids but will also help them managing the interfaces between the transmission and distribution systems and validate and provide energy services to the Transmission System Operators.

> Aside economic optimization there are two main drivers for automation: Speed of reaction and complexity. The required very fast response time is the reason, why protection in power systems has always been automated. With orders of magnitude more assets to be managed in future power system built on distributed resources decision-supporting systems will become increasingly important for all aspects of grid operation.

One another aspect of automation is the ability to embed the decision making withing the solutions themselves, speeding up the reaction to various events in the grid and providing the relevant speed to address the needs of the evolving system. With the proper automation system architecture and design, we can easily achieve operational autonomy of various parts of the system and even the system itself. Today protection of the system is highly automated, on one side because of millions of hours of design, engineering, and coding of protection algorithms in the protection relays and on the other side because protection has to react extremely fast and therefore does not allow human intervention. Similar, we can envision that the overall grid management will become more autonomous, with artificial intelligence taking over engineering and configuration of the system, at the guidance and guardrails of humans – and we also should be aware that the increasing complexity of grid operation will require such decision support for operators.

5.2.2. Energy infrastructure digitalization

To facilitate the adoption of automation but particularly to allow us to manage the future grids in a safe and secure way, we need to further expand the digitalization of the energy infrastructure. Accurate system state provided by data from sensors and algorithms coded in various applications will help transitioning to a sustainable energy system. The same sensors send relevant asset data which can be used by artificial intelligence algorithms deployed on high-performance computing to assess the health and remaining operating lifetime of the assets, such that we can optimize to even a higher degree the operations and maintenance plans across the system. This allows for a better utilization of the infrastructure and ensure cost-effective investments in keeping the power grid running.

With digitalization however, new challenges appear in the power grids, and the most concerning one is related to cyber-security. Power infrastructure is a critical and strategic asset for every country on the globe, therefore its protection is fundamental for a well-functioning society. The cyber-security aspects need to be properly addressed at the asset level as well as at the interfaces and interactions level.

Through edge and cloud solutions, aligned architecture and interoperability, digitalization helps to increase visibility into and controllability of the assets and fleets of assets. Augmented reality, machine learning and digital-twin technologies bring the next level of customer experience when it comes to serviceability and asset health management, allowing new concepts for training and safety assurance. Above all, new digital solutions and concepts will help the acceleration of the energy transition while ensuring a safe evolution of the system. Therefore, adopting digitalization is not an option anymore but an imperative for the power grids to evolve and support the transition to

5.2.3. Accelerating energy transition with new energy ecosystem

But digitalization does not only help gaining insights into the system and increase the functionality of it by proliferation of automation, but it also helps the stakeholders and players to interact and conduct transactions and business at a totally different level. Given the complexity and the size of the future system, with countless assets and players to provide system services, open, faster, more flexible energy trading and management platforms will be required. The universal and secure digital connectivity mentioned in Section 4.3.1 will be a key enabler for a seamlessly interaction of participants and a catalyst for accelerating a new energy ecosystem. This will also enable the participation of all technologies such as wind, solar, hydrogen, heating, energy storage, etc. to be integral part of the system, actively contributing to its stability and its security. Additionality, utilizing cloud technologies and interoperability of grid and energy management applications, we can reach the right scalability necessary to support the transition to a new energy ecosystem. This new ecosystem could resemble the proprieties of today's financial system where we trade financial assets in real time, allowing faster dynamics and quicker development of the markets. The participating parties will be able to manage their energy portfolios in a better and more effective way, having real time access to energy market and grid state information. This will enable a greater competition and offer for energy and grid services which in turn will bring the cost of energy down while increasing the resilience of the system and the security of supply.

5.3. Increase flexibility and resilience with power electronics

Traditionally, the reliability and resilience of the grid was addressed by proper design and sizing of operating margins for the hardware while the control and protection algorithms ensured the system operates within the prescribed margins.

With the transition of the energy system to a sustainable generation powered by renewables and modern loads interfaced by power converters, power electronics (PE) is at the heart of electrical power conversion, where electronics transform voltages and currents from one level and shape to another e.g. in a USB charger that converts 230V, 50/60Hz to 5V DC. Power conversion with PE is very efficient, and it is not uncommon to have efficiencies greater than 95%. Today 70% of electricity is processed by Power Electronics [19]. We use Power Electronics to charge our smartphones and electric vehicles, and we use it to increase cooking efficiency through induction cooktops/hobs. The world's industries are also becoming increasingly dependent on PE to increase efficiency in solutions. For example, PE is used to power large-scale aluminium production and efficiently transmit power across countries and seas. Power Electronics is revolutionizing the world's energy systems.

Power Electronics connects a world where both AC and DC power solutions coexist. It allows a smooth integration of various energy resources like solar PV, wind turbines, batteries, electrical vehicles and diesel backup power generation within an industrial facility like a mine, a data centre and even across islands - in a form of a microgrid. Power Electronics improves efficiency and resilience of our grid from generation to consumption. The journey to a more sustainable energy system will continue to drive this metamorphosis in the years to come.

Power Electronics systems are supervised and controlled by digital controllers, as performance is important in obtaining the optimal system operation. The evolution of digital technologies facilitates even higher controllability of the system and improves visibility by gathering and analysing data thus improving decision making and control outcomes. Owed to these digital controllers and the algorithms deployed on them, the assets interfacing the grid through power electronics bring a new whole wave of new functionality such as fault-ride through, virtual synchronous machines, fault current limiting and grid forming, to mention just a few. More importantly, power electronics provide a grade degree of active and reactive power control – which is critical to managing the complexity of the future energy system formed by a myriad of distributed resources.

While in the past the power flows in the electrical grid were dictated mainly by the voltage control at the generating facilities and FACTS (Flexible AC Transmission Systems), we can envision that we will soon be designing a fully electronic system, where power electronics will be the valves of the system, protecting and controlling tightly the power flows, voltages and the power quality, stringently orchestrated by a supervisory control system. Fig. 6 and 7 are illustrating this development.

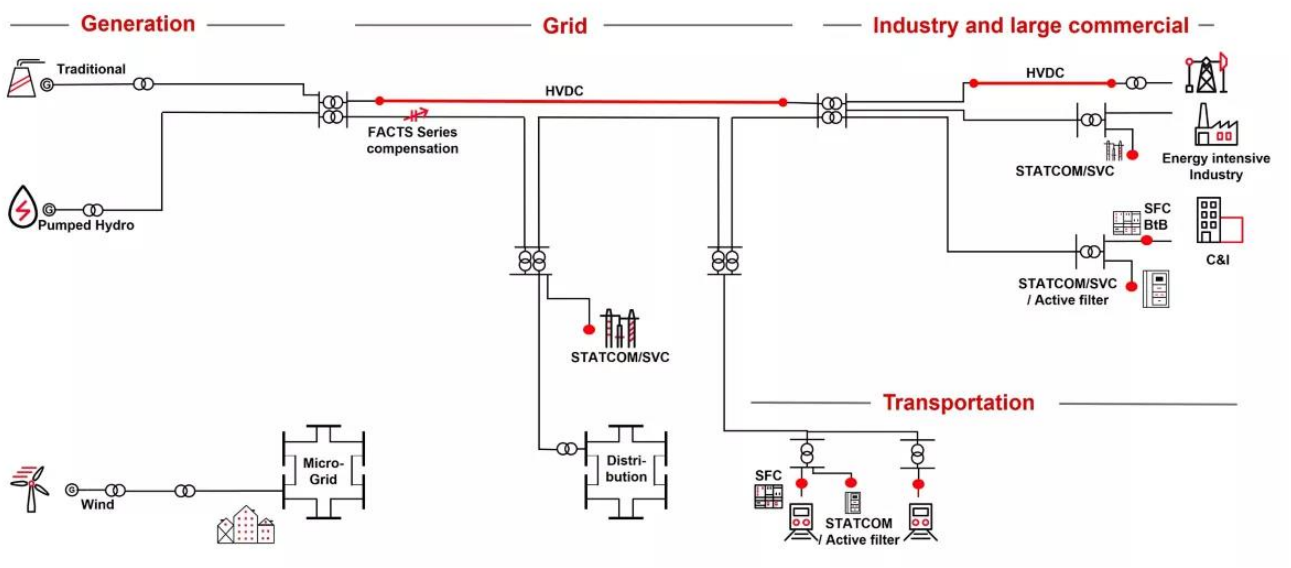

Fig. 6: The power grid in the past – clearly separated with generation, transmission & distribution layers

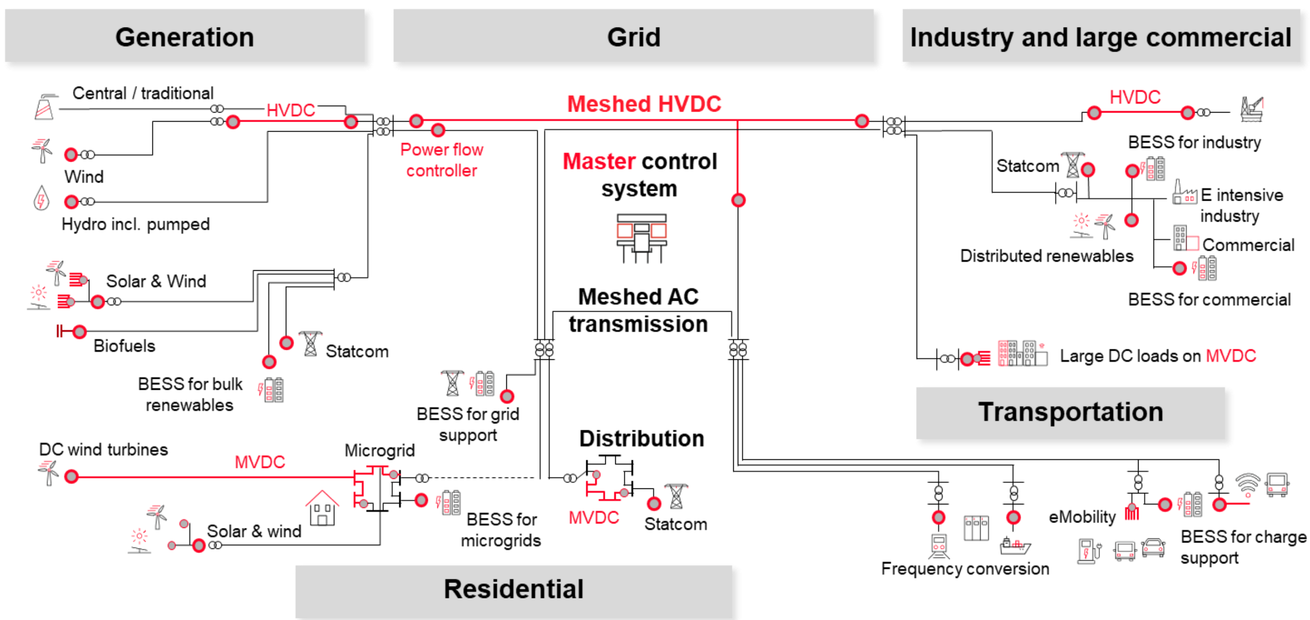

fig. 7: The power system of the future – much more interconnected, with power electronics (in red) as key power interface between the grid and the distributed energy assets

5.4. Drive sustainability through technological innovation

Although the energy transition points in the right direction and aims at decarbonizing the carbon footprint of the energy flowing through the grid, the power infrastructure needs to reduce its own CO_2 equivalent footprint by using new materials, innovating, and decarbonizing the manufacturing processes and adopting a circular design across for assets' lifecycle.

5.4.1. Innovation at the core of sustainability

A carbon-neutral energy system can only be achieved if everyone in the supply chain participates. From the extraction of raw materials to their processing and treatments, from designing new products to retiring them at the end of life, every single player and stakeholder in the value chain has a critical role to play. We need to find ways to decarbonize the supply chain through the adoption of electrification of the industrial sectors and use of green fuels when the processes cannot be electrified. Electrification of haul truck in mining, electric arc furnaces, increasing the efficiency of and purchasing of renewable power for the manufacturing facilities are just a few examples which can contribute greatly to the reduction of the CO_2 equivalent for the power grid infrastructure.

The existing RoHS [20] and REACH [21] regulations prevent manufacturers to use extensively hazardous substances of high concern, which minimize the adverse impacts on human health and the environment. However, more innovation is necessary to find solutions that fully replace such substances, like the the use of SF_6 gas in switchgears [22].

5.4.2. Reducing the use of resources through circular economy

Meeting the economic growth and the energy needs of our growing world should not come at the expense of our planet's well-being and limited resources. Maintaining the growth of global consumption in the long-term would require more supplies than we have to our disposal, as stated by the 12th United Nations Sustainable Development Goals: Ensure sustainable consumption and production patterns [23]. Moving away from the traditional linear value creation and adopting a circular mindset will facilitate continued economic growth. Circularity means that instead of using natural resources and raw materials into products that end up as waste, they can be reused to a larger extent.

Circularity in practice implies reducing waste to a minimum; reuse, recycle, or keep within the economy, wherever possible, the product components and materials at the end of its life, productively using them again and again, shifting from the linear economic model that has traditionally relied on large quantities of resources available (relatively affordable, easily accessible materials and energy).

This concept is known as the circular economy and is applicable at any level, either individual, corporate, regional, or global. Its implementation requires a systematic approach, collaboration, and focus, merging sustainability with business development with the goal to minimize environmental impact while at the same time maximizing the value creation for society.

Such an economy is based on a few simple principles coming from products designed and optimized since their conception for disassembly, reuse, or recycle. In case of a transformer - the working horse of the power grids - it is possible to recycle up to 99 % of the old transformers with 64 % material recycling, 35 % clean, low emissions efficient incineration for energy and the balance of 1 % as disposed waste [24]. The life extension of transformers is another approach to the circular economy, which may typically include rewinding and reusing the core and tank, with a renewal of accessories. Similar approaches must be adopted for the entire energy infrastructure.

6. Conclusions

The European Union has committed to cut greenhouse gas emission by 55% compared to 1990 by 2030, a key milestone in reaching climate neutrality in 2050. Direct electrification, complemented with the indirect electrification of hard-to-abate sectors, is at the centre of the road to cut energy sector emissions to net-zero by 2050. A broad set of initiatives and programs has been launched to transform the power generation sector as well as demand in order to support this objective. However, all of these measures will only be successful if power grids will be available in due time and with the right capabilities.

> Collaboration, early alignment, pro-active and parallel deployment and commitment of all stakeholders are key catalysts for an efficient but also sufficiently fast transformation of the European power systems.

The energy transition has become very urgent. When breaking the 2050 targets down to concrete actions it becomes very clear that there is no time to lose anymore – neither for sequential working nor for avoidable delays. Urgency requires a pro-active, highly collaborative and holistic approach, particularly in today's, unbundled framework of the European single market for electricity:

- **Pro-active:** We need to plan and implement grids and the massive new generation capacities simultaneously. And we need to roll out new infrastructure functionalities long before we recognize that they are missing.

- **Collaborative:** In order to minimise the risk of stranded investments, stakeholder groups need to align from the very beginning. They need to share their plans, discuss and agree on required measures and division or work and responsibilities across the entire power system value chain and commit to actions to be taken.
- **Holistic:** The future power system of Europe will benefit from international exchange and integration across all levels. Hence, it has to be regarded as a truly European system, with European decision and planning processes, with interdependencies and trust between member states and a truly European commitment. Moreover, it also has to be regarded as an integrated system across all of its levels. Planning and deployment have to be aligned from the offshore grids over the onshore transmission grids to the distribution grids.

Applying these principles can unleash several catalysts and enablers for the energy transition:

- If all stakeholders – those who are directly involved, but also those who are affected by the transformation of the energy system - are willing to engage in a collaborative approach from early planning to deployment**, predictability and certainty of implementation will increase**.
- In order to accelerate the transition, **all types of waiting times during planning and permission need to be minimized or even eliminated**. It therefore may even make sense to develop and even permit different grid scenarios in parallel in order to be best prepared when it becomes clear which of the scenarios materialises.
- Legislation and regulation need to focus **not only on collaborative planning but also on accountability in deployment**. As we are talking about the transformation of an entire system in which actors are depending on each other accountability includes financial compensation mechanisms in case parts of the system are deployed too late.
- Developing future grids should not be restricted to adding more wires. Future grids will have to offer new functionalities to accommodate highest possible shares of renewable generation with existing and new assets, to empower consumers, to integrate and coordinate distributed assets, just to give the most obvious examples. **Functional development of the power system is a coordinated effort of all stakeholders and needs to be orchestrated and driven accordingly.**
- Power systems are a technical infrastructure. Hence, **technology is a key enabler**. Technology providers have developed many solutions in the past, many of them also pro-actively and on their own risk. Therefore, the good news is that most technologies required for the achievement of near- and medium-term goals (e.g. till 2030) already exist. Expedited deployment of these technologies and rapid digitalization will be critical to achieve speed and scale required for reaching the net zero target in time.
- Technology providers are ready to support the next steps and at the same time are investing in R&D and production capacity. But without any doubt increased certainty and predictability is an important catalyst to accelerate these activities even further. **And beyond that manufacturers and grid operators need to find new ways to commit on mid-term demand and its coverage in a way allowing ramping up production capacities in time.**

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