Protection, Automation & Control World Americas, Raleigh, NC, USA 2014

An International Review of the Development of Technologies for Smart Grid

Carl Ohlen (1), Kjetil Uhlen (2)
STRI (1), NTNU (2)
Carl.ohlen @stri.se

Sweden, Norway

INTRODUCTION

Flexible and resilient electricity systems are vital to the deployment and integration of many clean energy technologies. Electricity networks worldwide are under increasing stress, because the sources and uses of electric power are becoming progressively more varied and complex. A growing amount of variable renewable energy generation, coupled with increasing consumer involvement through micro generation and flexible demand management, challenge the old ways of planning, operating, and investing in power systems. In most developed countries, the existing electric infrastructure and workforce is rapidly aging, while in many developing countries, demand for electricity is rapidly rising. Across this landscape of change, it is crucial for policy-makers to understand the synergies between grids and information and communication technologies. Only smart and strong grids will connect people with reliable clean energy. This paper presents a part of the work being done within ISGAN Annex 6 on Power T&D Systems. International Smart Grid Action Network (ISGAN) is an initiative within the Clean Energy Ministerial (CEM) and an Implementing Agreement within the International Energy Agency (IEA). For more information please go to www.iea-isgan.org, or www.cleanenergyministerial.org/Our-Work/Initiatives/Smart-Grid.

This work involves the major economies and consequently major energy users in the world and is addressing the challenges for a secure and clean energy system including the concerns put forward by Intergovernmental Panel on Climate Change (IPCC). IEA publish regularly the reports World Energy Outlook (WEO) and Energy Technology Perspectives (ETP). In addition IEA has published a number of Technology Roadmaps, e.g. on Smart Grids, Wind Energy, Concentrating Solar Power (CSP), Solar PV Energy and Energy Storage. All scenarios showed by IEA are indicating a further increase of electricity as energy carrier both due to the integration of Renewable Energy Sources (RES) and due to increased electricity consumption in many countries, besides common applications also due to increased use of home electronics, heat pumps, air conditioning and electrical transportation (e.g. electrical vehicles, high speed trains). Increased variable electricity production (large scale and distributed) will require mitigation from storage and/or demand response. This will give further demands for capacity, flexibility and reliability of the future power T&D system.

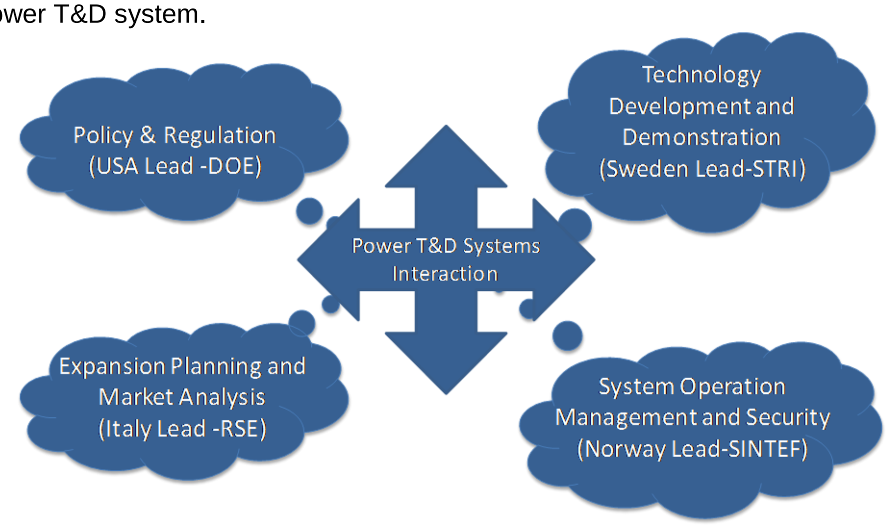

Figure 1 ISGAN Annex 6 Power T&D Systems with main tasks

The main objective of ISGAN Annex 6 is to establish a long term vision for the development of “Smarter and Stronger Power T&D Systems”. The Annex consists of efforts to improve understanding of Smart Grid technologies applicable to or influencing system performance, transmission capacities and operating practices; accelerate their development and deployment; and promote adoption of related enabling regulatory and government policies. The work has an integrated holistic system view including regulation, market, technology and operation initially focusing on power transmission system which later has been expanded to interaction between transmission and distribution.

This work has included several international workshops and meetings as well as involvement in other related international initiatives which are documented in a large number of internal reports as well as in technology brief and discussion papers available on ISGAN website. The published technology brief summarizes the vision for this work: “To create a seamless cost-effective electricity system, from generation to end use, capable of meeting all energy demand and capacity requirements, while allowing consumer participation and electricity use as desired.” This work has the ambition to bring together different influencing developments to a system view in order to support the understanding and process to plan and deploy necessary longer teem actions.

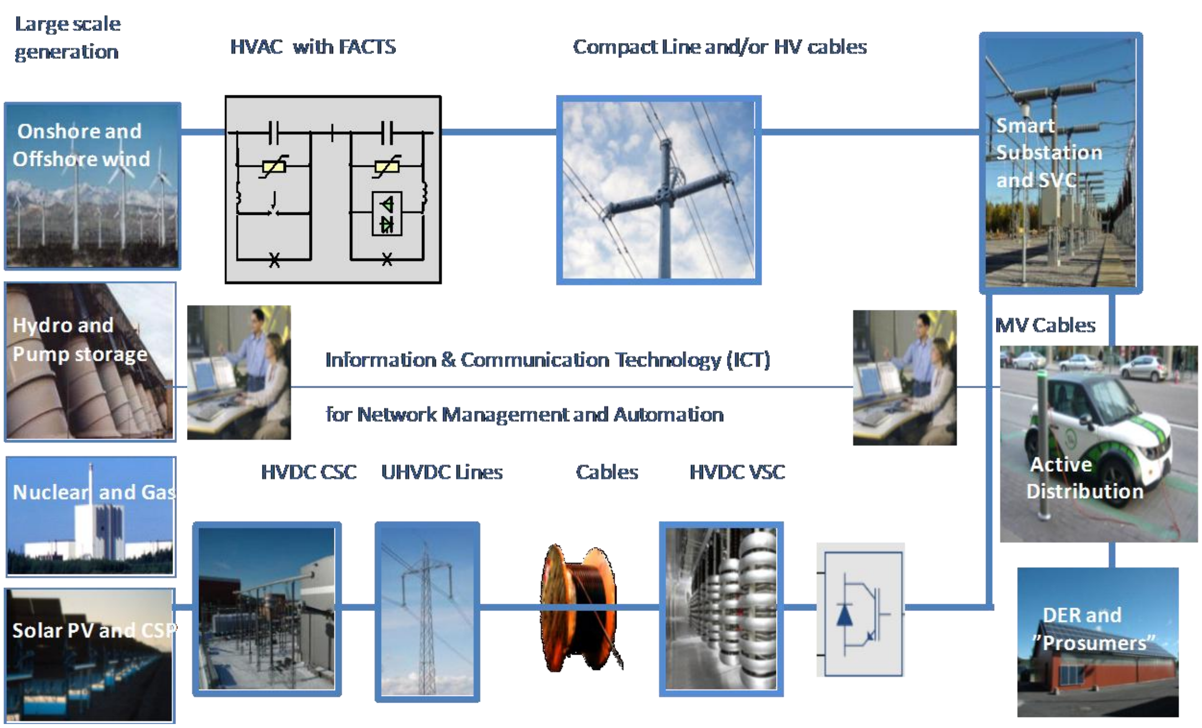

Figure 2 Main parts of the Smarter and Stronger Grid

Figure 2 illustrates the main parts of the smarter and stronger grid. Participating governments in ISGAN include 25 countries from five continents demonstrating there is not one Smart Grid suitable for all. There is however an evolving tool box to design and operate smarter and stronger grids. Since so many countries are participating in the ISGAN work the activities focus on real case studies for knowledge sharing. This is available on the ISGAN website, e.g. “Spotlight on Advanced Metering Infrastructure” and “Spotlight on Demand Side Management”. CEM has published “Global EV Outlook” and “EV City Casebook” describing the deployment of Electrical Vehicles. While the speed and scope of integration of distributed solar PV together with EV as well as AMI and demand response differs between countries and market models there are more common challenges for the transmission grid and the power system as a whole. Technology for HVAC, HVDC and ICT is ready for large scale demonstration and deployment. The main challenge is efficient integration including:

-Sustainable regulation and financing allowing long term planning and faster implementation
-Adoption of standards for system wide interoperability (e.g. IEC 61850, CIM, HVDC Grid)
-Holistic system design and operation tools with “MMORPG” competence and awareness

Therefore the way forward is varying also for transmission. Depending on type of generation and distances between generation and load the selection of technology will vary. Depending on how the electricity market, responsibility and ownership are organized the expansion planning will be different.

A GLOBAL POWER SYSTEM VIEW

The global energy system is based on fossil fuels. The global consumption of fossil fuels has increased five times during the last 60 years causing the increase of carbon dioxide emission. This is also the case for electricity generation. Most studies are predicting a significant increase of electricity generation from RES although some countries are investing in generation from nuclear energy and gas which could be other clean sources of energy providing the nuclear security and waste issues as well as the Carbon Capture and Storage (CCS) are resolved. Consequently there is not one energy road map forward but a number of scenarios. The energy mix and the per capita consumption vary today significantly between different countries which are illustrated in figure below.

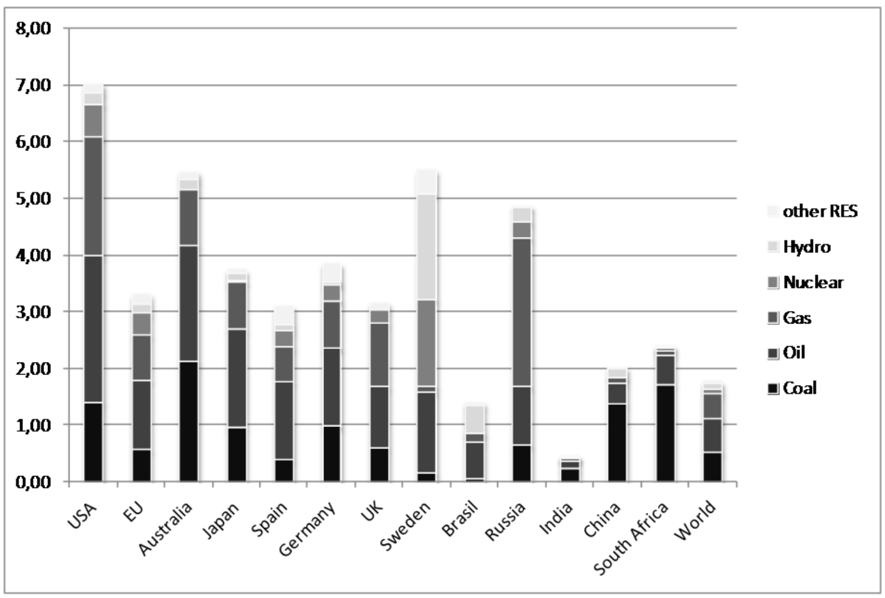

Figure 3 Per capita energy consumption in ton oil eq. (Based on BP Statistical Review 2012)

Despite of a rapid growth of solar and wind power generation in many countries this still represents less than 2% of total world energy consumption. With hydro power included this figure would still be less than 10% according to the calculation method used by BP Statistical Review for commercial energy supply. (Please note that BP, IEA, EIA and EU use different definitions and may slightly differ) EU 2020 goals include a 20% RES target for 2020, up from 13% 2011. This is distributed differently to the different EU member states. As an example Sweden should increase from 47% 2011 to 49% 2020 while UK should increase from 4% to 15% in order to reach the overall 20% for EU. Germany should increase from 12% to 18% but after the decision to close down nuclear power plants this share will be significant higher in the future. Sweden did 2012 reach 51% and EU 14%. Since 1990 the electricity share of total energy consumption has increased as seen in figure 4. In EU and USA the electricity consumption has increased while total energy consumption has decreased per capita. More RES will further increase the electricity share of total energy. The European Commission 2050 road map indicates that the electricity share for EU could be 35 to 40% by 2050. The electricity consumption of electricity is increasing globally and especially in China as seen in figure 5 who has a higher electricity consumption than U.S. and EU. In about ten years China has built a power system comparable with the total European power system.

	Year	Oil	Gas	Coal	Electricity	Other	Total	% EL
USA	**1990**	31 764	14 085	2 564	10 529	1 189	**60 130**	**17,5%**
	2011	27 821	12 166	915	12 134	2 945	**55 980**	**21,7%**
EU-27	**1990**	12 285	5 520	3 018	4 549	2 280	**27 652**	**16,5%**
	2011	11 206	5 766	930	5 499	3 018	**26 419**	**20,8%**
China	**1990**	867	91	3 262	400	2 186	**6 805**	**5,9%**
	2011	3 458	618	4 784	2 874	2 410	**14 145**	**20,3%**
India	**1990**	700	75	556	242	1 776	**3 350**	**7,2%**
	2011	1 325	2 769	803	623	1 616	**4 614**	**13,5%**
Central and South America	**1990**	4 178	828	222	1 162	2 175	**8 564**	**13,6%**
	2011	5 388	1 690	311	1 900	2 302	**11 591**	**16,4%**
World	**1990**	5 735	2 076	1 694	1 832	2 501	**13 838**	**13,2%**
	2011	6 073	2 307	1 510	2 644	2 370	**14 905**	**17,7%**

Figure 4 Per capita energy consumption in MWh and electricity share (Based on IEA statistics 2013)

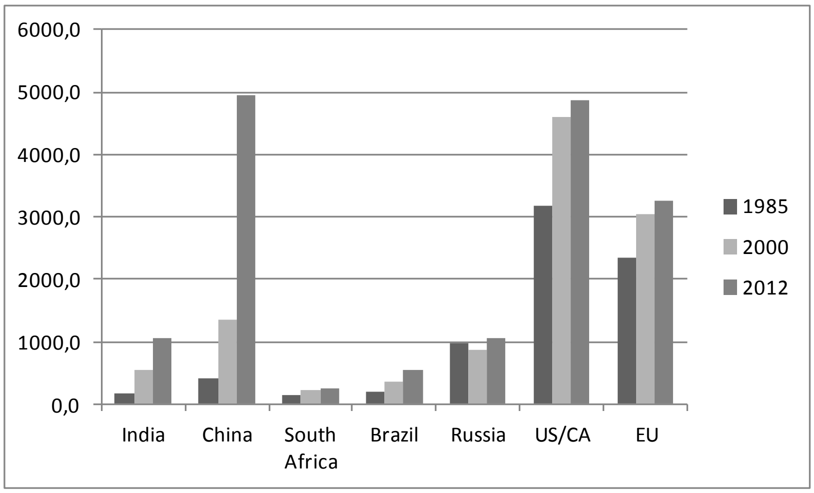

Figure 5 Electricity consumption in TWh (Based on BP Statistical Review 2012)

Development in U.S.

Although U.S. and EU have older power systems with similarities they still represent different models. The ISGAN Discussion Paper FLEXIBLE POWER DELIVERY SYSTEMS gives an Overview of Policies and Regulations and Expansion Planning and Market Analysis for the United States and Europe which illustrates the main differences and common challenges. The United States (U.S.) "grid" is a highly complex and dynamic system that operates in connection with Canada and Mexico (together comprising the North American grid). The U.S. electric system comprises three electrically independent networks—the Eastern, Western, and Electric Reliability Council of Texas (ERCOT) Interconnections—that are connected via direct current (DC) links. This system is further divided into over 140 control areas responsible for balancing generation and consumption of electricity at all times. The U.S. electric system has no linear or singular operational or management structure.

In the U.S., electricity markets and the electricity industry broadly have been undergoing major paradigm shifts over the past few decades. The introduction of open transmission access and restructured electricity markets in the 1990s has led to fundamental changes in ownership structures and planning and operational responsibilities. Because of the national scope of these issues, regional planning and cooperation among all levels of government and interested stakeholders have been encouraged by federal entities, including the U.S. Department of Energy (DOE) and the U.S. Federal Energy Regulatory Commission (FERC). One recent example of this is the DOE-funded Interconnection Wide Transmission Planning process in which five grantee-organizations within the three North American Interconnections in the U.S. have worked to analyze how best to approach the planning and build-out of their transmission systems moving forward.

Since the 1990s, changes across markets, technologies, and policies in the electric grid "space" have driven towards milestones and influenced further policies and market changes. The ISGAN discussion paper illustrates this historical development as well as the future vision by two figures from U.S. Department of Energy, "Plugging America Into Clean Energy: Future Needs of the Electricity Grid" (presented at Grid Tech Team Workshop, November 15, 2011).

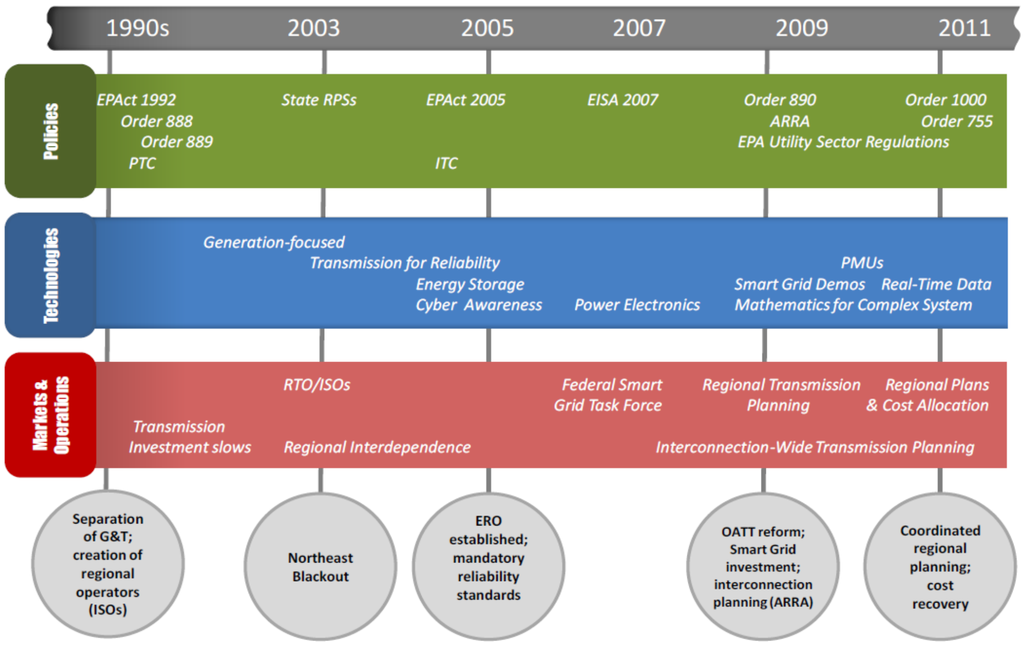

Figure 6 Historical grid investment drivers over time in U.S. (DOE/ISGAN)

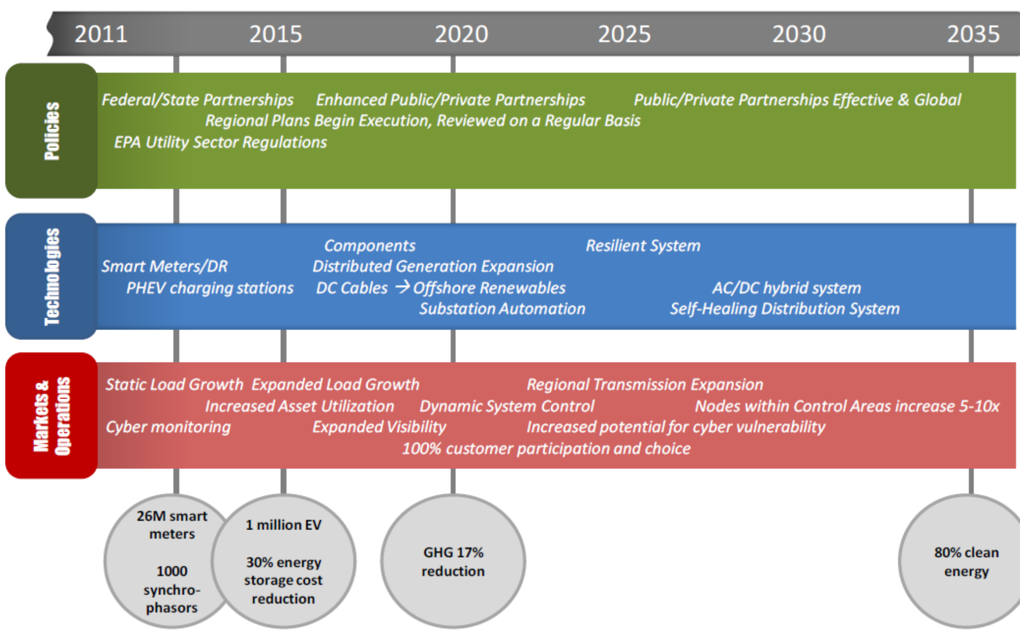

Figure 7 Targets and direction moving forward in grid space (DOE/ISGAN)

Development in Europe

Power transmission in Europe is characterized by a high degree of interconnections and inter-area power exchanges, congestion, volatility, and diversity of operating conditions. The power system is subject to the thrust of pan-European market integration and the need to face the variability of renewables such as wind and solar from a system-wide approach, while guaranteeing reliability of supply. The European grid comprises five synchronous areas, 34 countries, and 41 transmission system operators (TSOs).

In recent years, electric power systems have been experiencing profound transformations. In the European Union (EU), issues concerning security of energy supply, electricity market restructuring, and environmental constraints represent key drivers for new trends that may have significant impact on the design and operation of the electric power system; this is particularly true for the transmission system. Moreover, and most critically, the European energy sector has been deeply changing as the EU member states decided in 2007 to lay down ambitious environmental targets to be achieved by 2020. Through these efforts, the European electric grids are on a critical path to meet the EU's climate change and energy policy objectives for 2020 and beyond.

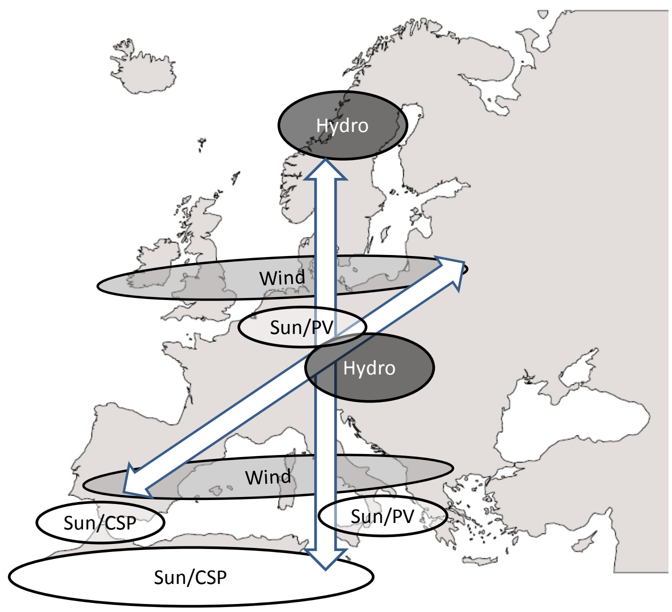

Figure 8 Power flow through Europe (Based on EC DG Energy vision)

Although each member state is responsible for each local power system the coordination within EU is more and more important. In view of fostering cooperation and harmonization in transmission planning and operation, as well as the dialogue between TSOs and institutions (primarily the European Commission (EC) and the regulating bodies), the EC promoted the creation of the European Network of Transmission System Operators for Electricity (ENTSO-E), the body of TSOs at the European level. An important contribution to the identification of common development according to EU objectives was given by the first (pilot) ENTSO-E Ten-Year Network Development Plan (TYNDP) 2010–2020, issued in 2010, extended then in 2012, and to be updated every two years thereafter. A common European electricity market is beside integration of renewable an important driver. As an example EC DG Energy proposes through Agency for the Cooperation of Energy Regulators (ACER) common network codes. Ten are in process and three are in a more advanced approval stage; Requirements for Generators (RfG), Demand Connection Code (DCC) and Capacity Allocation and Congestion Management (CACM).

The major challenges of transmission system operation in Europe are due to the extension of the electricity market and to the integration of large amounts of renewables, in particular wind and photovoltaic (PV), and DG. As security limits are tested, jurisdictional issues may prevent optimal decisions from being implemented. For example, the technology and control strategies of DG inherently modify the dynamics of the power system, possibly causing stability problems. Overall, increased TSO/distribution system operator (DSO) coordination is needed, with changes on both the technical and regulatory sides.

As seen in figure 8 the power flow through Europe will change significantly depending on what is generated when and where. This requires a more flexible transmission system which can handle much higher capacity compared to today. This includes the integration of offshore wind and is furthermore driven by the closing of the German nuclear power plants. In an EU directive each country shall develop a ten year plan for the transmission system which is the base for ENSTO-E ten year plan indicating more than 100 Billion Euro as projects of common interest. The Swedish and Norwegian TSO has each increased investments from a level of 100 million USD per year to almost 1 Billion USD per year for transmission. This includes uprating of the Norwegian 300 kV to 400 kV, modernization of substations and several HVDC links.

The 3E offshore study from 2011 estimates a potential offshore wind capacity of 150 GW 2030 mainly in Northern Europe. These plans are further developed within North Sea Countries Offshore Grid Initiative (NSCOGI). Friends of the Super Grid estimates that the transmission capacity through Europe has to increase from 34 GW to 127 GW if demand response is implemented and to 166 GW without demand response. Hydro power and pump storage will play an increased role to balance wind and solar power. For this reason a “Super Grid” or “Highway” has been discussed in Europe. The e-Highway2050 project is supported by the EU and is aimed at developing a methodology to support the planning of the Pan-European Transmission Network, focusing on 2020 to 2050, to ensure the reliable delivery of renewable electricity and pan-European market integration.

DRIVERS AND TRENDS

This paper is based on this ISGAN work and especially the first Discussion Paper from ISGAN Annex 6 SMARTER & STRONGER POWER TRANSMISSION: A Review of Feasible Technologies for Enhanced Capacity and Flexibility in terms of status and deployment. This includes both the primary AC and DC technology for the high voltage transmission grid as well as the information and communication technology (ICT) required efficiently supervising and operating the power system. Focus is on the development of power electronics including flexible AC transmission (FACTS) and high voltage DC (HVDC), the standardization within ICT such as IEC 61850 and Common Information Model (CIM) in order to obtain vendor independent interoperability and the progress of wide area monitoring, protection and control (WAMPAC). The combination of smarter ICT applications together with power electronics such as FACTS and HVDC can be described as a digitalization of the power system operation offering the required flexibility.

Protection and Control (PAC) has always been essential for power system reliability. However what we call “relays” are now multifunction IEDs, Intelligent Electronic Devices and the foundation of Smart Grid. It is here the real time information is collected and the fast protection and control commands are executed but the same accurate information is needed for new applications. The rapid development of ICT has empowered PAC but has also created new challenges. Protection and Control can no longer be seen as an isolated island but a system of systems in a Big Data Cyber Space. This paper describes these challenges and development such as interoperability and cyber security for the “Digital Substation” and the development of WAMPAC for the “Digital Power System”.

Future power systems will undergo a shift in paradigm brought forward by changes in electric power generation and increasing flexibility in consumption. The main points of our vision for the future smart grid are summarised below.

Drivers: The top drivers for power system evolution and development, stated at the political and economical level, are similar throughout the western countries. They have been summarised by the EC by the keywords:

•Sustainability. Power generation must rely more and more on renewables (also to reduce the dependence on fossil fuels) and low carbon technologies

•Competitiveness. The establishment of large power marketplaces is seen as a major driver for increased social welfare

•Security of supply. The above requirements must not affect electricity reliability, either due to power system operational problems or to fuel supply shortage

In the US similar objectives are pursued. In particular, climate change legislation initiatives are fostering significant increase in renewable generation.

Paradigm shift: According to the above basic drivers a paradigm shift will take place, characterised by the following features:

•Variable generation, such as wind power and solar, will constitute a main part of what could be called the base power generation. This is a consequence of the increasing penetration and large scale integration of variable renewable energy sources and distributed generation.

•Fossil fuel generation, on the other hand, and other sources that were previously referred to as "conventional" generation will have a less dominant role, and to a larger degree these will become peaking units that are necessary for balancing purposes.

•Power will flow across wide geographic areas to a far greater extent than today. This is a consequence of both the market requirements, and of the characteristics of the variable renewable generation. The former is aimed to guarantee that cheap generation can be accommodated on a wide area marketplace (e.g. whole Europe), to supply the load; the latter descend from the variability of the wind and solar sources.

•There will be an increasing need for power transmission capacity and, possibly, for energy storage as the value of power exchange increases, both related to bulk transmission and for shorter term power balancing purposes.

•Large capacity (multi-GW) connections will become more common. This is needed both to strengthen the existing networks, and to accommodate more power exchange between the present interconnected power systems. New high capacity networks are also needed to transfer and exchange power from large offshore and other remote wind farms to consumption areas

•Operational security will be guaranteed under very different circumstances, and in different ways from today's practice. New transmission and ICT technologies will play a role. Customer supply will no longer be a "must" requirement under all circumstances, as it was in the past.

•Transmission planning and operation will be coordinated over wide-area within new technical, organisational, market, and regulatory solutions.

Challenges: The above vision implies several high-level technical challenges which can be summarised as follows:

•Allow secure transmission of power generated in remote locations (where variable renewable resources are available) to the bulk power system and load centres; keep stability of operation of the interconnected system even with large amounts of remote generation. Large scale wind is remote and variable. PV is not necessarily remote but it is extremely variable.

•Cope with the variability, uncertainty, and volatility of the operating conditions leading to very diverse and rapidly changing generation and power flow patterns, caused by variable generation and market-based dispatch. In particular, manage the variability with proper technical and economic solutions, avoiding:

o Periods of generation surplus and risk of negative prices

o (Longer) periods of low wind and lack of production capacity

•Cope with the increased interdependence (on a wide-area scale) of the interconnected power system, avoiding the risk of widespread disturbances.

•Keep the current reliability levels. The development herein anticipated will challenge present security standards such as the deterministic N-1 criterion. It will not always be possible to maintain N-1 security as applied today without additional system protection solutions. In other circumstances the N-1 criterion may not provide sufficient security, and there should be a push towards development and application of additional risk based security standards.

The above challenges require both technical and organisational answers as illustrated in figure below. RES with lower capacity factor but also reserve capacity from gas will require much higher power capacity of the transmission system for certain periods with fluctuation also of power flow direction. Flexible Line Management (FLM) for dynamic loading in addition to more lines and other measures will be needed.

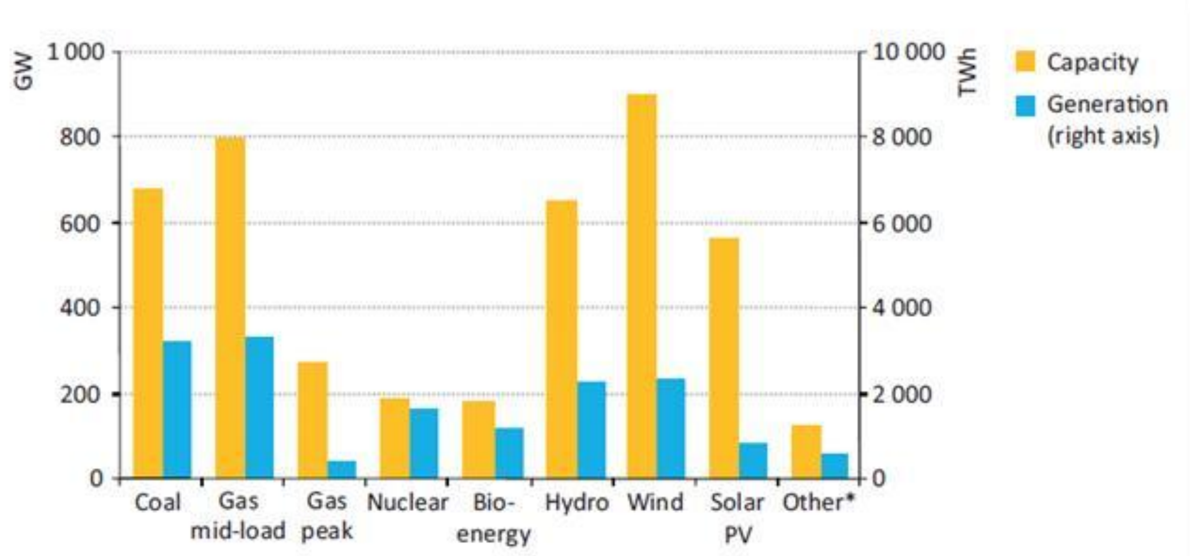

Figure 9 Global Power Capacity (GW) and Energy (TWh) additions until 2035 (IEA)

DEVELOPMENT & APPLICATION OF KEY TECHNOLOGIES

Given the reality that a major part of power production is now unpredictable, that both production and demand are dispersed, and that the magnitude and speed of variations for either is substantially increased, there is an urgent need for a wide area system approach and for the tools and controllable devices that are capable of balancing active power and reactive power. The world needs an integrated energy system in which each part interacts with all other parts in real time. This can be achieved by combining advances in power electronics with those in ICT for monitoring, protection and control.

In both AC and DC lines, power electronics using thyristors and transistors for high power applications offers more advanced options for flexibility and controllability such as FACTS and HVDC. Because reactive power cannot be transmitted across significant distances without excessive voltage or energy losses, managing its balance is more localized. Devices for reactive compensation and voltage control can be distributed throughout the power system, as in done in modern wind generators. Still this need to be coordinated with larger FACTS devices for series compensation as well as SVC and STATCOM.

Investments in smart power T&D infrastructure incuding both high voltage equipment and ICT are essential to enable an efficient global clean energy society. The increased electrification and growing complexity of supply and demand requires a holistic system approach for power T&D development – with connected supply and demand – for the following three reasons:

- The electric power system is ONE interacting system in which supply and demand have to be continuously balanced at every moment to maintain voltage and frequency within strict limits. This requires increased knowledge and supervision of system behavior and wide area implementation of ICT for monitoring, protection, control, automation and visualization, together with increased flexibility from power electronics such as FACTS and HVDC.
- The increased share from variable RES of total installed power, which can change generation instantaneously, creates a paradigm shift for power system operation with basically unpredictable and

rapidly fluctuating conditions requiring instantaneous system-wide compensation and balancing of frequency and voltage.

- With more small-scale solar, wind and hydro power as distributed generation and customer participation through demand response (sometimes in combination as “Prosumers”), the interaction among T&D systems will increase substantially.

A holistic system will require even more advanced, accurate and fast applications. Within a sound business management system (BMS), supervisory control and data acquisition (SCADA) will enable better, automated management of energy, assets, distribution and demand-side activities as well as substation automation. This complex interdependence raises one of the most critical issues: i.e. the urgent need for interoperability among different components and “systems of systems” from diverse vendors that need to “talk” to each other within the “digital power system”. Wide Area Monitoring, Protection and Contol (WAMPAC) will involve all major utilities in an interconnected power system. Integrated Network Information Systems (NIS) with mapping, work order and maintenance management are available. This is what can be compared with what is called Massively multiplayer online role-playing game (MMORPG) when multiple players with different roles will interact in a large energy game.

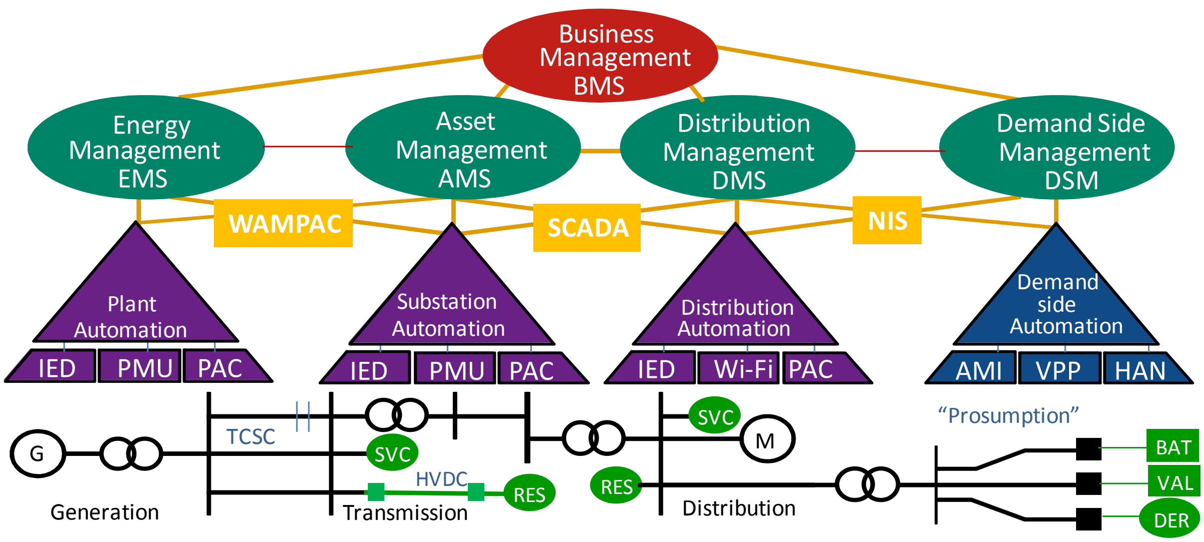

Figure 10 The Digital Power System

The basis for this digital power system is the information exchange with the primary equipment with intrument transformers and breakers through the old « relays » for protection and control (PAC) now also called intelligent electronic devices (IED) with new advanced performance such as Phasor Measurement Units (PMU). Other TLW such as automatic metering infrstructure (AMI), virtual power plants (VPP) and home automation networks (HAN) will add more information and control possibilities to be communicated with higher levels. Real time operation and automation with exchange of data between many devices and operators with different roles will create a need for an overall system view. Cyber security threats and a larger dependence on GPS will create new risks to be mitigated.

The level of interoperability needed in the digital power system will in turn require ongoing development and implementation of standards by dedicated organizations such as IEC, CENELEC and NIST. Such standards should allow the interchange of data while also ensuring cyber security. This will require cooperation among different stakeholders, planning and especially work-force empowerment through training and testing. Traditional skills in power engineering will need to be enhanced with new skills in ICT engineering. The implementation of new technology will drive the change and will affect the work force within the power T&D segment. Change management will be an essential part of the successful implementation of the digital power system in order to prepare the work force with necessary training.

HVAC and HVDC Power Electronics

The higher the voltage the lower the relative losses will be for AC and DC. This is illustrated in the figure below with increasing system voltage.

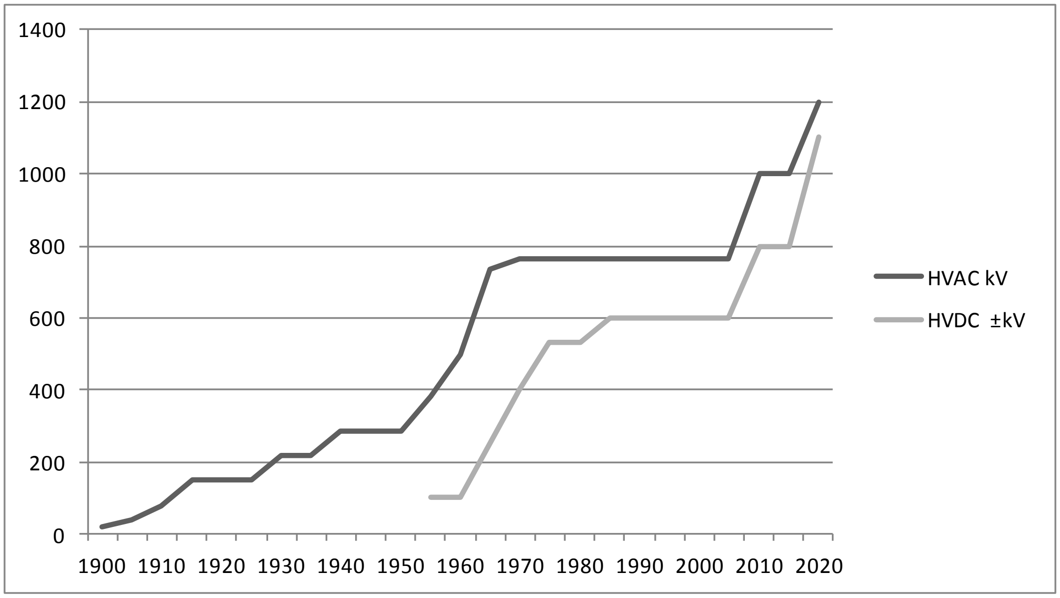

Figure 11 Development of voltages

The world´s first 400 kV transmission line in Sweden 1952 was the start for EHV and UHV applications. HQ in Canada increased to 735 kV 1965 and AEP in U.S. to 765 kV. The first seriescompensated EHV line (400 kV) and the the first HVDC cable in the world for commercial power transmission was put in service 1954 in Sweden. After a slow start these technologies spread to other countries with similar applications. The interies with long distance seriescompensation and HVDC became important technologies for BPA and HQ. Furnas in Brazil installed the first 765 kV seriescompensation and the first HVDC for +/- 600 kV during the 1980s. AEP tested a 2 million volt UHV transformers 1976 and former USSR built a 1150 kV line 1985 but since these are not in operation they are excluded from the figure above. Today the UHV development is mainly focusing on applications in Brazil, China and India.

Figure 12 Testing of UHVDC 800 kV for China and India and 1100 kV UHVAC GIS for China (STRI)

On behalf of ABB a long term test of the first UHVDC at +/-850 to +/-1050 kV as well as test on 1100 kV rated GIS was performed by STRI. STRI also performed dielectric and pollution tests for +/- 800 kV UHVDC insulators from three different manufacturers for applications in India and China.

Series compensation and HVDC as such are mature technologies which have been used for transmission of power over long distances on land or by long cables at sea. Today we have renamed reactive compensation to Flexible AC Transmission (FACTS) including series and shunt compensation which since long are used in many power systems. The further development of Power Electronics for FACTS and HVDC, has introduced new methods for new applications to create the Strong and Smart Power System. The figure below gives a summary of available technologies.

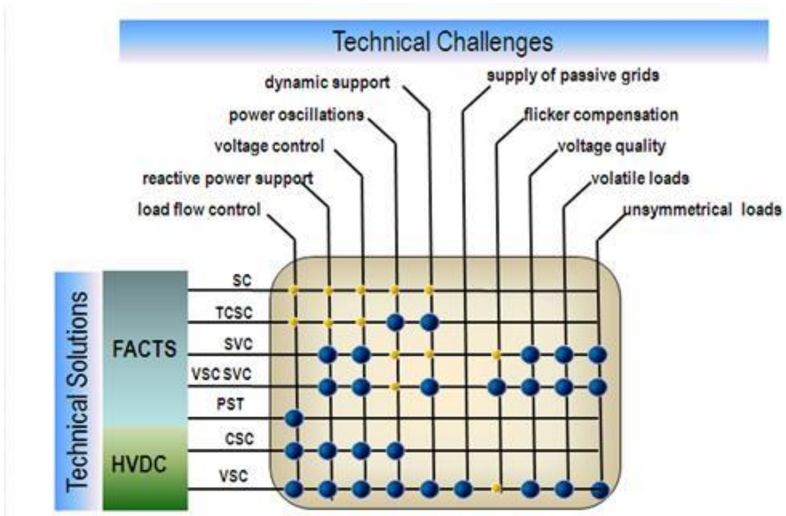

Figure 13 Available options for FACTS and HVDC (ABB)

The main reason for FACTS, UHVAC and UHVDC systems is to increase the transmission capacity over long distances. This is especially seen in China which is right now building up a UHVAC and UHVDC super grid capable to transmit hydro, wind and coal fueled power over very long distances from the west to the populated eastern China. The basic technology for the China Super Grid is shown in below figure.

Transmission	Voltage/current	Economical transfer capacity	Transmission distance
AC	500kV	1000MW	300~500km
AC	1000kV	5000MW	1000~2000km
DC	±500kV	3000MW	500~1500km
DC	±800kV/5000A	8000MW	1000~2000km
DC	±800kV/6250A	10000MW	1000~2000km
DC	±1100kV/5000A	11000MW	1500~3000km

Figure 14 UHVAC and UHVDC technologies in China (C-EPRI)

In July 2010, the Xiangjiaba - Shanghai transmission was the first UHVDC (Ultra High Voltage Direct Current) project to go into commercial operation in the world. State Grid Corporation of China (SGCC) is the owner and ABB was the main technology supplier. Now several UHVDC projects are in operation and under construction. While the first UHVDC and UHVAC installations were supplied by ABB and Siemens, China now has own resources for this technology. China State Power Grid which is one of the world´s largest corporations is together with China EPRI supplying HVDC projects for China and for export. Also India is building up a super grid from an 800 kV UHVAC ring supplemented by 800 kV UHVDC and a planned 1200 kV UHVAC system. The ±800 kV North-East Agra UHVDC link is supplied by ABB with a record 8,000 MW converter capacity, including a 2,000 MW redundancy, to transmit clean hydroelectric power from the north-eastern and eastern region of India to the city of Agra across a distance of 1,728 kilometers. The figure below shows installed and planned HVDC capacity. China had 6% of global installed HVDC capacity year 2000 which has increased to 33% 2012 and is expected to be 50% 2020.

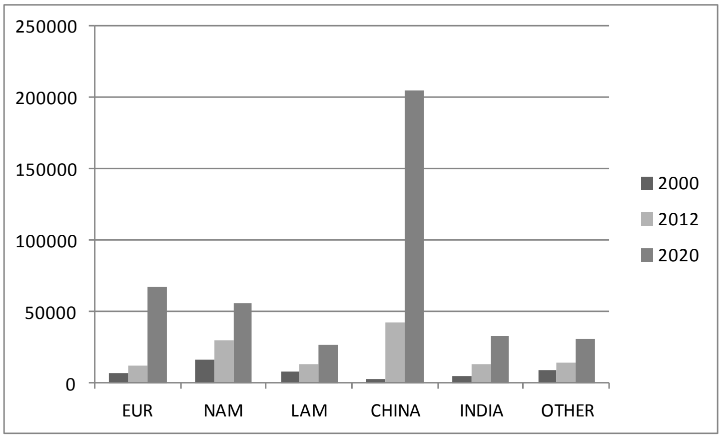

Figure 15 Installed HVDC in GW up to 2012 with plans for 2020.

While HVDC classic solutions with thyristors operating as Current Source Converters (CSC) have long experience from several manufacturers and users, the HVDC Voltage Source Converters (VSC) with transistors has more limited experience. The HVDC VSC was first tested by ABB 1997 in a full scale application outside Ludvika in Sweden and 1999 installed at the island of Gotland to connect wind power. Although the operational experience is limited to mainly ABB's HVDC Light the company has delivered 13 of the 14 commissioned VSC links in the world there are many projects being built, including offshore projects, by all three major manufacturers (ABB, Alstom, Siemens) with slightly different technology. In addition HVDC VSC has been developed and tested in China where three projects are planned including two with multi-terminal design.

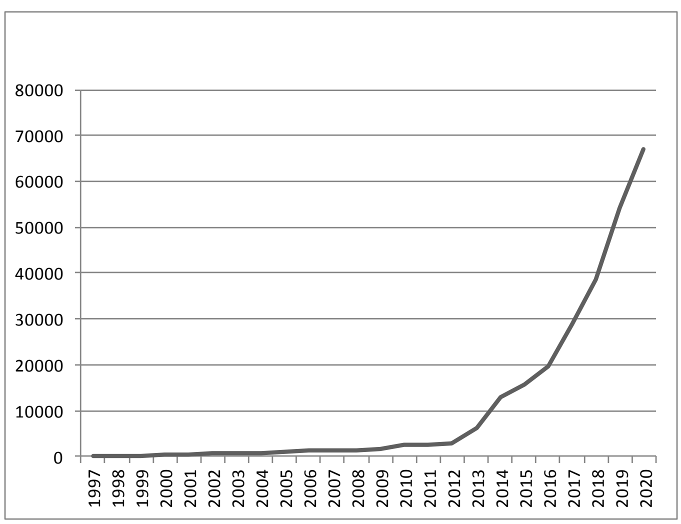

Figure 16 Installed HVDC VSC in MW up to 2012 with plans for 2020.

HVDC VSC has many advantages compared to HVDC VSC as indicated in figure 13 and one is the possibility to design DC grids. This would require fast fault clearing capability similar to and even faster than for HVAC systems. ABB has presented the design of a hybrid DC breaker which can operate in a few milliseconds. However the possibility of a DC grid raises here the question of interoperability between different manufacturers and how to design reliable and selective protection systems as well as efficient control. CIGRE and CENELEC are now working on these issues. The CIGRE work covers protection and control of DC grids which is a fundamental issue. Offshore HVDC transmission for wind farms represents huge investments requiring very high reliability and availability. At the same time, the consequences of a failure could be severe. There is a need to verify equipment and systems and also manage the risk. Therefore, an ongoing Joint Industry Project by DNV KEMA & STRI, with major stakeholders for the North Sea and Baltic Sea wind farm deployment, is working on this in parallel with the ongoing work on recommendations and standards within CIGRE and CENELEC.

When connecting the offshore wind farms to land, either with HVAC or HVDC, the onshore transmission grid has to be strengthened. In addition, introduction of onshore wind and solar generation requires enhanced transmission to handle the variation. This is very well described for Europe in the latest ENTSO-E ten year plan (TYNDP 2012). Besides the construction of new lines, a greater use of FACTS and HVDC offers solutions to increase flexibility and power transmission capacity in the existing transmission grid. The use of existing corridors and the conversion of existing transmission lines from AC to DC are being studied in Europe and the U.S. By converting an existing AC line to DC, it is possible to significantly increase the power transfer and by using HVDC VSC technology also enhance the flexibility. Finally, the planned increase of Concentrated Solar Plants in "the sun belt" would often need HVDC transmission to deliver the power to consumption regions. This includes the EUMENA DESERTEC vision of harvesting sun in Sahara to export to Europe, the Middle East and the rest of Africa. During the day, a small area of desert would suffice to produce all necessary energy.

Information and Communication Technology

With the greater application of ICT to handle the increased and faster communication flow between a larger number of actors in the Power System, there is now a common understanding of the need for standardization and interoperability of the ICT products and "systems of systems". This is handled globally within IEC as well as within CENELEC (Europe), NIST (USA) and other National or International organizations. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0 is structured in domain interconnected with electrical flows of energy as well as secure communication flows of information and commands. Version 2.0 was released in February 2012 and a Smart Grid Interoperability Panel (SGIP) has been created.

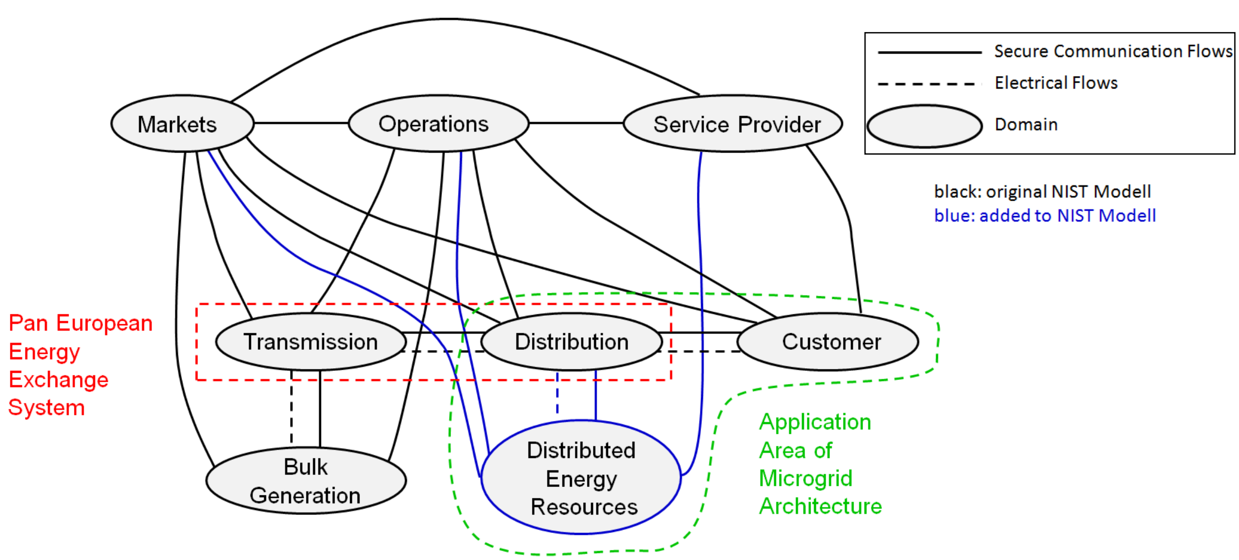

Figure 17 Smart Grid Architecture Model (CENELEC).

In December 2012, a set of comprehensive documents were published, provided by the CEN-CENELEC-ETSI Smart Grid Coordination Group (SG-CG), being responsible for coordinating the ESOs reply to M/490 (Mandate). This includes a Smart Grid Architecture Model (SGAM) which is an adaption of the NIST conceptual model for Europe extended with Distributed Energy Resources (DER) as well as a first set of proposed standards.

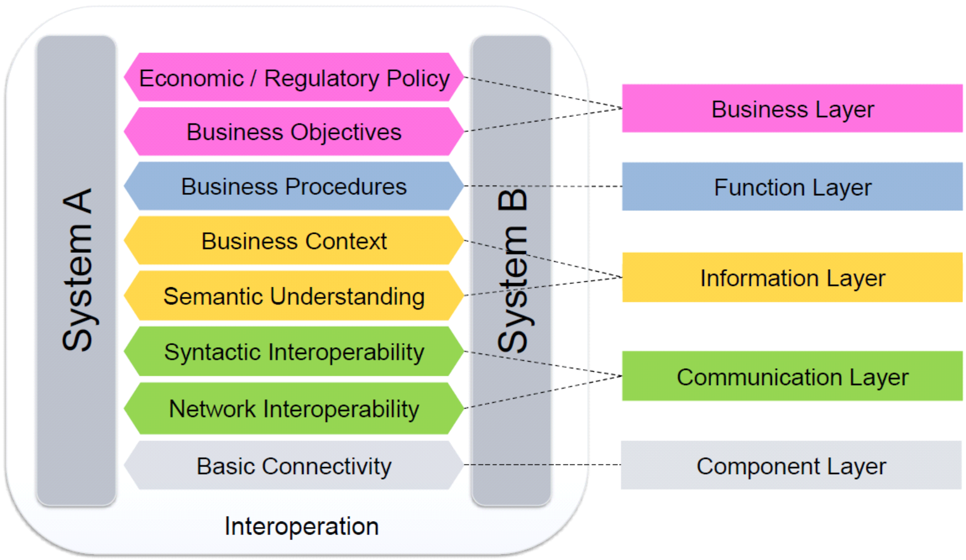

Figure 18 Grouping into interoperability layers (CENELEC).

Interoperability is seen as the key enabler of Smart Grid. Consequently, the proposed SGAM framework needs to inherently address interoperability. To understand interoperability in the context of Smart Grid and architectural models, a definition is given together with requirements for achieving interoperability.
IEC 61850 describes interoperability as “the ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct cooperation”. In other words, two or more systems (devices or components) are interoperable if they are able to cooperatively perform a specific function by exchanging information.

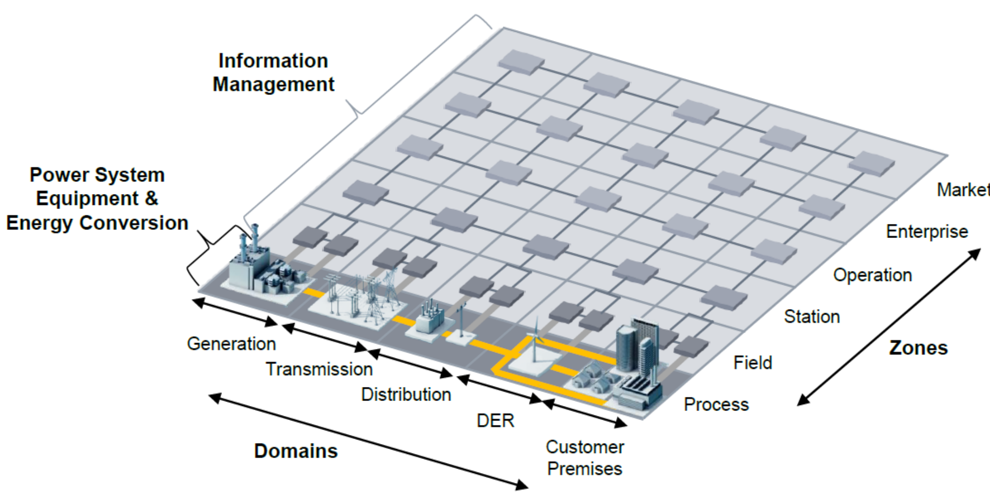

Figure 19 Smart Grid plane - domains and hierarchical zones (CENELEC).

The Smart Grid Architecture Model (SGAM) Framework consists of the five interoperability layers allowing the representation of entities and their relationships in the context of Smart Grid domains, information management hierarchies and in consideration of interoperability aspects.

Layer	Standard	Comments
Information	EN 61850-7-4 EN 61850-7-3 EN 61850-7-2 EN 61850-6	Core Information model and language for the IEC/EN 61850 series
Information	EN 61850-7-410	Hydro power plants
Information	EN 61850-7-420	DER
Information	IEC 61850-80-1	Mapping of IEC/EN 61850 data model over 60870-5-101 and 104
Information	EN 61400-25	Wind farms
Information	EN 61968 (all parts)	Common Information Model (System Interfaces For Distribution Management)
Information	EN 61970 (all parts)	Common Information Model (System Interfaces For Energy Management)
Communication	EN 61850-8-1	IEC/EN 61850 communication except Sample values
Communication	IEC 61850-90-1	Use of IEC/EN 61850 for the communication between substations
Communication	EN 60870-5-101	
Communication	EN 60870-5-103	
Communication	EN 60870-5-104	
Communication	EN 61850-9-2	IEC/EN 61850 Sample values communication
Communication	IEC 61850-90-5	Use of IEC/EN 61850 to transmit synchrophasor information according to IEEE C37.118. May also be relevant for use between substations
Component	EN 61869	Instrument transformers
Communication	IEC 62351 (all parts)	Cyber-security aspects (refer to section 9.3)

Figure 20 Substation automation system (Transmission) - Available standards (CENELEC).

IEC 61850 family and Common Information Model (CIM) are core standards of Smart Grid. The introduction of IEC 61850 gives many advantages and possibilities to digitalize the power utility monitoring, protection, control and automation system which can then be more reliable, informative, compact and “future proof”. It is a global standard now adopted by all major manufacturers and introduced by many TSOs and DSOs worldwide. It has also the potential to reduce investment and operation costs. Free allocation of functions allows Reliability Centered Design (RCD) system concepts with fewer components and wires. Also here a system view is important considering the primary substation layout, high voltage components as well as the protection and control system. The development of protection and control as such including the IEC 61850 family is covered in other parts of this conference and therefore not included in this paper. Furthermore see the latest issue of PAC World on IEC 61850 9-2 Process Bus.

However, it has to be understood that the implementation of new products and systems according to this standard will change the traditional work within a traditional power utility. The know-how of both traditional power engineering and IT need to be combined. Engineering, documentation, testing and maintenance will be different. Initial costs to the user include future planning and sufficient training of the work force with proper tools. The challenges will vary depending on the power utility’s own work and out sourcing of tasks, e.g. if substations are purchased “turn-key” with external service provider for maintenance or if the power utility has in-house engineering and maintenance personnel. Independent of this, the fundamental know-how is required to specify and document a digital system according to IEC 61850. This means to learn the concept, the model, the language and the structure of various files.

WAMPAC FOR THE DIGITAL POWER SYSTEM

The future smart grid with more variability and a larger mix of generation and loads bring about new challenges in grid operation, both on the transmission and distribution levels. This means there will be a need for improvements regarding situational awareness for operators, as well as improved means for protection and control. New measurement devices, fast communication and intelligent applications for monitoring and control are the keys to this development. Wide Area Monitoring, Protection and Control systems (WAMPACs) offers new possibilities and promising solutions that make use of the new technologies. The main objectives and motivation for WAMPACs can be summarized by referring to the NIST definition on main transmission applications; Control, Protect, Measure, Record, Stabilize and Optimize. This chapter introduces the technology with examples of applications and a discussion of the main challenges ahead.

The basic building block of a Wide area monitoring system is the Phasor Measurement Unit (PMU) that, through GPS time stamping, enables very accurate voltage and current measurements at any location in the power system. Time synchronization makes it possible to measure voltages and currents as phasors that refer to the same system-wide angle reference (FIG. 5.1). The PMU is therefore a measurement transducer where the outputs are commonly referred to as “synchrophasors”. The phasor measurements are streamed from their various locations (using different communication solutions) to Phasor Data Concentrators (PDCs) where the data is collected, processed or stored for further applications.

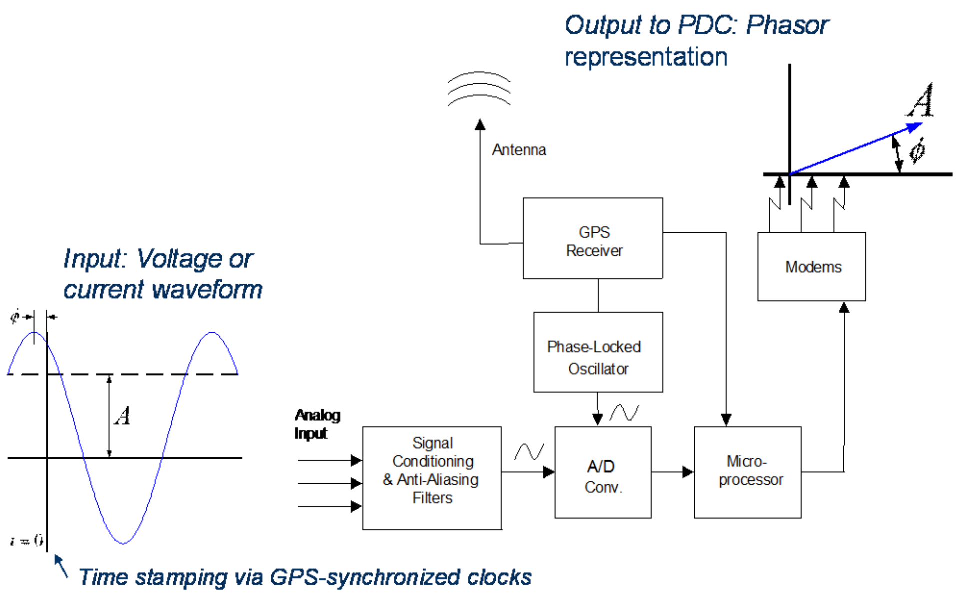

Figure 21 Substation Basic function of a Phasor Measurement Unit (PMU).

The application of PMUs can range from pure storing and simple display of phasor data to advanced post processing of information and possible use in protection and control systems. Depending on the nature and use of these applications, they are referred to as Wide Area Monitoring Systems (WAMS), Wide Area Protection Systems (WAPS) or Wide Area Control Systems WACS) – or simply WAMPACs.

Measure

Based on system wide information from PMUs, it is possible to monitor and observe the state of the power system in a way that was not possible with the conventional SCADA information systems based on RTUs. Wide area monitoring systems (WAMS) have been under development in different places and at different pace during the last 20 years. These are now starting to become mature solutions and suitable for integration in control centre environments. Vendors of control centre systems are also offering solutions with integration of synchrophasor data in their software.

The main purpose of WAMS is to improve the monitoring and observability of the power grid. State estimation in power grids is about estimating voltage phasors at all nodes, and thus providing a valid power flow solution. To replace conventional state estimators, WAMS need to provide additional information or more accurate and reliable information. With a sufficient number of PMUs in the system, the task of state estimation becomes faster and more accurate. By directly measuring voltage phasors we have a state measurement rather than an estimate. The high-resolution state measurement can be used to improve situational awareness and understanding of the state of the system in several ways:

-Faster and more accurate indicators can be provided about steady state security of operation. This enables almost immediate information of contingencies and analysis consequences in terms of overloads and voltage deviations.
-The high time resolution of measurements (up to 50 or 60 Hz) enables the implementation of dynamic state observers where the purpose is to provide information about system stability properties. Until now, most attention has been on development of algorithms for power oscillation and voltage stability monitoring. The aim of power oscillation monitoring (POM) is to estimate the natural modes and damping of low frequency inter-area resonances in the power system. Inter-area power oscillations are a true wide area phenomenon. Voltage stability, on the other hand, is considered more of a local problem. However, the identification of a potential voltage instability problem is difficult and the availability of phasor measurements at different locations has shown to be useful.
-Phasor measurement units are able to provide excellent measurement of system frequency. The importance of system frequency and the quality of frequency control in an AC interconnected power grid is undisputable. Therefore, it is also of highest importance that high quality frequency measurements are available, not only for control purposes, but also for monitoring and information to operators.

Record

Enormous amounts of data are collected and can be stored by a Wide Area Monitoring System. The main challenge is to gain useful information and knowledge from the data. The most widely and successful use of synchrophasor data until now has probably been in conjunction with forensic analysis (fault recording, disturbance analysis) and model validation. There are many examples where phasor data and WAMS information have been used to analyze and explain the root cause and development of high impact system disturbances. In addition, measurements from the many smaller disturbances provide useful information, e.g. for model validation purposes. In this way, WAMS have for many years contributed to enhance the understanding of power system dynamics, even though the full breakthrough of using WAMS in the on-line operational environment is yet to come.

Control, Protect

In this context we consider control and protection at a system level. Maintaining the overall power system balance through frequency control and congestion management is the main responsibility of the Transmission System Operators. Under critical operating situations, there are special emergency controls and protection schemes available, aiming at reducing the system consequences of large disturbances. These tools are usually referred to as System Integrity Protection Schemes (SIPS) or Remedial Actions Schemes (RAS). The most common system protection scheme is probably Under-Frequency Load Shedding (UFLS), but there are many other examples of solutions that take special control actions based signals like overloads, under voltage or under/over-frequency. The control actions include shedding of loads, tripping of generators, network splitting and fast control of generation or HVDC connections.

A new generation of system protection schemes is foreseen based on phasor measurements, however much more research is needed to develop the robust solution for the future. The potential for development of Wide Area Protection Systems lies, not so much in changing the controls, but in utilizing the accurate, system wide measurements to make better adaptive, and more reliable system protection schemes.
-One example is the possibility to develop faster and more precise fault location algorithm and component protection.

-Another example is smarter and more distributed UFLS. These schemes could be made smoother and more efficient with wide area measurements. In combination with Advanced Metering Infrastructure (AMI) such solutions could possibly become market based where almost any end user can participate.

Grid separation or islanding can be easily detected with system wide phasor measurements. This information can also be utilized for control and protection purposes by intentionally enforcing network splitting or islanding in critical situations. By utilizing the phasor information, it is possible to detect abnormal voltage angle differences that may be a risk to security and system stability. Special controls can then be designed to ensure stable island operation while minimizing the need for load shedding.
Such distributed control and protection solutions have the potential to revolutionize frequency control and balance management. We can imagine a future power system where the power balance and primary frequency control is never at serious risk. This is achieved through a combination of WAMS and AMI solutions enabling most consumers and generators to provide primary control services. This implies that from time to time there will be renewable generation that is lost and other times where loads need to be shed. Thus, the power balance will still come at a cost, but a balance is always found. The control objective would be to minimize the cost of energy not served.

Stabilize

In very many of the large interconnected power systems throughout the world, power transfer capabilities are limited primarily due to stability issues. This may be risk of voltage collapse or the risk of sustained power oscillations (that eventually might lead to a collapse).

The issue of power oscillations is related to damping of the inherent low frequency inter-area modes of the power system and is normally improved by the use of special controls on generators and FACTS devices, referred to as power system stabilizers (PSSs). The conventional power system stabilizer, however, is local control (using local measurements), while power oscillation damping can be a system wide problem. This has been a main motivation behind a lot of research work to develop Wide Area Power Oscillation Damping (WAPOD) controllers. The idea behind the WAPOD is to optimize and coordinate the stabilizing controls by utilizing system wide phasor measurements. With a number of PMUs available it is possible to choose one or a combination of measurements that provide the best observability of the mode to be damped. By implementing the controls in different units (e.g. FACTS devices) having the best controllability of the particular mode, the overall most efficient solution can be found. If there are several low damped modes in the system, it is also easier to design a coordinated control solution. Fig. 5.2 shows an example of a WAPOD solution that has been implemented and tested by Statnett on an SVC unit in Southern Norway.

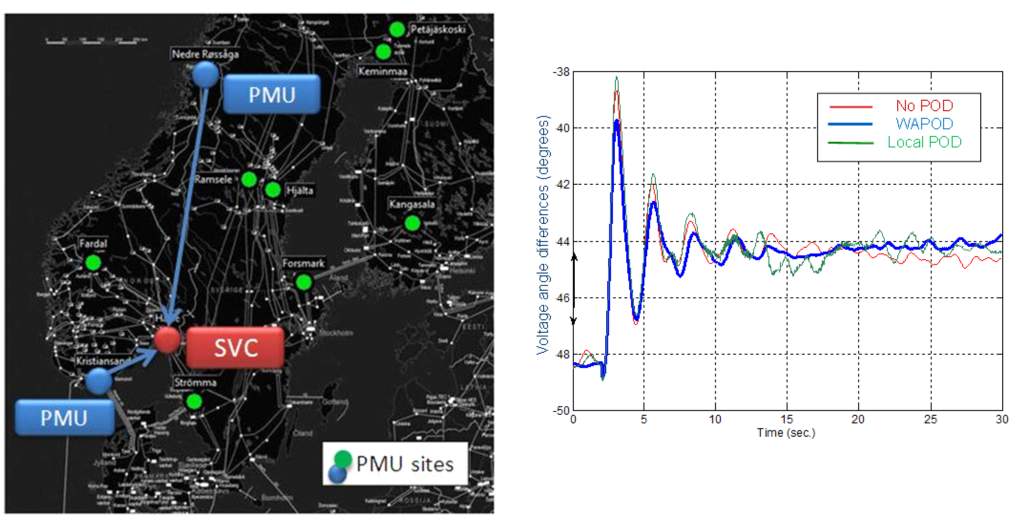

Figure 22 WAPOD implementation. Voltage phasors are measured at two remote locations, and the difference between the voltage angles is used as input to the stabilizing controller of the SVC unit

Optimize

Wide Area Controls related to the enhancement of voltage stability properties are somewhat less interesting, considering the more local nature of this problem. However, as stated above the identification of a potential voltage instability problem is difficult and with the availability of phasor measurements at different locations it is possible to make excellent state estimates that can also be utilized for control purposes. The control objective in this case would be to optimize the use of reactive power assets, for example, through coordinated secondary voltage control. With respect to voltage stability, a main objective is the ability to minimize use of reactive compensation in order to maximize the available reactive reserves.

A general objective is to optimize system utilization by combining wide area measurements in coordinated control solutions. This is all about taking advantage of the superior observability provided by WAMS and execution of control where it is most efficient.

Cyber security and ICT challenges

The whole concept of Wide Area Monitoring, Control and Protection relies on distributed measurements as well as control actions. Therefore, it depends heavily on communication infrastructure and available ICT solutions. This includes the ICT technology as such and the issue of managing the enormous amounts of data that becomes available. These aspects constitute major challenges and may be regarded as main vulnerabilities of WAMPACs. In addition to managing the data and information to develop useful applications, there are several questions to be addressed.

One important issue is cyber security and the vulnerability related to spoofing. To what extent is it possible to generate false GPS (or other time synchronizing) signals. What are the possible threats related to this and how is it possible to protect against it? What should be the requirements for internal clocks and reliability of the PMUs and communication systems?

Standardization and interoperability will certainly be important for further development in this area.

CHALLENGES AND SOLUTIONS FOR FLEXIBLE AND SECURE POWER SYSTEM OPERATION

As already concluded challenges and solutions do differ between power systems and different power markets around the world. However there is a common need to integrate more renewable energy for electricity generation. This in turn will require more implementation of UHV, FACTS and HVDC.

A large number of HVDC systems are in operation around the world and their performance is followed and reported by CIGRE. This technology is “mature” although it is still being developed to higher UHVDC systems and multi terminal applications. There are large HVDC and UHVDC projects planned and being built to harvest large hydropower resources in Brazil, India, Africa and especially China. In China, UHVDC is also planned to connect to remote coal resources as well as large wind parks. This so-called “classic” HVDC technology is based on thyristors technology and is supported by the major International suppliers and Chinese suppliers.

The introduction of HVDC VSC technology provided several advantages compared to the classic HVDC CSC technology. Simply put, HVDC VSC had the same functionality as HVDC and FACTS and could control power and voltage through the possibility to change the direction of active and reactive power. Just as simply, HVDC VSC can be compared with a combined generator and motor producing or consuming power. Although most HVDC VSC applications in the near future are radial point-to-point connections, it is necessary to be able to integrate at a later date several such links in a multi terminal application evolving to a larger DC grid. This is covered in several recent reports such as: FOSG, “Roadmap to the Supergrid Technologies” (March 2012 and updated March 2013), CIGRE 492 “Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other

AC and DC technologies" (April 2012), CENELEC, "Technical Guidelines for first HVDC Grids" (December 2012). CIGRE report 533 "HVDC Grid Feasibility Study" from Working Group B4.52 April 2013 was the start of several studies on specific issues such as control and protection.

Reactive compensation has since long been used for longer transmission links which now has been further enhanced with power electronics for different FACTS applications. Connection with offshore installations (for offshore wind or oil/gas platforms) requires cables. For this reason there is a technical and economical limit to the distance that can be served with AC cables. The capacitive, or charging, current has a limiting effect on cable rating capacity (MW). In case of long cable circuits, the compensation of charging current requires installation of shunt reactors connected at one or both ends of the cable. When connecting an offshore wind park with a longer cable, it may be a better solution to include the shunt reactor in a SVC.

The integration of high amounts of wind power into an existing power system will need investments to increase the hosting capacity. This may be a new line, FACTS or storage. One case study of this is found in Texas. In 2008, the Public Utility Commission of Texas (PUC) assigned close to 5 billion USD for CREZ (competitive renewable energy zone) transmission projects to be constructed by seven transmission and distribution utilities. The project will eventually transmit 18,456 megawatts (MW) of wind power from West Texas and the Panhandle to highly populated metropolitan areas of the state.

The connection of wind power and distributed PV, increased use of cables and more FACTS devises are all changes which will affect the basic protection and control systems in the substation. There is however also a need to develop more efficient tools and methods to have a better and faster understanding on the real time system behavior and to take action to prevent disturbances . PMU and WAMPAC is such an example which can interact with HVDC and FACTS.

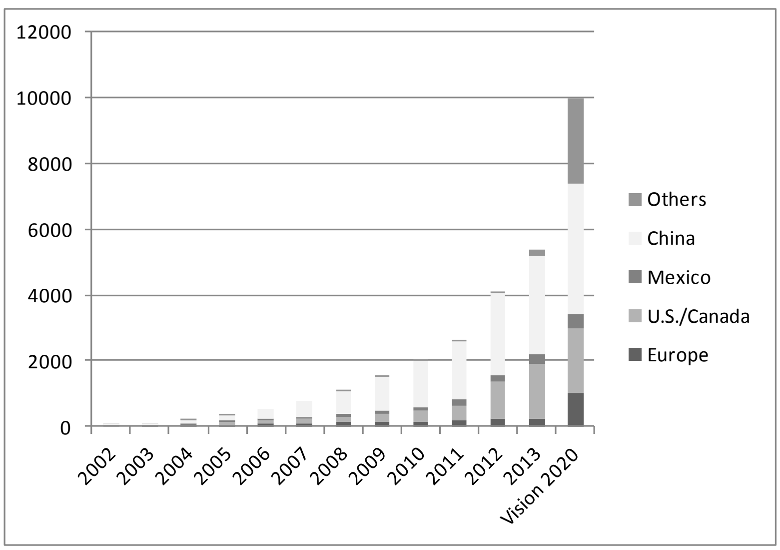

Figure 23 Installed and planned PMU

The estimated installed number of PMUs 2013 and vision for 2020 is shown in above figure. U.S. has more than 1600 PMUs installed primarily through Smart Grid Investment Grants (SGIG) and coordinated within NASPI, www.naspi.org. China has around 3000. It is our vision that Phasor Measurement Units (PMUs) will be installed in all major transmission level substations within the next one to two decades. This is crucial for the development and use of Wide Area Monitoring, Protection and Control Systems (WAMPACs). To fully utilize the potential information that becomes available by phasor measurements, new applications for on-line and off-line analysis need to be developed, along with closed loop control applications. The common objective for all these applications is to enhance observability and controllability to manage the variability and dynamics of the future power system systems.

Monitoring applications (WAMS) are now maturing through many good prototype and demonstration tools. WAMS applications are also seen to be integrated with the traditional SCADA/EMS solutions. This development has to continue. All the operational tools and applications must be integrated in order to release the full potential of WAMS. Only in this way will the operators gain experience with using the applications and thus be able to acknowledge the added information provided by WAMS.

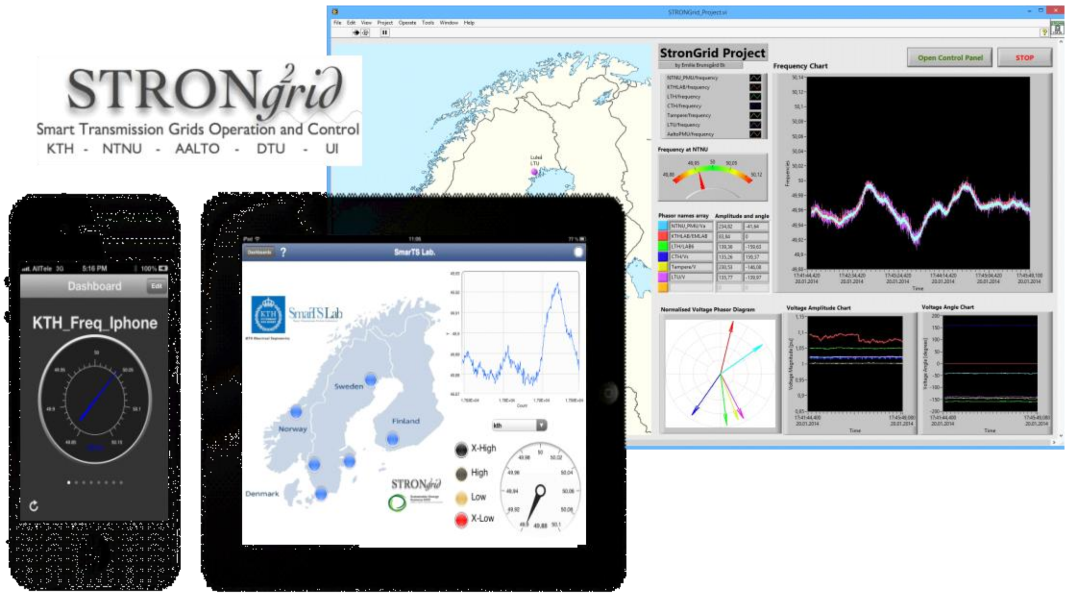

Figure 24 Examples of monitoring applications based synchrophasor installations at Nordic Universities through the R&D project STRONg^{2}rid.

Research and development must continue, in particular on the development of robust protection and control solutions. There are great possibilities in combining wide area measurements, communication and coordinated control to develop Smart Grid applications that will maintain the security and integrity of the future power system. This development is only limited by our imagination and ability to best use all available information.

An integrated part of the research challenge will thus also be to manage the cyber security aspects, which are brought forward by the dependence on information and communication technologies. There are still many open questions concerning the design of fast, reliable and secure ICT systems, including how to manage and make useful information out of the enormous amounts of data that will become available.

The European Electricity Grid Initiative (EEGI) has developed a Smart Grid roadmap and their Implementation Plan is issued every year. This work is coordinated by the R&D framework programs from the European Commission which at present is called Horizon 2020. In the latest document issued March 2014 by EEGI the following is stated regarding priority areas for Smart Grid R&D; *Assuming that the 2014 topics are focused on the system reliability and flexibility (with the demonstrations of future smart HV substations and the integration of Storage and Metering Data Systems for network management), the priorities for 2015 cover the objectives of network monitoring, control, flexibility and security.*

EEGI concludes that the increase of RES/DER is a reality in most of the main European networks. DER and RES penetration is requiring additional network hosting capacity, as well as electric system flexibility and reliability to cope with the problems coming from generation intermittency. The integration of large amounts of renewable generation with power electronic interfaces and addition of HVDC links into the power system will necessitate a review of the operation and control of transmission networks. Both transmission and distribution operators see asset management as a critical component of overall network management strategy to face the growing uncertainties of component life time brought by renewable in-feeds. Current maintenance practices by grid operators involve periodic preventive actions, based on the average values of reliability performances for homogeneous families of components. The integration of demand side management at DSO level to provide extra system services for TSO operation requires activities to make both networks cooperate more, in order to shape the coming new active role of electricity customers. Three of the important topics for R&D listed by EEGI for 2015 are concerning:

- TSO R&D on the development of control and protection for large power systems with a large amount of inverter-based components.
- TSO R&D on methods and tools to optimize asset management.
- A joint TSO/DSO R&D project aims at improving the observability of the distribution systems for transmission network management.

The "digital evolution" with fast communication offers new possibilities. In all the different definitions of Smart Grids, the increased importance of ICT is stressed in order to handle the increased complexity of the power system. The increase of variable generation form Renewable Energy Sources (RES) such as wind and solar requires increased flexibility and immediate adaptability. Larger disturbances have shown the need for "Visualization" and "Situational Awareness" on what is happening within a more complex power system. There is also a common understanding of the need for standardization and interoperability of the ICT "systems of systems". This is handled globally within IEC as well as within CENELEC (EUROPE) and NIST (USA). See http://www.iec.ch/smartgrid/standards/.

For Power T&D Systems IEC 61850, together with IEC 61970 and IEC 61968, covering a Common Information Model (CIM) necessary for exchanges of data between devices and networks, primarily in the transmission (IEC 61970) and distribution (IEC 61968), domains are core standards to ensure interoperability. Particularly the IEC 61850 standard, if fully applied, will radically change how systems for monitoring, protection and control are designed, operated and maintained. It is much more than a new protocol. It is a model with a common language on how to handle the communication of information in real time. It will change the work processes. This has to be fully understood by the main users (TSOs and DSOs) so the migration from present electromechanical and/or digital technologies are planned with involvement from all relevant parts of their own organizations as well as outsourced activities. If the full benefits of IEC 61850 standard, such as the "future proof" interoperability and standardized documentation, should be harvested, there has to be enough knowhow on both ICT and Power T&D applications. The preparation, training and motivation of involved personnel are essential for the success.

ENSTO-E and The Very Large Power Grid Operator Association, GO 15 published statements regarding this standardization work in beginning of 2012. "ENTSO-E calls for all IEC61850 stakeholders to take the appropriate actions in order to ensure the success of IEC61850 and to make sure the standard – and the technologies developed around it – remain sustainable and provide significant benefits for all stakeholders and the community. This statement addresses the main stakeholders involved in the development and product implementation of the IEC61850 standard on communication networks and systems for power utility automation: secondary systems suppliers, International Electro technical Commission (IEC TC57, WG10 and others), conformance testing companies, third-party tool developers. This standard is of potentially large benefit to electricity transmission system operators (TSOs) as it addresses across different vendors many crucial aspects of TSO communications, with the promise of seamless interoperability of different vendors' subsystems within the overall TSO system management architecture."

A similar statement came from the internal group of very large utilities which now is called GO 15: "The IEC61850 standard is of potentially large benefit to Power Grid Operators (PGOs) as it addresses across different vendors many crucial aspects of PGO communications, with the promise of seamless interoperability of different vendors' subsystems within the overall PGO system management architecture." This was further stressed by a statement in November 2012 from GO 15: • "We support the promotion of the worldwide harmonization of standards, which will provide for interoperability of the solutions in a reliable and efficient way."The above statements have helped to put focus on necessary work to be done. Please see:
https://www.entsoe.eu/about-entso-e/research-and-development/standardisation/Pages/default.aspx.

The Nordic Transmission System Operators (TSOs) have a long history of cooperation in grid development in NORDEL, the previous cooperative organization for the Nordic TSOs. The Nordic power systems (with the exception of Iceland) are strongly connected and interdependent on each other, and hence close cooperation is essential to ensure a rational development of the system. After the UK, the Nordic electricity market with Finland, Norway and Sweden were the first to deregulate in Europe and allow"Third Party Access". Furthermore, it became the first multi national electricity market. This process started in Norway 1991 and Sweden in 1992 with the creation of the Norwegian and Swedish TSOs.

In 1996, a joint Norwegian-Swedish power exchange was established. The exchange was named Nord Pool ASA. Finland joined Nord Pool ASA in 1998. The Nordic market became fully integrated as Denmark joined the exchange in 2000. Nord Pool Spot was established as a company in 2002 as the world's first market for trading power. Today it is also the world's largest market of its kind, and is the leading market for buying and selling power in the Nordic region. One consequence of the electricity market realignment is the increased need for data exchange between the actors in it. A practical prerequisite for meeting this need is some form of electronic data exchange, EDI (Electronic Data Interchange). For this reason a common EDI system called Ediel was developed. The Nordic Ediel Group was founded after Ediel Nordic Forum was reestablished as a pan European body under the name of ebIX (see www.ebix.org). As the Nordic market integrates with Europe, there is a need for a common standard. A Role Model has been developed by ENTSO-E, identifying roles and domains for an information interchange in the electricity market. The four Nordic TSOs and Nord Pool Spot have set up a project for migration of the message exchanges towards one common message standard. The operation of the Nordic system can be followed on line including the power exchange between different countries. As an exampel high solar and wind power production can be exported from Germany, Netherlands and Denmark to Norway, Sweden and Finland using HVDC links while high production of hydro and nuclear power can be exported the other way depending on spot prices.

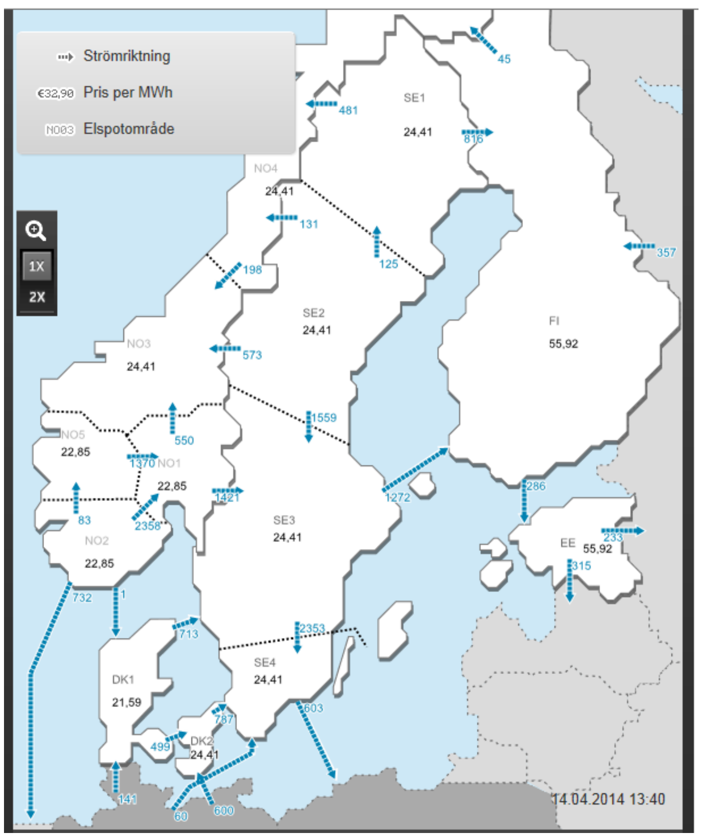

Figure 25 The Nordic power exchange

Nordic Operation Information System (NOIS) facilitates exchange of critical data between the Nordic TSOs within ENTSOE - RGN, Region Nordic (earlier named NORDEL). It is today integrated by the four Nordic National Control Centers (NCCs). After the large European disturbance 2006 a work was initiated for better coordination within the main land power system in Europe. EAS (ENTSO-E Wide Awareness System) was launched 2010 and 58 European TSOs participates today. In case of a stressed situation: to provide automatic or manual information shared to enable the TSOs to apprehend globally an endangered situation. In case of disturbance: to provide information to the TSOs to help them to identify its origin and its borders. Today four EAS applications are implemented:

- Frequency: "Where is over-/under- frequency or potential network split?"
- System State: "Where is critical system state and what is indicated by TSOs?"
- Exchange: "Where are exporting/importing areas and how are exchanges?"
- Imbalance: "Where are imbalanced areas and how are areas imbalanced?"

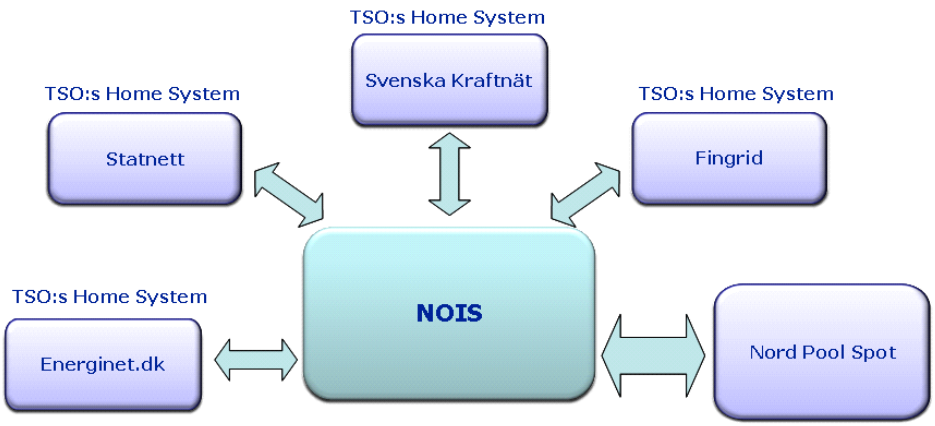

Figure 26 Nordic Operation Information System (Svenska Kraftnät)

Coreso (COoRdination of Electricity System Operators) was formed 2008 as a Regional Security Coordination Initiative (RSCI) and consists of several TSO; Elia (Belgium and Germany), 50 Hz (Germany), National Grid (UK), RTE (France) and Terna (Italy). Coreso work today with day-ahead and two-day-ahead forecasts.

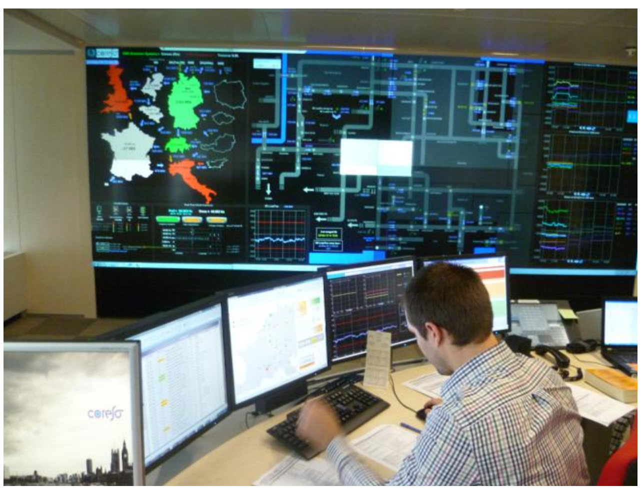

Figure 27 CORESO in Brussels

The challenge with variable wind and solar production is that both shorter and longer deviations cannot be predicted. Studies has been made on a future scenario with 150 GW installed wind power in Europe when longer winter periods with high consumption could have low wind conditions down to 20 GW. Solar PV could in the same manner have large short term variations during the day.

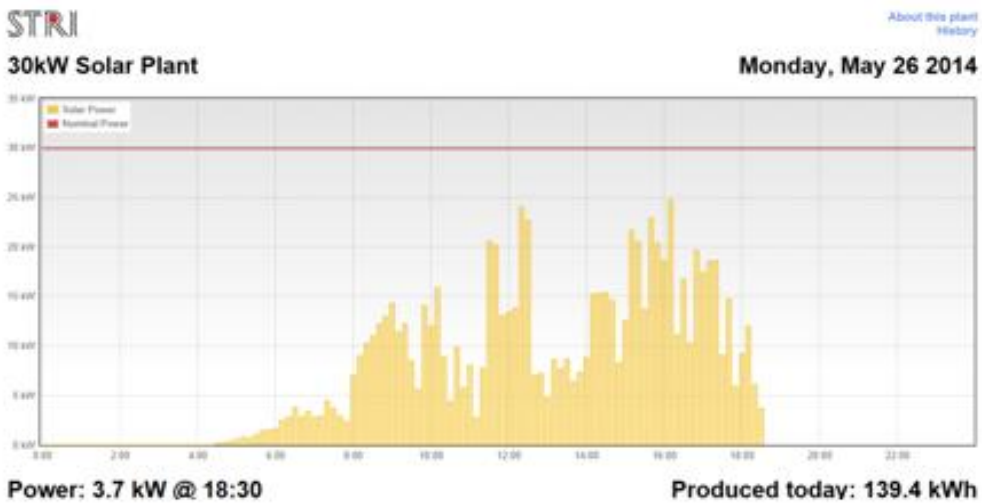

Figure 28 Variation in solar PV production (STRI)

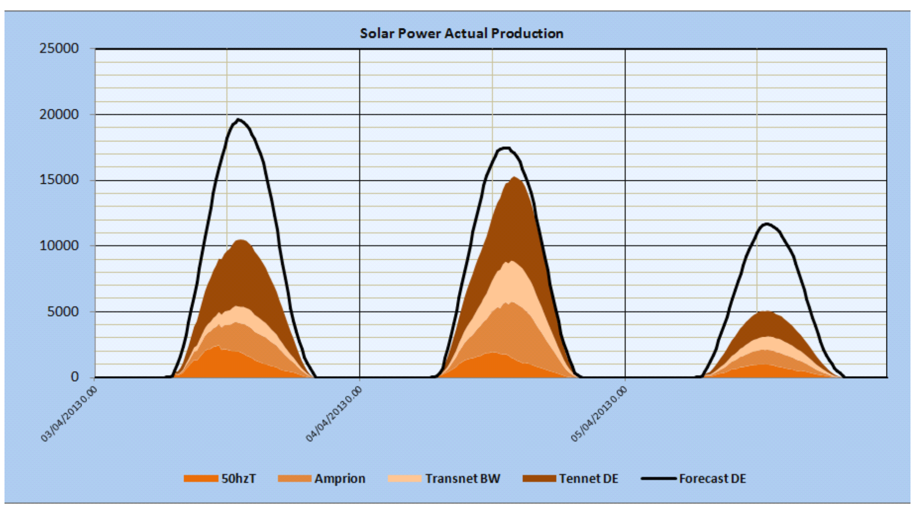

Figure 29 Deviation forecast and actual solar production (CORESO)

The European Electricity Grid Initiative (EEGI) has developed a Smart Grid roadmap and their Implementation Plan is issued every year. This work is coordinated by the R&D framework programs from the European Commission which at present is called Horizon 2020. In the latest document issued March 2014 by EEGI the following is stated regarding priority areas for Smart Grid R&D; *Assuming that the 2014 topics are focused on the system reliability and flexibility (with the demonstrations of future smart HV substations and the integration of Storage and Metering Data Systems for network management), the priorities for 2015 cover the objectives of network monitoring, control, flexibility and security.*

EEGI concludes that the increase of RES/DER is a reality in most of the main European networks. DER and RES penetration is requiring additional network hosting capacity, as well as electric system flexibility and reliability to cope with the problems coming from generation intermittency. The integration of large amounts of renewable generation with power electronic interfaces and addition of HVDC links into the power system will necessitate a review of the operation and control of transmission networks. Both transmission and distribution operators see asset management as a critical component of overall network management strategy to face the growing uncertainties of component life time brought by renewable in-feeds. Current maintenance practices by grid operators involve periodic preventive actions, based on the average values of reliability performances for homogeneous families of components. The integration of demand side management at DSO level to provide extra system services for TSO operation requires activities to make both networks cooperate more, in order to shape the coming new active role of electricity customers. Three of the important topics for R&D listed by EEGI for 2015 are concerning:

- TSO R&D on the development of control and protection for large power systems with a large amount of inverter-based components.
- TSO R&D on methods and tools to optimize asset management.
- A joint TSO/DSO R&D project aims at improving the observability of the distribution systems for transmission network management.

In a global perspective the main energy source for the future is solar power which then will be one of the main game changers for the power system. The sun is the origin for almost all forms of energy except geo thermal and nuclear power. 174 PW (peta = 10^{15}) is sent to the Erath although some is reflected and absorbed before reaching ground. There are different calculations on available potential but as an indication of scale 100 000 TW solar power can be compared with the potential of 1000 TW wind power and 10 TW hydro power. The feasible technical and economical potential could be around 10% of this. 2012 around 1 TW hydro, 300 MW wind and 100 GW solar power had been installed in the world. A know challenge with solar power (and wind power).

Figure 30 CSP Parabolic Through in night position (California) and active Stirling Dish (South Africa)

The basic principles for solar power are described by IEA in Technology Roadmap Solar photovoltaic energy (PV) and Technology Roadmap Concentrating Solar Power (CSP). While the development of PV has been rapid from 1 to 100 GW in about ten years due to falling prices and stimulation with Feed in Tariff (FiT), CSP has been slow. PV is suitable also for areas with colder climate and moderate sun such as in U.S. and EU. Germany has today about half of the 70 MW installed in EU. Although CSP technology has been installed in California since the 1980s the development has been much slower and so far limited to mainly U.S. and Spain. The potential for CSP is however huge within what is called the sunbelt. Actually a majority of the world population could be reached from CSP in desert areas with HVDC technology. This has been discussed in Europe as part of the DESERTEC initiative. PV can also be used in the sunbelt. However PV is less efficient in hot climate and therefore CSP (sometime called Solar Thermal Energy – STE) is foreseen an increased development in countries with suitable climate and a Direct Normal Irradiance (DNI) above 2000 kWh/m^2/year. A disadvantage for some CSP variants is that it is feeding heat fluid to a larger central turbine and requires large amount of water. To increase utilization heat storage is being developed. Decentralized Parabolic Stirling Dishes without water can be a more suitable technology but also here the market acceptance has been slow. In figure above a Stirling Dish for 30 kW each is shown from Upington in South Africa. This installation by Ripasso Energy has the world record with 1/3 of incoming sunlight converted directly to three phase electricity.

SUMMARY

During the next decades we will see a paradigm shift in the energy supply from fossil fuel to Renewable Energy Sources (RES) such as hydro, wind and solar energy using electricity as energy carrier. This development will be different in different parts of the world but we already now see the need to integrate larger power systems to handle large variations in power flow from different sources of energy. Below world maps gives a very simplified vision of this development.

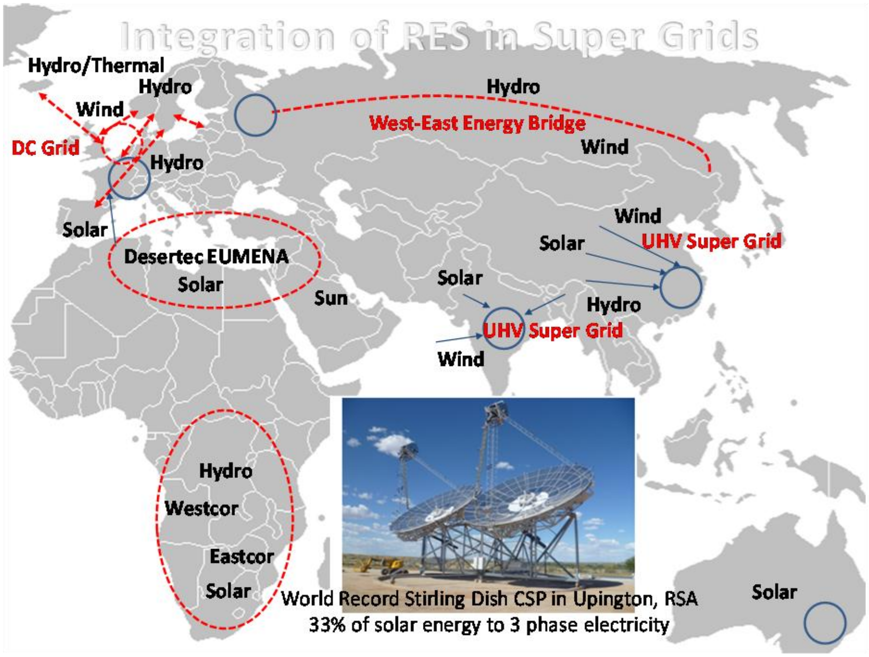

Figure 31 Larger scale integration of RES in Africa, Asia, Australia and Europe

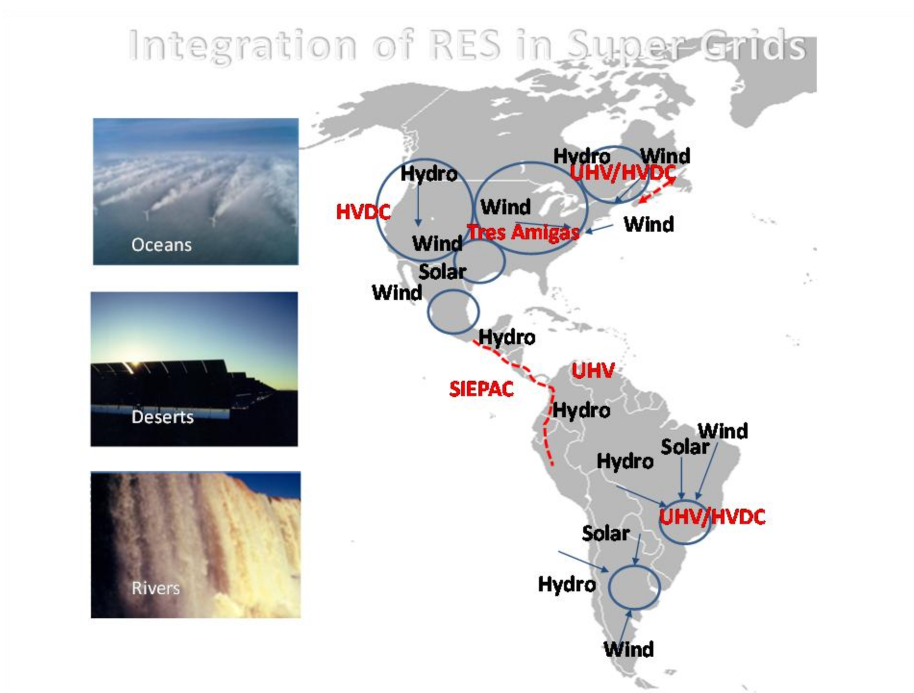

Figure 32 Larger scale integration of RES in Americas

Each power system is A SINGLE interacting system. The production and consumption of electricity has to be in balance at every moment 24/7 throughout the year. The system is also linked by value chain networks — changes in one link of the value chain can affect the whole system. Therefore, a holistic view across system planning, investment, and operation is needed to create a power grid capable of integrating the actions of all actors — including new market players — while maximizing the benefits and limiting costs.

Smarter and stronger grids will require investment at all levels of the grid. Priority investment should be targeted where the deployment of new technologies will immediately improve system operation and promote clean energy deployment. This calls for the introduction of both power electronics as well as Information and Communication technologies (ICT) to increase grid flexibility and to provide knowledge and control capabilities of system behaviour. More advanced Substation Automation Systems (SAS) for Protection and Control (PAC) will be fundamental for the Smart Grid interlinked with more advanced SCADA/EMS/DMS systems with real time wide area capabilities. Furthermore, as they are at the centre of power systems, interaction and coordination between grid operators at all levels and across regions should be enhanced to minimize cost and secure system stability.

At the latest CEM meeting 2014 ISGAN Annex 6 made the following conclusion on what policy makers should focus on:

1. The adoption of interoperability standards to accelerate technology deployment and innovation

•Local or national standards should be aligned with internationally developed “future proof” standards in order to drive both deployment of available technologies and ongoing innovation.

•Technical and financial know-how is a key element for making the policy and interoperability decisions. Policy education has to be provided and international expertise exchange should be leveraged to advance international cooperation.

2. Support the implementation of technology roadmaps developed by authoritative organizations (e.g. IEA)

3. Implement stable financial support regimes and clear regulations

•Governments and regulators should support investment decisions with stable financial support regimes for new technology and business model deployment.

•Transparent and well -communicated cost-benefit analyses are crucial for clear regulations and stable financial support regimes and increase public acceptance.

4. Support simplification of permitting procedures regarding implementation of necessary grid infrastructure 5. Roles and regulations must be developed in parallel with changing markets and actors

•The cooperation of utilities should be encouraged to align procedures, implemented technologies, standards and long term planning.

•The necessary information exchange between Smart Grid actors has to be identified and assured in order to manage the system in the most efficient way and to secure system stability.

REFERENCES

[1] P Overholt, D Cirio, ISGAN Annex 6 Discussion Paper FLEXIBLE POWER DELIVERY SYSTEMS An Overview of Policies and Regulations and Expansion Planning and Market Analysis for the United States and Europe, 2013

[2] C Ohlen, K Uhlen, ISGAN Annex 6 Discussion Paper SMARTER & STRONGER POWER TRANSMISSION: A Review of Feasible Technologies for Enhanced Capacity and Flexibility, 2013

[3] Other ISGAN publications available at http://www.iea-isgan.org/

[4] IEA publications such as WEO, ETP and technology roadmaps available at http://www.iea.org/

[5] CEM publications such as Fact Sheets and Case Books available at http://www.cleanenergyministerial.org/

[6] GSGF information available at http://www.globalsmartgridfederation.org/