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Power Transmission & Distribution Systems

micro vs *MEGA*: trends influencing the development of the power system

Discussion paper

Irina Oleinikova (Norwegian University of Science and Technology)
Emil Hillberg (RISE Research Institutes of Sweden)

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Disclaimer

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- Kjetil Uhlen (Norwegian University of Science and Technology, Norway)
- Antonio Iliceto (CIGRE, Italy)
- Kristina Hojčková (Chalmers University of Technology, Sweden)
- Danilo I. Brandão (UFMG - Federal University of Minas Gerais, Brazil)
- Danny Pudjianto, Xi Zhang & Goran Strbac (Imperial College London, UK)
- Katja Sirviö (University of Vaasa, Finland)
- Juan Carlos Gonzalez, Kosei Shinoda, Rayane Mourouvin, Jing Dai, Paul Vinson, Serge Poulain, Abdelkrim Benchaib & Bruno Luscan (SuperGrid Institute, France)
- Davood Babazadeh (OFFIS, Germany)
- Rajil Srivastava, Chandra Prakash Awasthi, Atul Kumar Bali & Kumud Wadhwa (Power Grid Corporation of India, India)
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- Alexander Fuchs (ETH Zurich, Switzerland)
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List of Acronyms

ACER	Agency for the Cooperation of Energy Regulators
BESS	Battery Energy Storage System
CDG	Community Distributed Generation
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
ETIP-SNET	European Technology & Innovation Platforms Smart Networks for Energy Transition
ETS	Electric Thermal Storage
EV	Electrical Vehicle
FACTS	Flexible AC Transmission System
FRT	Fault Ride Through
FTR	Financial Transmission Rights
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
MEMS	Microgrid Energy Management System
OHL	Overhead Line
OLTC	On-Load Tap-Changer
PCC	Point of Common Coupling
PE	Power Electronic
PTR	Physical Transmission Rights
PV	Photovoltaic
RES	Renewable Energy Sources
RoCoF	Rate-of-change-of-Frequency
RoCoV	Rate-of-change-of-Voltage
SVC	Static var Compensator
TES	Thermal Energy Storage
TNYDP	Ten-Year Network Development Plan
TSO	Transmission System Operator
UHV	Ultra-High Voltage
VSC-MTDC	Voltage Source Converter – Multi Terminal DC

Executive summary

The objective of this work has been to present a critical assessment of two trends which are largely influencing the decisions and the evolutionary process of power grids:

the **micro** and **MEGA** trends.

These trends are both aimed at enabling very high penetration of renewable energy sources in the electric power system, from two perspectives:

- the **micro** focuses on local solutions, while
- the **MEGA** focuses on system or even intra-system wide solutions

It has become evident that these trends have a large influence on each other and on the way the power system develops. Investment in micro and MEGA levels pertain to quite different spaces in the electricity supply chain and serve very different needs; a likely scenario is that the micro and MEGA perspectives will be co-existing in different forms in the future wider energy system.

Whole-system coordination between micro and MEGA, together with cooperation between different system levels, are needed to provide the most value of investments. The microgrid concept could provide a large range of economic, technical and social benefits to different stakeholders. However, depending on opted configuration and operation schemes for a microgrid, conflicting interests might arise. An optimal mix between micro and MEGA approaches should be considered to identify investment strategies that provide:

- the most socio-economic welfare, with decisions based on overall system optimisation
- increased reliability of the electricity supply
- optimal use of resources in a way to harness maximum utilization and integration of renewable sources and to minimize impact on the environment.

Renewable Energy Sources (RES), mainly as power electronic interfaced generation, play an increasingly important role in the power system. It is likely that RES will be the main source of electricity in the future, and power systems will need to evolve to meet this development. Significant investments are required in both the micro and the MEGA levels to allow the full utilisation and harvesting of available renewable resources. In the conclusion of this report, main messages are provided in the areas of technology, market, and policy, including:

- Large-scale investments are more sensitive to risk, with the risk for stranded investments increasing in times with significant technology and market developments
- Long-term strategies and strong political backup are needed to prevent unsustainable investments, and sustainable time horizons are required for investments to prevent the need for additional negative environmental impact
- Policies and subsidiaries which promote small- or large-scale solutions may inherently demote the other kind of investment even if such would have been more sustainable
- National strategies and policies have a significant influence on overall grid development, as highlighted by the various national directions regarding nuclear power and UHV power transmission.

Finally, reliability levels and criteria used today for operating and planning the power system may not be the optimal for the future power system. Considering diversified solutions for reliability and security of supply may lead to alternative decisions resulting in other directions in the development of the power system.

Table of Content

1. Introduction

This report is prepared within the framework of ISGAN Annex 6 (http://www.iea-isgan.org/our-work/annex-6/). The work of Annex 6, on Power Transmission & Distribution Systems, promotes solutions that enable power grids to maintain and improve the security, reliability and quality of electric power supply. This report is the outcome of an activity within the focus area System Operation and Security. The main objective of this focus area is to assess available methods and tools for operational monitoring and control, and in particular to identify the need for new tools and methods to manage future challenges in balancing control. Figure 1 positions this work in the ISGAN context.

Figure 1. Position of this report in ISGAN context

The goal of this report is to provide an extensive analysis of the *micro* and *MEGA* trends and provides an analysis of how they affect the development of the entire power system, supporting energy transition in a liberalised market environment.

Section 1 provides the introduction to the micro and MEGA expressions and the background to electric power industry development in mitigating climate change.

In section 2, the MEGA perspective, bulk scale developments for RES integration and challenges with more complexity in operation and planning is described.

In Section 3, the *micro* perspective is presented, with focus on more local solutions, including large penetration of distributed variable energy sources and the ability of demand to provide a flexible response.

In Section 4, we address *micro* vs MEGA perspectives, providing various view points and concepts including TSO-DSO coordination and regulatory aspects.

Conclusions and main messages from the report are presented In Section 5.

Case studies, examples and global views are provided in APPENDIX at the end of the document.

1.1. micro and MEGA perspectives

It is imperative for power systems all over the world to enable the integration of a considerable amount of renewable energy sources to meet international climate objectives. This implies a paradigm shift in grid operation and network expansion on two fronts:

- At the lower end - microgrids, local energy communities, distributed generation, local battery energy storage systems which contribute to enabling the subsidiarity principle when balancing the system locally as far as techno-economically feasible. This is achieved through local markets and other smart grid solutions. In this report, the investments and developments which focuses on small-scale local solutions are referred to as the **micro perspective**.
- At the higher end - enlarging the integrated power system through long-distance HVAC and HVDC interconnections, bulk-scale RES generation plants and battery energy storage systems and multi-national integration of electricity markets. Investments and developments, which encompasses the large-scale system or intra-system wide solutions are referred to as the **MEGA perspective**.

The micro and the MEGA perspectives are illustrated in Figure 2 which shows the entire power system, from supergrids to microgrids.

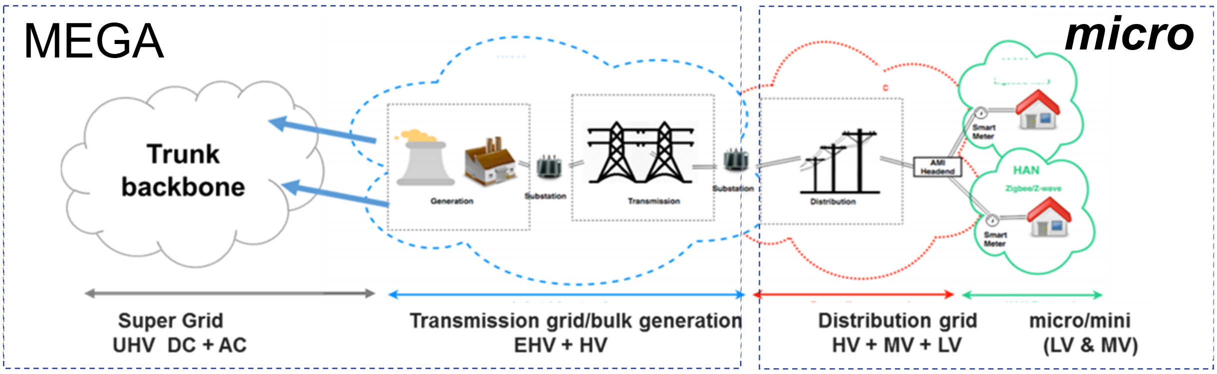

Figure 2. MEGA and micro perspectives in the setting of the entire power system

With the growing share of renewable energy sources (RES) and distributed energy sources (DER) worldwide, the existing power system impacted at all levels and is “going to the next level”:

- *On one hand, at the distribution level, the increased installation of RES is causing new challenges and calls for investment necessary to strengthen the local grids. This is in contrast to the conventional bulk scale generation plants generally connected at transmission level.*
- *On the other hand, at the transmission level, large scale RESs are being installed often in distant areas calling for investment required to strengthen the transmission grids that can transfer the energy to the demand regions.*
- *Furthermore, there are alternatives to strengthening the power grid such as new technology and methods to increase the flexibility in consumption, generation, and in power transfer capacity.*

Significant efforts and investments are made to develop different types of microgrids, local energy communities, distributed generation, local (battery) energy storage systems, as well as smart grids solutions based on demand side participation. Simultaneously, huge investments are undertaken to build long distance HVAC and HVDC interconnections, and other means of strengthening the bulk power system including bulk-scale generation, enabling closer integration of electricity markets on the global scale.

The role of renewable electricity technologies and related infrastructures in the long-term vision for a climate neutral economy is calling for new ways to enable/facilitate the improved cooperation between transmission and distribution system operation in the future. At the same time, technological evolution in the power industry as well as other related industries (IT, Mobility, batteries, fuel cell technology) also has significant impact on power system infrastructure planning and development.

It is important to mention that all grid infrastructure-related developments will need to take into consideration the new role of end-users (consumers, prosumers, and others) that can assist with the implementation of distributed energy technologies in order to directly participate in energy production and voltage support. Integrating prosumers in the existing power market will require extensive roll out of smart meter installations to secure a higher degree of measurability and enhanced market tools. With new pricing schemes and near-to-real-time dynamic price contracts, customers will be able to play an increasingly active and independent role in the market. For example, by forming energy communities through alternative prosumer-based market models[1].

These two trends, **the micro** and **the mega trends**, both aim at enabling very high penetration of RES. Both trends are largely influencing the decisions and the evolution process of the power grids, each with a different scalar focus. The **micro perspective focuses on local solutions while the mega perspective focuses on system or even system of systems wide solutions**.

Furthermore, solutions identified as optimal for a power system in one country, may be not be optimal in another country, due to differences in base scenario (grid structure, generation mix, etc.), available natural resources, existing legislation, social acceptance, etc. Despite such differences, all power grid developments need to consider fundamental physical requirements of the grid, including:

- transfer capacity needs between generation and demand

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[1] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

- equilibrium of energy contents (generation, demand, storage, exchanges with other sectors, losses) at all times
- the variability and degrees of uncertainty in generation and demand
- the critically of demand (cost of energy not served) as well as their flexibility
- to keep system frequency within acceptable limits in case of large disturbances
- voltage supporting possibilities, to maintain voltage levels at all the buses in the grid
- the amount of local resources to provide balancing services (including flexible demand).

The objective of this work is to present a critical assessment of these trends, based on the following key questions:

- Does one trend outcompete the other?
- Does increased microgrid investments increase the need for mega grid investments, and vice versa?
- To what extent can microgrids benefit from mega grid solutions, and vice versa?

The intention is not to proclaim one solution being superior to another, rather **to provide well informed insights to the needs of considering both perspectives during the planning and decision-making process for the sustainable development of the wider energy system**.

It is important to mention that the development of all present electric systems started at the end of the 19^{th} century as small isolated systems, i.e. as microgrids: pioneer generation machines (hydraulic at first) connected to local loads (public lighting at first) through a single line (no redundancy at first); rapid multiplication of users on one side and the addition of other generators made it look like a grid (at Medium Voltage), with some redundancy in electricity paths, since its use become so indispensable in industrial appliances and transport (tramway). These local grids were eventually interconnected among them at increasing voltage levels (High Voltage) in what has progressively become municipal, provincial and regional power systems. With the huge industrial uptake after World War II, the consumption rocketed, large concentrated generation plants where built (mainly thermal, where hydro resources were exhausted) and a meshed High Voltage grid (220 kV and 380 kV in Europe and many other areas) was realized. This backbone, with only transmission purposes (no consumer directly connected) is superimposed as a new layer and caters in an efficient way (2-3% losses) to the uneven consumption and generation patterns, also neutralizing the risk of unserved power, being designed and operated with the so called N-1 criterion. This criterion states that the grid must ensure fault-ride-through of any fault occurrence in any single component of the system (lines, transformers, generators, etc.), through an intrinsic and automatic reconfiguration of the grid, built by design and constantly re-assessed at short intervals in real time operation. In this way consumers shall not be affected by the fault, unless due to some exceptional events causing cascading effect on more grid components. In this way, the risk of consumer blackout remains at distribution level, especially for smaller loads (like domestic) served in low voltage, where the architecture is typically radial and not meshed due to economic reasons.

2. MEGA trends in electric power industry

In this report the expression MEGA related grid activities focus on the system wide, or even intra-system, perspective, meaning large-scale / bulk level investments and solutions in production and transmission. Examples of developments are large scale production, strengthening of power transfer corridors between production centres and load centres, strengthening of national/international connections for trading. This section provides the perspective of the MEGA trends.

Huge investments are undertaken to build long distance HVAC and HVDC interconnections, and other means of strengthening the bulk power system including bulk-scale generation, enabling closer integration of electricity markets on the global scale with aim to:

- Maintain the integrity of the synchronous power system
- Provide power to satisfy the demand of the system
- Provide grid capacity to the market for trading of electricity

Power transmission systems are the backbone of the electricity system, where transmission system operators have a crucial role in the necessary progressive decarbonization of the electricity sector and the transition to a more sustainable energy system. Decarbonizing the power sector can only become a reality by making transmission systems ready to integrate (operate) high shares of variable renewables.

European TSOs can be mentioned among the leaders to create a modern power system to support the “energy transition” and make it a reality. However, others are also not far behind such as TSOs in China and India who are currently developing large power corridors for transmitting renewable energy between distant geographical areas. Several Research, Development and Innovation (RD&I) activities are in force for enabling the necessary changes while maintaining adequate security of supply and system resilience along with facilitating competitive and efficient markets[2].

Five main challenges faced by the European power systems are shown in Figure 3:

Figure 3. Five clusters addressing the Energy System’s Challenges[3].

Information analysis from recent projects and its efforts from around the world could summarize the following perspectives:

[2] ENTSO-E, “RD&I Application Report 2016
[3] ENTSO-E RD&I Roadmap 2017-2026

System perspectives: balance of demand and production on all time horizons

- Adequacy
- Stable frequency
- Reliability of supply

Grid perspective: need for transfer capacities, voltage and power quality

- Congestion management
- Voltage stability

Challenges faced by the European power systems, summarised by the 5 clusters in Figure 3, could be considered as common issues faced by almost all countries where different strategies are evolved.

The European approach based on the Project of common interests, illustrated in Figure 4 is based upon ENTSO-E's cost benefit analysis for the planned infrastructure projects across Europe which have been approved by the European Commission for the TYNDP projects[4].

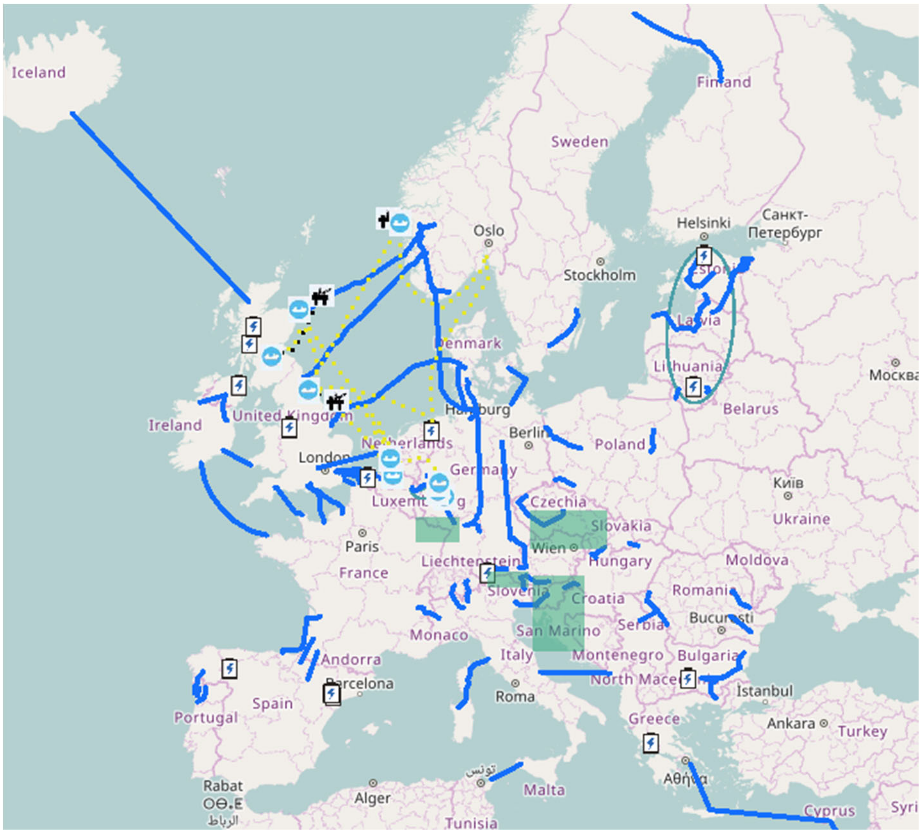

Figure 4. Project of common interest map (electricity and smart grids)[5].

During the past decades, USA intensified the deployment of renewables at distribution level, nearing 60 GW of grid-connected solar PV capacity. At the same time, the U.S. Department of Energy has become a global leader in research and development of innovative solutions to

[4] RGI, ENTSO-E, "Working paper - Value of timely implementation of better projects", 2019
[5]https://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer/main.html

address reliability, resilience, cyber-security, and affordable challenges under Grid Modernization Initiative[6].

In India, out of the total installed power capacity (359 GW), renewable energy constitutes almost 22% (80 GW). Furthermore, this renewable penetration is expected to almost double, with a target of 175 GW installed renewable capacity by 2022.

2.1. Characteristics, Drivers and Regulatory aspects

The MEGA perspective on grid development takes the top-down approach, and is characterised by interconnections between regions, nations and independent systems (synchronous or not). An illustration of the part of the power system included in the MEGA perspective is presented in Figure 5.

Investments in this area are bulk level, large-scale, power production plants (hundreds-to-thousands of MW) and massive high-voltage AC and DC power transfers (hundreds-to-thousands of kV). These investments typically require long term planning horizons, exemplified by ten-year network development plans and equipment lifetime of 40 years or longer.

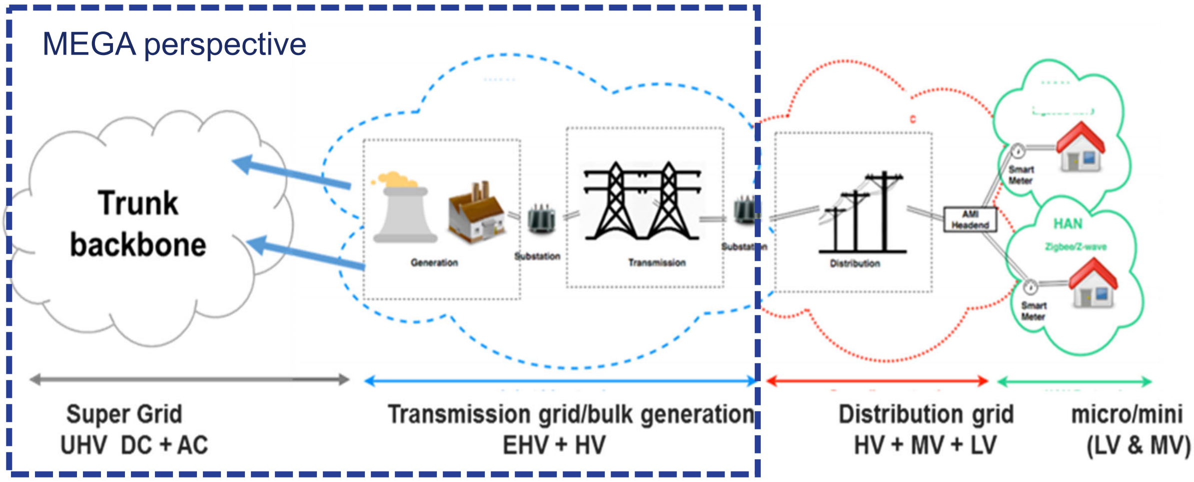

Figure 5. MEGA perspectives on grid development.

The significant requirements of expertise and capacity of participating actors, together with inter-regional and inter-national coordination and collaboration, results in the continued development among already established stakeholders within the energy sector. Actors are mainly large public and private stakeholders such as manufacturers, electricity producers, grid owners and transmission system operators, and typically require strong political backup in the form of intergovernmental agreements.

The European TSOs highlight three main drivers for investments in increased transmission capacity**: social economic welfare, security of supply, and the European climate goals.** The Nordic TSOs describe the following drivers for grid investments: consumption growth due to electrification and new industries, reduced nuclear and conventional units, strong growth of

[6] Barry Mather, Guohui Yuan. "Going to the next level, the growth of distributed energy recourses", IEEE Power&Energy Magazine, volume 16, Nr.6, November/December 2018.

RES – mainly wind power, reinvestments requirements to maintain existing grid capacity, and higher capacity between the Nordic system and other systems (to export power from renewable Nordic sources and to strengthen the security of supply). It is imperative that the uncertainties in these drivers and their impact on grid development should not be neglected.

The Nordic TSOs further address the value of grid development to eliminate bottlenecks, however stating that it is not socioeconomically beneficial to invest to such an extent that grid capacity fully eliminates all hours with price differences thus it is desirable that market solutions complement grid capacity investments in managing the supply-demand balance. [7]

The economy of scale supports investments of large scale renewable plants, optimally located in geographies where the primary resource is abundant while anthropic pressure is limited, thus requiring additional grid investments. Detailed analyses are required to establish the level of transmission infrastructure investments (and complementary technologies such as demand-side response and energy storage) required for various scenarios of renewable energy deployment. Studies carried out in the EU-IRENE 40 project are presented in the APPENDIX.

Institutional aspects. Scholars as well as many practitioners believe that if a regulatory framework for the intercontinental power grid was established today, our current technical abilities would allow us to build the supergrid within twenty years[8]. However, large-scale infrastructural projects across national boundaries require high level of institutional harmonisation[9] between and within the participating states. An important first step towards harmonisation is represented in a growing number of comprehensive vision statements, envisioning the supergrid as the electricity system of the future. Vision statements and roadmaps as well as expectations forming around the first transmission projects are thus representing the first cognitive institutional building blocks of the supergrid[10,11].

Roadmaps are being developed predominantly by knowledge platforms that bring industry and research together to create a common position on standards and regulations required for the construction of a large-scale, transnational energy grid. Knowledge platforms such as ENTSO-E, Friends of the Sustainable Grids (FOSG), and the SuperGrid Institute in Europe, Gobitec initiative in North East Asia and GEIDCO in China are key for attracting investors, technical capacity and governmental support.

MEGA projects are currently being hindered by high perceived commercial risk and a weak regulatory and institutional environment in some of the countries concerned (some examples are given in this report). In order to overcome negative expectations, a market and institutional mechanism of an integrated grid system should support confidence-building between all participating countries based on long-term negotiations and commitments.

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[7] Nordic Grid Development Plan 2019, ENTSO-E TYNDP 2018

[8] Dauncey, G., 2009. Build a Supergrid, The Climate Challenge: 101 Solutions to Global Warming. New Society Publishers

[9] Shuta Mano, Bavuudorj Ovgor, Zafar Samadov, Martin Pudlik, Verena Jülch, Dmitry Sokolov, Yoon, J.Y., 2014. Gobitec and Asian Super Grid for Renewable Energies

[10] Borup, M., Brown, N., Konrad, K., Van Lente, H., 2006. The sociology of expectations in science and technology. Technology Analysis & Strategic Management 18, 285-298.

[11] Van Lente, H., 2012. Navigating foresight in a sea of expectations: lessons from the sociology of expectations. Technology Analysis & Strategic Management 24, 769-782

Politics and market structure dynamics are closely related in the mega grid scenario. Mega grids just like previous large-scale infrastructural projects in history, requires long-term governmental support which restricts the market dynamics to create the opportunity for the large infrastructure to be built. Private investors are important in this scenario, yet they are reliant on governmental support that reduces the market uncertainty and secures return on investment over long periods of time (8-20 years). It can be assumed that, without a direct technology-specific governmental support for HVDC connections, the existing market structure will benefit microgrid developments that are much less dependent on governmental support.

2.2. Role of Novel Technologies and Power Electronics

This section provides several options and services that can be provided by recent technological developments in Power Electronics (PE) for improving the system operation and control.

DC technology can efficiently reinforce existing power systems. Large-scale grids based on DC transmission technology can offer additional flexibility to the traditional AC systems. As in the AC system operation, the DC grid needs to operate within a prescribed operational envelop for voltage, current, and power in order to protect system components. The need for smart devices and customized network solutions for various different industrial use cases are discussed here. It is also important to mention the diversity of high-voltage PE systems that are still under study or already implemented for future power system needs.

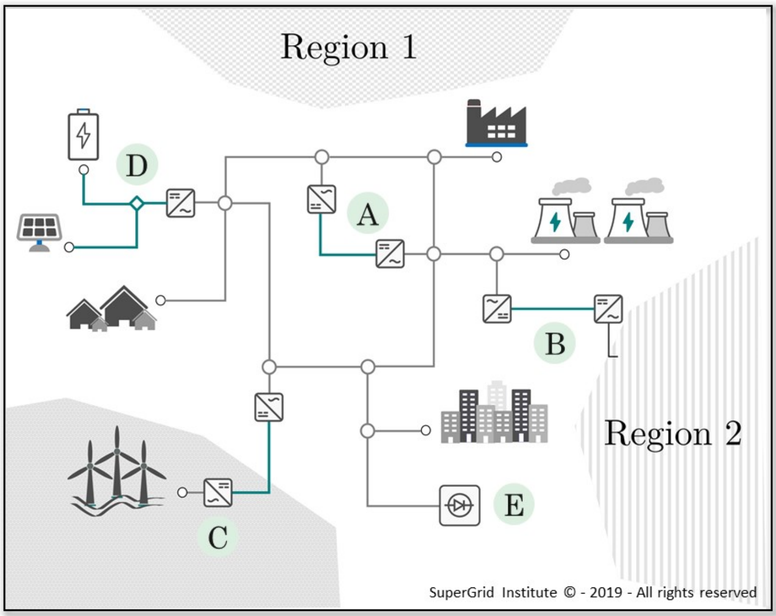

Figure 6. Illustrative scheme of the current existing power systems.

In the following, four categories of drivers for PE-based technologies in the existing power system, as illustrated in Figure 6, are discussed and analysed:

Increased power transfer capacity. This category gathers HVDC projects developed for the market-oriented design of the current power systems, DC power being much more controllable than AC in synchronous areas. Point A in Figure 6 corresponds to this usage. A real-life example is the HVDC interconnection between Spain and France, named INELFE[12], doubling the interchange capacity between the two countries from 1400MW to 2800MW.

Connection of asynchronous areas. With HVDC technology it is possible to interconnect two asynchronous areas as illustrated by item B on Figure 6.This is motivated by two criterions: economy and reliability. On one hand, having this connection makes energy trading between the areas possible, which is beneficial for the market-oriented European system. On the other hand, it enhances the reliability of all the systems since they can provide bi-directional help through these connections when one of them endure a critical contingency, e.g. a power plant loss. An example is the link between France and UK, which has existed for decades[13]. This category can be extended to the insular interconnections, which is an interconnection of asynchronous areas, omitting the scaling factor. For insular grid operators, this connection ensures regular power delivery in case of island equipment contingencies.

Connection of renewable energy sources. For a couple of decades, there has been an increasing development of RES, in particular wind and solar power. For offshore wind power, interconnections with the shore may require >30km-long submarine cables for which HVDC technology is much more appropriate. This type of interconnection is presented in Figure 6 by item C. The interconnection of wind farms with the grid is achieved using PE converters with various technologies. The DolWin1 project in Germany is providing 800MW to the mainland using Modular Multilevel Converter (MMC) technology. Regarding solar power, the generated power using photovoltaic panels is DC. The DC/AC conversion is naturally performed with PE converters, either series-connected medium voltage inverters or DC/AC high voltage converters. An illustrative example is given by item *D* in Figure 6.

Stability enhancement of critical zones. Some PE-devices endorse specific AC grid-oriented functionalities: these are the Flexible AC Transmission Systems (or FACTS). IEEE gives the following definition of FACTS: "alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability"[14]. Among the PE-based FACTS technologies there is the VSC-based STATCOM, which provides fast reactive power support. These kind of devices are strategically placed in order to improve the transient and static behaviour of critical zones, which are mainly weakly connected areas and centres of consumptions, e.g. large cities, as illustrated by item E in Figure 6.

Since there will be more and more PE Converters connected to the grid, it would be expected that they participate in the stability and reliability of the future power system. Here, we list several options and services that can be provided by PE for improving the system operation and control. This list is non-exhaustive and only focuses on VSC technology.

Connections to very weak grids. With an increasing number of Synchronous Machines (SM) being decommissioned and disconnected from the grid the voltage support decreases. The equivalent grid seen from the VSC point-of-view is sensed as a more distant equivalent source, i.e. with a higher impedance. In addition to the notion of low inertia power systems[15], the definition for the notion of high impedance power

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[12] https://www.inelfe.eu/en/projects/baixas-santa-llogaia
[13] "60 years of HVDC". ABB Group.
[14] Proposed terms and Definitions for FACTS, IEEE, 1997.
[15] F. Milano, F. Dörfler, G. hug, D.J. Hill and G. Verbic, "Foundations and Challenges of Low-Inertia Systems", in *Power Systems Computation Conference (PSCC),* 2018

systems can be defined. This corresponds to weak AC grids with few equivalent voltage sources which makes the system less voltage-stable and in other terms, with a higher equivalent impedance. In these conditions, VSCs may encounter difficulties to synchronize with the AC grid. In response, the grid-forming control has emerged as a solution since it provides a PLL-free synchronization scheme. This is a point that is often discarded in high level energy debates, since the main focus tends towards the renewable penetration rate and energy storage requirements. Nevertheless, it is important to keep in mind that 100% PE-based power systems will not be successful if PE are controlled as current-sources, i.e. following constant power references.

Frequency support. To provide the frequency response and the power balancing during contingencies that has been provided by synchronous power plants, some TSOs, such as National Grid or Scottish Power in the UK, now asked all large power suppliers to participate in the frequency response market[16]. This ancillary service may also be provided by specific storage system owners that would only take part in this service without providing any power in the nominal case. It is also possible for HVDC links between asynchronous areas to deliver some extra power with respect to frequency deviation but in this case, this service can be seen as the power reserve sharing between the two areas.

Power oscillations damping. For solving the power oscillation issue, TSOs have at first asked for additional services from the SM owners: this led to the development of PSS implemented in the Automatic Voltage Regulation (AVR) control[17]. However, with the increasing number of controllable PE-converters, Power Oscillation Damping (POD) controllers have emerged. Their design helps with the damping of inter-area oscillations by modulating their output power[18].

Increase of transient stability margins. When encountering topological disturbances on the grid, i.e. line opening, loss of generator, etc., it is important to be capable of maintaining the system transient angle stability without tripping additional equipment. This action is complementary to the POD action and may be named First swing stability enhancement which coordinates the active and reactive power injections to counteract power disturbances in case of inter-area oscillations. In addition, since the VSC are fully controllable, it is possible to impose margins and security levels for the maximum acceptable operating limits of the VSC and thus, mitigate the risks of sudden disconnections. Last but not least, when there is a fault near an operating VSC, it may be requested to keep the connection to the AC grid, even during voltage reduction to inject reactive power which will be useful for the AC protection strategies to detect the fault and act accordingly. This capability is mainly referred to in the literature as Fault Ride Through (FRT) capability.

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[16] "Mandatory Frequency Response: A guide to the services procured by National Grid to manage the system frequency". National Grid ESO

[17] C. Liu, R. Yokoyama, K. Koyanagi, K.Y. Lee, "PSS design for damping of inter-area power oscillations by coherency-based equivalent model", *Int. Journal of Electrical Power & Energy Systems*, 2004

[18] O. Kotb, M. Ghandhari, J. Renedo, L. Rouco and R. Eriksson, "On the design and placement of a supplementary damping controller in an embedded VSC-MTDC network," *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Torino, 2017, pp. 1-6

The VSCs will then become an interface between the AC and the DC grids. The features of this hybrid network as long as the dedicated protection coordination of the DC grid is discussed in the following paragraphs.

Hybrid AC-DC grids. In any power system, energy equilibrium must be ensured at every moment. In an AC system, energy is stored in the form of kinetic energy, and the system frequency acts as a global measure of the instantaneous balance between the total generation and load of the system. If this balance collapses, the system will experience frequency instability. The gradient of the frequency change (RoCoF: rate of change of frequency) depends on the amount of kinetic energy, which is predominately stored in the rotating mass of power plants turning synchronously in the network. In conventional AC systems, hundreds (or thousands) of generators with a substantial amount of energy are running synchronously and oppose frequency fluctuations. In the case of significant power imbalance, such as a sudden power deficit resulting from a trip of a generating unit, the system frequency will gradually decrease and deviate from the nominal value. A large deviation in frequency can damage equipment, degrade load performance, and trigger system protection relays, which may ultimately lead to cascading blackouts. In order to maintain the system frequency within a prescribed security range, AC systems commonly employ hierarchical energy balancing regulation schemes, which are collectively called frequency control. Each stage has a different time scale and typically arranged in the order of tens of seconds to several minutes. For a DC system, energy is stored in the form of electrostatic potential energy in capacitors. The DC voltage plays the same role as the frequency and as the power balance indicator.

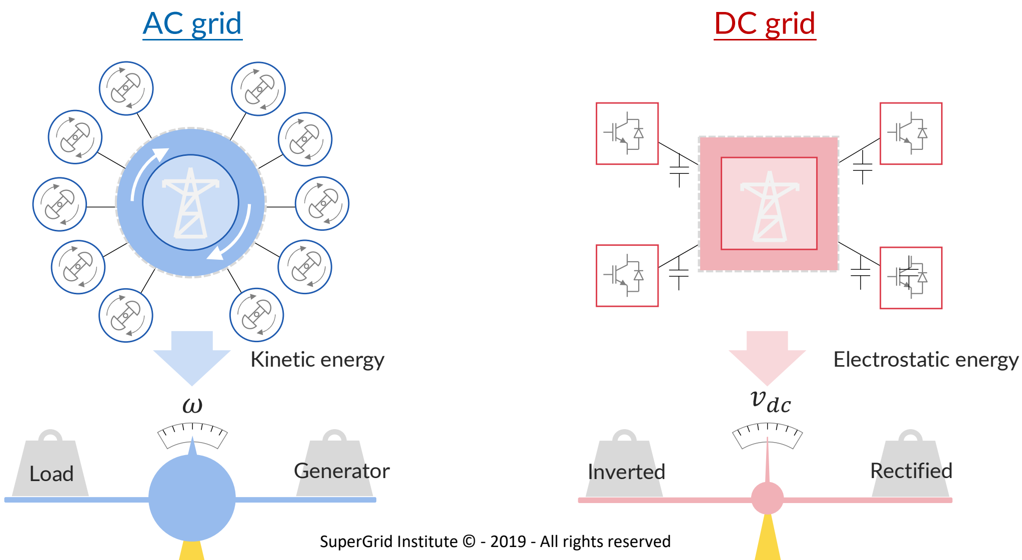

Figure 7. Comparison of AC and DC system characteristics.

In a similar sense that the frequency in an AC system reflects the balance between supply and demand of power, the DC voltage reflects the balance between the power injected and withdrawn from/to the system, as illustrated in Figure 7. The same logic applies to the relation between the rate of change of voltage (RoCoV) and the amount of electrostatic energy stored in the system. In DC systems, converters are the most vital components, and the energy stored in the capacitors embedded in the converters occupy the great part of the system energy. However, the amount of stored energy in a modern high-voltage converter is around 100 times smaller than the typical amount of kinetic energy in a generator of the same scale[19]. From this, it can be deduced that an energy imbalance in a DC system can result in a steep rise or drop of the DC voltage with significantly faster dynamics than that of the frequency in traditional AC systems. Therefore, DC systems require very fast energy balancing control strategies with typical time constant of the order of tens of milliseconds[20].

The power flow in the system is another important aspect to achieve reliable operation. In addition to meeting the requirement on the constancy of system frequency, AC system operation must pay careful attention to the system's resilience to maintain synchronism after being subjected to any credible contingency. There are two additional key operating variables to consider, namely: rotor angle and voltage. In AC systems, interchanged active power flow over a line is described by the well-known power-angle relationship. When the angular separation between two buses exceeds 90 degrees, a further increase in angle results in a decrease of transferred power.

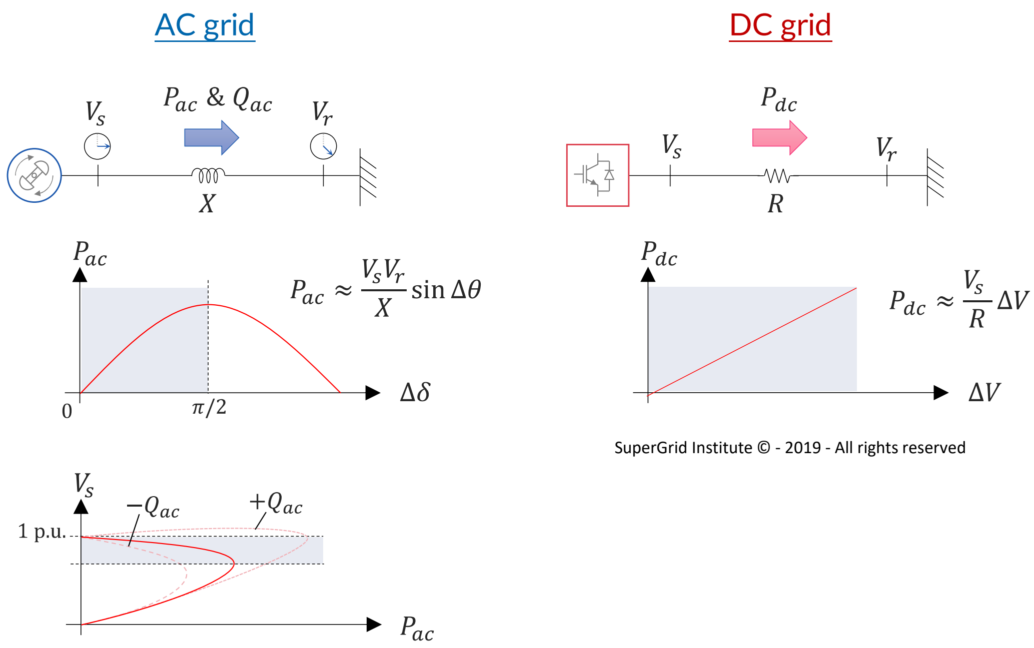

Figure 8. Comparison of AC and DC power-flow constraints.

When a system is subjected to a severe disturbance, the system response may involve the acceleration/deceleration of generators accompanied by rotor angle and phase angle deviations. If angular separations in the system exceed certain bounds, a loss of synchronism can occur, and consequently, the system splits. The voltage instability in AC systems stems from the inability to meet the reactive power demand of the load. In a heavily stressed network, a sudden increase in power demand or reduction in power factor may cause progressive and uncontrollable voltage sags, resulting in a total or partial blackout of the system. Figure 8 shows the comparison of AC and DC power flow constraints

[19] B. Jacobson, P. Karlsson, G. Asplund, L. Harnefors, and T. Jonsson, "VSC-HVDC transmission with cascaded two-level converters," in Cigré Session, 2010

[20] European Committee for Electrotechnical Standardization (CENELEC), HVDC grid systems and connected converter stations - guideline and parameter lists for functional specifications - part 1: guidelines, no. CKC/TS 50654-1. 2018

In DC systems, only the voltage is a crucial factor. There is no requirement of frequency synchronization; therefore, the stability concerns related to the loss of synchronism are disregarded. The power flow in DC systems is essentially governed by the voltage across the resistance. The reactance, which dominates line impedance in AC systems and imposes strict limitations on alternating power transmission, has no impact on the steady-state power flow in DC systems. Therefore, no real transmission limitation, apart from the thermal capability of transmission facilities, exist in practice[21].

To summarize, the DC systems have significantly faster dynamics compared to the traditional AC systems. It is, therefore, necessary to exploit the fast response of power electronic converters to ensure the reliable operation of the system. Unlike AC systems that require to monitor and control frequency, voltage angles and amplitudes to maintain the system stability, in DC systems, all disturbances are observable on the voltage. That is to say, DC systems are theoretically more stable than AC systems and could contribute to the electricity grid resilience and flexibility in a secure and reliable manner.

MTDC grid protection. Similar to AC grids, the operation of MTDC (Multi Terminal Direct Current) grids must cope with various disturbances. DC faults can cause particularly high stresses on the system components and may endanger the integrity of the system if they are not properly handled. Those faults can also lead to a temporary restriction in the entire power transfer, which may influence the underlying AC system stabilities. The objectives of protection schemes and devices are, thus, to minimize the impact of the faults and ensure the safe operation of the system. The faults need to be identified and cleared within a prescribed time, and the remaining parts of the system must resume normal operation immediately after clearing the fault.

The protection of MTDC grids has been a subject of many intensive studies and represents one of the major technical challenges for the large-scale realization of MTDC grids. Unlike the modern AC systems, standardization for DC grids is yet to be achieved due to the distinctive differences in fault phenomena and methods of fault clearing[22]. In AC systems, the AC fault current is limited by the relatively high line impedance. In contrast, due to the stray capacitances of HVDC cables and low impedance of the system, the fault current in DC systems can rise much faster and reach high amplitude, in the order of several tens of kA, depending on the number of converters installed in the grid. In general, power electronic equipment, especially the converters, have limited withstand capability against overcurrent. In the event of a DC fault, the presently preferred converter topology called Half-Bridge MMC turns into a blocking state and loses all controllability, resulting in a temporary break in power transfer. In order to contain the impact of the fault and avoid damaging the sensitive system components, the MTDC grid protection must act much faster than the AC counterpart.

Interrupting DC currents is significantly more difficult due to the non-existence of natural zero-crossings. In AC circuit breakers, the fault current can be easily interrupted at the natural zero-crossing point, where the energy to be dissipated by the breaker is trivial. This substantial difference makes the conventional AC breakers unusable for DC application. Various proposals for breaker designs have been made, and some of them are under full-scale

[21] A. K. Marten and D. Westermann, "Local HVDC grid operation with multiple TSO coordination at a global optimum," ENERGYCON 2014 - IEEE Int. Energy Conf., pp. 1549–1553, 2014
[22] M. Wang et al., "A Review on AC and DC Protection Equipment and Technologies: Towards Multivendor Solution," Proc. Cigre 2017 Canada, pp. 1–11, 2017

prototype validation. They comprise of mechanical breaker[23], solid state breakers[24], and hybrid breakers[25].

The protection strategies for DC grids vary depending on the system topology and the compulsory reliability requirements. Protection strategies are categorized according to the employed fault clearing philosophy that can be non-selective, partially selective or fully selective[26]. They differ in protection zones, the section to be disconnected in case of a fault, and each strategy imposes different requirements on the technology used for current interruptions:

- In the non-selective strategy, a DC grid is considered as one single protection zone. In case of a DC fault, the entire grid is isolated from the source of fault currents, i.e. AC grids, by using converters with fault blocking capability or breakers installed at AC or DC terminals of in each converter. The entire grid is de-energized during the fault clearance procedure. Therefore, the connected AC grids must tolerate a temporary outage of the DC grid.
- In partially selective strategy, the DC grid is divided into several protection zones by using a firewall where protection devices are installed between the zones. In case of a DC fault, the firewall isolates the faulty zone from the rest of the grid that remains operational and intact. DC breaker or DC/DC converters are considered suitable solutions as fire-wall protection device.
- In the fully selective strategy, each line and each node are individually protected using DC circuit breakers placed at each line end. The impact of a fault is mostly confined to the faulted line. Therefore, the healthy part of the grid remains intact.

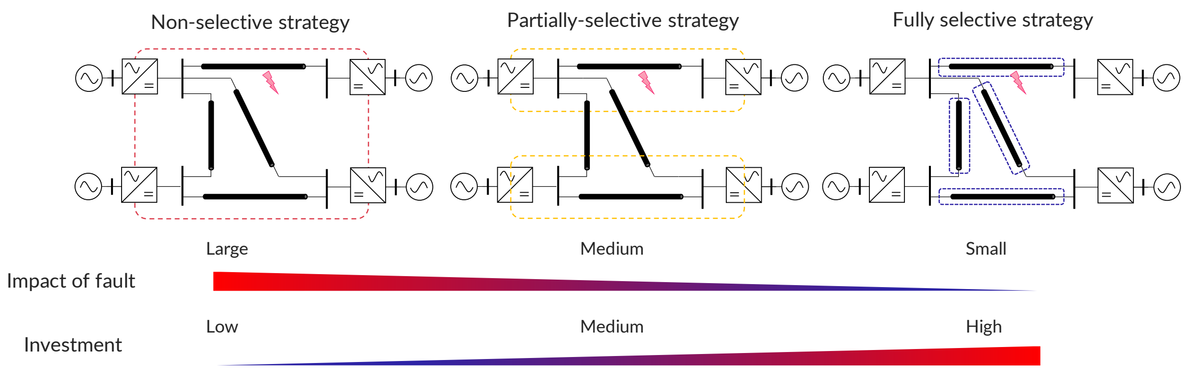

Figure 9. Comparison of DC protection philosophies.

An overview of DC grid protection strategies is illustrated in Figure 9. The optimum selection of the DC system protection strategy is a compromise among the constraints on the impact

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[23] L. Ängquist, S. Norrga, T. Modeer and S. Nee, "Fast HVDC breaker using reduced-rating power electronics," in Proc. IET ACDC 2017, Manchester, 2017

[24] J. Magnusson, R. Saers, L. Liljestrand and G. Engdahl, "Separation of the Energy Absorption and Overvoltage Protection in Solid-State Breakers by the Use of Parallel Varistors," #IEEE_J_PWRE#, vol. 29, pp. 2715-2722, 6 2014

[25] C. C. Davidson, R. S. Whitehouse, C. D. Barker, J.-P. Dupraz and W. Grieshaber, "A new ultra-fast HVDC Circuit breaker for meshed DC networks," in Proc. IET ACDC 2015, Birmingham, 2015

[26] W. Leterme et al., "Classification of Fault Clearing Strategies for HVDC Grids," Cigré Int. Symp. - Across Borders - HVDC Syst. Mark. Integr., pp. 1–6, 2015

that a strategy can cause to the DC and the interconnected AC system, the reliability of the strategy and the cost of protection equipment.

2.3. Future trends of AC at the MEGA scale.

In order to meet international climate goals, there is a desire to mitigate the impacts of the energy sector on climate change. On one hand, this objective means integrating an increased amount of RES through the grid, mostly through power electronics. On the other hand, it imposes that fossil fuelled thermal power plants have to be decommissioned. In parallel, most TSOs believe in enhancing their grid reliability by increasingly interconnecting more AC systems. In Europe, this has led to the interconnection of the continental grid with the Turkish power system in April 2015[27].

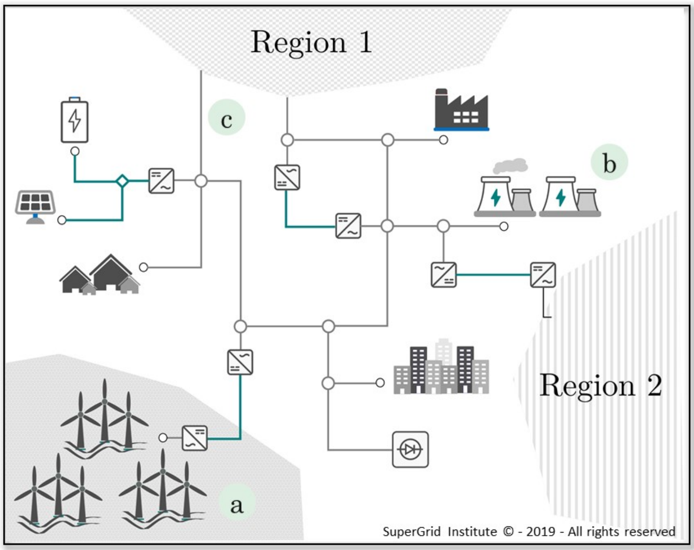

Figure 10. Illustrative scheme of the policy makers' tendencies regarding transmission grid.

The described tendencies are gathered in Figure 10 with *item a* corresponding to increased RES interconnected to the grid, *item b* which corresponds to the shutdown of thermal power plants and *item c which is* related to increased AC interconnections between AC grids. With the current trends of AC grids, weak areas will become a problem to be solved for operating reliable systems. In France for instance, the region of Brittany is a weak area in the system since it does not have many AC connections nor many nearby power plants. However, its interconnection with offshore wind farms in the Atlantic Ocean should drastically increase in the upcoming years[28], which may create voltage stability issues at the onshore connection points. At the same time, increasing the ratio of RES instead of connected Synchronous Machines (SM) is decreasing the physical inertia of the grid, i.e.: the natural contributions of SM to power unbalances. For future low-inertia power systems, coordinated actions will be needed for tackling this stability issue.

[27] "ENTSO-E at a Glance", ENTSO-E, June 2015
[28] "State aid: Commission approves support for six offshore wind farms in France", *ec.europa.eu*, 2019.

2.4. Digitalisation, data handling and data security

Nowadays, digitalisation has a significant impact on every power system control and operational functions. Digital technologies have been implemented to grasp the opportunities in all system levels. Figure 11 illustrates the impact of digitalisation in the different areas.

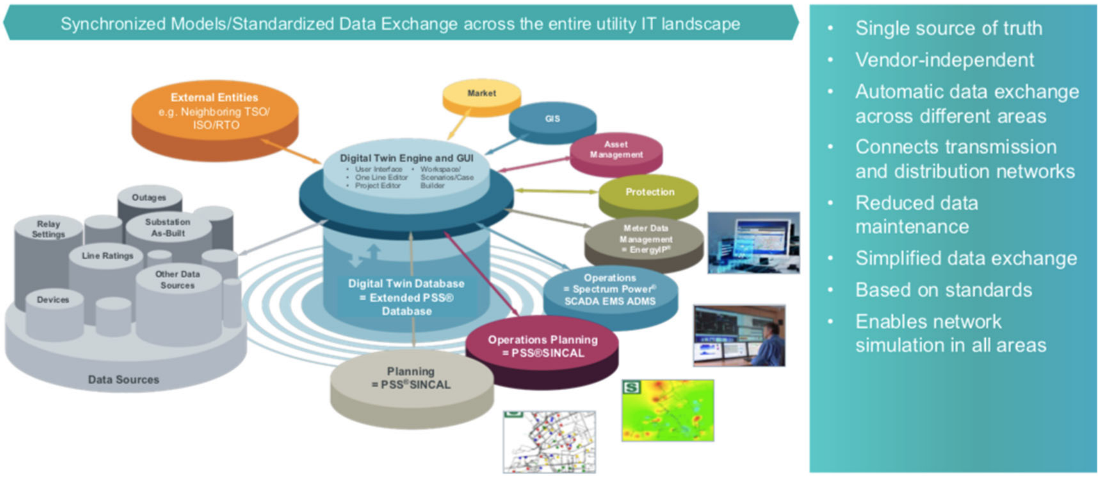

Figure 11. Digital twins as End-to-End Information Environment. ***Source SIEMENS*****.**

Cutting-edge predictive maintenance techniques, using artificial intelligence (AI), machine learning and big data, are providing increased insight for outage management, improving the resilience, availability and capacity of the grid. The installation of multitudinous sensors also enables a much greater level of observability of the network components. Thus, maintenance activities can be based on the collection of much more granular data sets than what has traditionally been available.

Analysis of TSO community projects and deliverables shows that most of the opportunities digitalisation brings are focused on increasing the overall system efficiencies (e.g. due to expanding a market or reducing constraints). Where digitalisation opportunities can be found in the grid cost efficiencies, in terms of improving asset management and reducing related costs and increasing the performance of assets. System risk management, security of supply and safety have been identified as opportunistic niches where digitalisation could bring added value. In this regard, international activities can be grouped into five focus areas[29]:

- Smart Industrial applications
- Smart Cities, Buildings and Homes
- Quality safety, Security and Risk Management
- Smart Things, Networks and Platforms
- Other Applications of ‘Smart Things Everywhere’

In the same way, systems used in real life have to guarantee safety, which translates to the need for admirable quality standards. A characteristic of artificial and self-learning systems is

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[29] M. Halker-Kusters, E. Schoitsch. “Smart Things Everywhere.” ERCIM Nr.119 October 2019

that they may have an unsupervised unpredictable behaviour. Based on the criticality of the application, different quality assurance and test concepts must be developed in order to guarantee that systems are secure and reliable and that standardization processes also have to be evolve.

2.5. Planning and deployment of large-scale solutions

Extensive research on megaprojects reveals important findings related to ambitious large-scale energy projects and their characteristics[30,31,32,33]. While megaproject-related research acknowledges the attractiveness of large-scale solutions due to their potential to solve global and society wide challenges, it also provides evidence that most of the megaprojects fail to get further beyond the planning stage. Those megaprojects that reach the deployment phase often experience delays, cost overruns and benefit shortfalls[31,32,33]. One important reason is the factors such as scale, complexity and long lead time of transnational megaprojects, existing across different national jurisdictions and markets, seem to be unable to benefit from and keep up with fast technological innovation, in contrast with smaller scale developments.

Existing historical studies show that megaprojects are not merely about the technological debates but also encompass highly political issues that require more attention. Learning from failed attempts is key to achieving progress on new large-scale transmission projects such as the more recent North Sea Wind Power Hub[34]. Van de Graaf and Sovacool[33] used the examples of DESERTEC Initiative in Europe and Gobitec in Northeast Asia as examples of electricity megaprojects that experienced complexities due to social, technical, economic, political as well as physiological factors (see Table 1). A similar analysis can be found in de Rubens and Noel[30], who compare the supergrid in USA and EU. Such type of projects can have a better chance to succeed if they include planning for failure, iterative negotiations, transparency to avoid authoritarian tendencies, cross-sectoral integration and potential downscaling of the projects[33].

[30] de Rubens, G.Z., Noel, L., 2019. The non-technical barriers to large scale electricity networks: Analysing the case for the US and EU supergrids. Energy policy 135, 111018
[31] Flyvbjerg, B., 2007. Megaproject policy and planning: Problems, causes, cures. Aalborg University
[32] Sovacool, B.K., Cooper, C.J., 2013. The governance of energy megaprojects: politics, hubris and energy security. Edward Elgar Publishing
[33] Van de Graaf, T., Sovacool, B.K., 2014. Thinking big: Politics, progress, and security in the management of Asian and European energy megaprojects. Energy policy 74, 16-27
[34] Sunila, K., Bergaentzlé, C., Martin, B., Ekroos, A., 2019. A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis. Energy policy 128, 775-782

Table 1 MEGA projects complexities from social, technical, economic, political and physiological factors

Dimension of failure	Examples	DESERTEC	GOBITEC
Social	Stakeholder fragmentation, different views and expectations, conflicting agendas, exclusion of key stakeholders, social opposition, geopolitical frictions	The EU, private investors and North African countries had diverging expectations from the project. These were not communicated clearly in the planning stage of the project, especially regarding where the energy will be supplied.	Participating countries and the local communities (in the Mongolian desert) have different perceptions and expectations from the project. Governments struggle with anxiety of import dependence while private investors hope for mutual benefits and peaceful unification of the region. In the past few years China has taken over in leading the development as a part of the OBOR strategy.
Technical	Technical complications, accidents, attacks that affect the system at large due to cascading effects. Wrong choice of technology.	CSP technology has been stagnating in terms of price and performance, outcompeted by PV. HVDC cable construction under the Mediterranean Sea posed significant construction challenges.	Uncertainties related to the variability of the CSP powerplants in desert conditions (drastic temperature change, dust). CSP technology has been replaced by wind and PV in the latest Gobitec plans.
Economic	Cost overruns, environmental and social cost externalities. Benefits remain in hands of a small group of elite or rent-seekers.	Expensive price tag challenged by the global finance crisis and decreasing oil and gas costs. Corruption, ineffective bureaucracies, political instability created investment barriers. Problem of “resource curse” for supplier countries leading to currency appreciation and loss of competitiveness. Environmentally, CSP needs water for cooling which is already scarce in the region and could affect water needs of nearby communities.	Gobitec will not contribute to solving energy poverty in Mongolia, which is planning to export most of the electricity produced in the Gobi Desert. It can interfere with local community livelihood in these areas.
Political	Megaprojects can lack transparency and be undemocratic. By working as a ‘closed system’ they can reinforce authoritarianism and support corruption.	Reinforcement of centralized power and existing energy sector monopolies might make the system more vulnerable to corruption.	Resource curse issue undermining Mongolia’s competitiveness, risk to stir corruption and erode democratic institutions. Local communities have not yet been consulted.
Psychological	Inflated positive and negative expectations. Benefits for investors are inflated and risks for local communities and environment are undervalued,	Concerns about using renewable energy sources as an “energy weapon” against Europe as well as about terrorist attacks. Oversold benefits that couldn’t be achieved.	Historical conflict in the region create negative expectations. Especially having to rely on a grid that goes through North Korea is concerning for the involved countries.

2.6. Market Aspects of Transmission Interconnections

Liberalisation, deregulation and privatisation have changed the roles of stakeholders in the electricity market. Competition is fundamental to most market reforms and it is introduced in order to reduce costs and increase efficiency. In the restructured environment, the functions of the transmission system have expanded beyond the roles of linking generation to load and ensuring system reliability. Interconnection enables more generators to compete in the market to serve the combined load. Inadequate transmission capability leading to bottlenecks enables generators at specific locations in the network to exercise market power in local markets. Investing in transmission systems, therefore, is the key for enhancing competition and mitigating market power in a restructured market environment.

In terms of transmission network investment, different stakeholders have different interests, which means that they will have different investment perspectives and strategies along the network expansion value chain. Where stakeholder communities consist of policy makers, regulators, producers, consumers, TSOs, network owners, network planners, private investors, and manufacturers amongst others.

One of the key issues concerning new transmission grid interconnection is the presence of asymmetrical benefits to the producers and consumers in the interconnected areas[35]. This leads to questions to how the costs or benefits of new MEGA grid interconnectors should be allocated to remunerate the investment costs. The problems become more complex when more than a single authority needs to approve the expansion plan as each of them will attempt to maximize and protect their own interests first. An illustrative example to explain the issue is provided in APPENDIX.

It is envisaged that: (i) the creation of single energy market for Europe; (ii) the development of appropriate regulatory frameworks for network pricing and access arrangements; and (iii) the stimulation of competition for the procurement and development of cross-border interconnection are important in overcoming the previously mentioned issue. In this context, one of the key challenges associated with the delivery of electricity transmission network expansion is to establish regulatory frameworks that facilitate timely and coordinated merchant investment in cross-border interconnections. Broadly, this requires synergies from all European members and in particular the intervention of regulatory agencies supported by ACER and the ENTSO-E.

From an actor perspective, the MEGA grid developments can be defined as ‘branching of the centralized production’ as the incumbent actors of the dominant energy sector are assumed to keep their positions, while electricity consumers remain a passive part of the system[36]. It follows ‘the government logic’ with a strong political influence, according to which national government actors together with a few large stakeholders (such as manufacturers, electricity producers, grid owners and TSOs) coordinate the system expansion to achieve energy policy goals[36,37]. This is based on the fact that building a cross-country energy system requires

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[35] D. Pudjianto, M. Castro, G. Strbac, Z. Liu, L. van der Sluis, and G. Papaefthymiou, “Asymmetric impacts of European transmission network development towards 2050: Stakeholder assessment based on IRENE-40 scenarios,” Energy Econ., vol. 53, pp. 261–269, Jan. 2016.

[36] Verbong, G.P., Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technological Forecasting and Social Change 77, 1214-1221

[37] S. Chatzivasileiadis, D. Ernst, G. Andersson, The Global Grid, Renewable Energy, Volume 57, 2013

expertise and capacity to create and coordinate such megaprojects.

2.7. Recognising the whole-market value of interconnection

At present, the benefit of interconnection is often calculated based on its impact on the production cost of energy despite broad recognition that the interconnection has multiple functionalities, i.e., enhancing security of supply, efficiency of system operation, ability to accommodate intermittent renewables through sharing of reserves and frequency regulation services. However, these benefits are often not rewarded due to the lack of cost-reflective commercial frameworks.

The present member-state-centric, not EU-wide, regulatory framework is creating barriers for recognising the value of interconnection. In the context of the capacity market, it has been demonstrated that 100 GW of peaking plant capacity could be saved by 2030 if an EU wide, rather than a member state-centric approach to security was adopted, and the cross-border interconnectors are not prevented from making contribution to security of supply. The savings in generation Capital Expenditure (CAPEX) achieved by sharing security across Europe, reflected in EU wide capacity mechanisms could reach up to €75 billion by 2030. It is vital that the role of interconnection, with respect to security of supply, is recognized when designing EU capacity markets. The British capacity market is currently the only market in Europe in which capacity contribution of interconnection is recognised. Under this arrangement, generation from other parts of Europe can access British capacity market through the interconnection, which directly enhances the value proposition of interconnection. As a consequence of interconnection contributing to security and displacing capacity of traditional power sources, the total installed capacity in the UK system is reducing and so too will the corresponding overall cost to consumers. [38]

The effects of cross-border interconnection transfers of energy and reserve have also been investigated. There may be significant benefits associated with enhancing interconnector capacity for reserve purposes (in addition to energy arbitrage) under future scenarios with significant penetration of renewables in EU. To be able to exchange reserves across interconnection (cross-border), however, a framework that remunerates interconnector developers for holding capacity headroom for reserve would need to be developed. The benefits of cross-border balancing market would be above €30 billion until 2030. Clearly, such a corresponding market framework would create appropriate incentives between the interconnector developers, system operators and market participants (generators / demand) located in each of the jurisdictions connected by the interconnector, to maintain (a) an efficient cross-border exchange of balancing services, co-optimised with energy exchanges, and (b) sufficient network headroom capacity in the long-term.[38]

2.8. Offshore grids strategic development

The benefits of changing the present policy for the development of North-Seas grid, from the incremental approach to connecting offshore wind farms to a coordinated, strategic approach that would coordinate development of offshore, interconnection and onshore infrastructure would bring very significant benefits. The modelling[39] thereof demonstrates the significance of the interaction between offshore grid and interconnection among North-Seas countries,

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[38] D. Newbery, G. Strbac, D. Pudjianto, and P. Noël, "Benefits of an integrated European Market", a report for Directorate General Energy European Commission, Booz&Co., London, 2013.

[39] Imperial College London, E3G," Strategic Development of North Sea Grid Infrastructure to facilitate least-cost decarbonisation", July 2014.

particularly under different levels of the EU electricity market integration. Given that the cost of offshore network infrastructure is significantly larger than on-shore, and due to the presence of significant economies of scale, coordinated and strategic approaches to offshore network development may bring significant savings, as also shown in the studies carried out by ENTSO-E[40] and EWEA[41].

One of the key challenges in designing the offshore grids is to include the uncertainty of time, location and amount of offshore wind generation deployment together with the need to assess flexible network investment propositions that would preserve future options for least-cost decarbonisation in high offshore wind deployment scenarios. Addressing the network planning problem under uncertainty, a min-max regret approach to the development of an offshore grid network has been investigated, examining the extent to which strategic infrastructure investment decisions could deliver the flexibility to accommodate various future wind development scenarios through facilitating multiple network designs that are not overly constrained by the design choices in earlier years. In contrast, the incremental approach focuses on optimizing the short-term benefits, which will impose substantial limits to the deployment of cost-effective offshore infrastructure, which will result in higher overall costs.[39]

The shift from the present incremental approach to the strategic approach will require a development of new regulatory and market approaches that would facilitate strategic and coordinated network planning. Investment under the uncertainty associated with low carbon technology deployment is necessary for achieving European decarbonisation targets cost-effectively. The growing interest in offshore wind introduces opportunities for transmission projects that cut across individual transmission regimes, i.e. onshore, offshore and interconnection. In this context, the evolution of the policy, regulatory and market frameworks to enable strategic and long-term based development of multi-purpose transmission projects is needed. This would require resolution of considerable legal, licencing and governance issues.

The strategic and integrated planning and operation of the North Seas grid region presents the opportunity to robustly deliver policy objectives at a significantly reduced cost compared to the current incremental and member state-centric approaches. The analysis carried out provided evidence that the potential advantages of the strategic approach are significant and that this should be made a high priority for energy ministries around the North Seas to consider how these benefits can be realised.

2.9. Supporting cost-effective deployment of renewable generation

While the 2009 EU Renewables Directive allows countries to purchase some of their obligation from other member states, no country has yet done so. Instead, countries in northern Europe have invested in solar power and some countries in southern Europe in wind generation, operating at low load factors. Modelling has demonstrated that these inefficiencies in deployment of renewables would lead to losses of €150bn-€250bn by 2030[42]. On the other

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[40] Offshore Grid Development in the North Seas ENTSO-E www.entsoe.eu/publications/system-development-reports/north-seas-grid-development/

[41] Offshore Electricity Grid Infrastructure in Europe. Online: www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/OffshoreGrid__report.pdf

[42] D. Newbery, G. Strbac, D. Pudjianto, and P. Noël, “Benefits of an integrated European Market”, report for Directorate General Energy European Commission, Booz&Co., London, 2013.

hand, if there was a true common market for renewable energy, as envisaged by the Renewables Directive, this would provide commercial incentives for implementing renewable generation at locations which would be most effective rather than where national policies direct. To access this new generation would require further investment in transmission and interconnection infrastructure, however, the overall cost of transmission investment is assessed to be less than 10% of the benefits delivered.

In addition to political issues associated with a member-state-centric deployment of renewables, the value of an interconnection proposition is significantly affected by the market rules governing cross-border exchanges of renewable energy. Currently, in line with the cross-border European market design (i.e., the Target Model), countries that exchange renewable energy are required to specify individual cross-border interconnectors along a "hypothetical" route of the electricity flow between the country of export and the country of import. Then, the appropriate capacity on all the interconnectors specified would need to be reserved so that this trade is firm, through purchasing Physical Transmission Rights (PTRs).

It is well recognised that this approach is inherently inefficient and will create barriers for market integration, particularity in the context of renewable energy exchange. As argued in a report presented to the European Union[43], Financial Transmission Rights (FTRs) could provide a solution to this problem, as these present an obligation between trading parties which would only specify the source/generation zone and sink/load zone of the electricity trade, but not all multiple interconnectors that might link these zones together. One of the key advantages of FTRs over PTRs is that contracts for exchange of power in different directions can be netted, so that the absolute value of the total volume of contracts from one country to the other can greatly exceed the actual cross-border network capacity, considerably enhancing competition in each market.

Furthermore, under the present PTRs concept, there is no provision for a long-term market for cross-border capacity. This puts a severe commercial risk on long-term renewable energy projects, as they have to continuously bid into the day-ahead capacity-market of specific inter-connectors with the associated uncertainty over price and availability of such capacity. On the other hand, long-term FTRs would facilitate trading for renewable energy generators by allowing them to sell power to customers across the European electricity network at a known trading cost. It is important to emphasise that there is considerable experience with FTRs as these have been successfully used for efficiently managing transmission access in congested networks, particularly in the United States.

Hence, two important conclusions are: (i) renewable energy related projects should have the opportunity to access long-term network capacity markets for projects that provide long-term stability and certainty to trading arrangement across Europe; and (ii) renewable energy projects that inject electricity at one point in the European network, and have customers that consume electricity at any other point, should face a cost that is related to the net flow of electricity in the network. It can be concluded that it is imperative that grid integration cost and benefits associated with connections of different types of renewable sources in different locations, are fully recognised within the design of the European electricity market to support the implementation of Renewable Energy Directive. Furthermore, analysis demonstrated that

[43] D. Newbery and G. Strbac "Physical And Financial Capacity Rights For Cross-Border Trade", report to the European Commission by Booz & Company, September 2011, http://ec.europa.eu/energy/gas_electricity/studies/doc/electricity/2012_transmission.pdf.

it would be beneficial to deploy interconnection between Europe and Middle East and North African (MENA) countries, but the present market arrangements cannot support this development[44].

[44] R Poudineh, A Rubino, Business model for cross-border interconnections in the Mediterranean basin, Oxford Institute for Energy Studies, 2016.

3. Developments of the *micro scale* solutions

This section gives insights into recent developments at the micro perspective with focus on local solutions, including large penetration of variable energy sources and the ability of demand to provide a flexible response. Though different in their individual designs and applications, all of these micro solutions applications serve one common goal: resiliency and quality of supply. Moving forward, such types of solutions expand even more rapid as a part of Energy and Climate policy at all system levels. Microgrid projects follow innovative industrial solutions, renewables integration plans and business models over geographic areas supporting end-users by market platforms. The history of microgrids can help us understand how to accommodate large penetration of renewables.

Microgrids as a concept dates back to the beginning of the power industry, where Thomas Edison opened his Pearl Street Station in 1882. It was a self-contained system, powered by coal fired steam engines with six DC generators each with a capacity of 1100 kW. The steam engines were also used to supply heat to buildings in the vicinity, similarly as todays combined heat and power plants (CHP). The Pearl Street Station system consisted of batteries to provide energy storage and it served only a few blocks in each direction due to restrictions of the DC distribution network. At this time there were no defined standards for electrical generation-distribution systems and subsequently the system was designed according to immediate needs. Amazingly, Edison's Manhattan Pearl Street Station was aligned with the criteria for what is presently considered as a microgrid system.[45]

3.1. Microgrid Definitions and categories

The definitions extracted from the standards IEEE 2070.3 and IEC-TS 62898-1 as well as U.S. DOE MEG, ANEEL and the CIGRE WG C6.22 WG[46] are provided.

IEEE 2070.3

> A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes.

In IEC-TS 62898-1

> Group of interconnected loads and distributed energy resources with defined electrical boundaries that acts as a single controllable entity and is able to operate in both grid-connected and island mode. (The definition covers both utility microgrids and customer microgrids)

U.S. Department of Energy Microgrid Exchange Group:

> A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect

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[45] Gene Wolf, "A Short History: The Microgrid", https://www.tdworld.com/digital-innovations/short-history-microgrid, 2017

[46] https://building-microgrid.lbl.gov/microgrid-definitions

to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.

CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap:

Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

ANEEL (n. 674, 11th August of 2015) - The Brazilian Electricity Regulatory Agency (in Portuguese, Agência Nacional de Energia Elétrica, ANEEL):

Electric network that can operate independently of in the distribution power system, been supplied directly by a distributed generation unit. CIGRÉ C6.22 Definition Qualifiers:

Generators covers all sources possible at the scales and within the context of a microgrid, e.g. fossil or biomass-fired small-scale combined heat and power (CHP), photovoltaic modules (PV), small wind turbines, mini-hydro, etc. Storage Devices includes all of electrical, pressure, gravitational, flywheel, and heat storage technologies. While the microgrid concept focuses on a power system, heat storage can be relevant to its operation whenever its existence affects operation of the microgrid. For example, the availability of heat storage will alter the desirable operating schedule of a CHP system as the electrical and heat loads are decoupled. Similarly, the pre-cooling or heating of buildings will alter the load shape of heating ventilation and air conditioning system, and therefore the requirement faced by electricity supply resources.

Controlled loads, such as automatically dimmable lighting or delayed pumping, are particularly important to microgrids simply by virtue of their scale. Inevitably in small power systems, load variability will be more extreme than in bulk-scale systems. The corollary is that load control can make a particularly valuable contribution to a microgrid.

Figure 12 provides an overview of an embedded microgrid with dedicated monitoring and control of the internal and external system.

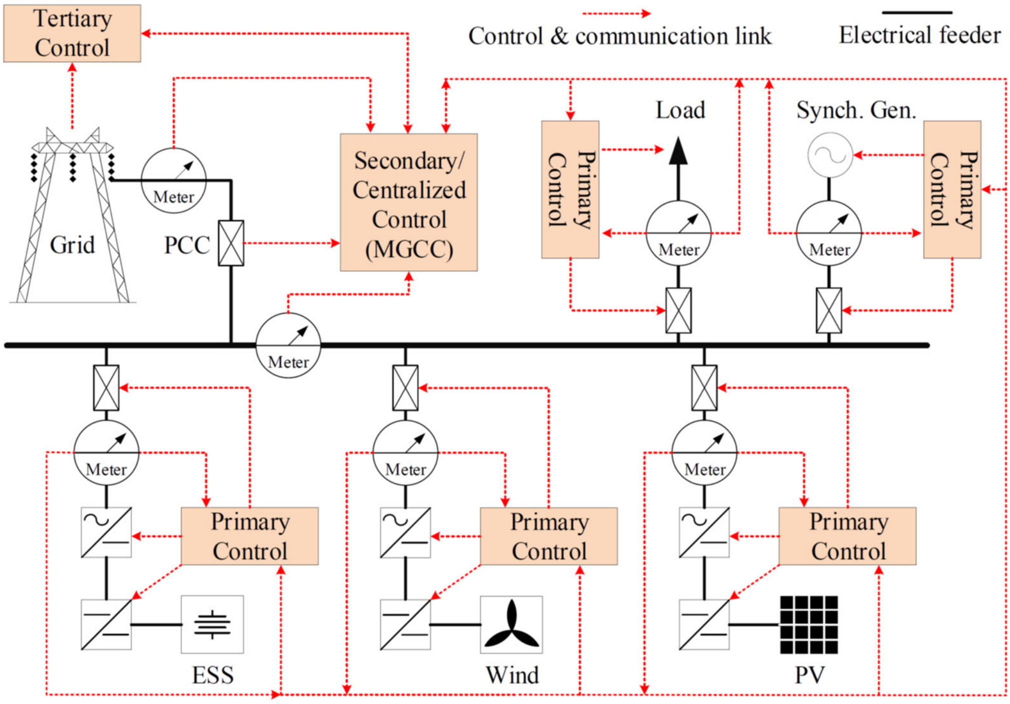

Figure 12. Typical concept of an embedded microgrid[47].

An illustrative explanation of the configuration of microgrids and the versatile impacts on the operation of the grid is given in Figure 13.

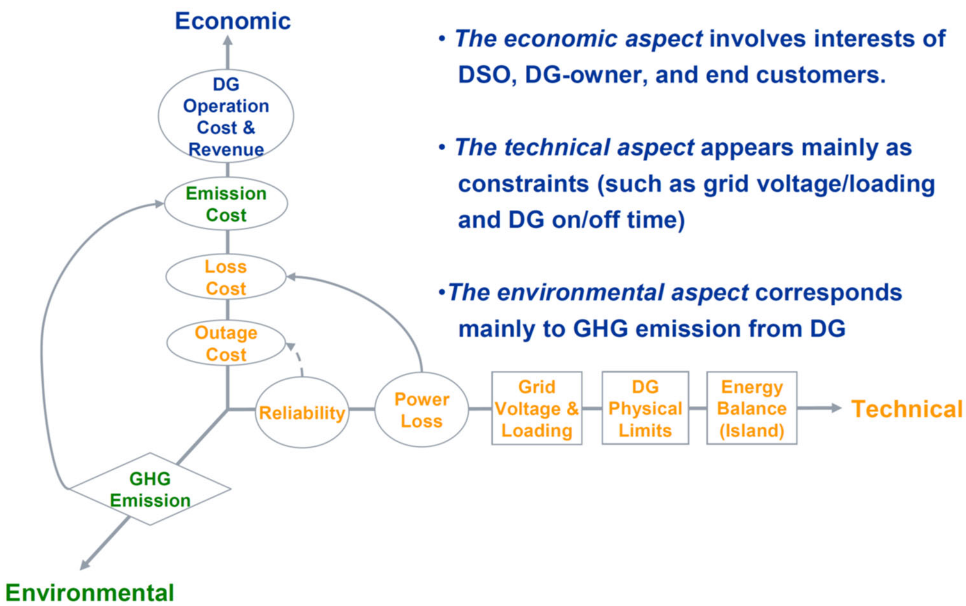

Figure 13. Configuration of microgrids and the versatile impacts on the operation of the grid[48].

[47] M. Farrokhabadi et al., "Microgrid Stability Definitions, Analysis, and Examples," in IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 13-29, Jan. 2020.
[48] More Microgrids, " DG3&DG4. Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation", 2009

Microgrids can be built based on various beneficial expectations, which can be improved reliability, economy or disaster preparedness. In addition, geographical location sets the conditions for the feasibility of a microgrid[49]. Therefore, the use of microgrids can be classified as follows:

- Improving reliability; a distribution microgrid (a part of a distribution grid, a campus, or another activity zone) or a facility microgrid (in a customer installation, a military base, a hospital, etc.)
- Electrifying remote areas; an isolated microgrid (in rural areas, or islands)
- Reducing energy cost; the microgrid users offer ancillary services through flexibility provision on a market
- Providing disaster-preparedness; asset optimization due to critical conditions (a disaster-prone area).

A further differentiation of active control management of the controllable resources in the distribution network, following the microgrid concept, can be:

- **Isolated microgrids**, which operate in an islanded mode, means that there is no exchange of energy with the main distribution grid.
- **Embedded microgrids**, which can be both operated and controlled under interconnected mode (i.e. connected to the main distribution network) or islanded mode.
- **Energy communities**, which typically refer to the cooperation among the consumers (or prosumers), in order to order to accomplish the satisfaction of their communities (e.g. neighbourhood) energy needs using solely local production sources (i.e. DER sources).

In the literature, there is a particular effort on identifying multiple kinds of communities for the microgrids such as homogenous energy communities, mixed energy communities and self-sufficient communities. This kind of categorization refers to energy communities which could facilitate the power grid to advance energy management and enable microgrids to trace cooperative peer microgrids that substantially share energy to each other. Other research efforts are focused on identifying communities according to spatial and geolocation data.

Energy Communities.

- Both microgrids and Energy Communities[50] can have a potential impact on distribution system development, as well as to advantage of the end-users and network owners. According to the European's Commission Package entitled 'Clean Energy for All Europeans'[51], there is a particular attention to place citizens as the central players into the energy markets future, as part of the decarbonization effort and targets of 2050. Towards these efforts, the Energy Communities -newly arisen concept- can drive and empower the end-users to consume energy following a more responsible manner, contribute to energy savings and steer the grid to become more flexible.
- The European Commission endeavours to form a supportive legal framework for Energy Communities, that clearly identifies who these Energy Communities are and how they can differ from traditional players. Most notably, the Energy Communities

[49] IEC, Technical Specification 62898-1 Microgrids - Part 1: Guidelines for microgrid projects planning and specification, May 2017
[50] Various expressions such as *Local Energy Community*, *Citizen Energy Community* and *Renewable Energy Community* have been in use, here we only use the more general expression
[51] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

are opposed to solely profit-driven purposes -such as commercial energy companies. Other issues that are still under discussion and definition concern the network charges and remuneration for self-consumers and energy communities. This issue is rather complex since in current market models consumers are bundled with incentives to engage in demand response, renewables self-consumption (coupled with storage) and electrical vehicle charging, without rewarding the choice for smarter and more efficient behaviour on a long term basis. Distribution tariffs should promote such attributes by incorporating reflective price signals that deliver versatile benefits (i.e. societal, environmental, energy system).

3.2. Data handling and security

Since microgrids are designed to be self-sufficient, they need efficient generation-load balancing mechanisms. Information and Communication Technology (ICT) systems can provide the necessary communication infrastructure to exchange data between the actors within the microgrid for improved coordination. Additionally, due to the stochastic nature of RES, efficient forecasting and scheduling algorithms are needed to exploit the available flexibilities. One of the prime challenges regarding ICT in microgrids is the fact that microgrids are on the distribution side which currently have limited ICT penetration. Enhancing the ICT penetration on the distribution side would vastly benefit both the micro as well as the Mega paradigm. Furthermore, the various new services offered by the microgrid, rely upon the transmission of large amounts of data. Therefore, a communication infrastructure for supporting the required data exchange of these applications, among end-users and other stakeholders of the grid (e.g., operators, aggregators, etc.), is a central subsystem of the microgrid. The ICT systems should utilize the available communication resources efficiently and be capable of detecting and handling malicious behaviour. For some technologies like wireless communications and agent-based architectures, the unavailability of resources, as well as the costs that are associated with its access, may lead to communication bottlenecks, negatively affecting the perceived quality of service.

A current “resilient of digitalized energy system”[52] working group in ESYS initiatives in Germany recommends that the major contribution to resilience can and must in future be made more from the distribution network (including energy quartier and microgrids). In the event of a malfunction, those responsible for system security in a particular grid area are given the legal and technical opportunity to control the power generation and consumption of individual systems up to an agreed limit. This is achieved in such a way that they do not exceed a certain residual load at the same time as all other market contracts lose their significance. In the event of a large-scale, prolonged blackout, a local emergency supply can be temporarily implemented (island operation) with suitable technical regulatory measures until the network is restored.

3.3. Integrating DER

Globally, the pace of developing efficient renewables energy technologies is accelerating. Distributed energy resources (DER) will play an increasingly important role in the modern power system. DER growth is driven by several related factors. First, technology development is reducing the cost of DER. Photovoltaic (PV) technology has either reached or is not far from reaching grid parity in the load centres; parity will only increase as technology costs fall and electricity rates increase. Second, consumers are willing to play an ever-increasing role in the

[52] https://www.acatech.de/projekt/esys-energiesysteme-der-zukunft/

way they use energy and are becoming “prosumers”. New technologies particularly IOT-enabled, is making this possible at a relatively low cost. Third, electrification is making entirely new resources available to support the grid and the integration of variable renewable energy generating technologies: e.g., electric vehicles, smart heating and cooling equipment. While these devices also contribute to increased loading of the network, they can offer a source of flexibility to ease their integration.

To economically integrate variable renewables and new electrical demand, DSOs will have to capture the flexibility potential offered by DER and by future energy communities. The following concepts are being explored to enable this:

- Artificial intelligence – algorithms to improve load forecasting and optimize the control of DERs.
- Digitalization – the use of ICT to manage, monitor, and/or control DER elements in a coordinated fashion with or without direct DSO input.
- New business models – methods by DSOs, product manufacturers and installers, and property managers to both facilitate consumer engagement and increase cost-benefit; may include, e.g., transactive energy concepts
- Regulatory sandboxes – the ability of DSOs and other related entities to conduct pilots outside the normal regulatory requirements, particularly with respect to the buying and selling of energy.
- Virtual net-metering – the ability to apply net-metering to an entity’s assets spread across a number of physical meters.

In addition to normal differences in resources and loads between networks, Canada for instance, has the additional challenge of both deregulated and vertically-integrated environments co-existing in the country; thus a large, diverse set of solutions and options must be explored.

The excessive penetration of DER into electrical networks may lead to various power quality issues and operational limit violations. The main operational limit violations are overvoltages, excessive line loss, overloading of transformers and feeders, voltage unbalance and high harmonic distortion levels. The problems occur when the system exceeds its hosting capacity (HC) limit. For the purpose of this paper, the HC is defined as the maximum amount of DER that can be integrated into the electrical system above which the system technical performance becomes unacceptable.

To increase the penetration of DG systems without increasing their curtailment, two approaches can be adopted:

- The first approach is based on intervention in the electrical network through the refurbishment of LV networks, division of grids, relocation of loads, replacement of transformers, and adjustments of transformer tap changers, etc.
- The second approach is based on intervention in the DG systems themselves, through grid-support functions, like: volt-var function, volt-wat function, freq-watt function, etc.

Additional details are provided in APPENDIX.

3.4. Microgrid functional requirements

It is expected from the microgrid model perspective that the microgrid structure be capable of at least complying with the following functional requirements:

1) The microgrid structure must be seen by the distribution system operator as a single-controllable entity. This implies that microgrids must the dispatchable, or quasi-dispatchable, structured in terms of active and reactive power, in order to enhance the hosting capacity limits of distribution power system.
2) The microgrid structure must be capable of operating in both grid-connected and islanded modes, in order to improve system reliability.
3) The microgrid structure must have a sufficient power sharing capability among the DG units, safe operability, and stable operation in order to guarantee its efficient operation under different operational conditions.

Functional requirements for microgrids are based on the requirements of the purpose that a microgrid is used for. There are several methods to perform the functions for the power system, metering as well as grid operations. There are general functions defined for microgrids management but depending on the application some functionalities may not be applied.

Functional requirements for microgrid management according to the IEEE 2030.7 standard are dispatch and transition functions[53]. The dispatch function is a command for the microgrid components or their separate controllers that might be open/close, start/stop, set the generation levels, or reduce the load. The control system has to dispatch the microgrid assets in terms of power. The dispatch function should apply in the grid-connected, islanded, and in transition mode. The dispatch function provides three core microgrid functionalities that are:

1) balancing load and generation in normal islanded operation mode
2) re-dispatching controllable resources in response to internal events related to the load and generation profiles
3) responding to external orders, for example, interconnection agreement requirements, and external events by re-dispatching resources.

The transition function can be planned or unplanned. Also, reconnection to the grid and black start are transition functions.

IEC Technical Specification (TS) 62898-1 defines that functions of a microgrid control system should include power balance, demand-side management, and economic dispatch. Also, the grid-connected microgrid should be able to exchange information with the main grid.

Both IEEE and IEC standardization recognizes a Microgrid Energy Management System (MEMS). MEMS is considered for long-term energy management as well as short-term power balancing. A microgrid management system (MMS) is responsible for the coordination of the microgrid's protection, where the protection system is adaptable depending on the operation mode of the microgrid (grid-connected or island), and if necessary, on the changes of the generation and the demand.

Functional requirements defined for a microgrid controller by Oak Ridge National Laboratory (ORNL) are frequency and voltage control, intentional or unintentional islanding, black start, transition to grid-connected operation, energy management, protection, ancillary services, as well as user interface and data management.[54]

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[53] IEEE Standard for the Specification of Microgrid Controllers, IEEE Std 2030.7-2017, pp. 1-43, 2018
[54] Y. Xu, G. Liu and J. Reilly, "ORNL microgrid use cases," EPRI, 2014

3.5. Resilience enhancement through multi-energy microgrids

The increased urban electric load driven by electrification of transport sector, cooling/heating technologies, various forms of energy storage technologies, advancements in distributed generation, demand-side response, etc. will fundamentally transform the operational paradigm of future urban energy infrastructure. In particular, in the future, reliability will not necessarily be maintained through asset redundancy at the national level, but rather through smart control of multi-energy systems at the local district level, by making use of local backup generation, energy storage, electric vehicles, demand-side response technologies and control of local urban energy infrastructure.

Multi-energy microgrids, as shown by the schematic framework demonstrated in Figure 14, will potentially constitute the cornerstone of the future inner-city energy systems in which the electricity supply will be delivered by local resources at the district level, which will be particularly relevant for mega-cities. To support such a paradigm shift, a fully intelligent and sophisticated coordination of the system through corrective control actions is required.

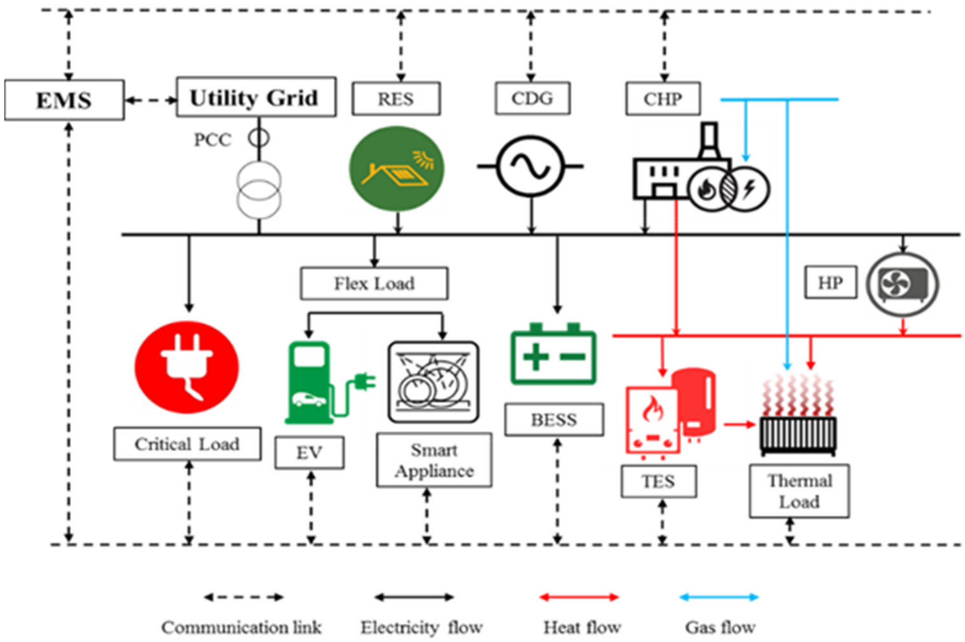

Figure 14. Schematic Framework of Multi-Energy Microgrid

In light of the increased occurrence and severity of power outages in recent years, more attention is attracted to improve the resilience performance of the power system. Although there is not yet a consensus of the definition of the resilience in power systems, it is widely accepted that resilience can strengthen the immunity of the power system to high-impact low-probability disruptive events and gracefully reduce the magnitude and duration of outages while enabling rapid self-recovery to the normal state of the power system. Microgrids can increase the resilience of the local energy system, through islanding the microgrid from the overlaying grid and self-supply the local load using various distributed energy resources coupled through strong links between different energy vectors, thus mitigating the adverse effects (e.g., frequency drop) posed by the power imbalance of the interconnected grid.

Resilience Enhancement through Preventive Preparation. Due to dynamic restrictions of various components within a microgrid (ramp rate, start-up time of dispatchable generation units), significant load shedding may be caused due to the inability of fast response of local resources upon a disconnection of the microgrid from the overlaying grid. The capability of the microgrid in preserving load is not fully exploited, leading to additional undesirable but potentially inevitable load shedding. To enable a seamless islanding on demand, the EMS of the microgrid needs to optimise the dispatch of local resources prior to supply interruptions from the upstream grid to make sure that adequate energy resources are online to preserve the load at the maximum level.

Resilience Enhancement through Corrective Smart Control of Differently Prioritised loads. Once the microgrid is disconnected from the overlaying grid, all the loads have to be supplied by local energy resources, the ability of microgrid to sustainably supply the local energy demand is limited by the capacity of generation units and the amount of stored energy. Disregarding shortage of fuel supply and failure of microgrid components, local generation units can keep stable and reliable outputs within its capacity regardless of the duration of supply interruption from the upstream grid. However, pre-stored energy will be consumed in an unsustainable manner which means the benefits it brings will diminish over time. Therefore, compromise of load supply can be inevitable during long-lasting disruptive events, introducing the necessity to optimise curtailment strategy related to loads characterised with different priorities.

3.6. Stability support from DER

The change from large-scale synchronous generator-based production to distributed PE-interfaced production has a direct impact on the power system dynamic behaviour. This change leads to loss of rotational inertia, reduced passive damping torque and stabilizing generation controls, leading to an increase in system-wide frequency violations, local transient voltage angle violations and the overall system fragility after disturbances. Voltage and frequency stability are key for secure power grid operation. Frequency stability relates to the need of maintaining the system frequency within a prescribed security range, and deviations are managed through balancing of demand and supply. Voltage stability relates to maintaining the voltage levels on all system busses within prescribed security ranges.

In a microgrid, additional stability phenomena are needed to be considered in addition to the classical stability definitions. Figure 15 provides an overview of different stability phenomena of microgrids.

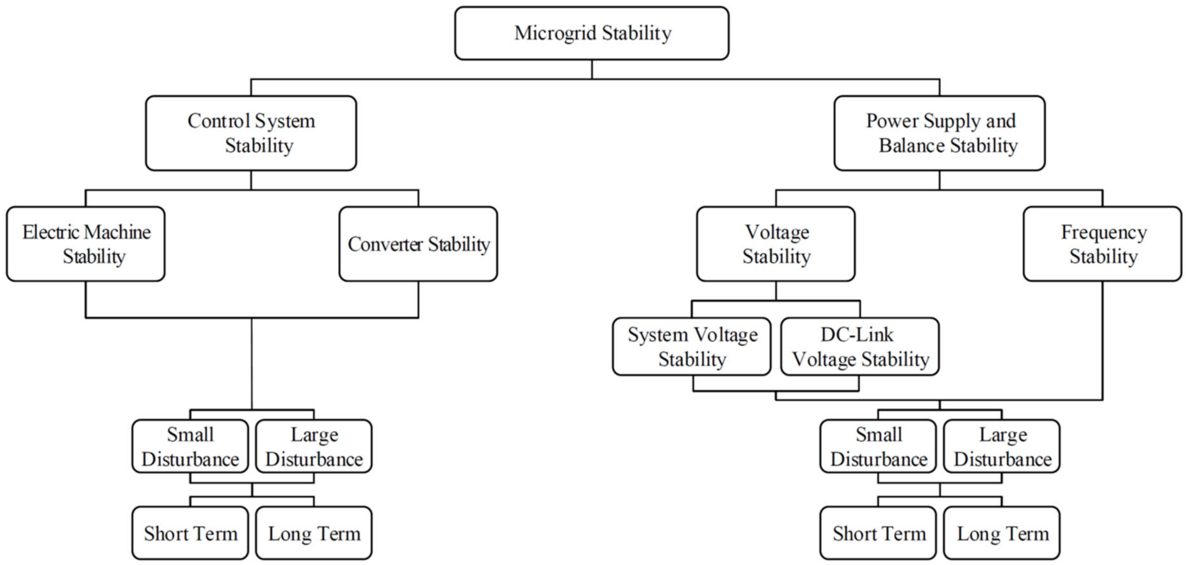

Figure 15. Stability classification in microgrids[55].

The dynamic challenges of converter-based DER can be addressed using modern converter control approaches. Most of today's converter controls for renewable generation are equipped with a simple converter current controller with the single objective of supplying the available power to the grid. However, newer types of converter controls include different forms of synchronous machine emulation to provide inertia, damping and other types of stability enhancing actions to the grid. In combination with local energy storage from batteries, these control systems could also support temporary islanding operation of the microgrid.[56,57,58] Power system stability support from distributed power-electronic sources can be classified as follows:

- Local support for weak local grids:
  - Damping of local oscillations due to poorly tuned power electronic devices
  - Compensations of critical load steps in the grid
- Temporary islanding operation
  - Support of the transition to islanding modes during forced or voluntary islanding operation of the microgrid
  - Coordination of local generation sources and power-electronics connected storages for stable load balancing
  - Generation of a local frequency signal for the islanded grid, tracking of the frequency reference from higher grid levels after reconnection
- Support for higher grid levels:
  - Aggregated damping support for oscillations in the higher grid levels by local damping control

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[55] M. Farrokhabadi et al., "Microgrid Stability Definitions, Analysis, and Examples," in IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 13-29, Jan. 2020.
[56] M. Larsson. Harmonic Resonance and Control Interoperability Analysis for HVDC Connected Wind Farms. Invited panel talk, August 2017
[57] D. Gross, S. Bolognani, B.K. Poolla, and F. Dörfler. Increasing the Resilience of Low-inertia Power Systems by Virtual Inertia and Damping. In IREP Bulk Power System Dynamics & Control Symposium, February 2017
[58] A. Fuchs, T. Demiray: Simulation results of benchmark scenarios in the ENTSO-E power system. SCCER-FURIES D2.1.2

◦ Droop control and reserve power during large-scale disturbances in the higher grid levels, e.g. separation of the grid into multiple synchronous areas.

The change in generation mix also requires development of new services (related to as ancillary services, system services or flexibility services) to maintain the frequency and voltages in the interconnected power system. Development of existing markets and deployment of new markets are needed and will have to involve smaller units and rely on the participation of distributed resources.

Ancillary services are a set of functions agreed upon by TSOs to the guarantee security of the power system. These include black start capability, frequency response, fast reserve and the provision of reactive power. The access to services includes generators but also demand response offered by a wide range of providers.

Two important ancillary services are regulation and the utilization of reserves. Regulation services are utilized to control the small mismatches between demand and generation. Regulation services can be for example:

1) Load following: bases on hour-to-hour regulation
2) Peaking: regulates power generation to meet peak demands
3) Ramping: regulates energy output based on variations of power generation like RES (within seconds to minutes)
4) Frequency regulation: controls the electricity supply up or down according to demand (within seconds)

Reserves can be divided into spinning reserves and non-spinning reserves or supplemental reserves. The spinning reserve is the extra generating capacity available by increasing the power output of the power system connected generators. The non-spinning reserve or supplemental reserve is the capacity not connected to the power system but can be dispatched with a short delay. Reserves help to restore system balance, for example, in case of loss of a large generator which results in a large impact on the system. Marketplaces for the reserves exist, which can be also divided into three groups based on their purposes.

1) Frequency containment reserves (FCR) are used for the constant control of frequency, which includes frequency controlled normal operation reserves (FCR-N) and frequency controlled disturbance reserves (FCR-D).
2) Frequency restoration reserves (FRR) aim is to return the frequency to normal range and to release FCR back into use. FRR includes automatic frequency restoration reserve (aFRR) as well as manual frequency restoration reserve (mFRR).
3) Replacement reserves (RR) are generators capable of starting up if not already operating, synchronizing with the grid and ramping up or can also be provided by controllable demand

The increasing amount of wind and solar power generation increases variability and uncertainty in power grids, which leads to the increasing need for various ancillary services. An emerging concept is flexibility reserves for addressing variability and uncertainty.

Short-term forecasting of electricity production and consumption has traditionally been relatively easy. At any given moment, electricity will be produced at exactly the same amount as it is being consumed. Therefore, the marketplaces for electricity have largely evolved to meet the traditional time-frame profiles for electricity consumption and production planning.

For example, one day earlier, the temperature forecast can be used to make a relatively accurate estimate of the electricity consumption and production needed for the following day.

On the day-ahead market, electricity is sold and purchased for the following day. Trading is based on operators' plans for electricity needs, either for resale on the retail market or for consumption at an industrial plant using electricity. The intraday market complements the day-ahead market. For example, if the wind or temperature forecast changes during the day, the intraday market can be traded based on the situational changes. The intraday market enables electricity market players to balance their electricity purchases and sales closer to the point of use.

In the future, the electricity procurement and sales will be focused more closely on the moment when it is used, as the variable production and the difficulty of predicting it increases. At the same time, this requires the development of all marketplaces. The most obvious need for a change is in the short-term intraday and real-time markets.

3.7. Local market mechanisms

Increased RES and DER penetration introduce new market players such as active consumers, prosumers and aggregators. To use the advantages and new opportunities these players can offer, market mechanisms and regulatory framework need to be implemented. Changing the regulatory framework for DSOs by introducing new incentives will adapt network operation and support energy transition. Innovative solutions at distribution level include:

- smart meters
- real-time monitoring systems
- aggregation opportunities
- local marketplace/platforms

This will include creating charging systems for EVs, creating online marketplaces for energy products and services and developing storage systems on the demand side[59].

Also, the grid-support functions reward themselves by allowing more RES and DER units to be connected to the same electric feeder. Inverter grid support functions like volt-var, volt-watt or volt-freq may be required to guarantee a sufficient and stable electric power operation. It may be implemented through grid code requirements, supporting the new role of the DSO and through TSO-DSO coordination.

The storage-energy and communication-based functions may be remunerated for ensuring services of active power supply needed to maintain the power balance in the system. Functions like peak-power limiting, load and generation following, energy time shift, load-levelling and spinning reserve power may be remunerated by the transmission system operator or local distribution system operator. It may be implemented through a new market mechanism.

Depending on the role and stakeholders involved, the microgrid or local energy system could include a local market. Such markets could, for example, facilitate local energy transactions through lowering thresholds for local actors, and enhance the interaction with the overlaying

[59] IRENA 2019. Future role of distribution system operators. Innovation Landscape brief

system and market regarding energy exchange and provision of system services such as frequency or voltage control.

The market structure and design can vary significantly between local markets. Examples include peer-to-peer markets applied to facilitate local energy exchange as in Brooklyn Microgrid[60] and studies performed in Australia[61]. The Fossil-Free Energy District project[62] is an example of a centralized pool-based local market where local actors can trade energy as well as ensure supply of energy from the overlaying market.

Growing share of local distributed systems calls for new business models that could better reflect their physical and market structure. A variety of business models have been proposed, with different levels of interdependence between the microgrid and the rest of the system.[63]

3.8. Drivers

Micro perspective investments could provide a range of economic, technical and social benefits to various stakeholders. The type of investments and categories of microgrids provide different values and have different drivers.

Following the electricity market deregulation, improved technological performance and falling prices of distributed energy technologies, companies as well as individuals are gradually shifting and adopting small decentralised production units[64,65].

Motivations for micro perspective investments are also context specific, influenced by the local and national political agendas. In the US for example, the main driver is improved resilience and reliability of the islanded grids as many states across the US suffer blackouts due to severe weather events. In this context, small-scale solutions can supply electricity locally and more securely, support the local community and alleviate risk of cascading blackouts due to failures in the centralised energy system. Local systems are also perceived as less vulnerable to cyber and physical attacks if they are able to disconnect in case a key component of large-scale infrastructure is affected[65]. Local authorities, small energy companies and citizen communities often support local microgrids because they can provide new revenue streams and economic development to the local community[66]. In Europe, a strong motivation for micro perspective investments is related to providing flexibility and reduce congestion on the transmission level. Especially in regions where the increasing load from distributed energy technologies are already causing congestion on the existing grid infrastructure, new local efficiency-related solutions are being deployed as an alternative to traditional grid extension and additional capacity building.

Europe is also leading in terms of local bottom up energy user communities that are building local microgrids motivated by strong community and environmental values and efforts to

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[60] https://www.brooklyn.energy/
[61] https://arena.gov.au/projects/agl-solar-project/
[62] https://www.johannebergsciencepark.com/projekt/fed-fossil-free-energy-districts
[63] IEEE power & energy magazine Vol 17, No 1, Jan/Feb 2019
[64] T. Van de Graaf, B.K. Sovacool, Thinking big: Politics, progress, and security in the management of Asian and European energy megaprojects, Energy Policy 74 (2014) 16-27.
[65] A. Hirsch, Y. Parag, J. Guerrero, Microgrids: A review of technologies, key drivers, and outstanding issues, Renewable and sustainable Energy reviews 90 (2018) 402-411.
[66] K. Hojčková, B. Sandén, H. Ahlborg, Three electricity futures: Monitoring the emergence of alternative system architectures, Futures 98 (2018) 72-89.

contribute to the sustainability of the energy system[67],[68]. In Australia, one of the strongest drivers for more distributed solutions are high electricity prices that are a result of an overbuilt infrastructure and generation capacity across a large area with dense population. As the prices of small-scale generation are falling, many individuals and business are opting to invest in their own solar PV and battery systems to save on their electricity bills. However, they also defect from the larger system, which becomes more expensive for those that can not install PV systems as a consequence. Building local microgrids is, therefore, a way to reduce electricity prices through more efficient utilisation of the existing infrastructure, to shave the duck curves by local balancing and to re-engage prosumers with the larger grid to avoid the poor and the disadvantaged to bear the costs for the existing infrastructure[69]. In Africa, local microgrid solutions are thriving as the large grid extension is often too expensive or not available, especially in remote areas. The opportunity to create local microgrids powered by renewables to bring electricity to remote villages for the first time provides an opportunity to accelerate the implementation of more affordable and more scalable solutions instead of waiting for traditional grid extension[66,70].

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[67] G. Walker, S. Hunter, P. Devine-Wright, B. Evans, H. Fay, Harnessing community energies: explaining and evaluating community-based localism in renewable energy policy in the UK, Global Environmental Politics 7(2) (2007) 64-82.
[68] T. Hoppe, A. Graf, B. Warbroek, I. Lammers, I. Lepping, Local governments supporting local energy initiatives: Lessons from the best practices of Saerbeck (Germany) and Lochem (The Netherlands), Sustainability 7(2) (2015) 1900-1931.
[69] K. Say, M. John, R. Dargaville, R.T. Wills, The coming disruption: The movement towards the customer renewable energy transition, Energy policy 123 (2018) 737-748.
[70] H. Ahlborg, L. Hammar, Drivers and barriers to rural electrification in Tanzania and Mozambique–Grid-extension, off-grid, and renewable energy technologies, Renewable Energy 61 (2014) 117-124.

Table 2 Social aspects driving microgrid development.

Resiliency, reliability	Microgrids can 'keep the lights on' in case of failure in the large system. By having energy generation and storage locally available, customers don't have to rely on external supply[65].
Individual and community benefits	Microgrids provide new opportunities and revenues to the community. Instead of relying on an external provider, local communities can potentially improve the localised value of their energy, manage energy supply and trade with the rest for the system. Some believe that microgrids create new jobs related to the installation and maintenance and improve local economic development[71,72].
Energy democracy	Instead of prices set by producers and grid owners, in microgrids prosumers can (in theory) decide about the price and use of their self-generated/stored electricity. They can for example decide the price range they are willing to pay, they can decide to donate electricity to a local school, or simply store it and use it within the community instead of trading with the larger system[73].
Increased value of self-generated electricity	Today, self-generated electricity can only be sold to the centralized system, compensated via subsidies or Feed-in Tariffs. In the future, the value of self-generated energy will increase - valued for demand response or as contribution to balancing the local level as well as the rest of the energy system for example.
Co-ownership	Microgrids co-owned by companies and citizens were found to have higher levels of social acceptance and are considered more trustworthy[71].

Society and actors engagement. Besides the traditional energy sector actors interested in local grids such as electricity producers, retailers and DSOs, an increasing number of private consumers and businesses are, by installing small-scale renewable energy technologies, becoming an active part of the electricity system as 'prosumers' that both produce and consume electricity. While in Europe, in countries such as Switzerland, Germany and Austria, microgrids are predominantly advocated for by local or regional grid operators, in Australia, actors from other sectors develop microgrids in their niche markets[71]. This is the case in a number of housing developments in Western Australia, where residents are allowed to manage their energy consumption as a part of strata management[73]. On the east coast of the same continent, battery company Sonnen set up a residential microgrid in order to trial their battery technology in this context. Furthermore, homeowners, small businesses, energy cooperatives, and small- to medium-size energy companies are also playing an important role in niche developments for microgrids. Although actor contestation has been observed in many of the microgrid developments, research has shown that productive encounter that leads to

[71] T. von Wirth, L. Gislason, R. Seidl, Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance, Renewable and Sustainable Energy Reviews 82 (2018) 2618-2628.
[72] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, C. Weinhardt, Designing microgrid energy markets: A case study: The Brooklyn Microgrid, Applied Energy 210 (2018) 870-880.
[73] J. Green, P. Newman, Citizen utilities: The emerging power paradigm, Energy Policy 105 (2017) 283-293

collaboration among a new, diverse actor group is essential to gain momentum for microgrid development.

Deployment niches. As indicated above, one of the benefits of deploying local-scale electricity systems is the opportunity to experiment in protected spaces, usually provided by other sectors, shielded in a regulatory sandbox behind the meter. Examples of such deployment spaces are university campuses, military microgrids, residential apartment buildings and communities as well as remote rural areas. The benefits of trialling local microgrids behind the meter are multiple. Firstly, the generation and grid infrastructure are usually owned by a single or few entities, which makes the decision-making and investment more manageable. Any changes that are experimented with behind the meter will likely not have a significant effect on the legal and regulatory frameworks regulating the large energy system, allowing for trial and error, gradually reducing innovation-related uncertainties. Furthermore, such shielded environment does not require one-size-fits-all solutions and actors can explore the most suitable solutions for the given context and local conditions. The downside of keeping microgrids behind the meter is that it doesn't allow for the economies of scale and benefits of diversity of generation and loads that would require to scale the microgrid across the meter[65]. Doing so comes with a number of technical, institutional and social challenges. Institutional and legal complexities exist within the microgrids themselves but also from the perspective of the microgrid towards the rest of the system and vice versa. Some of the reasons are that microgrids are set up by new actor constellations, new to the traditional energy system, they come with new business and ownership structures that blur the lines between generation, distribution and consumption. This leads to unclear roles and difficulties to create new business models as well as regulatory frameworks for these systems.

Within microgrids. Creating institutional frameworks within microgrids is not always simple. Participants in the microgrid must have a good understanding of who owns the distributed infrastructure before they can design a model for cost-benefit sharing as well as the liability for potential cost-related complications (such as non-paying customers) and system failures. As an example, in a microgrid with a grid and building facilities owned by the university, generation plants and storage by a third-party developer and management software owned by a software company, the pricing mechanism inside the microgrid needs to reflect the ownership to fairly redistribute the costs and revenue and possible motivate for future investment. This becomes increasingly complicated when a microgrid involves a community of distributed residential solar PV owners and individual customers. Participants should also communicate their expectations from the system, which can be self-sufficiency, community trading or sharing, or overall microgrid efficiency among others. A suitable business model can then be easily set up reflecting and fulfilling the purpose of setting up a microgrid. Aligning expectations between participants with diverging incentives can prevent future conflicts and disappointment among the participants. From a technical perspective, participants should make sure that their 'system components' such as metering devices are interoperable to avoid extra time and costs for alignment of these in later stage of the system development.

Local decarbonisation/environmental goals. Local stakeholders, which could be local communities but also cities, municipalities or industrial sites, may choose to make micro scale developments with the aim at integrating larger amounts of renewables, reaching more ambitious climate goals, increasing the pace of the transition or increasing environmental benefits (e.g. improved local air quality). This can be a strong rationale for the involved stakeholders: increasing their own health or well-being, increasing the engagement in tackling climate change and/or creating a greener image for the site or region.

Increased integration of renewables. The technical and financial optimum for integrating large amounts of renewables, when considering a predetermined planning horizon, is a balance of many factors and goal of many research projects. In a number of cases this will be the driving factor for micro perspective investments, where these can be alternatives to being dependent on developments of the regular grids. Advantages may include decreasing energy transfer losses, proximity of flexibility options and electricity customers, linking electricity networks to transport or heating networks (which are always local) or to take other advantages of the small scale (e.g. new business models).

Electrification of remote areas. One purely practical driver for microgrids is the electrification of remote areas with no or weak connection to the centralized energy systems. Especially for more than 1.2 billion people who do not have access to electricity, the traditional approach to extend the central grid is technically and financially inefficient due to a combination of capital scarcity, insufficient energy services, extended implementation times and construction challenges to connect remote areas. Adequately financed and operated microgrids based on renewable and appropriate resources can overcome many of the challenges faced by traditional lighting or electrification strategies, according to Carvallo et. al.[74], who measure the success of the microgrid based on reliability and financial viability.

[74] Carvallo, Juan & Schnitzer, Daniel & Lounsbury, Deepa & Deshmukh, Ranjit & Apt, Jay & Kammen, Daniel. (2014). Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. 10.13140/RG.2.1.1399.9600

4. micro vs MEGA perspectives

This section is intended to address influencing factors between the micro and MEGA trends in the grid development, how they form coexisting perspectives and can advance together. This provide a discussion on the trend's 'interoperability', the influence on each other and the ways of development. The micro and MEGA levels pertain to quite different spaces in the electricity supply chain and serve very different needs; a likely scenario is that the micro and MEGA perspectives will be co-existing in different forms in the future wider energy system.

4.1. Holistic view of micro and MEGA in the future energy systems

This concept is graphically represented in Figure 16, where the storyline of climate-energy development is streamlined in steps of logical consequences stemming for the paramount challenge of climate change: in extreme synthesis, the reduction of CO_2 emissions affects primarily the energy sector, and so far in particular the electricity sector, because zero-emission generation sources can be deployed at competitive costs and scalable pace. Such deployment is proceeding steadily in two archetypes:

- dispersed and micro level generation (buildings, residential sector, industrial sites, cooperatives), ushering in microsystems based on the subsidiarity principle; microgrid architecture is enabled by fast progressing ICT technologies for controlling the network, optimising the local resources and the interchanges with the rest of the system.
- bulk-scale generation plants, located in geographies where the primary resource is abundant while anthropic pressure is limited, calling for bulk transmission (long distance, high capacity), enabled by technology advancements in cables, UHV OHL and HVDC; HVDC links so far have been realised as point-to-point connections embedded in a wider HVAC grid, with converter stations located at both terminals or point-to-point interconnections between separately-operated power systems typically also in different jurisdictions; such architecture may eventually evolve into a meshed one, to form a regional/continental block and eventually to a global grid spanning across different continents.

Both archetypes are being realised, since both are necessary to additionally cater for other needs:

- distributed generation and microgrids serve the aim to empower consumers/citizens to become at the center of the power system, which in many parts of the world has been set as an additional social target of energy policy;
- bulk-scale production and grid are necessary to cater for large and/or concentrated consumers and energy intensive industries, which constitute the larger consumption portion in all developed economies.

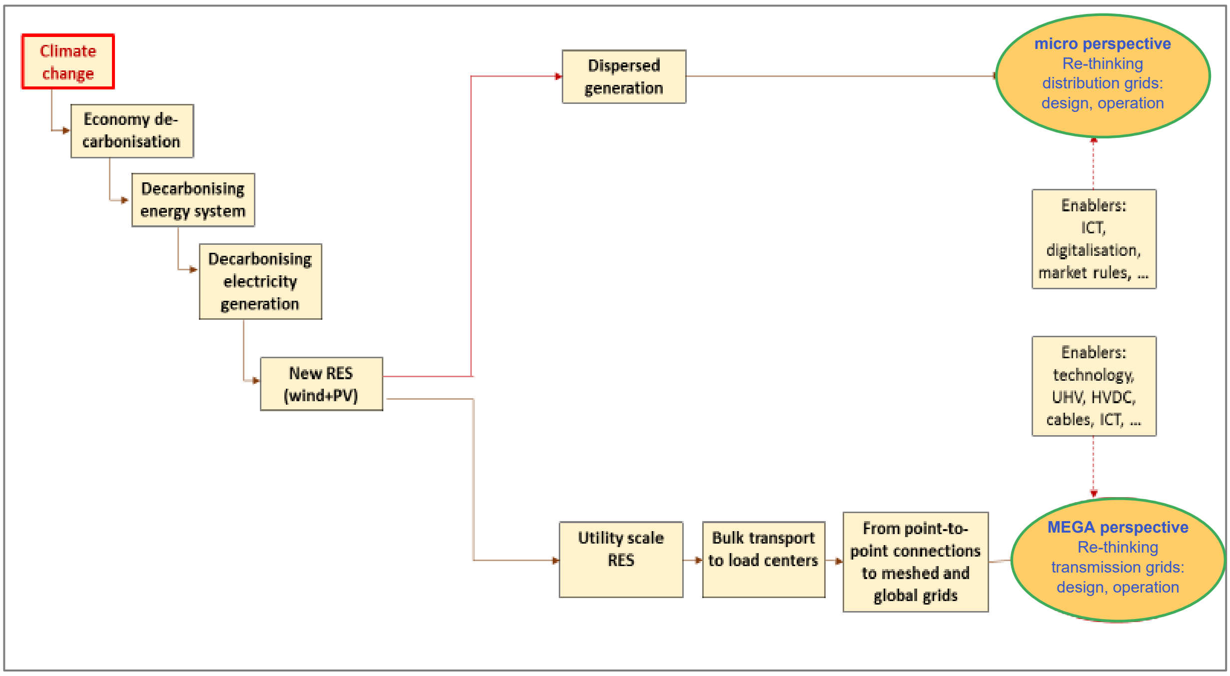

Figure 16. Conceptual scheme of climate-energy paradigm shift affecting grid architecture.

It is useful to enlarge the view to the array of challenges brought in by intermittent RES and the related possible solutions, most of which fall under the label of flexibility, as schematically represented in Figure 17.

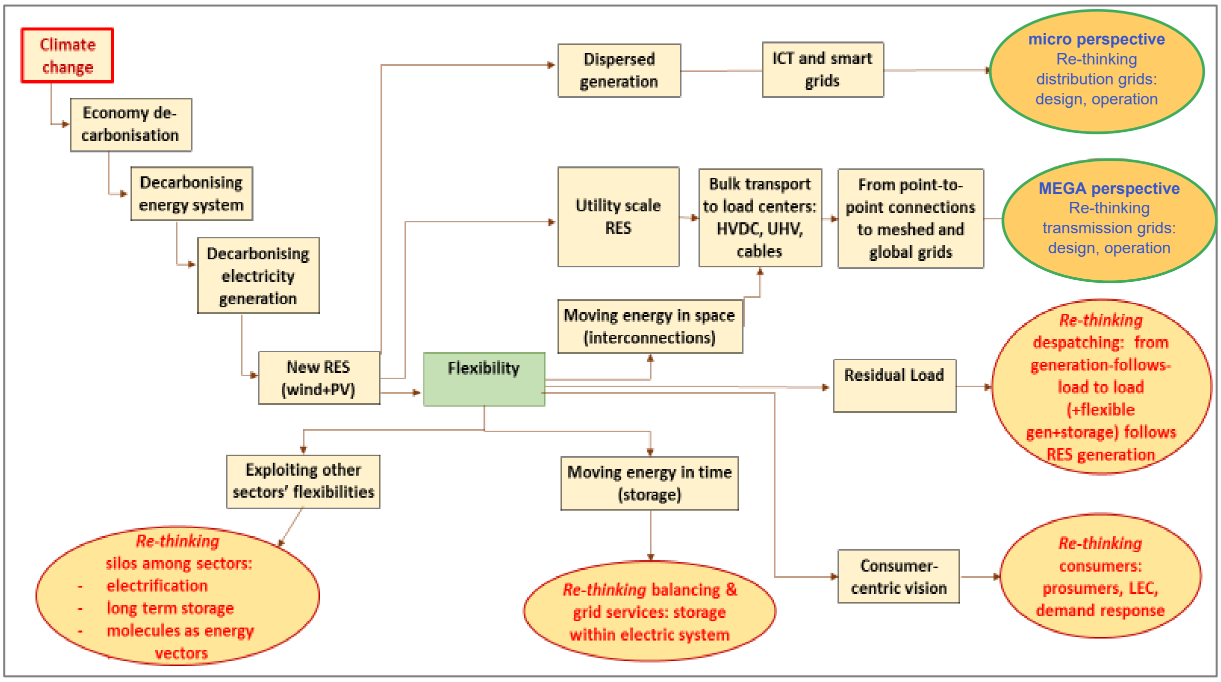

Figure 17. Conceptual scheme of main challenges to the power system and their drivers.

Here it is appreciated that micro and mega grids are both part of a diversified set of options, including non-wired alternatives to grid developments, some spanning outside of the electricity sector; such options encompass, conceptually:

- moving energy in space → power lines or green molecules
- moving energy in time → storage or exploiting other energy systems' own pattern
- moving consumers behaviour instead of moving energy → demand response, non-wire options
- moving operational paradigm from generation-follows-load, valid in the past when load was inflexible and generation mostly flexible, to load-follows-generation, future situation with most generation from inflexible sources and load mostly flexible, once supported by storage, sector coupling, etc.

Also, digitalisation shall support optimised and interconnected services, providing real-time information to operators and aggregators as well as to users connected to any energy network thereby enhancing system balancing and resilience at all time scales from seconds to weeks and in the case of any unforeseen contingencies. The growing electrification and the more decentralized deployment of renewable power generation will require reinforced and smarter electricity networks, able to accommodate both centralized and decentralized elements and to make the most of RES allocation.

4.2. Integrating DER and micro level energy systems in EMS

To use the potential of many production units and integrated energy systems for system security, it is necessary that every unit or system larger than a certain size are connected in terms of communication technology to the network operator. Thus, the functions of the unit or system can be accessed by the network operator's control system [75]. For the responsible grid operators, it must be possible to integrate DER with all their functionalities into their control systems in a cost-efficient manner. It must be taken into account that not all of them can be directly integrated into the control system due to the large number of decentralised plants. For this purpose, suitable, possibly hierarchical solutions need to be developed, based, for example, on intermediate instances - similar to aggregators. International standardisation on interfaces and on interoperability are needed to improve connectivity of aggregators and platforms. Standard based platforms are considered a proven means of achieving the desired connectivity.

Direct access by the network operator to private households - for example to the energy management of the household, in which a PV system and the charging station are integrated - has not only technical but also social aspects. These must be considered in the design of regulator directives. Microgrids or energy community concepts in particular could play a special role in this context. Social actors, such as residents, must be extensively involved to ensure the necessary acceptance.

In addition, systems must also be capable of receiving control signals from network operators or aggregators, providing system services, being able to start up or able to adjust system settings in a flexible manner. These innovations need financial incentives if they are not refinanced on an energy market. It is important that the implementation of these measures is tackled at an early stage in order to bring many devices with required functionality into the field. Otherwise, newly installed systems which do not provide these functions will be subject to becoming obsolete.

From a system perspective, the growth of microgrids could have both positive and negative implications. On a positive side, microgrids can assist in balancing the increasingly

[75] https://www.acatech.de/projekt/esys-energiesysteme-der-zukunft/

unpredictable system based on renewables by providing flexibility and reducing congestion in the grid. On the opposite side, increased self-consumption of microgrids could erode the revenue model that incentivised further investment in public infrastructure.

If an isolated microgrid is to connect to the rest of the system and become an embedded microgrid, the microgrid owner needs to request permission from the distribution system operator in accordance with local regulation. The permission to be integrated into the larger system or use the public infrastructure in not always granted, especially in case of microgrids that are in competition with the incumbent utilities, who usually possess a competitive advantage. In addition, microgrids often don't fulfil the 'traditional utility' description as wholesale and retail market participants due to unclear categories of generation, distribution and transmission. Allowing for interconnection to the rest of the system is important to reap the benefits of the revenue the microgrid could receive for grid related services to the rest of the system with diverse generation and load, improving the microgrid business case. On the contrary, fitting a microgrid into the existing legal frameworks could allow existing state regulators to decide over the scale and the rights to generate as well as the prices of the purchased energy from the microgrid, possibly having limiting implications for the business case of the microgrid. In addition, the interconnection process, as with the registration process, is not yet standardized and uncertainties prevail around the terms for microgrid connection and islanding. The choice of the business and ownership model can be a decisive aspect of the likelihood of being connected and registered as a licensed energy provider[76].

Best practice regarding preparations for isolated microgrids to become embedded include: preparing the microgrid right from the planning stage for integration. For this option to become a reality, the microgrid equipment needs to comply with the technical requirements of the over-laying distribution grid. The specific technical requirements should be evaluated in detail for each case and the consequences of the interaction between the microgrid and the distribution grid should be analysed. Further, the roles of the microgrid owner, the distribution network operator, governmental actors and local stakeholders should be addressed to ensure an appropriate interaction framework. [77]

Local systems such as microgrids have the potential to lower thresholds for end-users and small-scale actors to engage in the market and to provide (excess) generation and flexibility to the system. Unlocking flexibility from end-users is considered to be of vital importance to facilitate a power system with large shares of variable generation, and hence the grid on the MEGA level can benefit from this flexibility on aggregated levels for balancing purposes. This can be adjustable to variations in generation capacity between hours, but also system services such as frequency control. A central component of microgrids are storage solutions, which could also provide balancing services for longer time horizons, from days to seasonal storage. Hence, in this view, microgrids and local markets can provide an aggregator role for overlaying system, not only considering system services but also for wholesale markets not being (easily) accessible for small-scale end-users. What distinguishes the local market in this respect to the role of retailers or aggregators is that local markets can combine the view of the local grid and

[76] A. Hirsch, Y. Parag, J. Guerrero, Microgrids: A review of technologies, key drivers, and outstanding issues, Renewable and sustainable Energy reviews 90 (2018) 402-411.
[77] J. Tjäder and S. Ackeby, "The role and interaction of microgrids and centralized grids in developing modern power systems – A case review," ISGAN Annex 6 Power T&D Systems, 2016

system with the overlaying market and system; thereby bringing flexibility to wholesale and system services markets without compromising local grid constraints.

4.3. Synergies of MEGA and Micro developments

Flexibility services delivered by DER could bring significant benefits to several sectors of the electricity industry, including generation system operation, distribution networks, transmission networks, and investments. However, energy supply, transmission, and distribution networks are operated by different entities with a level of coordination that is currently limited. Instead of using the DER-based services to maximise the whole-system benefits, individual entities tend to use these resources for maximising their own benefits, without considering the impact on other entities. Managing synergies and conflicts among the distribution network, transmission network, energy supply and international decarbonisation objectives when allocating DER flexibility will be critical for the optimal development of the system.

As a consequence, there will be a need for stronger coordination between system operators at both transmission and distribution levels. This coordination will enable the use of all available flexibility resources while managing synergies and conflicts across the different networks. A whole-system approach will be required for both operation of the system and management of future networks at maximum efficiency.

In order to reach set sustainability goals, the future power system needs to use all available renewable resources. Micro developments can, in this respect, facilitate the integration of DER in the local context, which also supports the overall renewable generation targets. Local markets have the potential to incentivise actors to invest in local generation through the use of different pricing schemes and tariffs, which might not be available on the overall perspective encompassing several countries or regions.

Apart from facilitating operation of the local system, micro developments can support the development and operation of the overlaying system and market in different ways. DER, flexible demand resources and storage solutions, have the potential to supply system services and renewable energy to the overlaying market and grid. In this view, distribution grids constitute cells connected through the transmission grid, and hence on aggregated level constitute a valuable resource for the system operation.

In order for micro developments to be able to efficiently support and contribute to the overall system, there are several factors that needs to be addressed. The technical systems interacting between microgrids, distribution grids and transmission grids must be compatible, and ICT systems must be interoperable. Furthermore, if encompassing local markets, these should be aligned with markets on higher system levels (national and international) in order to facilitate efficient use of available resources. Having poorly aligned market designs can potentially lead to market inefficiencies. If these requirements are fulfilled, micro developments could provide efficient support for development and operation of the overall grid.

4.4. Perspectives for micro and MEGA

The micro and the MEGA perspectives provide two views on the development of the entire power system. Developments from both perspectives aim at enabling very high penetration of renewable energy sources, where the micro perspective focuses on local solutions, while the MEGA perspective focuses on system or even inter-system wide solutions. The two perspectives co-exist, and it is likely they will continue doing so in the future. The micro and the MEGA views are illustrated in Figure 18 covering the entire power system, from supergrids to micrognds energy system.

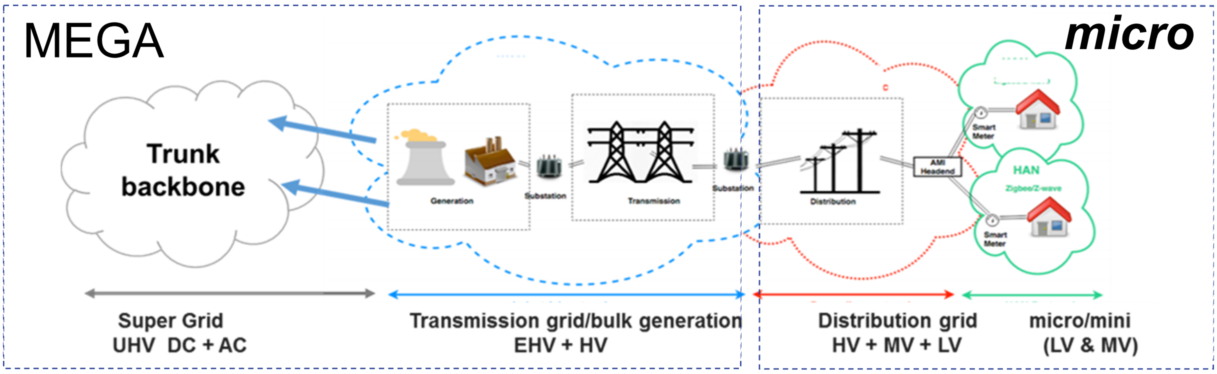

Figure 18. MEGA and micro perspectives in the setting of the entire power system

The **rationale for microgrids** has always been present in small isolated areas, far from the main national grid, and more generally in the case of low load density areas. Microgrid there is the only option, and nowadays they can benefit from modern devices (renewable microgeneration, storage, electronic controls) to improve the quality of service to customers.

In areas already served by distribution grids, the rationale for increased local development stems from the spreading of distribute energy sources, again generation and storage, which triggered the principle of subsidiarity: serve local needs with local resources first, and keep the main interconnected grid as a backup; this minimize power losses and simplifies the operation in steady state, provided that a reactive action plan is in place to be adopted in case of contingencies. Microgrid solutions are also well suited for enacting sector coupling at local level, evolving in multi-energy systems (Figure 19).

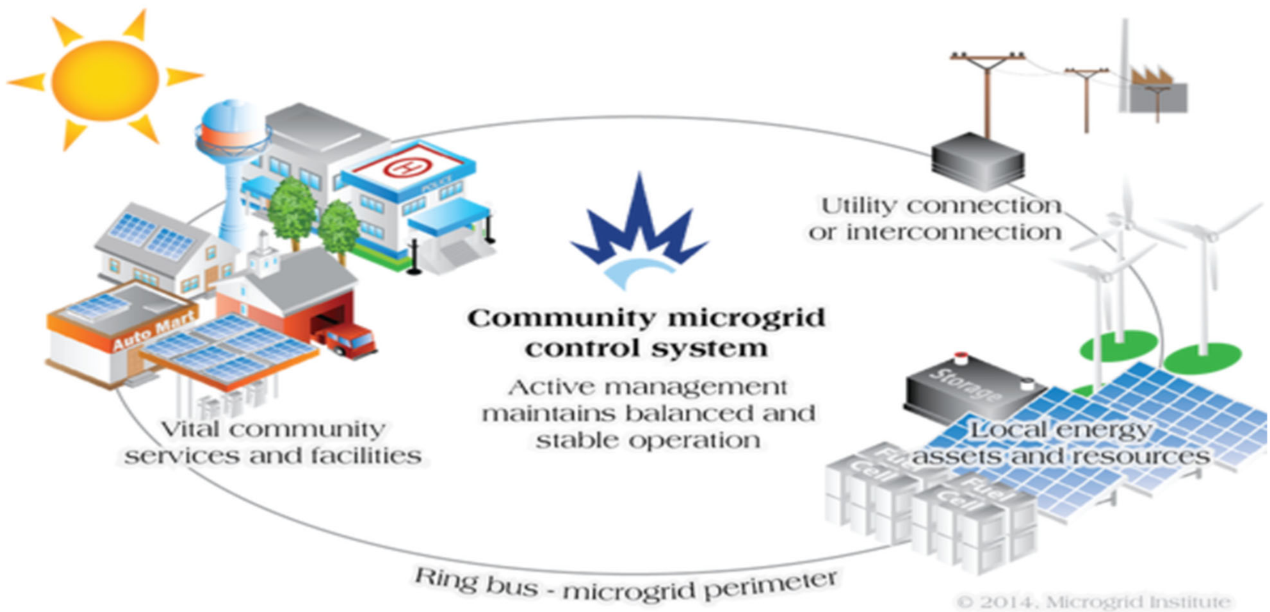

Figure 19. Microgrid serving local community needs.

A further reason for micro scale development is a deeper involvement of local communities and empowerment of citizens-consumers, with a local system tailored to the needs of residents: there are no large infrastructures overrunning the local territory, which attracts negative moods because they are not serving local needs.

The **rationale for MEGA investments** is primarily to extend the present meshed transmission grid to interconnections with neighbouring regions, countries and systems, to provide increased energy trading and reliability of the interconnected power system. The MEGA development could eventually grow into a global grid which interconnects the entire globe, where present technologies (HVDC, UHV AC lines, land and submarine cables), with some needed upgrading, allow such vision. The realization of large-scale interconnections heavily depends on non-technical preconditions to be met:

- technical interoperability and standards, as well as operational issues;
- market rules and business models for efficient exploitation of the interconnections;
- business models for financial viability and construction challenges (project finance and project management);
- legislation & regulation frameworks necessary to authorize, own, build and operate strategic infrastructures;
- political support from stakeholders, relying on robust cooperation and mutual trust.

Major corridors are already being realised for bulk transport of renewable energy to load centres: point-to-point power lines up to 1000 kV in HVDC and to 1100 kV in HVAC are already in operation in China, Brazil, and India, and are under consideration in Africa, Middle East, Australia, and Americas.

The aims underlying the rationale of long distance, high capacity power lines are three-folds:

1) Improve effectiveness of decarbonisation, through exploitation of RES in best location (highest primary resources and/or available empty space);
2) Exploit geographical diversity, both of generation pattern: variability and intermittency are smoothened if wider areas are interconnected (for solar this is particularly true on the West-East axis), and of consumers' load profile (again this is particularly true for on longitudinal axis);
3) Provide flexibility to grid operation, by controlling load flows between regions according to surplus/deficit occurrences.

From an economic and market point of view, MEGA investments enlarge trading volumes and customer supply options. From a socio-political point of view, MEGA investments, being capital intensive and territorial infrastructures, require long term agreements often at governmental level, thus they constitute a strong link among partners and mutual trust, so strengthening positive relations among interconnected countries.

4.5. Market structures

When it comes to **power markets and market structures**, there are at least two major trends that influence grid developments. One is the trend towards closer integration of power markets, and the other is related to markets and services toward the end users of electricity.

It is often stated that transmission grid developments, and in particular the increasing number of HVDC links across synchronous interconnections, are enablers for integration of power markets. Electricity market integration is high on the agenda in Europe but is also occurring elsewhere on various levels. In Europe, market integration has implemented first on the whole sale level, but increasingly also on balancing markets. Thus, market structure also influences grid developments. Effective wholesale markets and a technically viable integration of balancing markets require strong interconnections. This is a driver for the MEGA grid developments.

On the other end of the scale, distributed generation, local energy storage, electric transport and changes in demand are the main influencers for local grid developments. Increased distributed generation, electric transport and appliances that demand high power challenge the way electricity is distributed and sold to customers. The fact that energy from renewable sources have very low marginal costs but grid installations needs to be reinforced to accommodate peak demand stimulate new market arrangements. It is no longer efficient or even fair to sell electricity to end users in the form of kilowatt-hours (kWh). The energy share of the total costs is reducing, whereas the fixed investment costs (for grids and power plants) are rising. The trend is towards selling electricity as a service, often packaged with other services such as internet access. It is believed that access to a service is the key from a grid development point of view. One example is related to the need for EV charging at home for people living in cities:

> New service providers are becoming available, who take the responsibility for installing or upgrading the low voltage installations at zero cost. Then, the offer of services to the customers in form of different subscriptions with monthly fees, not for the kilowatt-hours that is consumed but rather depending on the type of car one has and the number of kilometres one expects to drive per year. Such services will definitely impact how local grids develop, in particular affecting low voltage distribution grids.

4.6. Need for whole system view for expansion planning

The planning of transmission and distribution systems, which are natural monopolies, needs as its major input, future generation capacities including their locations. In an integrated electricity monopoly, this means generation, transmission and distribution should be optimized together. Especially in China, where the integrated optimization approaches employed towards this goal considers ever more parameters and uncertainties. In a liberalised electricity market, instead, the TSO may need to simulate expected or optimal generation additions not because the transmission monopoly would invest in them, but to derive the most realistic assumptions for these important input data to its transmission plan optimization. Similarly, in a market, each generation company needs to assume not only how much and where its competitors will build new generation capacity, but also how much additional transmission and distribution capacity will be available, in order to forecast nodal prices for its own most realistic estimate of profitability of its generation investment.

Since it is not optimal to expand network capacities to the extend where every potential generation from any node can reach the highest value load anywhere in the network, the value or price a generation unit can achieve depends on the node where it is located, and the network congestion around it (nodal pricing).

Increasingly, transmission and distribution planning depend strongly on each other: as distribution-connected resources tend to be the majority of total generation investments in many countries; as demand becomes more flexible and responsive to price signals; and as heating and transport are becoming electrified. In the EU, the 110 kV level is not only planned together with the 230 and 400 kV levels in countries where the TSO operates all networks down to 110 or even 90 or 63 kV, but also increasingly in countries where so far, 110 kV was considered distribution and is operated by the DSO. The EU network codes require intensive data exchange between TSO and DSO at the 110 kV level. Another example of mutual dependency of transmission and distribution planning comes from EV charging: If DC fast charging at 150 or even above 500 kW becomes commonplace, and if it occurs in concentrated spots like garages or “mobility hubs” at the edges of downtowns, charging stations could easily reach capacities for which an HV connection needs to be considered. Network reinforcements need to be planned individually for each such charging station, by TSO and DSO together, and indeed in very close cooperation with city planners, as such mobility hubs will play decisive roles in the look and feel and quality of life of cities.

This sort of “vertical” interconnections call for a tighter cooperation in planning grids at different voltage levels in the same area. This will likely lead to an integrated TSO-DSO planning process, at all stages, starting from scenario definition-raising issues such as:

- How are plans coordinated and costs allocated between different network owners?
- Do different rules at network ownership boundaries lead to sub-optimal connection locations and network investment?
- How are bottom-up and top-down approaches integrated in forecasting (e.g. DSO on lower voltages and TSO on higher voltages)?
- How are renewable energy source and distributed energy resource forecasts in line with rapidly changing technology?

Realization of international interconnections, not only at intercontinental but also at regional level, typically faces extra hurdles on top of those characterising any large infrastructure with visible territorial footprint and technical complexity. Such extra hurdles derive from their nature of being multi-jurisdictional and multi-party. This calls for deeper consideration of the evaluation principles and allocation criteria for costs, benefits and related risks on both sides of the link. In particular, where the cost-benefit analysis shows an asymmetry of advantages for the involved parties, this also calls for asymmetric burden sharing for which no clear consensus rules have emerged yet, neither in a horizontal dimension (TSO-TSO projects) nor in a vertical dimension (integration between TSO, distributors and other grid operators). In Europe and elsewhere, the “merchant lines” concept is applicable for fully private investments, but is not the only option, especially when a mixed approach to private-public-partnership or multi-party links are considered. The intrinsic flexibility of the merchant line mechanisms and the possibility of asymmetric cost/benefit sharing between investors in interconnection projects gives rise to innovative and case-tailored implementation schemes, and some existing projects already present innovative examples of such business models.

The key determining characteristics which shape the business models are: nature of investors; prevailing direction of energy flows and related benefitting actors; capital intensity; geographical and topographical distribution of the assets (in particular, when transit territories or international waters are involved); technology - HVDC and/or submarine cables necessarily imply a unitary approach for the whole link regarding design, engineering, procurement and construction).

While costs (CAPEX and OPEX) are relatively easy to estimate, the assessment of benefits differs very much according to the point of view and the subject under consideration: investing company (looking for profitability), TSO (looking for system performance), electric system as a whole (with possible external factors), end-consumers (looking for energy price and reliability), and transmission tariff payers. This adds to the already challenging and controversial exercise of benefits evaluation, since operational issues (like security of supply/system stability) and social issues (like social acceptance/environmental impact) are difficult to quantify and have no uniform metric.

All such considerations deserve extensive attention in the early stages of interconnections' project set-up, in order to determine the most suitable cost-benefit splitting and therefore the business model to be employed.

4.7. TSO-DSO interaction and regulatory frame

DSO-TSO interaction means a collaboration between the Transmission System Operator (TSO) and Distribution System Operator(s) (DSO) where various areas of cooperation can be included in the interaction. According to ENTSO-E, interactions between TSO and DSO include the following domains:

- The market and its framework, which can be used to acquire reserves for different types of system services.
- Operation, which will ensure security of supply in a cost-effective manner. Where the TSO remains responsible for overall system security while DSOs are responsible for the safe operation of their respective grids.
- Planning, which will combine knowledge from local and regional development patterns as well as system-level needs.
- Handling data in a safe and transparent manner, based on current regulations.

The distribution of energy across different types of end-users will remain broadly similar to today's image in Europe until 2050, with the transport and housing industry which accounts for the bulk of energy consumption (32% and 27% of final consumption, respectively, in 2030). Industry's share of total energy demand will be reduced, from 28% in 2005 to 23% by 2050, mainly due to improved energy efficiency in non-energy intensive industries. The tertiary sector (services and agriculture) will maintain a stable share of around 17%. [78]

These changes in the consumption mix will have an impact on the power system, which can be summed up as follows:

- Demand for electricity will increase and will correspondingly increase the risk of overload and local voltage problems. This will happen, especially in the distribution network, where most of the additional load due to electrification of heating (domestic and tertiary sector) and transport will be located, and where the distributed RES generation will be added.
- Due to the increased portion of electric heating / cooling (still after heat pumps), consumption will be much more temperature dependent (hence less predictable) and varying. On the other hand, these loads will represent a great potential for flexibility in the network.
- Electric cars also represent a great potential for flexibility in the network.
- Growth in varying consumption, based on weather conditions and mobility needs, will increase the risk of aggregation of peak load, which in turn results in high electrical flow and bottlenecks.

A closer cooperation between TSOs and DSOs will be required to reduce the negative consequences of such volatile consumption and generation in the power grid. Some studies show that there is a need and opportunity to change the structure of the grid tariffs to be

[78] EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050

capacity based and reduce problems with increased peak load and bottleneck[79,80]. However, peak loads and bottlenecks usually have short duration and varying localization, which means that a market based solution for flexibility might be a relevant solution. An example of such market has been proposed as a single marketplace for flexibility intended to meet the requirements for the coordinated use of flexibility by TSOs and DSOs[81]. Furthermore, the transition from energy to capacity-based distribution tariffs can be very useful.

New role and tasks of DSOs are emphasised in the Clean Energy for All Europeans Package. It provides greater legal certainty regarding specific activities, such as flexibility services and providing electric vehicle (EV) charging points. The document aims to continue to engage ongoing European discussions on the future role of the DSO, to start distinguishing DSOs activities from the core - operating, maintaining and developing the distribution system - and describing the physical boundaries of the distribution system.

The creation of a new EU DSO Entity will allocate more competencies to electricity distributors in the elaboration of European network codes at the distribution level[82]. It is well known that currently DSOs play a key role in the energy transition by facilitating market and empowering active consumers. Also, DSOs participation in innovative projects gives the opportunity to maintain expertise which goes beyond the operation of the grid and increasing experience of DSOs.

In the same way, any innovative step undertaken by DSOs requires a supportive regulatory framework and the effort of all system stakeholders. Here, regulatory authorities must identify an appropriate framework for future electricity market design and cooperation between electricity TSOs and DSOs. In the future, this framework will provide technical requirements and rules for the deployment of RES and DER, ensuring interoperability and facilitating flexibility services.

- This expertise can be seen today through various European R&D&I projects, where DSOs have spent more than 800 million EUR in smart grid projects with a focus on smart meter roll-out and its functionalities integration, smart grid operation, open data and new services such as flexibility and e-mobility. Moreover, DSOs forge active cooperation with other stakeholders, for example, with the TSOs on network codes and guidelines implementation, data management and active system management, ensuring cooperation and coordination between DSOs and TSOs.[79]
- The European climate and energy policy goals and targets to a fully decarbonised and sustainable electricity system, challenging also European TSOs to create, develop and implement various solutions to adapt and extend the existing system. Numerous challenges are highlighted here, which can be grouped into three main categories: challenges in terms of technology, implementation and financing. In performing its functions, it shall solve grid capacity scarcity problem, which not only severely hinders the further RES integration but also leading to the grid congestions, which in return should be mainly resolved via expensive and CO_2 intensive re-dispatch measures.[80]
- In the TSO-DSO coordinated operation, it is important to establish smart and secure collaboration schemes between TSO, DSO and consumers in order to increase the

[79] E.DSO, ”Key Messages to the new European Parliament”, 2019
[80] ENTSO-E. “Network development enforcement and incentives - Advocacy paper”, 2019
[81] A. Zegers and T. Natiesta, “Single Marketplace for Flexibility,” ISGAN Annex 6 Power T&D Systems, 2017
[82] Regulation (EU) 2019/943 on internal market for electricity, Article 55.

energy system resiliency[83]. TSOs and DSOs are responsible for the safe and reliable grid operation and they both have a specific need for flexibility. The DSO's roles would shift towards an active system operator. New tasks might be the procurement and activation of flexibility in order to avoid congestions or voltage problems. Where the DSO products would be applicable for congestion and voltage management purposes and would consist of active and reactive power flexibility. For such type of DSO products, the geographical aspect is particularly important. Therefore, the products must be tagged e.g. with the metering point reference number allocating them to the respective network node. Therefore, the range of possible actions could be identified to provide Mission Model (beyond economic benefits) with focus on electrification and citizen's acceptance and involvement.

[83] https://coordinet-project.eu/projects/coordinet

5. Conclusions and main messages

The objective of this work has been to present a critical assessment of the micro and MEGA trends, based on the questions:

- Does one trend outcompete the other?
- Does increased investments from one perspective increase the need for investments from the other perspective?
- To what extent can one perspective benefit from the other perspective?

It has become evident that these trends have large influences on each other and on the way the power system develops. Investments in micro and MEGA levels pertain to different spaces in the electricity supply chain and serve very different needs. A likely scenario is that the micro and MEGA perspectives will be co-existing in the different forms in the future wider energy system.

Whole-system coordination between micro and MEGA, together with cooperation between different system levels, are needed to provide the most value for potential investments. The microgrid concept could provide a range of economic, technical and social benefits to different stakeholders. However, depending on opted configuration and operation schemes for a microgrid, conflicting interests might arise. An optimal mix between micro and MEGA perspectives should be considered to identify investment strategies that provide:

- the most socio-economic welfare, with investment decisions based on over-all system optimisation
- increased reliability of the electricity supply
- optimal use of resources in a way to harness maximum utilization and integration of renewable sources and to minimize impact on the environment

The current reliability levels and reliability criteria used for operating and planning the power system may not be the optimal for the future power system. Considering diversified solutions for reliability and security of supply may lead to alternative decisions resulting in other directions in the development of the power system.

5.1. Main messages

RES, mainly as power electronic interfaced generation, play an increasingly important role in the power system. It is likely that RES will be the main source of electricity in the future, and power systems will need to evolve to meet this development. Significant investments are required in both the micro and the MEGA levels to allow the full utilisation and harvesting of available renewable resources. Here, we highlight some of the main elements of the power system evolution for: Technology, Market, and Policy.

Technology

Technology developments are driving the growth of demand and RES deployment through:

- decreasing the investment costs especially for PV and BESS;
- enabling consumers to become "prosumers";
- and increasing the electrification of transport and heat sectors, e.g. EV and heat pumps.

MEGA investments profit from the economy of scale, which to a large extent is dependant on the technology itself. Additionally, large-scale generation and high-voltage power transfer provide higher efficiency; efficient long transmission technologies are already in satisfactory operation in China and elsewhere. However, due to the scale, complexity and long lead time of transnational megaprojects across national jurisdictions and markets, seem unable to benefit from and keep up with fast technological innovation in contrast with smaller scale developments. For storage systems (particularly batteries), micro-perspective shall profit from technology advancements as exemplified by the worldwide annual BESS deployment (2018) behind-the-meter being significantly larger than on grid-scale[84].

A large part of the growth is user-centric and takes place in the distribution grids, where the various new services rely upon the transfer of large amounts of data. This means that ICT infrastructure is required to enable interaction among stakeholders of the grid, to support participation in local markets, as well as providing possibilities to utilise distributed flexibilities at the system level. Thus, enhancing ICT penetration in the distribution grids would benefit particularly the micro-perspective.

Today, digitalisation is already an essential factor for assessing the state of the system and planning measures, especially on the transmission level. Increased penetration of ICT also at distribution level leads to greater dependencies, increasing the risk of large disturbances due to ICT system malfunction. In order to mitigate the effects of erroneous information, the condition of ICT systems should be part of the situation assessment[85].

Market

Liberalisation, deregulation and privatization have changed the roles of stakeholders in the electricity market, where competition is now fundamental. New ways of cooperation are required, not only between transmission and distribution levels but also to the extremes. From a systems perspective, large interconnections enable generators to compete at an international level, while local markets and solutions can assist in balancing variable RES by providing flexibility and reducing congestions. Market solutions should always complement grid capacity investments in managing the supply-demand balance.

More distributed generation, together with more electric transport and appliances that demand high power, challenge the way electricity is distributed and sold to customers. The fact that energy from renewable sources has very low marginal costs, but grid reinforcements are needed to accommodate peak demand, stimulate new market arrangements. It is no longer efficient or even fair to sell electricity to end-users in the form of kilowatt-hours. The energy component of the total costs is decreasing, whereas the fixed investment costs (for grids and power plants) are rising. The trend is towards selling electricity as a service, often packaged with other services such as internet access. It is believed that access to a service is the key from a grid development point of view.

At the micro level, a range of new stakeholders emerges. New market structures are needed to incentivize these actors through pricing schemes and tariffs. This opens new revenue

[84] IEA "Tracking Energy Integration", 2019, iea.org/reports/tracking-energy-integration
[85] M. Brand, S. Ansari, F. Castro, R. Chakra, B. H. Hassan, C. Krüger, D. Babazadeh and S. Lehnhoff, “A Framework for the Integration of ICT-relevant Data in Power System Applications”, IEEE PowerTech, Milan, Italy, 23-27 June, 2019

streams and economic benefits to the local community, but only if a good cooperation is established within the new, diverse actor group. However, these schemes might not be available on the overall perspective or could be unfavourable for larger investments with long planning horizons. Moreover, increased self-consumption could erode the revenue model that incentivizes further investment in public infrastructure.

With the increased amount of electricity coming from solar & wind, hourly fluctuations of prices for produced electricity are foreseen to become larger. This will lead to an increased number of hours with extreme prices, both zero or negative prices as well as extremely high prices[86,87].

Flexibility solutions supporting the needs increased by the integration of intermittent RES can be provided from different levels in the power system. Several projects and efforts are developing markets and business models to make this flexibility available to the system.

There are benefits from cross-border interconnections which remain untapped due to the lack of corresponding framework and markets. Future mega scale investment decisions could also benefit from more strategic investments approaches, in contrast with an incremental approach which focuses on optimizing short-term benefits. In addition, integrated TSO-DSO expansion planning procedures are becoming increasingly important and valuable. In order to gain the most value from all available resources and making sustainable investments, whole-system approaches will be required.

With significant levels of distributed BESS, well-functioning local market solutions can provide new possibilities on how to operate and plan distribution networks. The utilisation of distributed energy storages can support voltages and power quality, as well as preventing peak loading scenarios.

Furthermore, enhancements in forecasting and scheduling methods and tools are becoming increasingly important. The uncertainties related to operational planning are increasing, largely influenced by intermittent production but also from active demand and storages. Dedicated Renewable Energy Management Centres, implemented at strategical levels of the power system, can support the integration of renewables to realise the sustainability targets [88].

Policy

In order to fully utilise available renewable sources, significant investments in both micro and MEGA solutions are needed. Long-term strategies and strong political backup are needed to prevent unsustainable investments. Therefore, it should be a requirement for both micro and MEGA-perspective investments to have a sustainable time horizon to prevent the need for additional negative environmental impact and depletion of natural resources.

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[86] Nordic TSOs, "Nordic Grid Development Plan 2019", June 2019

[87] A. Clerici, "Energy transition with holistic, pragmatic and sustainable approaches part 2: Challenges for integration in electricity systems of variable renewable energy resources", CIGRE - Electra305, Aug 2019

[88] Transmission Plan for Envisaged Renewable Capacity, Vol-I & Vol-II, Power Grid Corporation of India Ltd., 2012, www.powergridindia.com/sites/default/files/Our_Business/Smart_Grid/Green_Energy_Corridor_Report/Vol_1.pdf; .../Vol_2.pdf

Large-scale investments are more sensitive to risks, and the risk for stranded investments are increasing in times with significant technology and market developments. However, MEGA-perspective investments may be categorized as critical infrastructure and may in that sense receive additional benefits as national strategical investments, which local small-scale investments do not.

Institutional and legal complexities exist within microgrids and from the perspective of the microgrid towards the rest of the system and vice versa. This leads to unclear roles and difficulties in creating new business models as well as regulatory frameworks for these systems. A benefit of local systems is the opportunity to experiment in protected spaces, shielded in a regulatory sandbox behind the meter, gradually reducing innovation-related uncertainties. However, policies supporting small-scale electricity production, as subsidies for micro-perspective investments, can make it economically difficult for large-scale investments even if such would have been more sustainable.

Furthermore, national strategies and policies have a significant influence on overall grid development, as highlighted by the various national directions regarding nuclear power and UHV power transmission.

5.2. Final discussion and afterword

This paragraph provides the final reflection and afterword, with the aim to identify possible missing elements and further challenges. This comprehensive section is considered a valuable closure of the concluding section.

At the end of this work it is important to generalize the main findings from the system development planning perspectives.

Based on the fundamentals in optimisation, the MEGA vision is tendentially more optimised since it is able to provide a broader optimum (while the micro perspective only provides local sub-optimum solutions). In a traditional power system planning vision there is no doubt that the MEGA approach shows its superiority, where:

- a **small number of technologically advanced large power plants** feed
- a **strong network** in which the sub-transmission grids can be assimilated to a single bus-bar (meaning local congestions are neglected or moved to the main transmission level), supported by
- a condition of **regulatory homogeneity**.

The difficulties arise where one or more of the three elements are missing. Today, large power plants are being decommissioned and replaced by distributed RES generators, which are characterized by lower (or quasi null) variable costs. The distributed RES may or may not be able to provide the services the network is requesting (e.g. voltage and frequency support). So, the advantages achieved through a lower marginal generation cost could be lost by an increase in real time market expenses. Nonetheless, as RES generators are distributed in the grid, the need for a very strong network could apparently seem no longer a stringent requirement. However, a strong network is limiting grid congestions and is providing possibilities for big markets. This is a pre-condition to avoid market domination which is a risk with local markets. Hence, investments in networks are not only needed for security of supply but also to ensure a reasonable competition as an outcome of the energy markets. Finally, regulatory homogeneity is a pre-requisite for a MEGA vision and a sustainable power system development.

The energy sector is challenged by two issues which are in fact two faces of the same coin:

- **the disorderly development of the generation** - small RES are installed everywhere and the plans of private investors are very difficult to forecast with regards to conventional plans of the integrated companies to install large generation. Consequently, new bulk scale network investments (e.g. trans-European networks) request a lot of effort, increased expenses and lead time for approval and construction, leading to increased risks for stranded costs.
- **the strong need to compensate the decommissioning of large power plants** is keeping the pace to provide services to compensate the non-negligible effects of RES variability. Hence, the strong need to obtain reserves and system services from DER and distributed storages where the micro view becomes relevant. Furthermore, with distribution grids becoming increasingly active, and power often remounting from LV towards HV, makes it unavoidable that DSOs abandon the old “fit and forget” policy. The DSOs need to start monitoring their networks and controlling them, at least concerning local services (local congestion and voltages). Whether this concept can further be extended, so DSOs can provide services to the TSO, depends on the strength of the interconnection between the two systems and on the complexities introduced by the DSO-TSO need of real-time coordination. In any case, centralised service markets are needed from an optimisation perspective.

Storage and flexibility solutions can support power system planning, especially where congestion is created from variable RES resulting in peak flows in the grid. Local problems can more easily be locally compensated by storage and flexibility. However, there is a regulatory intricacy: storage investments should be given to potential private investors by the national regulatory authorities, but only upon suggestion by the system operator, who by contrast have a strong incentive to build new lines (due to the CAPEX driven remuneration). Thus, it is needed to set up an efficient triangle between system operator planning, regulatory incentives and investments which can be difficult to realize. Additionally, the system operator should be incentivised to abandon the present investments driven perspective by changing their remuneration from CAPEX driven to TOTEX driven (which several European authorities are planning).

Finally, it is not possible to develop the system in an optimal way through the MEGA vision without considering necessary details on the micro level (e.g. DER, distribution grids and flexibility potential). Vice versa, the micro vision will only result in sub-optimal solutions if not considering the larger perspective.

APPENDIX

This section provides some country examples and solutions focusing on specific problems, provided by ISGAN experts.

A. Control and operational aspects, local coordination etc.

The low-voltage microgrid presented in Figure 20(a) is used herein to illustrate a typical microgrid model in a real aerial distribution network. This network consists of six DERs; twenty-three loads distributed randomly and unbalanced; and a three-phase grid-forming converter, named herein as utility interface (UI), connected to the microgrid PCC. This infrastructure is distributed over the twenty-seven nodes of the microgrid (i.e., N_0 ~ N_{26}). Node N_1 is the PCC of the microgrid, where the branch from the main network (N_0), the UI converter, is connected, in addition to the Master controller (MC. The connection of the six single-phase DERs occurs between line-to-neutral and the phase distribution occurs according to: phase *a*: DER_{aN15} and DER_{aN26}; phase *b*: DER_{bN4} and DER_{bN12}; and phase *c*: DER_{cN7} and DER_{cN21}. The DERs can be equipped with any type of primary energy source (e.g., solar or wind with possible battery association), and communication module. All DERs, especially those based on solar and wind, are controlled as current sources in synchronism with the fundamental component of the microgrid voltage, operating permanently in grid-following.

The UI converter is a three-phase four-wire converter equipped with an energy storage unit and is capable of injecting negative and zero sequence currents and contribute to harmonic compensation[89]. However, its main objective is to guarantee sufficient islanding operation and smooth transition between grid-connected and islanded mode, and vice-versa.

The centralized control architecture used is embedded in the MC which is present in the PCC of the microgrid. The MC collects information shared by each DER and UI, processes the algorithm embedded in the secondary level of the microgrid hierarchical architecture (power-based control – PBC and power quality improvement), and thereupon transmits the power references to the DERs local control loops by broadcast message.

Figure 20 (b) shows the centralized hierarchical architecture used in this study. The first hierarchical level of control, embedded in the digital signal processors (DSPs) of the distributed agents is the fastest level (reaching a few kHz) responsible for the local operation of the DERs and UI (i.e., basic and specific functions). This level of control is responsible for the control loops of the electronic power converters, in addition to services based on local quantities. In addition, the primary level of control does not depend on the communication link, giving support to the operation of the microgrid in case of communication infrastructure failures.

The first layer of secondary control level has the function of power sharing, avoiding undesired circulation currents between the generating units, having a frequency of operation equal to the fundamental frequency of the electrical network (period of approximately 16.67 ms), which provides good response to variations in load and generation. This is processed in the MC and has dependency on the communication link, but a failure in the communication infrastructure does not represent a collapse for the microgrid operation, since the DERs start to operate

[89] Tenti P, Caldognetto T, Buso S, Brandao D. I., "Control of Utility Interfaces in Low Voltage Microgrids," Brazilian Power Electronics Journal, vol. 20, no. 4, pp. 373 – 382, 2015; doi:10.18618/REP.2015.4.2556

through the local control discussed in the primary hierarchical level. This level of control is accomplished by means of the power-based control (PBC) algorithm[90].

The second layer of secondary level is the slowest of the three (between 1~60 seconds period) autonomously regulating the power flow between the microgrid and the main network, in order to maximize the active power injection through the DERs, minimize the reactive power and unbalance in the PCC of microgrid. Such an algorithm can make use of multi-objective optimization problem to track the most efficient operational point.

Finally, the tertiary level is the slowest of all and communicates with the DSO (approximately 15~60 minutes period) to define the active and reactive power flow constrains exchanged with the main grid. This level ensures the long-term energy planning of the power distribution company. Such approach is model-free and can be applied to both radial and meshed microgrid topologies.

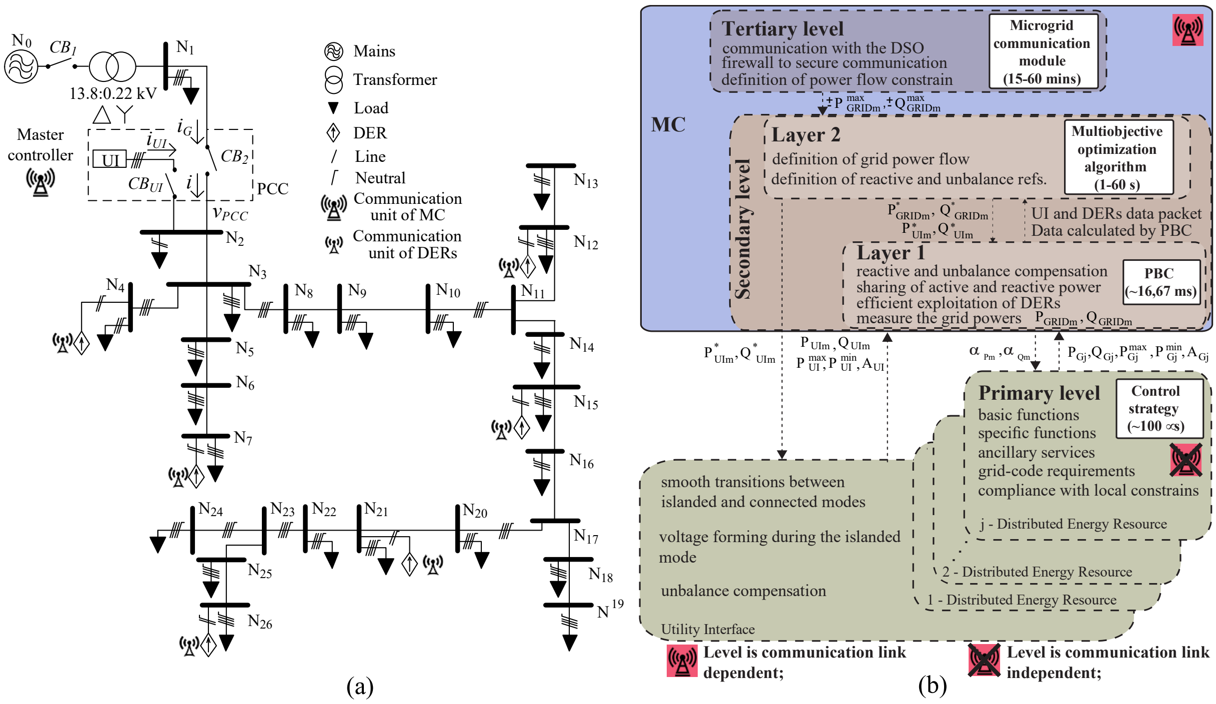

Figure 20. low-voltage microgrid (a) and centralized hierarchical architecture (b).

The microgrid line impedances and maximum loads are shown in Table 3 and Table 4, respectively. Table 5 shows the parameters of the stepdown transformer for connection to the low-voltage network. The capacities of the electronic power converters present in the DERs and UI are shown in Table 6, as well as the maximum capacity of the primary energy sources (i.e., Max. active capacity), and their energy storage capacities (i.e., Min. active capacity).

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[90] Brandao D.I., de Araújo L. S., Caldognetto T, Pomilio J.A., "Coordinated control of three- and single-phase inverters coexisting in low-voltage microgrids," Applied Energy 2018;228:2050–60. doi:10.1016/j.apenergy.2018.07.082

Table 3 Power line impedances values.

From	*To*	*Z [mΩ]*
N_1	N_2	32+*j*11.7
N_2	N_3	20.6+*j*7.5
N_3	N_4	3.7+*j*2.1
N_3	N_5	0.1+*j*0.1
N_5	N_6	27.8+*j*10.2
N_6	N_7	37.8+*j*13.8
N_3	N_8	8.4+*j*4.6
N_8	N_9	17.2+*j*9.4
N_9	N_{10}	18.8+*j*10.4
N_{10}	N_{11}	12.5+*j*6.9
N_{11}	N_{12}	12.9+*j*7.1
N_{12}	N_{13}	18.8+*j*10.4
N_{11}	N_{14}	7.3+*j*4.0
N_{14}	N_{15}	20.6+*j*11.3
N_{15}	N_{16}	22.1+*j*12.1
N_{16}	N_{17}	1.5+*j*0.8
N_{17}	N_{18}	5.6+*j*3.1
N_{18}	N_{19}	35.4+*j*13.0
N_{17}	N_{20}	20.2+*j*7.4
N_{20}	N_{21}	28.5+*j*10.4
N_{21}	N_{22}	30.0+*j*9.9
N_{22}	N_{23}	12.6+*j*4.6
N_{23}	N_{24}	6.0+*j*2.2
N_{23}	N_{25}	12.3+*j*4.5
N_{25}	N_{26}	34.5+*j*12.6

Table 4 Load active and reactive power values.

bus	*Pa [W]*	*Pb [W]*	*Pc [W]*	*Qa [var]*	*Qb [var]*	*Qc [var]*
N_1	1270.0	635.0	635.0	508.0	254.0	254.0
N_2	100.0	0	0	40.0	0	0
N_3	1270.0	635.0	635.0	508.0	254.0	254.0
N_4	0	2286.0	2171.7	0	1016.0	965.2
N_5	0	1447.8	1524.0	0	603.3	635.0
N_6	1016.0	1016.0	508.0	381.0	381.0	190.5
N_7	1016.0	508.0	1016.0	381.0	190.5	381.0
N_8	508.0	2032.0	2032.0	158.8	635.0	635.0
N_9	3429.0	1714.5	1131.6	1270.0	635.0	419.1
N_{10}	335.3	1016.0	1016.0	125.7	381.0	381.0
N_{11}	0	0	0	0	0	0
N_{12}	2000.3	2667.0	666.8	857.3	1143.0	285.8
N_{13}	0	698.5	698.5	0	317.5	317.5
N_{14}	0	2032.0	508.0	0	1143.0	285.8
N_{15}	5588.0	2794.0	3492.5	2794.0	1397.0	1746.3
N_{16}	1047.8	1397.0	698.5	476.3	317.5	158.8
N_{17}	0	0	0	0	0	0
N_{18}	1905.0	1905.0	952.5	762.0	762.0	381.0
N_{19}	419.1	1270.0	952.5	167.6	508.0	381.0

N_{20}	1587.5	1270.0	1270.0	508.0	508.0	508.0
N_{21}	1397.0	2095.5	2794.0	508.0	762.0	1016.0
N_{22}	698.5	461.0	1397.0	317.5	209.6	635.0
N_{23}	0	0	0	0	0	0
N_{24}	1016.0	1016.0	1016.0	381.0	381.0	381.0
N_{25}	422.9	635.0	1270.0	209.6	317.5	635.0
N_{26}	1270.0	635.0	0	508.0	254.0	0
Total	**26296.3**	**30166.3**	**26385.5**	**10861.7**	**12369.8**	**10845.8**

Table 5 Parameters of the step-down transformer.

A = 75 kVA	
V_H = 13.8 kV	V_L = 0.22 kV
R_H = 0.0076 p.u.	R_L = 0.0076 p.u.
L_H = 0.0157 p.u.	L_L = 0.0157 p.u.
R_m = 227.27 p.u.; L_m = 32.59 p.u.	

Table 6 Parameters of the DERs.

Parameters	***UI***	***DER (N_{15}, N_{23}, N_4 N_{18}, N_9, N_{19})***
Converter capacity (kVA)	8	(4.0, 8.0, 4.0, 5.0, 6.0, 9.0)
Max. active capacity (kW)	0	(4.0, 8.0, 4.0, 5.0, 6.0, 9.0)
Min. active capacity (kW)	0	(0.0, 0.0, 0.0, 0.0, 0.0, 0.0)

B. MEGA grid investments for RES integration between wide spread regions

Studies carried out in the EU-IRENE40 project demonstrate, as shown in Figure 21, that the 2050 scenarios with a large reliance on renewable energy (High Renewables), and especially remote renewables in North Africa, *drive the largest requirement* for new Pan-European interconnection capacity. For example, the largest capacity upgrade requirement of more than 30 GW is found at the Spain–France (ES-FR) interconnector and it occurs in the DESERTEC scenario. Harnessing the energy from very remote areas, such as the north African desert, and transporting it to the demand centres in central Europe will require substantial reinforcement of the European grids. Another 14 corridors would require an upgrade by more than 10 GW under the same scenario. In contrast, under the Business-as-Usual (BaU) and Carbon Capture and Storage (CCS) scenario, all upgrades are 10 GW or less since generators are more controllable and can follow the variability of electricity demand in their respective regions. This allows the demand to be supplied locally.

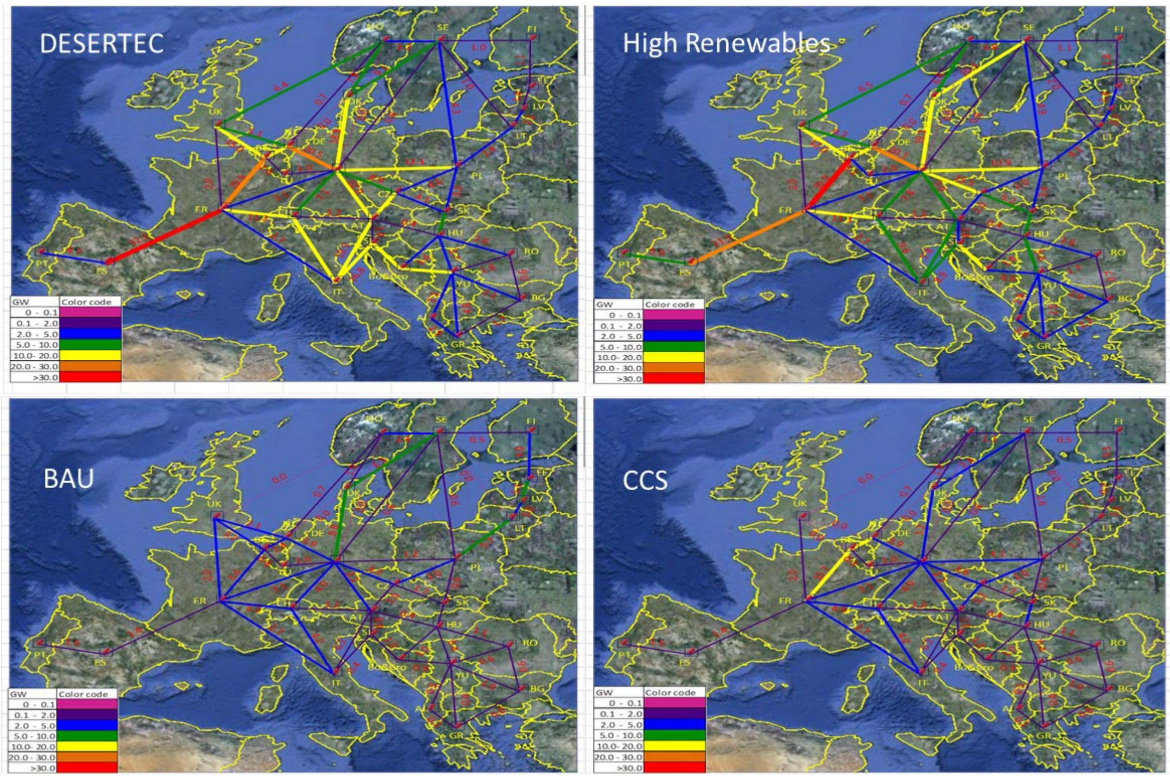
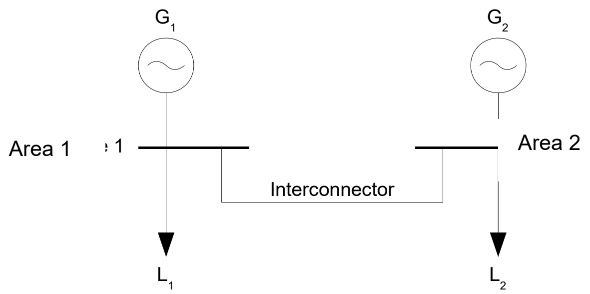


Figure 21. Renewable growth will drive MEGA grid investment in Europe.

These examples highlight that the MEGA grid investment will be driven primarily by the need to bring the renewable energy from remote places to the demand centres. However, the capacity required for each corridor varies significantly across the scenarios used. This increases the uncertainties in development of the MEGA grid interconnections since it can take over 10 years to complete the process of building high capacity and long-distance interconnectors and over that time the policies which drive system development may have changed substantially.

C. Asymmetrical benefits from interconnections

Figure 22 shows the effect of arbitrage trades between adjacent markets on social welfare. It is assumed that Area 1 is characterised by lower production costs and hence exporting, while Area 2 characterised by higher production costs and hence importing. The market equilibrium in both areas is affected by the presence of an interconnection.



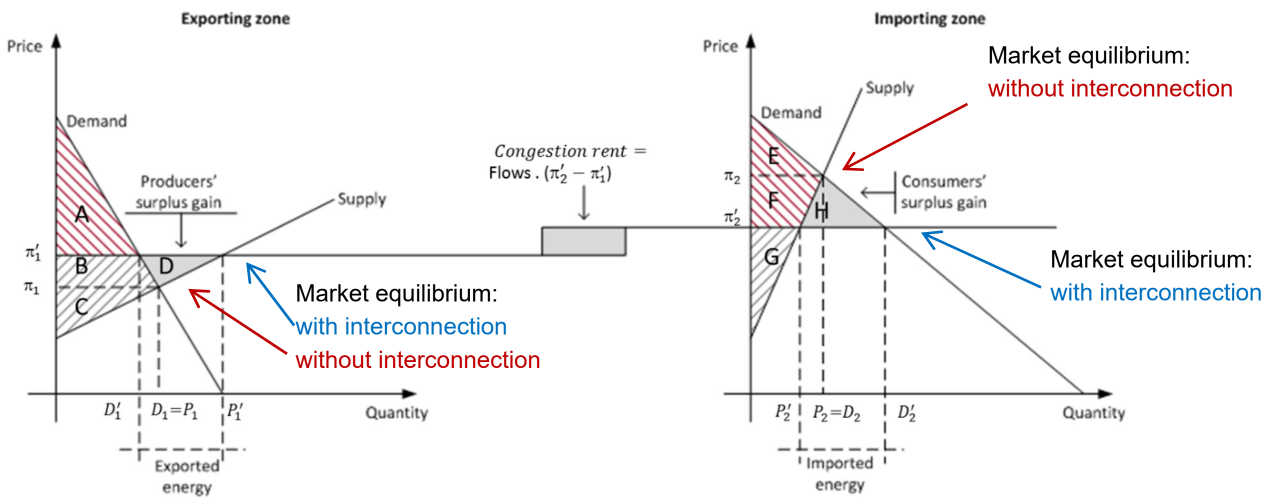


Figure 22. Arbitrage trades between adjacent markets.

Comparing the case of the interconnected areas with their separate operation, the prices are changed, and the producer and consumer welfare are changed as follows:

- In the exporting area (Area 1), the market price increases from π_1 to π_1' leading to a further gain in producer surplus, from C to C+B+D, as producers generate additional volumes at a higher price;
- The consumer surplus in Area 1 decreases from A+B to A due to the higher market price. As a consequence, electricity demand in area 1, if it is elastic to price, will reduce. It is important to note that part of the consumer surplus (B) has been shifted to the producer surplus due to interconnection;
- There is an increase in the overall social welfare of the exporting Area 1 due to interconnection. It is represented by area D, the triangular area shaded in grey ("producers' surplus gain");
- In the importing area (Area 2), the market price decreases from π_2 to π_2' resulting in a further gain in consumer surplus, from E to E+F+H, as customers consume higher volumes at lower prices.
- In contrast, the producer surplus in Area 2 decreases from F+G to G as the volume of local electricity production is lower responding to lower electricity prices. It is important to note that, in contrast to Area 2, there is a shift of welfare from producers to consumers in Area 2;

- Area 2 also gains an increase in the overall social welfare due to interconnection. It is represented by area H, by the triangular area shaded in grey ("producers' surplus gain");
- Due to price differential between Area 1 and 2, there is congestion rent that can be collected. If the development of transmission is optimal, in theory the cost of transmission will be recovered by the congestion rent.
- It is important to note that the congestion rent does not encompass the additional social welfare (D+H). This means that not all benefits of interconnection will be allocated to the interconnector; some of the benefits will be distributed to producers and consumers.

It can be concluded that development of interconnection, if it is carried out in an optimal fashion, will improve social welfare in both exporting and importing Areas; however, the benefits are asymmetrical; not only between the connected regions but also asymmetrical across producers and consumers, e.g.:

- Consumers located in importing zones have access to competitive offers from producers located in adjacent zones. The local market price decreases resulting in a further gain to consumer.
- Producers located in importing zones experience lower energy prices and a potential decrease in energy production for higher marginal cost plants (i.e. mid-merit and peak plants) which in turn leads to reduced revenues and surplus.
- Producers located in exporting zones potentially produce higher volumes of energy from lower marginal cost plants (i.e. renewable energy sources, baseload and mid-peak plants) which are sold at higher prices permitting them to secure further producer surplus.
- Consumers located in exporting zones observe higher energy prices resulting to an increase of the payments incurred for the consumption of electricity.

These asymmetrical impacts can potentially delay the development of transmission grid cross-border interconnectors as it opens the question as to who is responsible for the capital costs of the investment. The dissimilar impact on interconnectors caused by different electricity market participants signals that costs allocations need to be aligned in accordance with the value that each market participant places on the interconnection.

Furthermore, the analysis has shown that it is possible that investments in cross-border interconnection based on merchant trading incentivises investment below the optimal capacity level. In this sense, it is observed that transmission surplus for some cross-border interconnectors becomes negative resulting in a non-profitable business and possible deferral on investment.

D. Grid hosting capacity and inverter generations

System hosting capacity (HC) can increase by a factor of 1.5 to 2 if reactive power functions are properly considered[91]. For instance, considering the Brazilian scenario with a typical HC of 20% of the MV/LV transforming rating, applying the reactive power functions (i.e., grid-support functions) the HC is expected to increase to 30-40% of the MV/LV transforming rating.

If it is desirable to increase the HC value even further, then again two approaches can be adopted: intervention in the electrical network and intervention in the DG systems through communication-based functions in which many DG inverters are coordinated to provide improved system performance.

Such inverters endowed with communication module are used into the microgrid model, in which many arbitrary connected inverters are coordinatingly controlled in order to achieve global targets. The evolution of the inverters responsible to integrate the DG systems can be classified into three generations, as it is shown in Table 7.

Table 7 generation of grid-tied inverters for distributed generation energy.

Inverter Generation	Description
First generation	Inverters capable of injecting active power into the grid with fixed power factor
Second generation	Inverters capable of injecting active power into the grid with variable power factor. The active / reactive power injection is a response to the frequency / voltage variation at the point of DG system connection (local)
Third generation	Inverters capable of injecting active power into the grid with variable power factor controlled remotely through the embedded communication module. The active / reactive power injection is a response to the frequency / voltage variation at the point of DG system connection (local), but can also be regulated by a central controller installed at the point of connection between the main grid and the microgrid

HC limits are quantified based on the DER rating in comparison to the MV/LV transformer, or the total DER rating in comparison to the short-circuit capacity at the PCC. In South Africa and Portugal the HC limit is 25% of the MV/LV transforming rating; in Italy it is 65%; and China and USA the HC limit is 10% of the short-circuit capacity[91]. Finally, in Brazil (São Paulo state) the HC limit is 20% of the MV/LV transformer rating, in which the most restrictive technical impacts are: overvoltage (61.5%), conductor thermal capacity (27.7%) and voltage unbalance (9.6%)[92]. The excessive power line loss and power transient are technical indexes that may be also observed. Additionally, it was concluded that in Brazil the undervoltage, overloading of transformers, protection failure, harmonic distortion level, and voltage transient are not critical operational limits under excessive penetration of DER[92.]

[91] S. M. Ismael, S. H. E. Abdel Aleem, A. Y. Abdelaziz, A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," Renewable Energy, vol. 130, pp. 1002-1020, January 2019

[92] R. Torquato, D. Salles, C. Oriente Pereira, P. C. M. Meira and W. Freitas, "A Comprehensive Assessment of PV Hosting Capacity on Low-Voltage Distribution Systems," in IEEE Transactions on Power Delivery, vol. 33, no. 2, pp. 1002-1012, April 2018

E. Whole-system centric approach[93]

The modelling results in Figure 23 show that a whole-system-based network management approach may result in 30% and 100% higher savings in the investment and operation cost of the system relative to transmission- or distribution-centric approaches, respectively.

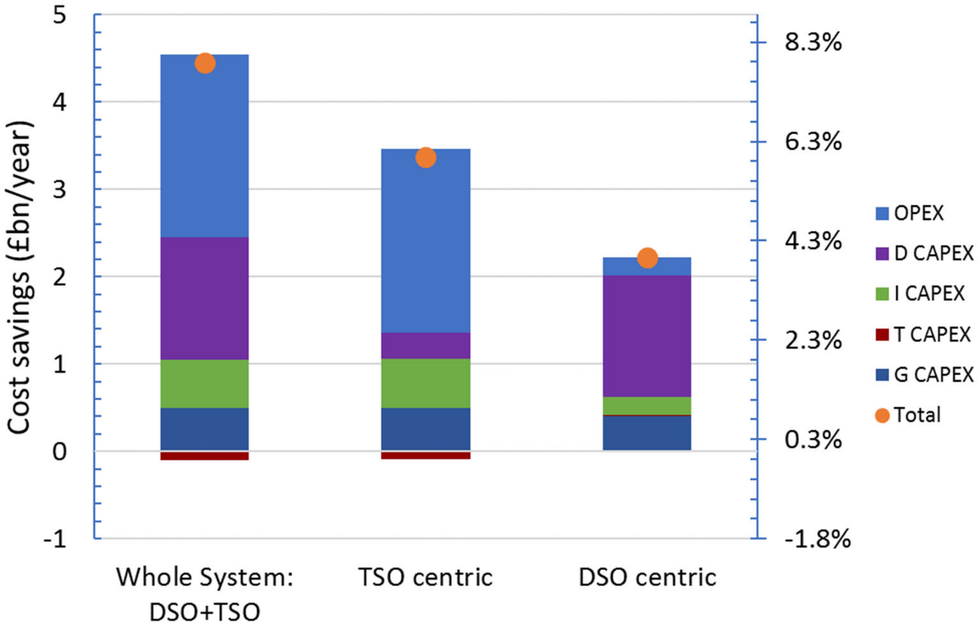


Figure 23. Potential benefits of improved transmission and distribution control interface. Right vertical axis shows cost savings relative to total system cost without added flexibility.

In this case, the DSO-centric approach focuses on the use of DER for deferring distribution network investment by reducing peak demand, although this may not be optimal for transmission system operation and investment. On the other hand, the TSO-centric approach focuses on deferring transmission and interconnection investment as well as reducing system operating costs, while disregarding the potential value of using DER in reducing distribution network costs. In contrast, the whole-system approach would allow the DER to be utilized in order to meet both local and national infrastructure objectives by managing the synergies and conflicts between various DER applications.

Figure 24 shows the total system benefits between the solutions that optimise the utilisation of demand-side flexibility obtained using the whole-system and DSO-centric approaches, in the case of relatively inflexible generation systems (with respect to the ramping, start-up and frequency regulation capabilities of conventional generators). The whole-system solution is expectedly characterised by lower cost than the DSO-centric approach, hence resulting in net savings.

[93] Goran Strbac, Danny Pudjianto, Marko Aunedi, Dimitrios Papadaskalopoulos, Predrag Djapic, Yujian Ye, Roberto Moreira, Hadi Karimi, Ying Fan, “Cost-Effective Decarbonisation in a Decentralized Market: The Benefits of Using Flexible Technologies and Resources,” IEEE Power and Energy Magazine, Vol 17, February, 2018, pp. 25-36

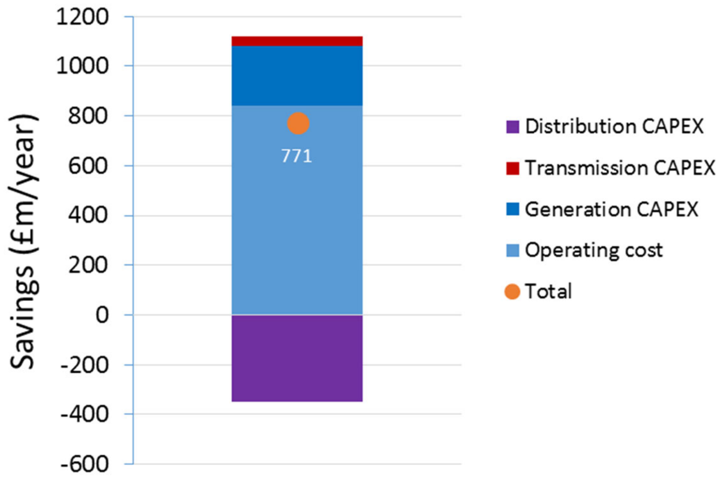


Figure 24. System cost savings from deploying demand-side flexibility based on a whole-system rather than a DSO-centric approach.

However, realising this additional potential requires close coordination between system operators, with clarity on their future roles and responsibilities, which would be achieved through a decentralised, fully cost-reflective market design.

The benefit of the whole-system solution highlights the need for a more intensive system coordination, as the modelling demonstrates that the entire system would also benefit from investment in distribution network reinforcement. Such investment would enable end-use flexibility to reduce the system operating cost and also reduce the corresponding generation CAPEX needed to reach the CO_2 target cost-effectively. In this case, flexible consumers would be willing to pay for distribution network reinforcement, as the revenues from providing balancing services at the national level would be greater than the cost of distribution network reinforcement, which would subsequently reduce their overall energy bills.

From these studies, it can be concluded that it will be important to manage the synergies and conflicts between distribution networks, energy supply, and transmission networks when allocating DER flexibility. It will be essential to acknowledge the value of decentralised flexibilities by incorporating them into electricity markets which provide cost-effective price signals, reflecting both national and local-level costs and benefits. Such decentralized, market-integrated flexibility will enable consumers to make appropriate choices to facilitate cost-effective decarbonisation while reducing their energy bills.

F. Impact of decreased synchronous generation in the integrated power system

For illustration, consider a system scenario which splits the ENTSO-E grid into 3 zones as show in Figure 25. The selection is motivated by an actual European system split into 3 synchronous areas which occurred in 2006.

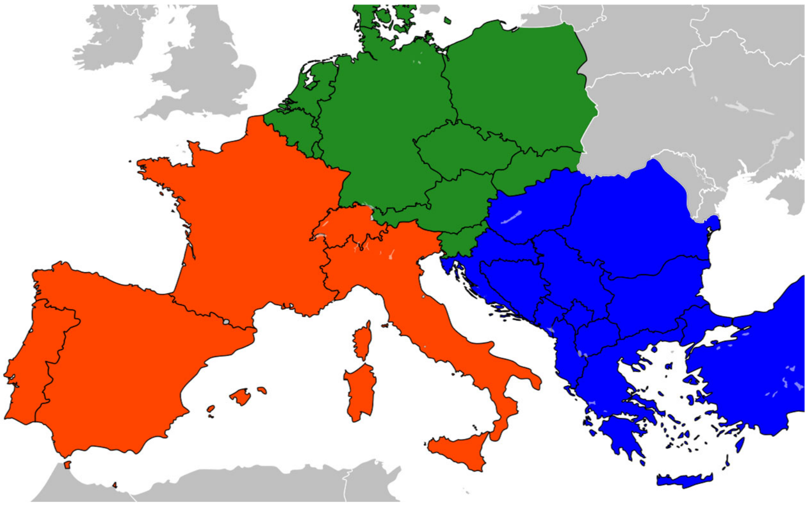


Figure 25. Central European grid split into 3 zones.

Currently, the dynamic stability after such a large-scale disturbance is considered one of the key challenges of the energy-transition. Before the system split each of the 3 areas has a production between 110GW and 175GW with a total of 458GW. In each area, the total load is slightly smaller than the total generation with a net export from the south-west region to the other two regions.

Figure 26 shows the resulting frequency transients of the 1013 system generators, coloured by area. Some transmission lines are exporting while others are importing, leading to both positive and negative initial frequency deviations.

The import dynamic indicators of this scenario are:

- The steepness of the frequency deviation in each area (known as Rate-of-change-of-frequency, ROCOF, measured in Hz/s). If the ROCOF of individual units is too high, they will be disconnected. If the overall mean ROCOF of the area becomes too high, the risk of a black-out entails.
- The final frequency value after the transient, depending on the initial load imbalance and the available fast reserve power in the area. If insufficient fast reserve power is available in the area, the frequency deviation becomes too high and the risk of black-out entails.
- The internal frequency oscillations within each area. The new islanded parts of the grid may show internal oscillations, that may lead to increasing relative frequency oscillations. If the oscillations are poorly damped, the risk of black-out entails.

The more conventional generation in the grid is replaced by DER, the more critical the frequency transients become (steepness, relative oscillations, fast frequency reserve). Simulations of this challenging dynamic scenario validates that DER and distributed storages with dynamic support function (e.g. virtual synchronous machine control) can support and mitigate all of these dynamic stability challenges. They allow for the reduction of the initial ROCOF, dampen local frequency oscillations and temporarily deploy power from distributed battery sources to provide the fast frequency reserve[94]. The dynamic performance depends on the amount, type and distribution of the available inertia in the system.

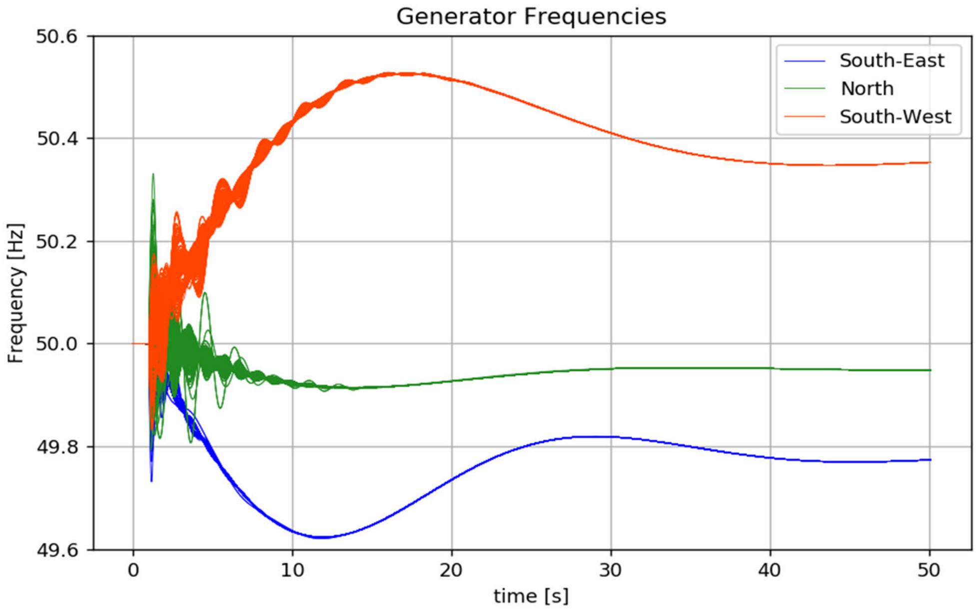


Figure 26. Dynamic frequency transients at different buses in the three zones of the ENTSO-E system after the system split.

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[94] Alexander Fuchs, Turhan Demiray: Simulation results of benchmark scenarios in the ENTSO-E power system. SCCER-FURIES D2.1.2

G. Micro MEGA cooperation examples

Cooperation between micro & MEGA levels

One possible architecture of future grids integrating both micro and MEGA solutions is depicted in Figure 27, where the transmission level — composed mainly by industrial loads and synchronous generation— is divided into synchronous or asynchronous areas. Different areas of the transmission level are interconnected through an overlaying HVDC grid creating a wide area system. Inside the different areas of the transmission level, distribution grids are present for the integration of DER mainly to feed local loads. These distribution grids can be either connected directly to the HVDC grid or the AC grid through power electronics, depending on the architecture of the local grid.

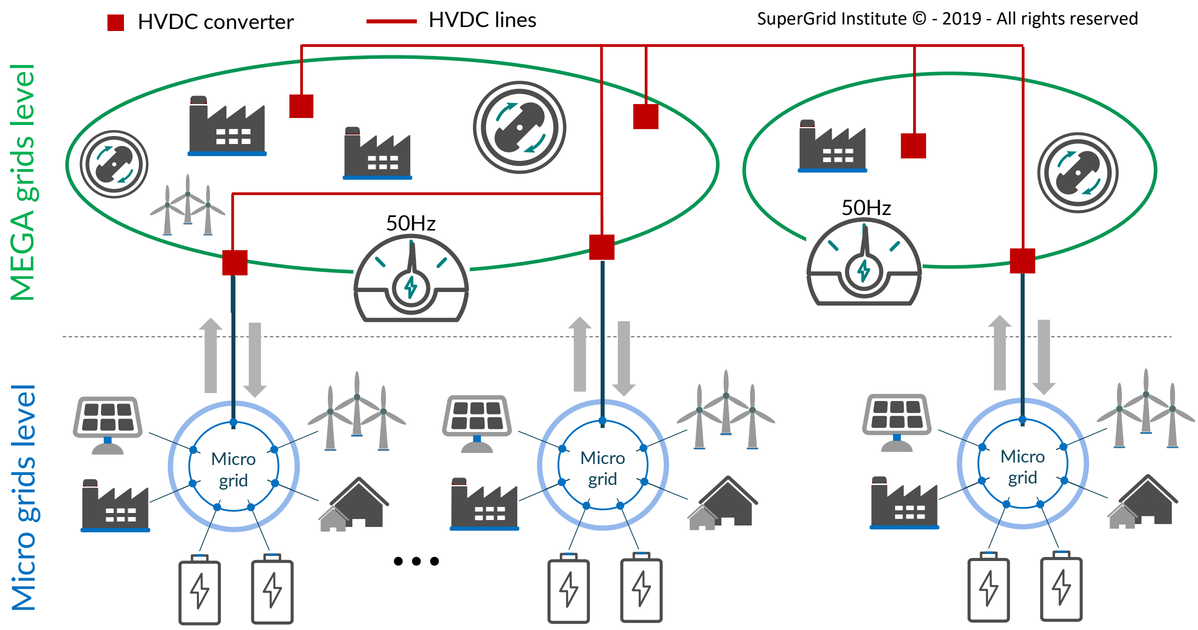

Figure 27. Example of a future grid integrating micro and MEGA grid levels.

At the local grid level, energy storage plays a major role in the operation of the local grid especially in islanded microgrid mode. In a power network with high penetration of distributed storage, the amount of aggregated stored energy can become significant for the transmission system. This stored energy can allow the local grids to increase the overall system reliability.

At the transmission level, the HVDC grid represents an adapted means to transfer energy reserves from one point to another in a controlled way. The HVDC grid will allow power exchange between:

- Different distribution grids,
- Different AC transmission areas
- Distribution and transmission grids.

In this context, the balancing of the system will be one of the responsibilities of the HVDC grid. It is evident that an optimized cooperation between both the micro and the MEGA grid levels is necessary in order to increase the reliability, the flexibility and safety of the whole system.

How the micro developments can support the MEGA level

Example 1: In a scenario with low synchronous generation, if the loss of a generating unit takes place, the energy imbalance might lead to large frequency deviations, leading to an inadmissible situation for the system operator. To face this problem, the stored energy at the distribution grid level can be injected into the transmission grid in an aggregated manner to support the lack of energy at the transmission level. When the transmission grid is brought back to a stable condition, storage systems in the distribution grids can be recharged in a controlled manner by absorbing energy from the transmission system.

This situation is depicted in Figure 28.

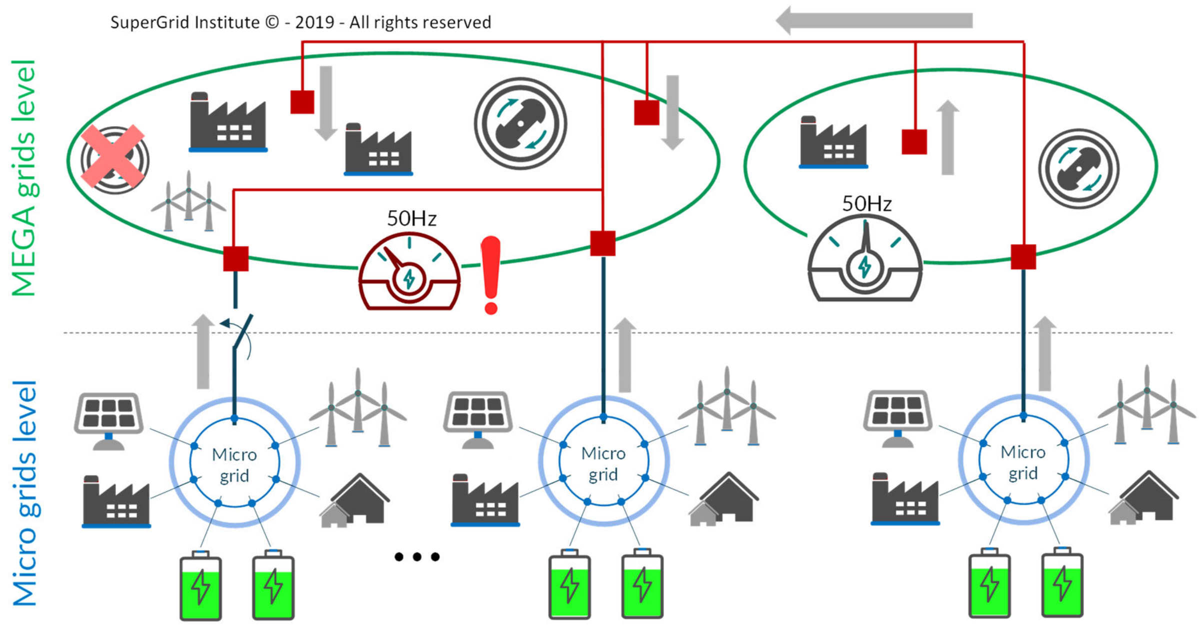

Figure 28. Example of how microgrids can support the mega grids

Example 2: Compared with AC systems, the HVDC system has a volatile nature due to the low electrostatic energy stored its passive elements. When a disturbance take place in the HVDC grid (e.g., loss of a station), large DC voltage deviations can take place. Through the control of the converters, the energy in the distribution grids connected to the HVDC grid can be quickly shared with the HVDC grid to contain the DC voltage deviation between its acceptable limits. Once a stable situation is reached, the stored energy in the distribution grids can be used to restore the voltage of the HVDC grid.

Example 3: In the case distribution grids are connected directly to the transmission system through a power electronics converter, they can provide services as any power electronics-interfaced source such as: reactive power control for voltage support, low-frequency power oscillation damping, etc. [95]

[95] Gopakumar, Pathirikkat, Maddikara Jaya Bharata Reddy, and Dusmanta Kumar Mohanta. "Phasor Measurement Sensor-Based Angular Stability Retention System for Smart Power Grids With High Penetration of Microgrids." IEEE Sensors Journal 18.2 (2017): 764-772

Example 4: Aggregated dynamic support from DER in the distribution grid. A crucial example for the distribution grid support for transmission grids is the interplay during large-scale dynamic transients in the transmission grid.

How MEGA developments can support the micro level

Example 1: The first and more evident situation is the case when microgrids are connected to the transmission system. In this situation, for the microgrid, the transmission system represents a strong grid to be connected to. Acting as a strong grid, in a fast time scale the transmission system can compensate any power mismatches in the microgrid (losses or disturbances). In a larger time scale, the transmission system can support the microgrids by recharging its storage elements in case of lack of reserves.

Example 2: If microgrids are directly connected to the HVDC grid, through the control of the interfacing converter, the HVDC grid can be seen as a strong grid absorbing all the power mismatches in the microgrid (As proposed for offshore windfarms connected to a DC grid[96]. Also, the fast active power control capability of the HVDC system is an adapted channel for the fast exchange of power between microgrids. For example, if some microgrids present a lack of reserves, the HVDC system can be used for transporting energy from the recharged microgrids to the uncharged ones. This situation is represented in Figure 29.

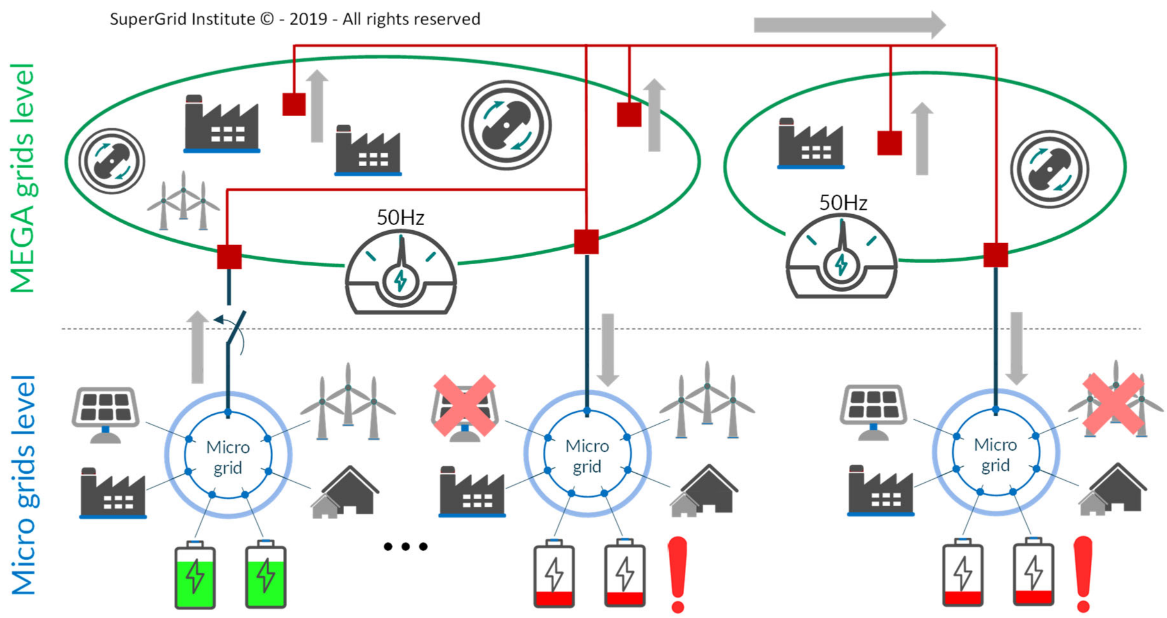

Figure 29. Example of the Mega grid supporting the microgrids

[96] Ramachandran, R., et al. "AC Grid Forming by Coordinated Control of Offshore Wind Farm connected to Diode Rectifier based HVDC Link-Review and Assessment of Solutions." 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe). IEEE, 2018

H. Integrating fossil free production – Indian case

Govt. of India has set a target to establish 175 GW renewable capacity comprising 100,000 MW Solar and 60,000 MW Wind generation capacity by 2022. RE generation is characterized by intermittency and variability with a low gestation period. Presently 81 GW of renewable capacity is integrated into the grid at various voltage levels. This renewable generation is divided into three main schemes:

Green Energy Corridor (GEC):

To facilitate the integration of large scale renewable generation capacity addition envisaged in the 12th plan (from 2012-17 period) in eight (8) RE resource rich states viz. Rajasthan, Gujarat, Tamil Nadu, Maharashtra, Karnataka, Andhra Pradesh, Himachal Pradesh and Madhya Pradesh, a comprehensive plan comprising of transmission as well as control infrastructure was identified as a part of "***Green Energy Corridors***". These states are predominantly located in North Western, Western and Southern part of India except Himanshu Pradesh which is located in Northern Part of India.

The plan includes strengthening of the Transmission infrastructure at Intrastate and Interstate level whereas control infrastructure comprised of forecasting of renewable generation, establishment of Renewable Energy Management centers (REMC) at SLDC/RLDC/NLDC level etc. The detailed report on development of transmission system in Green Energy Corridor is available from the following sources:

http://www.powergridindia.com/sites/default/files/Our_Business/Smart_Grid/Green_Energy_Corridor_Report/Vol_1.pdf and http://www.powergridindia.com/sites/default/files/Our_Business/Smart_Grid/Green_Energy_Corridor_Report/Vol_2.pdf

Intrastate Transmission systems of the GEC is being implemented by respective State Transmission Utilities (STU) and Inter State transmission system (ISTS) is being established by POWERGRID. The majority of the GEC-Inter-state transmission schemes are already commissioned, whereas balance system i.e. 765kV Bikaner-Moga is in its advanced stage of implementation. Figure 30 shows the details of green energy corridors.

Figure 30. Details of Transmission System in Green Energy Corridors Part-I.

To address forecasting and scheduling of RE generation, establishment of Renewable Energy Management Centres (REMCs) comprising of RE forecasting & RE scheduling systems, integrated with existing SCADA co-located at SLDC/RLDC/NLDC is being implemented by POWERGRID from the Ministry of Power allocation

- Total 11 locations [in state of Tamil Nadu, Andhra Pradesh, Karnataka, Gujarat, Maharashtra, Madhya Pradesh & Rajasthan, and regional Load Dispatch centers of Northern Region, Sothern Region, Western Region and National Load Dispatch center
- REMCs in Western Region Load Dispatch Center & Southern Region Load Dispatch Centre already commissioned and in Northern Region is expected by Nov’2019.

A brief block diagram of REMC is given in Figure 31.

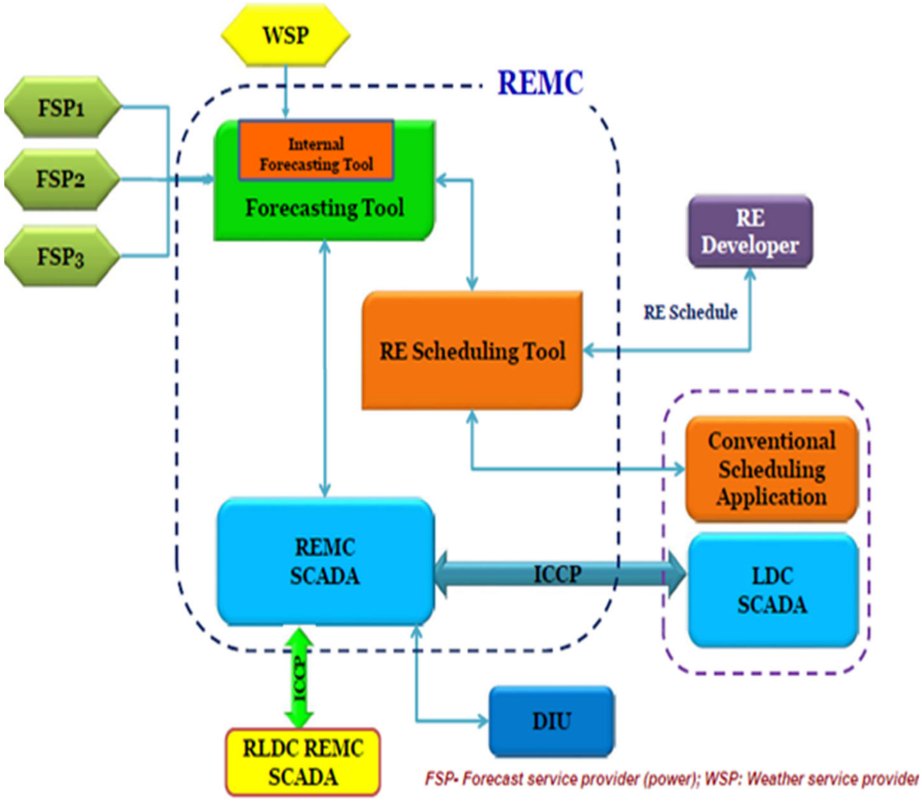

Figure 31. Block Diagram of REMC.

Transmission scheme for Ultra mega solar power parks

Government of India plan to implement a total of 100,000 MW of Solar which includes 20 GW through solar power parks (mostly ultra-mega solar power projects) in various States. To evolve plan for Grid integration of 34 nos. solar power parks, POWERGRID evolved comprehensive transmission plan for evacuation of about 20,000 MW capacity through solar power parks envisaged through Intra state & Interstate system & prepared report titled ***"Green Energy Corridors-II".***

Transmission scheme for seven (7) solar parks (about 6450MW) for evacuation through ISTS network viz. Ananthapur (1500 MW), Pavagada (2000 MW), Rewa (750 MW), Bhadla-III (500 MW), Bhadla-IV (250 MW), Essel (750 MW), Banaskantha (700MW) is being implemented by POWERGRID.

Out of this, transmission scheme for Ananthapur Ph-I to III (Gen Commissioned: 650 MW), Tumkur Ph-I (Gen Commissioned: 1650 MW), Rewa Solar Park (Gen Commissioned :735 MW, Bhadla Ph-III (Gen Commissioned: 200 MW) & Bhadla-IV (Gen Commissioned: 250 MW) is already commissioned by POWERGRID. Transmission scheme for Pavagada Ph-II (350MW), Bhadla-III (300 MW), Essel (750 MW) & Banaskantha (700MW) solar parks is under various stages of implementation. The location of these parks identified in Figure 32.

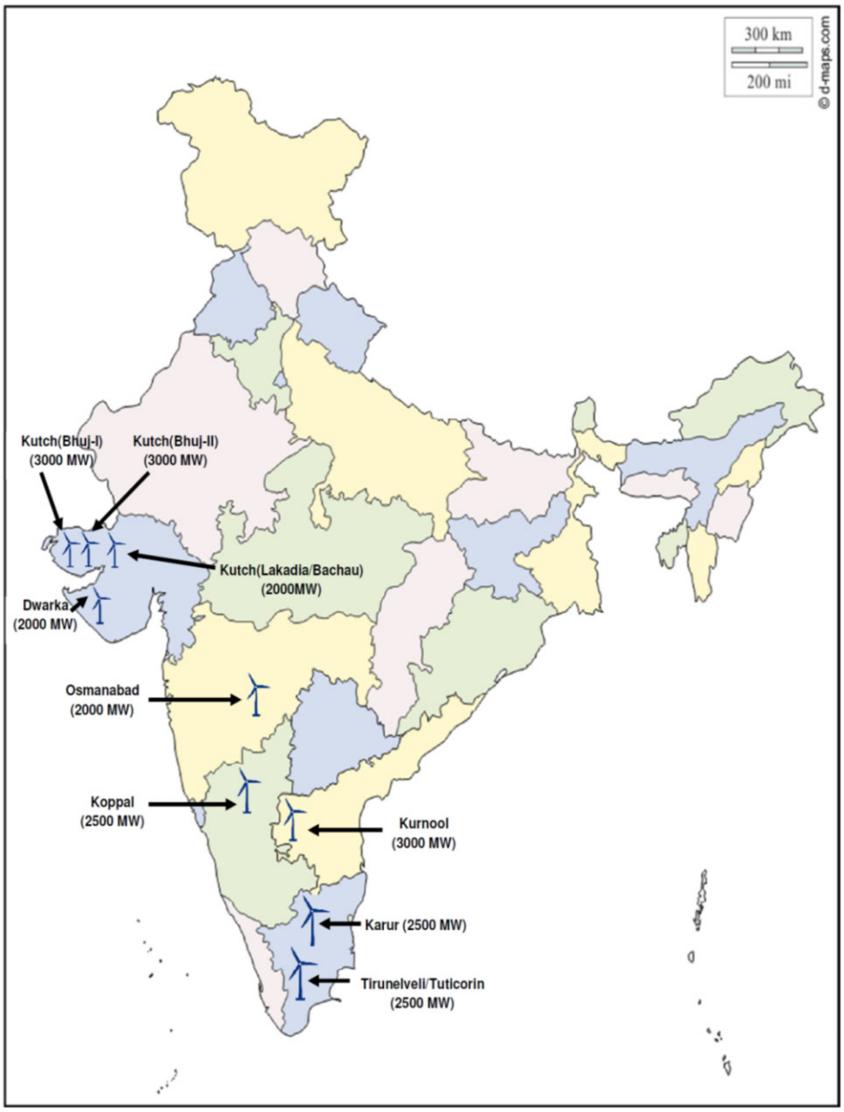

Figure 32. Location Ultra Mega Solar Park.

Inter State Transmission scheme for Renewable Energy Zones (REZs) [66.5 GW] on potential basis

Further Solar Corporation of India Limited (SECI) under the Ministry of Non-conventional and Renewable Energy (MNRE) have identified potential wind/solar energy zones (66.5GW) in Seven (7) RE resource rich states viz. Tamil Nadu, Andhra Pradesh, Karnataka, Gujarat, Maharashtra, Rajasthan and Madhya Pradesh. SECI has prioritized the RE generation capacity addition programme in above REZs in three phases i.e. 12.4 GW (by Dec'20), 26.1 GW (by Dec'21) and balance (28 GW) beyond Dec' 21.

Central Electricity Authority (CEA*)/Central Transmission Utility (CTU[@]) have evolved a comprehensive transmission scheme integrating above renewable energy zones. As the gestation period of these RE generation is much less as compared to construction time required, for Transmission system, the identified Transmission schemes are being considered for implementation in a progressive manner. The detailed of identified REZ are indicated in Figure 33.

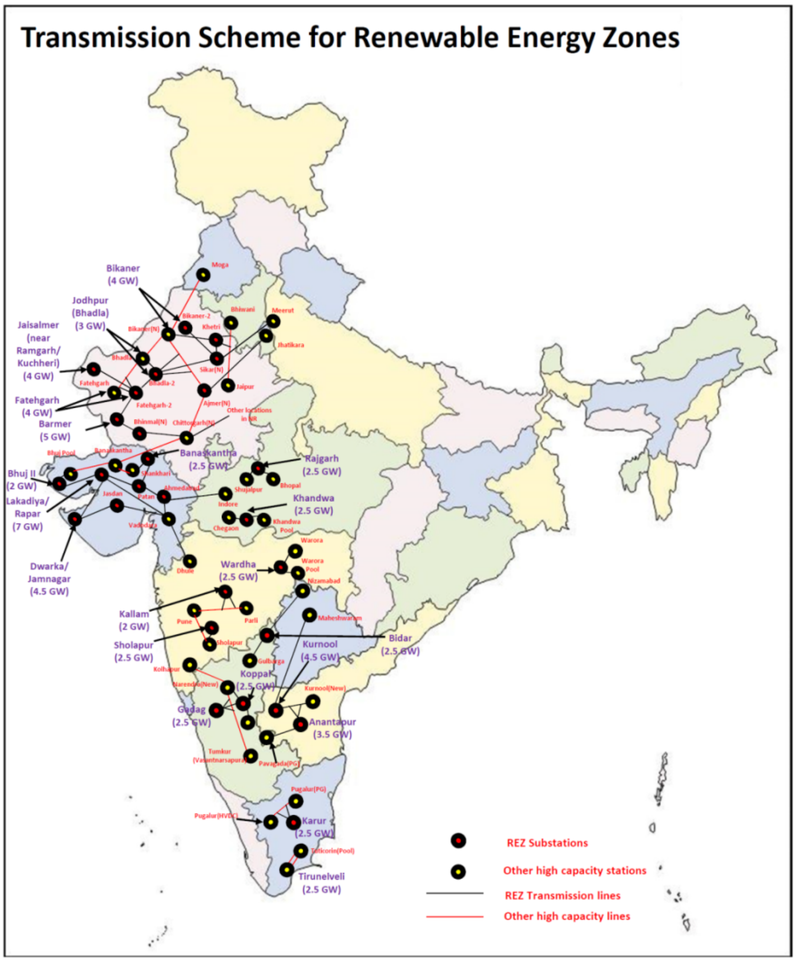

Figure 33. Identified REZ and Transmission System in India.

"*": CEA is apex body of Government of India

"@": CTU is responsible for Transmission planning in India along with all stakeholders.

I. Integrating fossil free electricity – Canadian case

Success of Canada's energy future will depend on the increasing roles of both the megagrids and microgrids. The former is already a source of a large portion of Canada's clean and renewable energy demands; an increasingly electrified economy will depend on their expansion to include even more clean and renewable resources. Furthermore, increased regional integration between megagrids will be necessary to take advantage of resource diversity. Complementing megagrids, flexible smart energy communities must also play a larger role to ensure a successful transition to a cleaner grid. Electrification will drive increasing demands on the grid, control of which will be necessary to integrate renewables in a cost-effective fashion.

Today, over 60% of Canada's electric energy demand is met from large hydro. As a renewable, long-lasting and low-cost energy source, it will remain key to Canada's clean energy future. It also offers unprecedented flexibility and long-term storage – key requirements to integrating future variable renewables. With most capacity located far away from load centres, megagrids will continue to be necessary to deliver electricity from hydro stations to consumers.

Wind will similarly have a role in Canada's future grid, and like large hydro, a large portion of it is located at distances far from load centres. The Pan-Canadian Wind Integration Study[97] has shown that bulk-scale wind will be part of the solution in achieving decarbonisation of Canada's economy, but that it will need to be enabled by transmission reinforcements. Thus, from a generation standpoint, large transmission, or "electricity highways" that form a megagrid, will be core to meeting future energy needs.

Europe has, and currently benefits from, a highly integrated network between regional entities or countries taking advantage of regional diversity in resources and loads. Canada is similarly looking at increasing intertie/transmission capacity between regions and has completed two analyses demonstrating the benefits: the a) Western and b) Atlantic Regional Electricity Cooperation and Strategic Infrastructure studies[98]. At a continental level, the North American Renewable Integration Study, a collaboration between Natural Resources Canada, the US Department of Energy, and Mexico's Secretaría de Energía, has looked at, among other things, benefits to increase transfer capacity between regions in North America.

[97] https://www.nrcan.gc.ca/energy/funding/current-funding-programs/eii/16634
[98] https://www.nrcan.gc.ca/climate-change/canadas-green-future/clean-energy-and-electricity-infrastructure/21294

J. Global grid

Numerous of projects for regional/continental interconnections and/or coordinated operation have been studied, on top of existing macro-grids in Europe, North America, India, see Figure 34 and Figure 35).

The next step, at least conceptually, is to study a global grid, as recently done by Cigre (Technical Brochure 775, Figure 36). To date, few studies of such a future global network have been undertaken, and barriers for its realization would be paramount, including political vision and worldwide collaborative mood. However, the potential high rewards of such a concept deserve a scientific, expert-based and truly international effort

This Cigre study shows that, within the limits and boundary conditions adopted, the added value of interconnecting the continents in comparison with keeping them separated emerges clearly, in all the considered cases and sensitivities; currently, the role of storage and demand response are being analysed in more detail based on a three variables co-optimisation process: generation-transmission-storage.

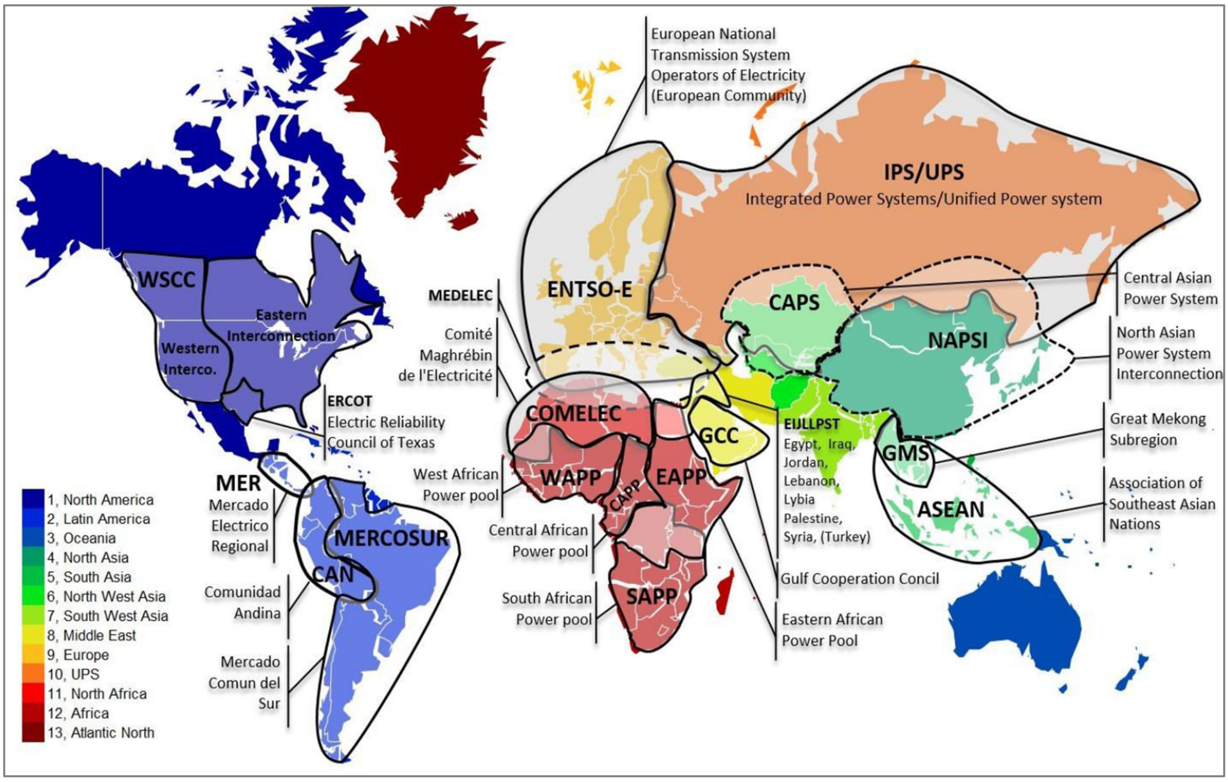

Figure 34. Existing interconnected and/or coordinated operation area.

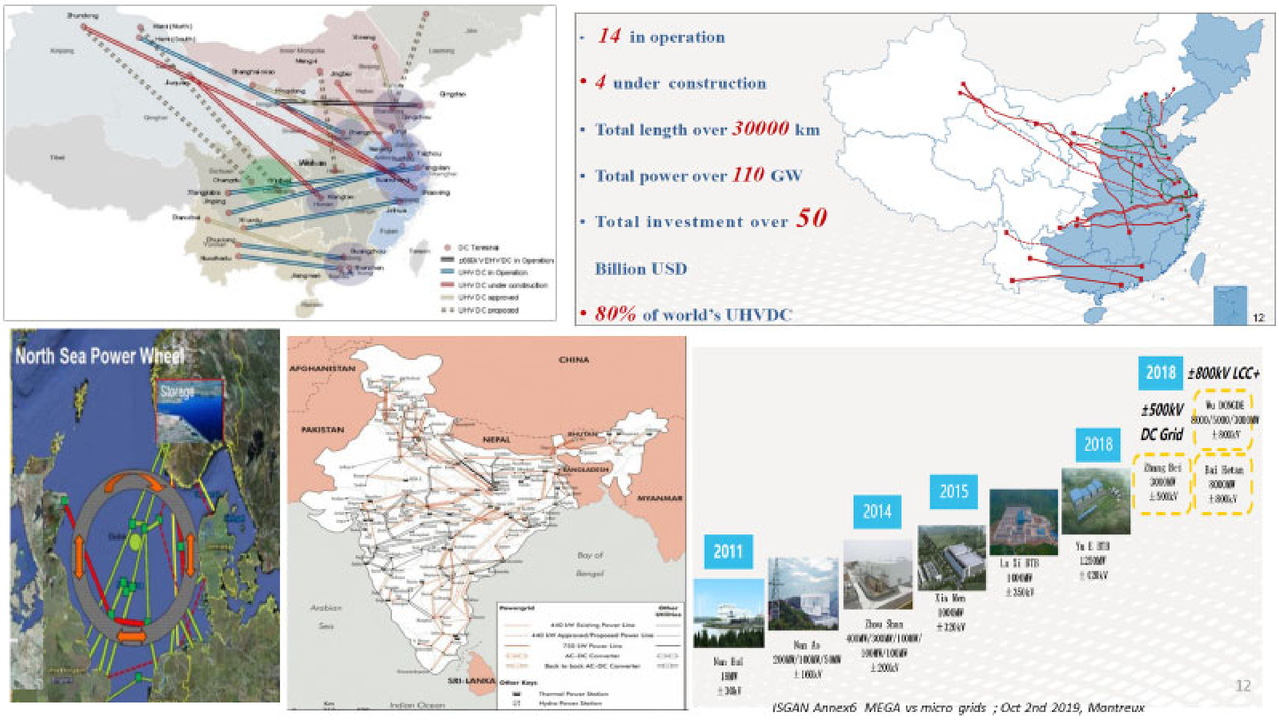

Figure 35. Examples of existing macro grids and enabling technologies.

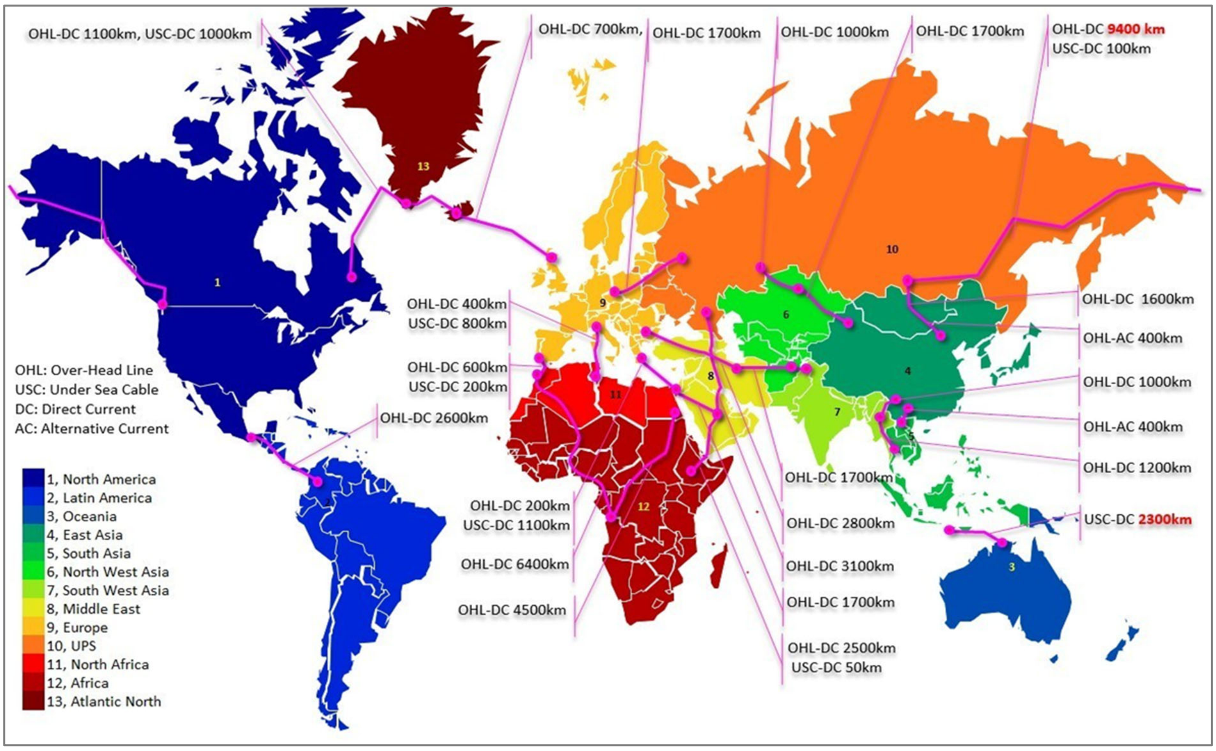

Figure 36. Cigre feasibility study on global grid.

K. Multinational MEGA grid developments

The most active actor constellations promoting ideas of the global and regional power grid exist in Northeast Asia and Europe. Here, the megagrid developments have been ongoing since the 1990s with multinational negotiation processes as well as initial investment and planning.

Perhaps the most well-known actor promoting large-scale transmission grid systems in the wider European region is the Desertec Foundation and the Desertec Industrial Initiative (Dii), both founded in 2009. Desertec Foundation was formed as a non-profit network of scientists, politicians and economists from around the Mediterranean region with a plan to use HVDC to power Europe by Saharan large-scale CSP. Dii was established as an 'international' consortium of companies with the target of converting the Desertec concept into a profitable business[99]. However, as discussed in the report, Desertec project has despite its high ambitions never proceeded past the planning stage. In parallel with the Desertec project, the European Commission has in 2008 called for the construction of regional transmission grids that could eventually be linked into a pan-European supergrid and supply Europe with renewable power generated from the Mediterranean region to the North Sea[100]. The European Network of Transmission System Operators (TSOs) for Electricity (ENTSO-E), an association of 42 TSOs has been given the responsibility to develop a roadmap towards a pan-European grid, known as e- Highway by 2050. Since 2012, the industry association Friends of the Sustainable Grids (FOSG) has been publishing annual reports on the roadmap[101]. FOSG represents the entire supply chain required for construction of a European grid, comprising of TSOs, experts from cable manufacturers, project developers, consultants and logistics companies[102]. More recently, FOSG has been promoting sectoral coupling between the electricity and gas network to improve the system efficiency and increase mutual benefits.

Inspired by the Desertec concept, an Asian version known as the Gobitec Initiative was proposed in September 2009 by academics in Northeast Asia. The Gobitec Initiative triggered an interest in constructing an Asian supergrid, which would connect grids of China, Japan, Korea, Mongolia and possibly Russia (more speculatively Taiwan, Thailand, the Philippines, and India) and transmit wind, solar and hydropower produced electricity from remote areas of Mongolia and Russia to load centres in China, Japan and South Korea. The Asian supergrid was proposed by Son Masayoshi, CEO of Japan's Softbank, in 2012 after the Fukushima disaster. Later the same year, the first agreement was announced with a Mongolian company, Newcom, on developing a giant wind farm in the Gobi Desert that would be connected to the supergrid[103,104]. In 2016, the world's largest electricity utility company, the Chinese State Grid,

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[99] Hamouchene, H., 2015. Desertec: the renewable energy grab?, New Internationalist Magazine, newint.org

[100] Gellings, C.W., 2015. Let´s Build a Global Power Grid, IEEE Spectrum.

[101] Which will be the Supergrid benefits to Europe?, http://www.friendsofthesupergrid.eu/about/faq/

[102] MacLeod, N.e.a., 2015. A Technological Roadmap for the Development of the European Supergrid, Lund, Sweden, https://library.e.abb.com/public/323e5c246dee456c8219f05d9b58ae55/A%20Technological%20Roadmap%20for%20the%20Development%20of%20the%20European%20Supergrid.pdf

[103] Christoffersen, G., 2008. Chinese, Russian, Japanese, and Korean Strategies for Northeast Asian Cross-Border Energy Connectivity. JOINT US-KOREA, 95.

[104] Mathews, J.A., 2012. The Asian Super Grid. The Asia-Pacific Journal 10.

officially joined[105,106]. The Chairman of the Chinese State Grid, Liu Zhenya, publicly supported the Asian supergrid and the Chinese president Xi Jinping proposed an initiative on establishing a Global Energy Interconnection Development and Cooperation Organisation (GEIDCO) to meet global power demand and green alternatives [106,107]

Large-scale grid developments are less popular in North America, especially in the USA, where a historical heritage of local grid infrastructure with multiple ISOs and regulatory structure has hindered upgrades of the U.S. transmission network and the construction of a North American supergrid[108]. A project in this direction is known as 'Tres Amigas', proposed in 2009 with the aim of connecting three separate grids: the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection[109]. In 2015, however, the billion-dollar plan to connect the three grids had failed to meet its milestones due to lack of financing, operational delays and stakeholder conflicts[108,110]. In other parts of the world, such as South America, Australia and Oceania, or Sub-Saharan Africa, few or no actors promote projects aiming at building a cross-border HVDC supergrid.

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L. The European framework[111]

The future energy system will have to rely on advanced balancing capacities, including: improved interconnections on all grid levels, extending pan-European, national electricity grids and connection to neighbouring areas with high renewable potential that would improve the match between supply and demand and unlock the potential of large offshore wind farms (e.g. in the North Sea) or solar energy (e.g. in the south of Europe).

Micro perspective developments:

- Implementing the subsidiarity principle is a prerequisite for a well functioning integrated energy system; the recent clean energy legislation requires that Electricity Markets are created with "active customers/consumers and citizens" and "energy communities". Renewable self-consumers are to be empowered to generate, consume, store, and sell electricity without facing disproportionate burdens, and without liability for any double charge, including network charges, for stored electricity remaining within their premises. Final customers (such as household customers), are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers.
- Communities who participate in large-scale energy community demonstration projects will be able to handle, through proper interaction and validation from network operators, the variability and peaks for their net energy consumption, but also for their net excess energy production in times of high amounts of community-PV infeed. They shall be enabled through smart software solutions for balancing community demand, generation and conversion of different energy carriers (electricity, gas, etc.) to and from locally connected storage.
- Digitalisation will provide better, user-friendly services to all kinds of customers for planning, maintenance and operational issues, fostering information, analytics and connectivity; user-friendly services and products will be offered for the prosumer or community-based energy system.
- Millions of households shall actively participate in real-time, automated demand response (electricity, heating and cooling) with connected appliances and equipment, in addition to the existing and emerging solutions for industry and commerce, through aggregation of smart charging technologies for electric vehicles, stationary batteries, heat pumps and power-to-gas provides controllable electricity loads.
- Easy, reliable, interoperable and scalable solution examples for the cyber-secure or privacy-guaranteeing aggregation of any measured electricity quantity (beyond energy) need to be implemented for any energy community.
- Decentralised control techniques and peer-to-peer electricity trade permeates local energy communities and their interconnection to the electricity system. Shared platforms facilitate data exchange and decision-making in all parts of the integrated energy systems, thus enabling advanced planning, operation, protection, control and automation of the energy systems. Shared platforms shall be realised for the most sensitive electricity system related integration needs (for data and for decision making) such as smart metering active and reactive power, voltage magnitude, network topology and model parameters, device power, thermal and other limits, o sub-system reliability and resilience parameters, o user decision-related parameters (service options and energy prices) and bidding possibilities.

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[111] ETIP SNET Vision 2050

Mega perspective developments

- At same time, EC is encouraging more interconnections in order to foster the internal energy market and possibly extend to neighbouring countries in the South (see MedTSO initiative) and Esat (Energy Community).
- Substantial financial support is given through several funding programs, among which TEN-E for feasibility studies and CEF for realisation phase, to projects labelled as Projects of Common Interest (PCI) after a selection & assessment procedure part of TYNDP elaboration.

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