Smarter & Stronger Power Transmission: *Review of feasible technologies for enhanced capacity and flexibility*

ISGAN Executive Summary

August 2013

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Abstract: Transmission and distribution (T&D) systems are facing new challenges linked with the introduction in the generation mix of a progressively increasing share of unpredictable energy sources and variable generation from renewable energy sources (RES), as well as changing patterns of demand that new types of load such as electric vehicles (EV) will introduce. Large and unpredictable fluctuations in the power balance as well as variations in voltage can jeopardize the quality and availability of power. The T&D system has to be stronger and smarter to provide the real-time flexibility needed to efficiently handle the new conditions. Investment needs in the power T&D infrastructure are large and require long term planning and deployment. The environmental concerns and public acceptance issues that often arise when constructing additional conventional transmission lines will require more efficient solutions with lower environmental impact.

This Discussion Paper from ISGAN Annex 6 Power Transmission & Distribution Systems Task 3 and 4 focuses on "Smarter & Stronger Power Transmission" and is a review of feasible technologies for enhanced transmission 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 to efficiently supervise and operate 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 as well as 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. Most of the examples given are from the Nordic European power system, reflecting the participation of the authors from ISGAN Annex 6 Task 3 and 4, with additional input from North America and selected International case studies.

About ISGAN Discussion Papers: ISGAN Discussion Papers are meant as input documents to the global discourse about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in the different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, rather to lay the ground work for further research and analysis.

Acknowledgements: This Discussion Paper was prepared during Q1, 2013 by the task leaders for ISGAN 6 Power T&D Systems, Carl Ohlen (Task 3) and Kjetil Uhlen (Task 4). The Authors used information and knowledge from the Swedish and Norwegian ISGAN Annex 6 technical experts and could benefit from their direct experience in Smart Grid projects, the International Electrotechnical Commission (IEC), the Council on Large Electric Systems (CIGRE) and other initiatives. This combined expertise is documented in three Special Reports from ISGAN Annex 6 Task 3, dealing with Technology Development and Demonstration.

This report is mainly based on the development and case studies from Norway and Sweden. Additional information was also used from the work of the Authors and other technical experts involved.

FACTS and HVDC technologies were first introduced in Sweden during the 1950s, and supplemented by a national “Internet-like” communication (TIDAS) for remote control which was introduced in the 1970s. Both developments contributed to the evolution of the Nordic power system towards one of the first multinational deregulated markets.

Comprehensive data from studies, projects and products have been gathered by ISGAN technical experts in Norway and Sweden. This paper includes detailed information from selected case studies. Part of the material has been produced by the Company ABB, who introduced some of these technologies and can claim a long global operational experience with FACTS, HVDC and substation automation technologies. It is however important to highlight that ABB is nowadays only one of the many technology providers in this field: other international companies such as Alstom Grid and Siemens, as well as local suppliers, like CEPRI in China, already have or are developing power electronics technologies as UHVDC and HVDC-VSC. The same is valid for ICT and power utility automation, both of which have a very long list of technology suppliers.

As this “digital power system” technology is now being deployed globally, this report focuses especially on interoperability among products and systems from diverse vendors as a fundamental challenge for creating a Smart and Strong Grid. Therefore, the paper refers to available work and reports from CIGRE, IEC, the National Institute of Standards and Technology (NIST), the European Network for Transmission System Operators for Electricity (ENTSO-E) and the European Committee for Electrotechnical Standardization (CENELEC), along with ongoing joint industry initiatives. This Discussion Paper also draws on earlier work within International Energy Agency (IEA) Implementing Agreement on Electricity Networks, Analysis, Research and Development (ENARD), as well as ongoing work within ISGAN Annex 6 (with its participants during 2012 from Austria, Belgium, Italy, Norway, Sweden and the United States), which includes conclusions arising from several ISGAN Annex 6 workshops held in 2012 and 2013. Finally, the work within the US Department of Energy (US DOE) on Transmission Systems and the North American Synchrophasor Initiative (NASPI) project has been a valuable contribution through ISGAN Annex 6 Task 1 Leader Phil Overholt. Specific references are listed separately.

The paper’s Executive Summary was edited by Marilyn Smith.

Acronyms and abbreviations

AMI	automatic metering infrastructure	**PAC**	protection and control
BAT	battery storage	**PMU**	phasor measurement unit
CSC	current source convertor	**PV**	photovoltaic
DER	distributed energy sources	**RES**	renewable energy sources
EV	electric vehicles	**SC**	series compensation
FACTS	flexible AC transmission system	**SVC**	static var compensation
HAN	home automation network	**TCSC**	thyristor controlled series compensation
HVDC	high voltage direct current	**T&D**	(power) transmission and distribution
ICT	information and communication technology	**VAL**	variable load
IED	intelligent electronic device	**VPP**	virtual power plant
NIS	network information system	**VSC**	voltage source convertor
OHL	over head line	**WAMPAC**	wide area monitoring, protection and control

Power T&D systems are vital to clean energy deployment

THE FUTURE IS ELECTRIC!

Recognising that energy is vitally important for future economic growth, many countries are making it a priority to establish a clean and efficient energy system. Three main factors drive the share of electricity as a primary energy carrier:

- Increasing demand associated with global efforts to bring modern energy to the more than one billion people in the world who are currently without electricity and to many more with insufficient electricity supply, and from new applications for electrical power (such as computers, cell phones, electric vehicles, etc.).
- The urgent need to decarbonise the energy system through an increased use of renewable energy sources (RES) and other clean energy sources generating electricity.
- The need to reduce overall primary energy demand by making energy consumption more efficient; here, electricity offers smarter electrical solutions (such as heat pumps).

SMART & STRONG POWER SYSTEMS ARE NEEDED TO KEEP PACE WITH ELECTRICITY DEMAND!

Modern society depends heavily on the continuous delivery of reliable and efficient electric power to homes, offices, industries, shopping centres and transportation systems. To manage uncertainty and variability, increased electrification requires more intelligent operation of smarter and stronger power transmission and distribution (T&D) systems to:

- Connect large-scale RES (hydro, wind, solar) facilities from remote regions, link generation and consumption areas (such as offshore wind farms and growing of mega-cities) and integrate additional infrastructure for storage, balancing and reserves.
- Support installations of intermittent power generation from distributed energy resources (DER) based on solar and wind, as well as consumer demand response.
- Modernize and strengthen ageing T&D infrastructures in many countries to meet future challenges and ensure reliable power delivery.

WE NEED TO INVEST IN A SMART & STRONG GRID!

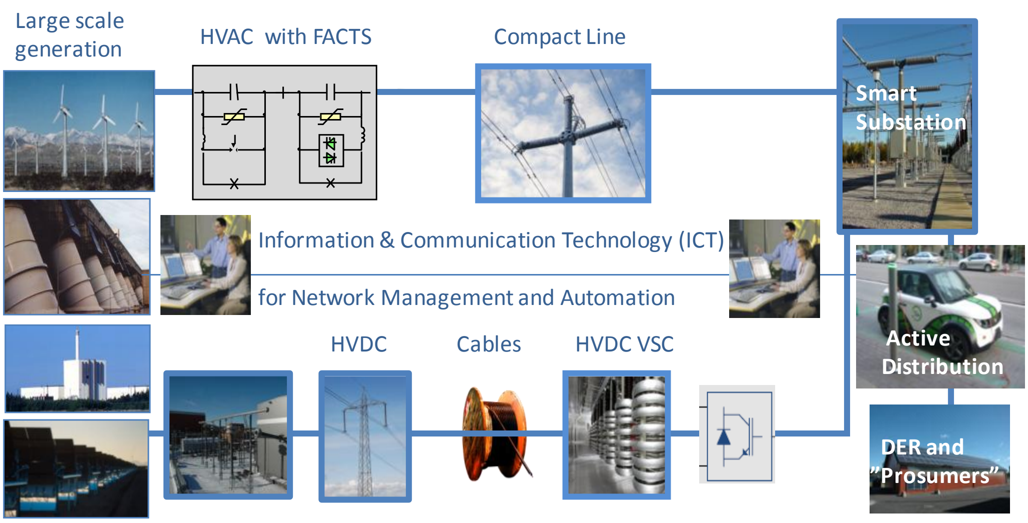


Figure 1. The smart and strong grid

BACK TO BASICS: A PRIMER FOR NON-EXPERTS

Understanding a few basic concepts will be useful to non-experts who participate in energy planning and decision-making.

When electricity became a part of society at the end of the 19th century, a "war of currents" quickly arose. Thomas Edison promoted an option known as direct current (DC), while Nicholas Tesla and George Westinghouse were proponents of alternating current (AC). Agreement was reached to standardize certain elements of the new technology, such that electric power (P) came to be measured in watts (W) and the two factors that determine power were designated as; current (I), which is measured in amperes; and voltage (U), measured as volts.

From the start, transporting electricity from the point of generation to that of use was a challenge as a portion of the power was lost along the way, due to electric resistance of the line. AC had the advantage that transformers could be used to increase the voltage in steps, thereby allowing power transmission over longer distances whereas DC was limited by the low voltage range allowed by generators and suitable only for shorter distances.

As a result, AC was adopted by other inventors such as Jonas Wenström, who patented a complete three-phase power system with generator, motor and transformer, which was tested 1890. A simplified three-phase AC power system can be seen as a generator supplying electricity to a motor at a defined frequency (normally is 50 Hz or 60 Hz). The generator produces active power (P), which the motor consumes: if the production is higher than the consumption, the frequency of the system will increase; if the production is lower, the frequency will decrease (Figure 2).

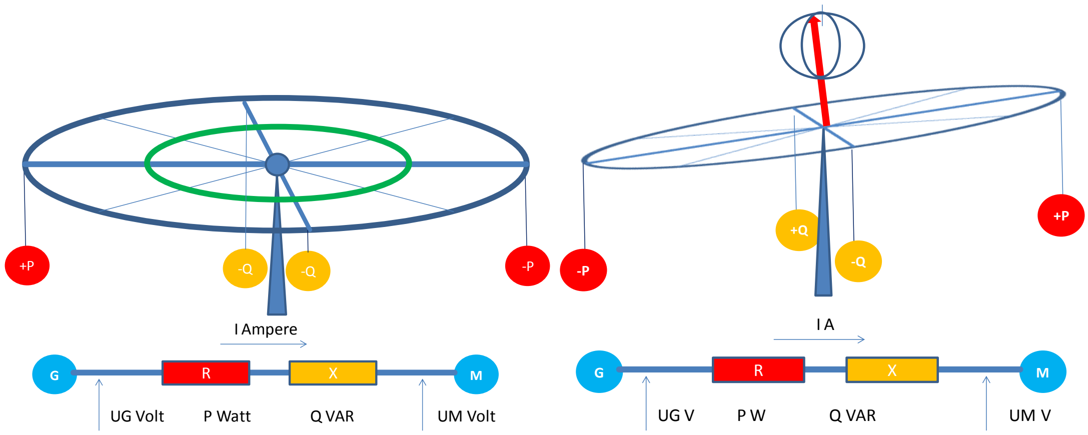


Figure 2. A simplified power system shown in balance and out of balance

In reality, such systems include a large number of generators and an even higher number of motors and other types of load that are "synchronized" and connected by the power T&D grid. Production and consumption for the complete system need to be in balance at any time, while also taking into account that losses will occur within the power T&D grid.

T&D losses result from the fact that the resistance (R) of a transmission line consumes active power (P), thereby reducing the voltage. Further reduction in the voltage is caused by inductance of the power line that introduces the reactance (X), which is higher than the resistance and consumes reactive power (Q).

AC transmission was further developed for higher voltages during the first half of the 20th century. In 1952, Sweden achieved an industrial first by introducing a 400 kV AC line; just two years later, the Swedes established the world's first high voltage DC (HVDC) line, which provided a cable link spanning almost 1 000 km to the island of Gotland.

Several approaches have been developed to minimize losses on long transmission lines. Many power companies now install conductors with a larger cross section (to reduce resistance) and/or several (bundle) conductors per phase (to reduce reactance). Others use reactive power compensation, in which series capacitors provide negative reactance to compensate for the positive reactance from the inductance of the line. A third option is to install shunt capacitors at the end of the line to provide reactive power and increase the voltage, or shunt reactors to reduce the voltage.

With these advances, both types of systems have become widely used, often complementing each other. AC systems of 400 kV, 500 kV, 800 kV and 1 000 kV AC are in operation around the world, while HVDC transmission up to +/- 800 kV is used for many applications.

ENERGY BALANCING UNDER A NEW PARADIGM

By its very nature, electricity adds a complex dimension to energy delivery: because it cannot be stored, power companies need to anticipate – down to the minute – the level of demand (i.e. how much electricity will be needed by whom). In fact, the level of demand drives the amount of generation required, and meeting demand requires that a synchronized power system be continuously balanced both for active power (frequency) and reactive power (voltage). Unbalance between production and consumption may cause a power system to break apart. Moreover, the T&D grid is exposed to weather, vegetation, pollution, and other events that can create disturbances and faults (such as flashovers). Strategies to predict demand and manage balancing within traditional energy systems are well developed.

Energy systems are changing in ways that make old strategies obsolete. The introduction of renewable energy sources creates variability on two levels. First, the availability of the resource – sun, wind or hydro – is less predictable than using fossil fuels for a primary source. Second, rather than having one massive plant, many RES technologies are small scale and distributed over wide areas (such as wind or solar farms). A third factor that influences balancing is the possibility to influence the load patterns (i.e. actual electricity use) through demand-response mechanisms.

Instead of a long-term plan for a balanced power system with minor deviations from predictions, this new paradigm requires the ability to adapt rapidly to changes and large fluctuations throughout the power system. Larger numbers of new types of generation in multiple locations often means increased use of cables, which influences the reactive power balance and the voltage in different parts of the system.

In today's more diversified yet integrated energy systems, there are critical locations at which a fault that is not cleared with sufficient rapidity may result in a major disturbance: one subsystem may accelerate while the other lags behind, creating a risk that the two systems will separate. The new system requires innovative mechanisms by which a short circuit fault can be instantaneously detected and disconnected by the protection and circuit breakers, respectively.

Thanks to the rapid development of power electronics, old applications with switched capacitors and reactors can be optimized with thyristors and transistors in what is known as flexible AC transmission systems (FACTS) and with HVDC. Wide area monitoring, protection and control (WAMPAC) can interact with available FACTS devices and HVDC. This creates increased flexibility to respond to sudden changes of active and reactive power flows in the system: in effect, "smarter" monitoring, protection and control systems are better able to act on "smarter" primary systems.

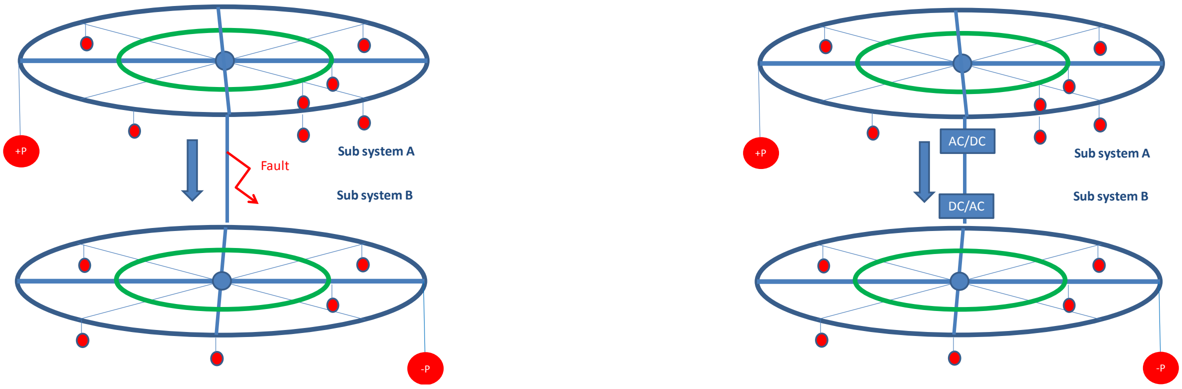
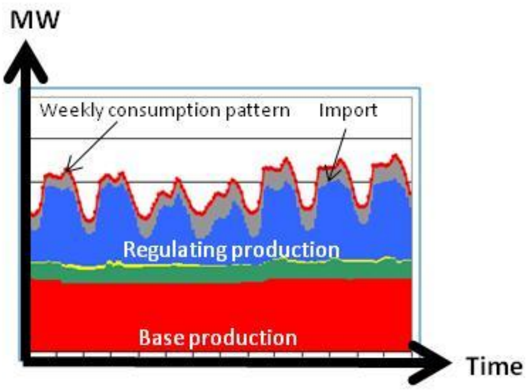


Figure 3. Inter connecting two sub systems with AC or DC

Since DC is not affected by reactance, HVDC is preferable for long-distance transmission and for longer offshore cable connections. DC can also be used to direct the power flow and act as a "switch" between different AC systems. Although the present applications of DC is to connect two terminals without any intermediate station, DC meshed networks are also discussed for the future smarter grid. The use of HVDC to separate two AC sub-systems, or as "embedded" HVDC, can improve the performance of existing HVAC systems. The evolution of power transistors replacing power thyristors paved the way for the new HVDC with voltage source converter (VSC) technology, which controls both active and reactive power. VSC is now in service in several applications around the world.

Historical data show power consumption and production for a typical week in Sweden (Figure 4). Because the pattern is predictable, it is quite simple to balance the system using nuclear power for base production (red) and hydro power (blue) together with import from other countries (grey) to balance the variations. Hydro power has the advantage that it can be stored (in reservoirs) and dispatched (run through the dam) when required, and can be used as a spinning reserve. In effect, the hydro station (the generator) is synchronized to the system without producing any power but ready for activation when needed.



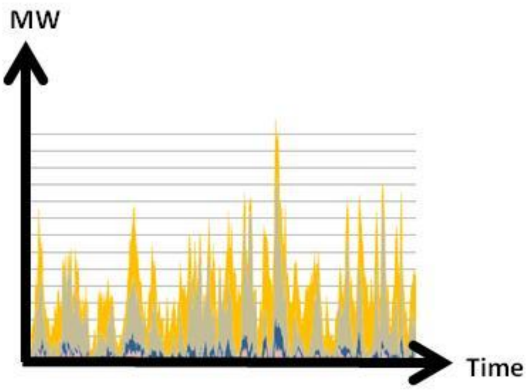


Figure 4. Weekly power balance

Figure 5. Variable production

With the introduction of more wind and solar power in the system, production is variable and more unpredictable (Figure 5). Thus, managing a given energy system becomes a more complex matter of balancing variation in both consumption and production. Based on the simple formula "Energy = Power x time", because production from renewable energy sources has a lower capacity factor (i.e. lower capability to produce the rated power during time, because of the variability of the primary source) compared to conventional generation, it is necessary to install more power in MW to get the same amount of energy as MWh.

Under this new scenario, peak power production can be very high and theoretically equal to all connected RES, while there can also be periods of variable duration with practically no generation. It is important to note that RES is not completely unpredictable – and prediction methods are improving. While solar may have large variations during the day, it is more predictable than wind power since no solar generation occurs at night.

A strategic combination of capacity, flexibility and controllability of the power system is needed to handle these variations, along with storage and demand response.

DEVICES FOR IMPROVING FLEXIBLITY AND CONTROL IN POWER BALANCING

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, such devices need to be coordinated with larger FACTS devices for series compensation as well as SVC and STATCOM.

A SYSTEM VIEW IS NEEDED

Investments in smart power T&D infrastructure 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".

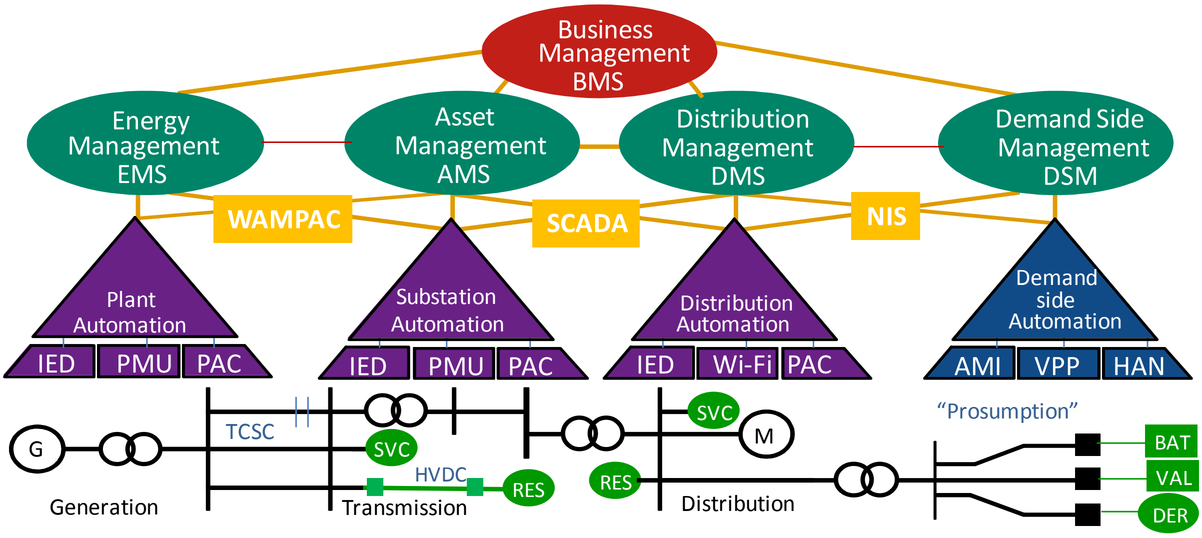


Figure 6. The digital power system

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.

TO PREDICT THE FUTURE, YOU HAVE TO CREATE IT!

There is near-consensus among energy sector players regarding the substantial challenges that lay at the interface of energy and the environment. Stakeholders also agree that most of the technologies needed to transform the energy sector are already available, and can be rapidly demonstrated and deployed. Unfortunately, the development of these technologies and actions seems to be progressing too slowly if considered in the diverse scenarios that highlight the consequences of both action and non-action (see e.g., IEA's *Energy Technology Perspectives 2012*).

A smart and strong electrical infrastructure can make substantial contribution to meeting energy and climate goals, but decarbonisation of energy will require increased electrification. In the European Union, for example, different scenarios aim to increase the share of electricity from a current level of 20% to almost 40% by 2050.

There is, however, no single universal solution. Industry should avoid any contradiction of the “grid vs. ICT”; one cannot solve everything only by building more transmission lines or with new “apps” or smart meters. Both elements are vital to a strong *and* smart power T&D system and new power electronics can help both elements. FACTS, especially VSC-based devices for compensation at the transmission level, together with boosting the development of VSC technologies for HVDC, provides increased flexibility to support smoother RES integration, voltage regulation and reactive power control. In the future, distribution systems with more connected DER will be similar to transmission systems. A static synchronous compensator (STATCOM) is based on VSC technology with power transistors and provides dynamic voltage control in transmission and distribution systems. Distributed FACTS (D-FACTS) and devices for distribution, such as D-STATCOM, can provide similar flexibility for distribution applications. These are the smart and strong “apps” needed. The technology is available but has to be demonstrated and deployed.

History demonstrates the value of close cooperation between state-owned utilities (which were often vertically integrated to manage generation, transmission and distribution) and private companies (which have their own R&D resources and in-house power system expertise). New approaches are needed to stimulate early investments in infrastructure with a system view. Thus, it is important that policy makers, regulators and governments establish the framework to allow for and finance necessary R&D and long-term investments.