C13 - Smart Grids

In the 1930s, the exponential growth of electricity demand required the creation of power systems, which performed extremely well until today. In fact, many of world's power systems still rely on 1970s technology, while trying to cope with the present necessities, when the electricity markets and the proliferation of renewable energy resources push their operating limits to the extreme. In order to respond to these challenges, and aiming to accommodate future technologies that are around the corner, such as electric vehicles and energy hubs, the smart grid concept is designed to be the next generation of power systems, built for the needs of the 21st century.

The British Institution of Engineering and Technology (IET) defines the Smart Grid as "an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies." [factbookIEC]

The US Department of Energy states that "the digital technology that allows for two-way communication between the utility and its customers, and the sensing along the transmission lines is what makes the grid smart. Like the Internet, the Smart Grid will consist of controls, computers, automation, and new technologies and equipment working together (...) to respond digitally to our quickly changing electric demand."

There is no single agreed definition for a smart grid, but there are some general characteristics universally accepted as forming a smart grid:

- integration of modern digital automation, monitoring and measurement equipment, and new electricity storage technologies in all sections of a power system (production, transmission, distribution, consumer);
- effective and efficient integration of small-scale distributed resources (DER) in the system dispatch and in the electricity market
- empowering of the small consumer with choice and decision opportunities, by allowing real-time direct two-way communication between the utility and its clients.

However, the transition to smart grids must be done "on the fly", because the existing power systems cannot be simply shut off for a couple of months. This chapter aims to describe the developments envisioned by upgrading today's power grids into smart grids. Starting from a brief description of the current situation in production, transmission, distribution and consumer sectors, the advances proposed by smart grids are described, and the current state of smart grids in Europe is presented.

The production side of Smart Grids

Traditional power systems were created for economic reasons, with the idea of building large production facilities in a minimal number of locations which would serve a wide territory via the HV transmission system. The main priority was the supply of all potential consumers at the lowest price, and the climate change factor was not a concern.

Thus, large plants of hundreds and thousands of megawatts installed power were built, fired by conventional fossil fuels such as coal and petroleum. Later, large nuclear power plants were commissioned. The only "clean" energy source was hydropower.

This arrangement was optimal for the vertically integrated business model in the electricity sector, where a single company controlled everything from production to supply.

In the mid 1990s, two key factors changed:

- the energy sector deregulation encouraged the proliferation of privately owned electricity producers, who competed in liberalized electricity markets.
- world governments became aware of the climate change problem and began supporting the implementation of incentive plans for large and small scale clean renewable energy sources (RES).

These factors changed fundamentally the production sector configuration in developed countries. A relevant example is that of Denmark, as seen in Fig. 13.1.

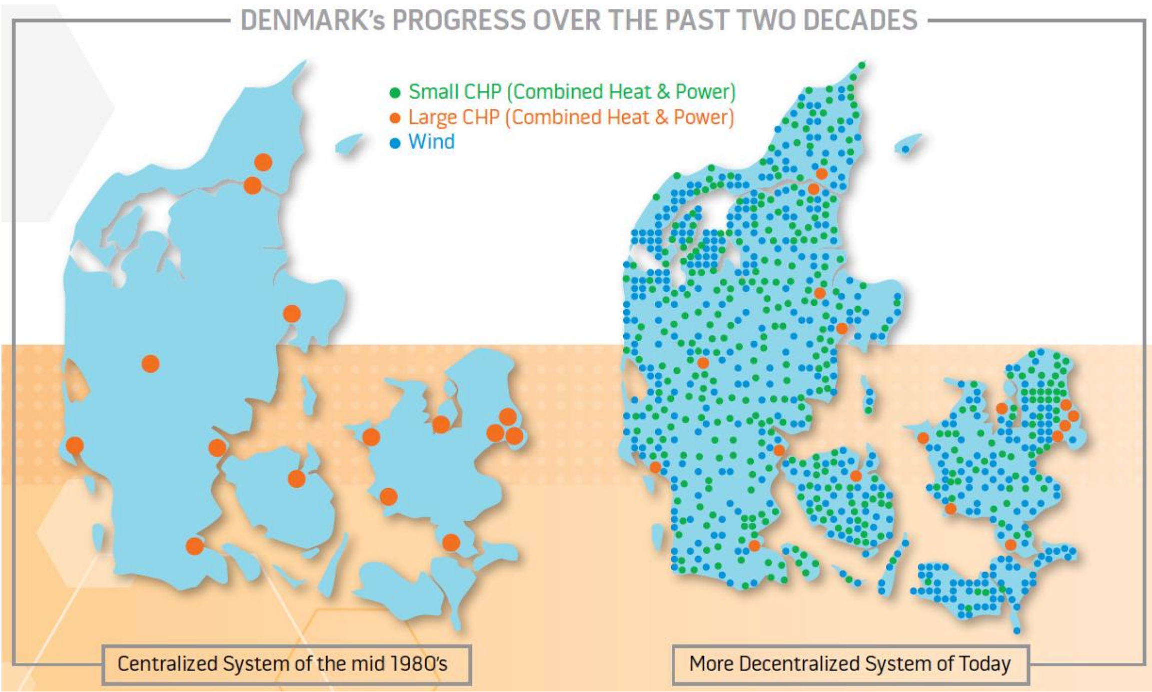

Fig. 13.1 - Production sector changes in Denmark, for two decades (image source: [reportUS])

Different production technologies have different running costs and start up times.

- fossil fuel plants have high and volatile variable costs with fuel, high start up times (tens of hours), and high pollution costs. Their advantage is the reliable supply in large quantities.
- nuclear plants have the disadvantages of high initial investment costs and high starting time of a nuclear reactor (1-2 days), and the potential environmental problem of accidents and radioactive waste. Their advantages are high availability, high output, low production costs and clean operation, with no pollution.

- hydroelectric plants have the disadvantages of high initial investments and water supply limitation, and the advantages of the lowest production costs and fast start up times (of minutes)
- renewable sources (photovoltaic and wind) have the disadvantages of high initial investment costs and running unpredictability. Since sunlight and wind cannot be controlled, the solution chosen often by system operators is full or partial backup with conventional production reserves, which incur additional costs and technical constraints. Their advantages are low running costs, because they do not require any fuel, and the absence of pollution.

For achieving the world's environmental targets, the non-polluting production facilities are given priority in the market. While in the centralized model it was economically efficient to run large fossil fuel power plants to cover the base load, and the peak hours were covered by hydroelectric power plants and fossil (for high peaks), now priority is given to nuclear and renewable sources, while peaks must still be covered by starting expensive fossil fuel plants (Fig. 13.2).

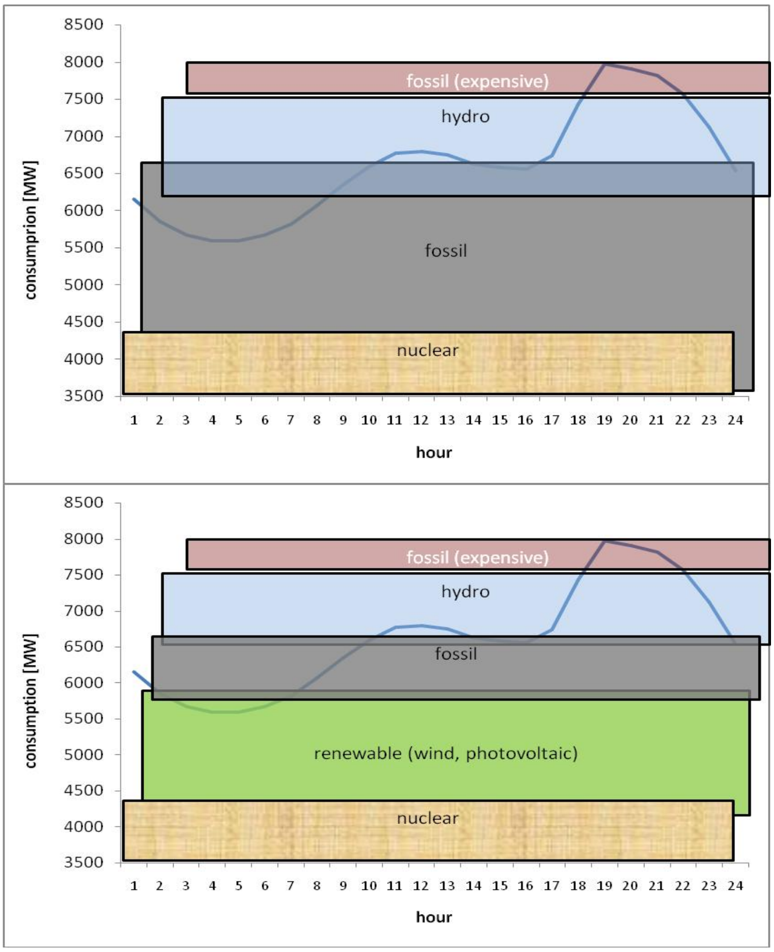

Fig. 13.2 - Changes in the generation dispatch brought by the proliferation of renewable resources

Also, many renewable sources are small-size producers, such as households and business buildings. Given their high number and small output, their dispatch is a problem in the current configuration of power systems monitoring and control infrastructure.

Smart Grids come to address exactly this problem. By increasing the "smart" component of the system with Intelligent Electronic Devices (IEDs), grid automation and two-way communication, these small scale producers can be included in the dispatch mechanism and in the electricity market.

The transmission and distribution side of the Smart Grid

In the high voltage transmission grid, system control and monitoring is already "smart" to a large extent, HV stations and control being already upgraded to the state of the art in monitoring equipment and analysis tools. The electricity demand increase will require further investment for reinforcing the grid by adding more HV lines. Another solution for the future is the use of DC lines, which offer more capacity and are most suited for interconnections between high electricity consumption places, but currently are more expensive to build than AC lines.

In distribution systems, things are different, and it's here where the implementation of smart grids will bring the most radical changes. The continuous increase of electricity demand will make the existing infrastructure insufficient in the next decades both in supply capacity and operation reliability.

Another problem is the integration of small scale producers, the so-called Distributed Energy Resources (DER). The existing distribution systems were built for the traditional power system model, in which they were passive, i.e served only to one-way delivery, from HV to LV, with no local generation sources. Currently, DERs are in their early development stage, their impact on the grid operation is low and they are managed as non-dispatchable sources, but it is expected that their number will increase dramatically in the next decades, with the trend of small consumers to seek energy independence. With such a scenario, especially for wind power plants, where the peak production hours do not necessarily match the peak local demand hours, there could be significant power flows from the distribution to the transmission network (Fig. 13.3).

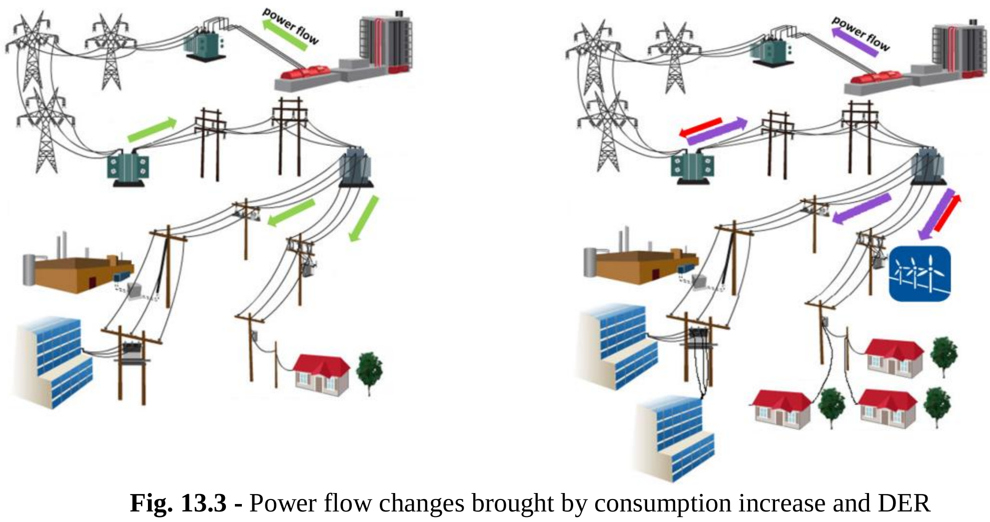

Fig. 13.3 - Power flow changes brought by consumption increase and DER

The Smart Grid automation and intelligent devices aim to create a sophisticated monitoring and control infrastructure at the distribution level for addressing this kind of problem. Moreover, a smart distribution system would enable voluntary islanding, reducing the dependence of consumers from the utility. When the supply fails or a wider area blackout has occurred, local communities could cut themselves from the main grid and operate as small islands, sharing the local generation capabilities to cover their immediate needs. This addresses the key point of supply reliability.

Another benefit of creating a system-wide monitoring infrastructure is the increase in efficiency of operation. In the USA alone, the electricity demand doubling by 2050, investments in infrastructure needed to support this growth are estimated to mount to $1,5 trillions. The improved efficiency brought by Smart Grid technologies is expected to ease congestion and increase utilization, thus eliminating or at least postponing the necessity of building new costly lines and substations. The 2004 US Department of Energy report on Smart Grids [reportUS] estimates the gains from improving the efficiency of grid use in the following terms: " If the grids were just 5% more efficient, the energy savings would equate to permanently eliminating the fuel and greenhouse gas emissions from 53 million cars" and "It is estimated that Smart Grid enhancements will ease congestion and increase utilization (of full capacity), sending 50% to 300% more electricity through existing energy corridors."

The consumer side of Smart Grids

At household consumer level, the implementation of Smart Grids brings two main changes:

- the generalization of smart metering;
- automation and two-way communication with the utility, for enabling demand response (DR).

Smart meters are intelligent meters, capable of measuring more data than just daily active energy consumption (kWh), like today's analogue meters do. They are envisioned to bring several advantages to both consumers and electricity utilities:

- implementation of differentiated tariffs, where energy prices vary according to the hour of day when it is consumed, giving the consumer more power of choice and enabling him to save money by shifting consumption in the low demand hours. The ultimate goal is the implementation of real time electricity pricing;
- for small scale renewable generators, such as roof solar panels or small wind turbines, real time reading of consumption and generation makes possible the implementation of more accurate tariff schemes for paying household producers for the electricity delivered to the grid;
- the utility can read the home installed meters at a distance, eliminating the need of employing reading personnel and the current practice of estimated bills and periodic settlement.

The EU member states are required to ensure the implementation of smart metering under EU energy market legislation in the Third Energy Package. If a preliminary long-term cost-benefit analysis is positive, a roll-out target of at least 80% market penetration for electricity by 2020 is imposed.

The benefits of large-scale implementation of smart meters were proven by the first nation-wide rollout commenced by the Italian company ENEL, with more than 30 million meters installed by 2006 in the Telegestore project. Its main outcomes are summarized in [reportEU2011] as:

- approximately €500 million in yearly savings
- management of 3,027,000 bad payers in 2008
- decrease of cash cost/customer from €80 to €48 from 2001 to 2009.

Household equipment automation enables a new range of consumer services related to demand response, consumer flexibility and differentiated tariffs. Demand response means voluntary consumer cut-off from the grid at peak hours, with the aims of preserving system operation security (instability prevention) and peak consumption alleviation, which saves money and addresses the problem of high cost power plants needed for covering the demand at peak hours, a problem described in the previous paragraphs. Utilities would be able to shut off heavy consuming user appliances by sending automated commands from the dispatch centre to each household, by agreement with the consumers, who, in their turn, gain access to the electricity market, acting as buyers and sellers when grouping under an aggregator.

In summary, as described in [reportUS], a Smart Grid is

- Intelligent – capable of sensing system overloads and rerouting power to prevent or minimize a potential outage; of working autonomously when conditions require resolution faster than humans can respond, and cooperatively in aligning the goals of utilities, consumers and regulators;
- Efficient – capable of meeting increased consumer demand without adding infrastructure;
- Accommodating – accepting energy from virtually any fuel source including solar and wind, as easily and transparently as coal and natural gas; capable of integrating any and all better ideas and technologies – energy storage technologies, for example – as they are market-proven and ready to come online;
- Motivating – enabling real-time communication between the consumer and utility so consumers can tailor their energy consumption based on individual preferences, like price and/or environmental concerns;
- Opportunistic – creating new opportunities and markets by means of its ability to capitalize on plug-and-play innovation wherever and whenever appropriate;
- Quality-focused – capable of delivering the power quality necessary – free of sags, spikes, disturbances and interruptions – to power our increasingly digital economy and the data centres, computers and electronics necessary to make it run;
- Resilient – increasingly resistant to attack and natural disasters as it becomes more decentralized and reinforced with Smart Grid security protocols;
- "Green" – slowing the advance of global climate change and offering a genuine path toward significant environmental improvement.

Current state of developement

The [reportRU 2011] summarizes the following facts:

- According to the International Energy Agency (IEA), Europe requires investments of €1.5 trillion over 2007-2030 to renew the electrical system from generation to transmission and distribution, investments for Smart Grid implementation and for maintaining and expanding the current electricity system being included;
- In the United States of America, $1.5 (€1.06) trillion is necessary to update the grid by 2030 (under current trends and policies) of which $560 (€395) billion is needed for new and replacement generating plants and $900 (€635) billion for transmission and distribution together; benefits from Smart Grids being estimated to be up to $227 (€160) billion over the next 40 years.

The Joint Research Centre of the European Commission report on Smart Grid development for 2014 gives the following statistics (graphs source: [reportEU2014]):

Fig. 13.4 - Summary of Smart Grid Projects in Europe up to 2014

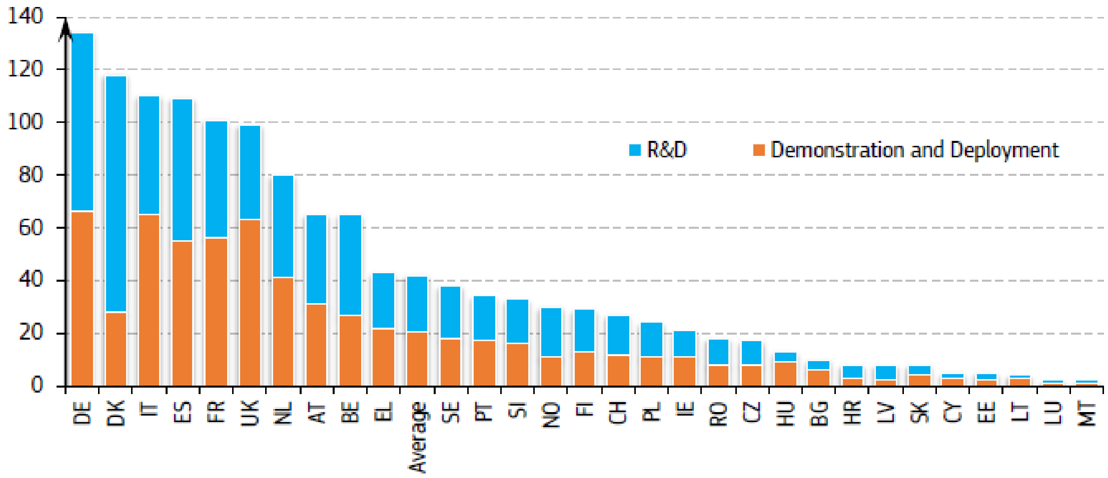

Fig. 13.5 - Distribution of projects by number

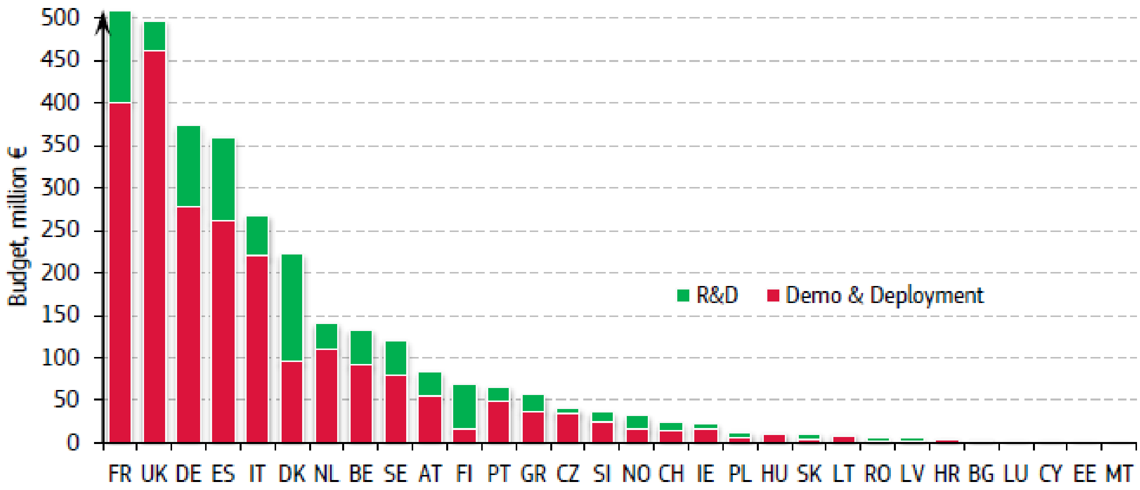

Fig. 13.6 - Distribution of projects by total budget

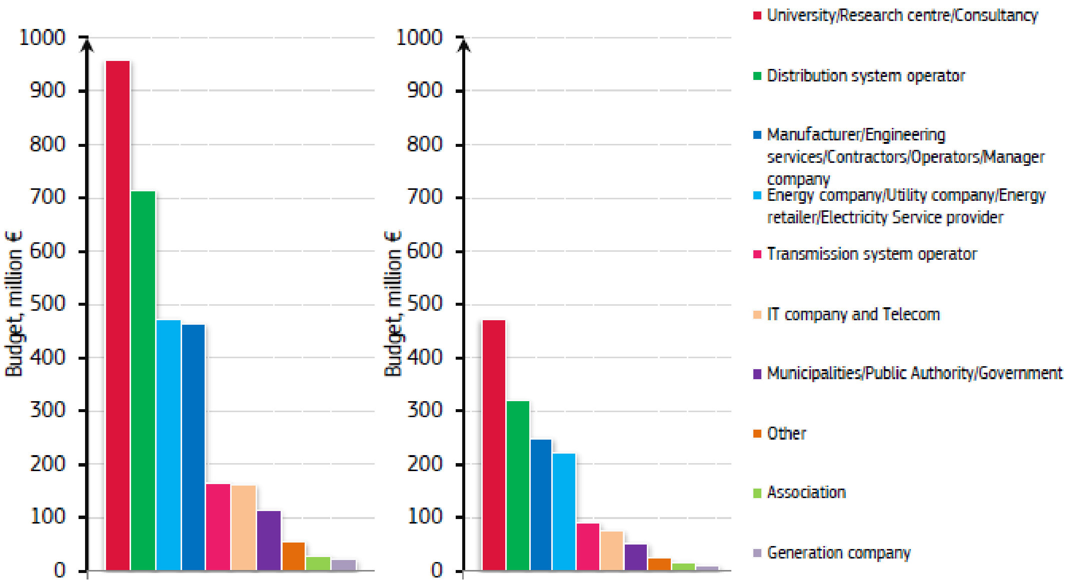

Fig. 13.7 - Investments (left - total, right - private) by organization type

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[factbookIET] What is a Smart Grid? - A Briefing provided by The Institution of Engineering and Technology, UK, 2013, available online at http://www.theiet.org/policy/key-topics/smart-grid/

[reportEU2011] Smart Grid projects in Europe: lessons learned and current developments, an report prepared by Vincenzo Giordano, Flavia Gangale, Gianluca Fulli (JRC-IE), Manuel Sánchez Jiménez (DG ENER), Reference Report by the Joint Research Centre of the European Commission, document code EUR 24856 EN, December 2011, available at www.smartgrid.gov/document/smart_grid_projects_europe_lessons_learned_and_current_developments

[reportEU2014] Smart Grid Projects Outlook 2014, Authors: Catalin Felix Covrig, Mircea Ardelean, Julija Vasiljevska, Anna Mengolini, Gianluca Fulli (DG JRC), Eleftherios Amoiralis (External), report by the Joint Research Centre of the European Commission, document code EUR 26651 EN, 2014, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/smart-grid-projects-outlook-2014

[reportUS] The Smart Grid: An Introduction, prepared for the U.S. Department of Energy, http://energy.gov/oe/downloads/smart-grid-introduction-0