CHAPTER 1

DRIVERS FOR THE DEVELOPMENT OF HVDC GRIDS

Dirk Van Hertem
Research Group Electa, Department of Electrical Engineering, University of Leuven, Leuven, Belgium

1.1 INTRODUCTION

For a long time, the electric power industry was seen as a stable and fully matured sector, which was operating well without much innovation. Over recent decades, the situation has changed drastically, with a rapid development and innovation process. There is a strong interest from the general public for a cleaner and cheaper supply of electric energy. At the same time, the security of energy supply must be kept at the existing level, or should even be increased. The consequences are seen throughout the industry and throughout the world, with as a consequence fundamental changes in the generation of electrical energy. From a transmission point of view, this results in the need to fundamentally invest in the transmission system and to move towards a smarter and more flexible use of the grid. Different geographic, social, and historic influences have led to a different evolution over the continents. In this chapter, the different drivers of the energy revolution are discussed and the effect that these drivers have on the development of the electrical energy system is sketched. The focus is on the developments on the bulk power transmission level.

This chapter describes the evolution and the drivers in energy policy, resulting in a strong move towards the development of the offshore grid and supergrid. As the perceived drive is strongest in Europe, the main focus is on the evolutions there.

1.2 FROM THE VERTICALLY INTEGRATED INDUSTRY TO FAST MOVING LIBERALIZED MARKET

1.2.1 Brief History of the Transmission System Before Liberalization

After the introduction of electricity, the power industry has been in continuous evolution throughout the twentieth century. The earliest systems consisted of a single

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generator connected to one or more nearby loads. A generator company owned the generation unit and the grid connecting the loads. This generator company sold electricity directly to its customers. In order to increase reliability, facilitate a growing demand, and provide a sufficiently flexible grid operation with a minimum of assets, these local grids were connected to form interconnected grids. The outage of a single generator no longer led to supply interruption. As loads increased, more systems were interconnected, the total generated power grew and higher voltage levels had to be used. Longer distances were covered. Step by step, entire countries were electrified and smaller independently operated power systems were connected.

In continental Europe, the establishment of international interconnections really started after World War II. This led in 1951 to the establishment of the "Union for the Co-ordination of Production and Transmission of Electricity" (UCPTE) [1]. Since then, an international transmission system was developed with strong interconnections at the 380-kV level. UCPTE originally oversaw the development of economic activity through the improved exploitation of primary energy resources associated with the interconnection of electricity systems. Gradually, UCPTE also organized the international cooperation between the electricity system operators and set common operational rules, amongst which is a strict frequency control. NERC[1] fulfilled a somehow similar role in the United States, where different synchronous zones cooperated from the early 1960s.

On a local level, a consolidation of power companies led to the situation in the 1990s in which each country in Europe had one or more vertically integrated companies, each dealing with their own zone. They were responsible for generation and transmission of electricity, and in some countries also for distribution. This included the planning, operation, maintenance, and exploitation of the transmission system as well as the power plants. Often these companies were state-owned or state-controlled. The power system is still operated as such in a significant part of the world.

In the vertically integrated system, operation is done from a best engineering practice point of view. To ensure a high reliability, investments are done in a coordinated manner: Generation and grid development are planned by the same group of engineers or at least within one firm. The focus is to provide an adequate energy supply with a grid which is sufficiently secure. Also, the management of the entire power system is within a single entity. As the entire supply chain is within a single company, there is a tendency to favor generators which are "grid friendly." This generally means large, controllable generators with a high availability and predictable energy supply. In such a utility, "economies of scale" resulted in large centrally planned power plants, mostly using fossil fuels or nuclear energy, or hydro power where available.

As stated before, connections between zones also existed in the vertically integrated system. On the one hand, they allowed for support during events that threatened the secure operation of the power system, enabling each zone to operate more economically, with fewer reserves needed. On the other hand, long-term contracts between countries existed, allowing international trade. This made the cheap hydro power from the Alps and the cheap and abundant nuclear power from France

[1]North American Electric Reliability Corporation (NERC), http://www.nerc.com

available to other European countries. Mainly AC links were used, connecting the different zones into synchronous zones, but also asynchronous links existed in the form of HVDC connections between different synchronous zones.

As a whole, the vertically integrated power sector in industrialized countries was a slowly changing and well-established business, with limited, well-defined problems. This was especially so after the economic development in the industrial world became mature and the increase in energy consumption dropped to a few percent per year. However, as there was no competition, the power system was not necessarily operated at the highest techno-economic optimum.

1.3 DRIVERS FOR CHANGE

Although that the implementation and the priorities concerning energy policy differs between countries and regions, they are generally built around the same main pillars. Energy policy has the objective to ensure an energy provision that is reliable, cost-effective (cheap), and sustainable (Figure 1.1).

Given the importance of energy to the overal economy, a secure energy supply is crucial to the modern industry and society as a whole. The security of supply (SoS) requires the system to have sufficient resources available (adequacy), the infrastructure available to transmit the energy from the source to the consumer with sufficient redundancy, and the ability to deliver the energy at any given moment. Failure to do so leads to short-term economic and national security concerns in the form of (local or wide-scale) blackouts. The relative economic position of a country or region can be compromised if the security of supply is threatened over a longer period of time.

The second aspect is a cost-effective energy supply, which also has a direct impact on the economy of a country or region. A cost-effective energy supply requires access to the cheapest energy sources.

The last pillar of energy policy is a sustainable energy supply. Sustainable can be understood as an energy provision that can be maintained on a longer time horizon (e.g., using only sources that are non-exhaustible) or more narrowly as an energy provision that can be maintained over a longer time horizon taking into account the environment and society effects (e.g., using only renewable energy sources).

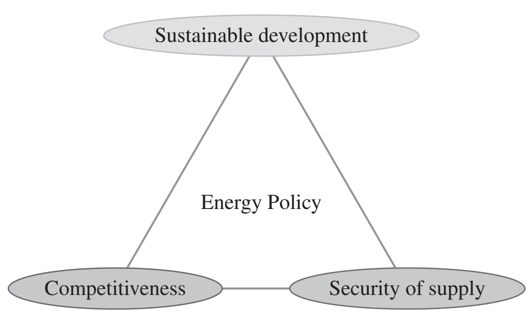

Figure 1.1 Policy drivers for the energy supply of the future: competitiveness, sustainable development, and security of supply [2].

The main concern dealt within this book is related to the reliable transmission of electrical energy from source to consumer using the appropriate transmission infrastructure for electricity. However, to understand the drivers for transmission developments, the entire energy system context needs to be considered. Over the past few decades, fundamental changes in energy policy and technology development have caused a significant change in the energy system, which in turn result in a energy system where HVDC connections are gaining importance and where HVDC grids can be developed. The specific drivers for HVDC grids are the liberalization of the energy sector and the increase of renewable generation in the energy mix.

1.3.1 Liberalized Energy Market

Economic theory suggests that competition leads to price reductions and higher economic efficiency [3–6]. With this theory in mind, different countries decided to introduce the concept of competition in the electricity sector. This process was started in the late 1980s in the United Kingdom, and it was soon followed in other countries.

1.3.1.1 Liberalized Energy Market in Europe Also the European Union decided to liberalize the electricity market in the entire EU. The basis was laid in the treaties of Rome (1957) and Maastricht (1993) as the foundations for the creation of an Internal European Market (IEM), where people, goods, and capital could freely move. In 1996, the Directive 96/92/EC [7] was published, which initialized the liberalization process for the electricity sector by setting the general conditions for the creation of an IEM. The directive included the opening of the market by slowly increasing the numbers of consumers that had the freedom to negotiate the sale and purchase of electricity. Customers were free to choose their suppliers in the European system. Furthermore, grid access was defined and regulated. Thirdly, the tasks and structure of the system operator were set. From then on, system operators had to be administratively unbundled from the generating companies [8]. The transmission and distribution of electric power was split from generation and brought into separate companies. The first directive was later replaced by a second and third energy package and is still under development. The current energy policy foresees among other things:

- Full unbundling of generation and transmission of both electricity and gas
- A (pan-)European Network for Transmission System Operators for electricity and for gas (ENTSO-E and ENTSO-G)
- A European regulatory body ACER,[2] with binding decision powers, to complement national regulators
- Increased power and independence of the national regulators
- Further promotion of cross-border cooperation and investments
- Greater transparency
- Increased solidarity
- Full internal European Market for energy

[2] ACER: Agency for the Cooperation of Energy Regulators http://acer.europa.eu/

While the vertically integrated system predominantly depended on long-term planning from within a single firm, the liberalized market encourages a more dynamic market mechanism, with more competing players. It becomes possible to trade electricity throughout the European Union, gradually leading to an increase in international flows. The interconnected transmission system has links between zones, originally intended for security and limited transfers, but not to enable large international transfers. As a result of these increased flows, congestion occurs in the transmission system, often at country borders.

1.3.1.2 Consequences of Liberalization The consequences of the liberalization process are far-reaching and have fundamentally altered the manner in which the power system is planned and operated. A first important change is the number of stakeholders involved. A complete new set of players was created, with different responsibilities, possibilities, and limitations compared to the earlier vertically integrated companies. On a local level, companies are split or new companies arise. On the international level, new organizations were created that aim at ensuring a system that is transparent and tries to steer the system towards an operation with maximal social welfare.

The following (new) entities are important to mention with respect to the development of the energy system after liberalization in Europe.

Generator company: Generator companies compete in the liberalized market. The companies are free to offer their generation portfolio (both in terms of quantity and duration) in the marketplace. There, generation and load bids are matched and a price is found against which the energy is traded. This transaction happens both on long and short term. Not all energy is traded on a market as also direct “over-the-counter” (OTC) trade is done. As the European market is open, every generator company is free to sell its energy to any market participant. This results in a competitive marketplace, which in principle leads to increased efficiency.

Investments in generation are done when perceived economically worthwhile. As such, only the most economical investments are done. This should benefit the end user, but also could lead to underinvestment in generation on the long run. On a national level, the self-sufficiency of energy supply in countries is no longer guaranteed during peak load conditions, possibly resulting in an increased dependence on import.

TSO: Transmission System Operator must ensure a safe operation of the transmission system (keeping the lights on), provide adequate asset management (investments and maintenance) and facilitate the market in a nondiscriminating manner. The TSO is responsible for balancing generation and load and within its control zone to match the scheduled import and export. The transmission system is operated as a monopoly under regulated supervision.

TSO boundaries often coincide with country (state) borders, although there are several exceptions where there are multiple TSOs per country. The TSO can be split into a system owner and a system operator.

In Europe, ENTSO-E[3] is the organization joining the different TSOs in Europe (within EU and beyond).

Merchant investors: These are investors that have received exemption from normal regulations are not owned by the system operator and remuneration of their assets goes through special (usually market-based) schemes.

DSO: Distribution System Operator is the entity responsible for the distribution network.

Consumers/retailers: These individuals have the right to choose their provider of electrical energy. Smaller consumers are supplied by retailers, while larger ones can buy directly in the commodity market, not bounded by country borders. The time frame in which contracts take place can be long or short. As a result of both the variable source and sink location, power flows throughout the power system become less predictable.

Regulator: Next to the companies involved in the trading process, a regulator is appointed to supervise the market and to advise the government on the organization and functioning of the electricity market. As such, the regulator sets the tariffs for transmission and distribution. They also approve the investment plans proposed by the regulated and nonregulated investors.

Throughout Europe, as a rule, one regulator is assigned per country for the transmission system. These regulators do not all have the same powers, competences, and legislative framework. The proposed third energy package of the EU intends to improve this aspect with a better cooperation between regulators, or even an overseeing regulatory agency (ACER).

It is clear that the interaction between several stakeholders, which were formerly operating under a single organization, is more difficult and can lead to inefficiencies.

1.3.2 More Renewables in the Energy Mix

The energy mix influences the future grid in a number of ways that are addressed here. A more in-depth discussion of the foreseen changes in the energy mix can be found in Chapter 2.

1.3.2.1 Increasing the Share of Renewable Energy Sources Throughout the world, a growing awareness concerning the environmental footprint of the human species is noticed. Especially greenhouse gases are considered problematic for contributing to global warming. As the generation of electricity from fossil fuels is an important contributor to CO_2 emissions, these sources are increasingly replaced by renewables. Europe has been a strong advocate of the development of renewables for electricity generation by publishing a directive to increase the renewable energy production from 14% to 22% between 1997 and 2010 [9]. In January 2008, a new directive was proposed and adopted by the Commission, and binding targets for individual countries were set in the so-called 20–20–20 targets [10]:

[3]ENTSO-E: European network of transmission system operators for electricity, http://www.entsoe.eu

- A 20% reduction in EU greenhouse gas emissions from 1990 levels
- Raising the share of EU energy consumption produced from renewable resources to 20%
- A 20% improvement in the EU's energy efficiency

Also post 2020, a continuation of the effort for more renewables in the energy supply is foreseen, with binding targets of a share of 27% of energy consumption generated from renewable energy sources by 2030 [11].

Although electric power from renewable energy is not directly related to the liberalization of the electricity market, the influence of the latter may not be underestimated. During the pre-liberalization period, generation was usually based on well-known technologies with a high-capacity factor. Typical examples of such power generators are nuclear, coal, combined heat and power, and large-scale hydro. Variable renewable energy like wind and solar was usually seen as low power, inefficient, difficult to operate in the system, and above all costly. The liberalization ensured that any amount of energy, no matter the scale, could be sold with potential profits. In the wind sector, small-scale generation became popular and increased rapidly, partly driven by support mechanisms. This led to the continued development of increasingly larger and more economic installations. Today, wind farms in the same range as medium-sized fossil fuel-based power plants are no oddity.

The different possible renewable sources for electricity generation are solar, geothermal, hydro, tidal, wave, biomass, and wind energy. The use of geothermal, tidal, and wave energy strongly depends on the location, and the majority of large-scale European hydro power reserves are already in use today. This leaves biomass, solar, and wind energy as the main possibilities to increase the use of renewable energy sources in Europe on the short term. Although biofuels can be and are used for electricity generation, the main aim is currently to use biofuels as a renewable source of energy for the transport sector. As a result, the main increase in electricity generation from renewables within the EU is coming from wind and solar energy. It is important to note that the development of these technologies has been strongly driven by policy and, most importantly, by the support schemes and subsidies for these energy sources. The same increase in renewable energy sources, albeit a bit delayed, is also seen in other parts of the world.

1.3.2.2 Foreseen Changes in Energy Mix and the Effect on Grids In 2013, wind energy passed the 120-GW installed capacity threshhold in Europe [12]. In Germany alone over 34 GW of wind and 35 GW of solar power was installed by end 2013 [13], which equals to over 17% of the installed capacity in Germany each. Especially for wind and solar power generation, a strong further increase of generation capacity is expected until the middle of this century [14–16]. A strong increase in generation from renewables is also expected in the rest of Europe, with an anticipated increase in installed capacity from offshore wind power to exceed 150 GW [17]. At that moment, the installed onshore wind power generation will amount to about 250 GW. As such, a big part of the electricity generation mix will be provided by wind power [17]. The best sites for wind power plants are situated in the North Sea region and the western part of Europe (Figure 1.2a). On the other hand, the best sites for large

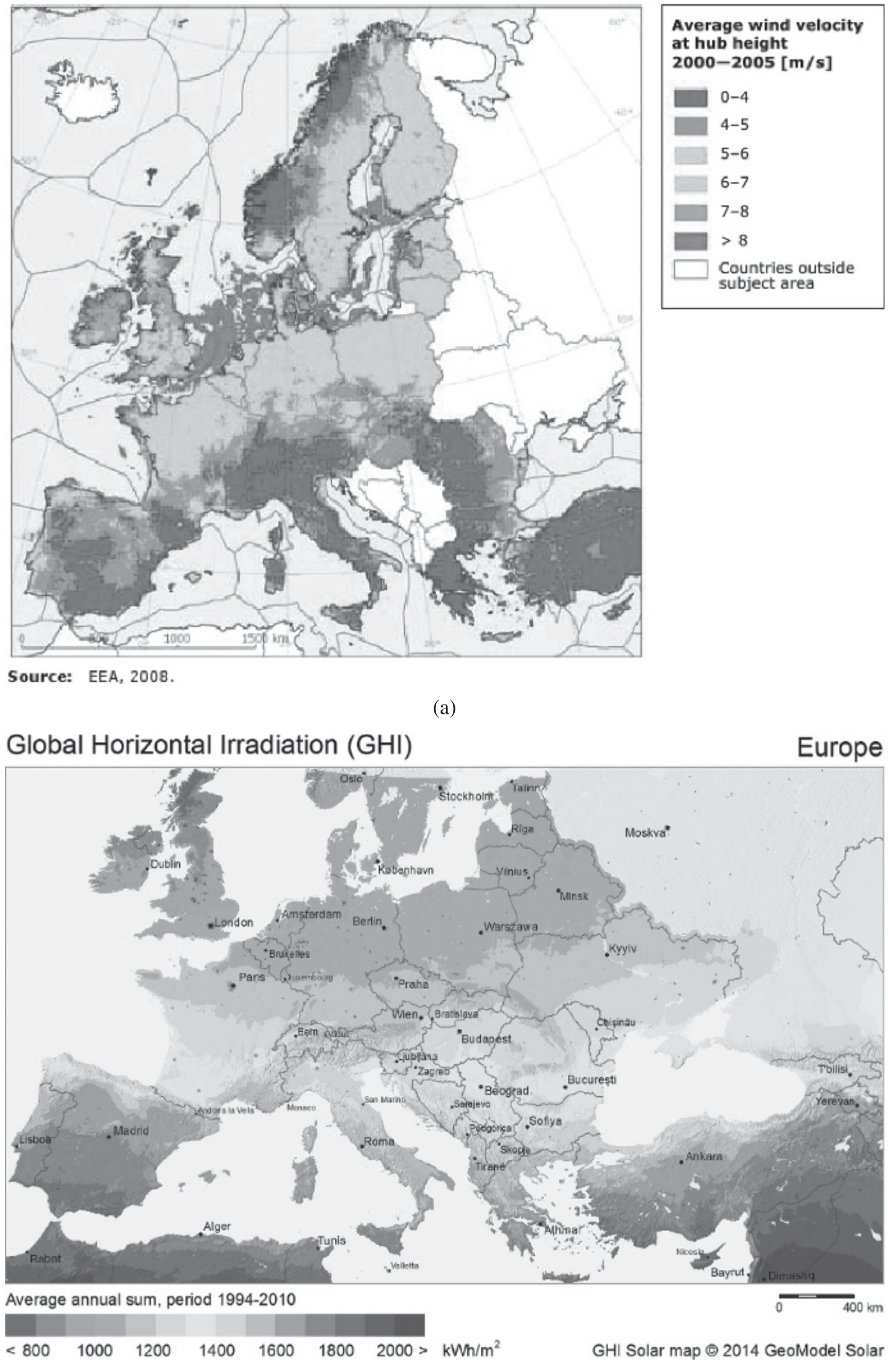

Figure 1.2 Location of wind and solar resources. (a) Average wind profile in Europe. (*Source*: EEA) [18]. (b) Average solar radiation in Europe. (*Source*: SolarGIS. Copyright ©GeoModel Solar.)

scale solar power plants are situated around the Mediterranean Sea: in Spain, Italy, and Northern Africa (Figure 1.2b). Classical generation (fossil fuels and nuclear) will not disappear and completely be replaced by RES on a short time horizon, but the system will evolve towards a new generation mix, with the traditional generation not necessarily located at the same location as it is now. Where the generation originally was placed near the load center or near the source of primary energy, a shift is noticed towards the latter. For the European energy supply, this means a shift of classical generation towards the borders of the system, specifically towards harbors. Overall, it can be seen that electrical energy is transmitted over longer distances, a tendency which is expected to continue.

A second consequence of an energy mix with more renewable energy sources is the more pronounced need for balancing services (not necessarily local) and the limited capacity factor of these energy sources. While the transmission investments need to accommodate the generation capacity (power rating), the transmission investments connecting towards that generator will be less efficient as the link will have a lower amount of energy to transport. Not only this effect is valid for direct connections to renewable energy sources, but throughout the grid a higher reserve transmission capacity is needed to accommodate for an equal amount of energy transferred. When hydro energy from Scandinavia or the Alps is used to balance the fluctuating generation from renewable energy sources, they also need sufficient transmission capacity to perform this balancing.

Much of the renewable energy is connected to lower-voltage networks at the distribution grid. These generators are generally not controllable by the grid operators, and their operation is even not transparant to the grid operator. As a consequence, each connection to the distribution grid, which was always acting as a slowly varying and predictable load, is now a much more variable and uncertain. Furthermore, the generation and consumption of energy is not simultaneous. Solar integration is a good example of this change. Although the load profile of solar largely coincides with that of the general system load, it does not coincide with that of the residential customers who have these devices mounted on their rooftops and generally consume less during the day. As a result, the load profile of that residential area shows even larger differences in the load profiles over the course of a day. The power system acts as a buffer. An option which receives much attention at the moment is the inclusion of integrated local energy storage to compensate for peaks in generation (and load). Such systems can limit the need for investments in grids, specifically at the distribution level.

Because the load centers are situated in central Europe [the region roughly comprising the Benelux, the north of France (including Paris), (Western) Germany, and north of Italy] and England (Figure 1.3), it will be inevitable to build new north–south and west–east connections within Europe to secure electricity supply to the demand centers. Furthermore, the load centers are getting more concentrated as there is a noticeable shift of the population and industry towards the city.

Although the energy consumption is getting increasingly efficient, the consumption of electrical energy is expected to continue to rise slowly over the next decades. Not only is there a general tendency towards a higher level of comfort, there is also a fundamental shift of energy consumption towards electricity—for example, through the anticipated introduction of electric vehicles.

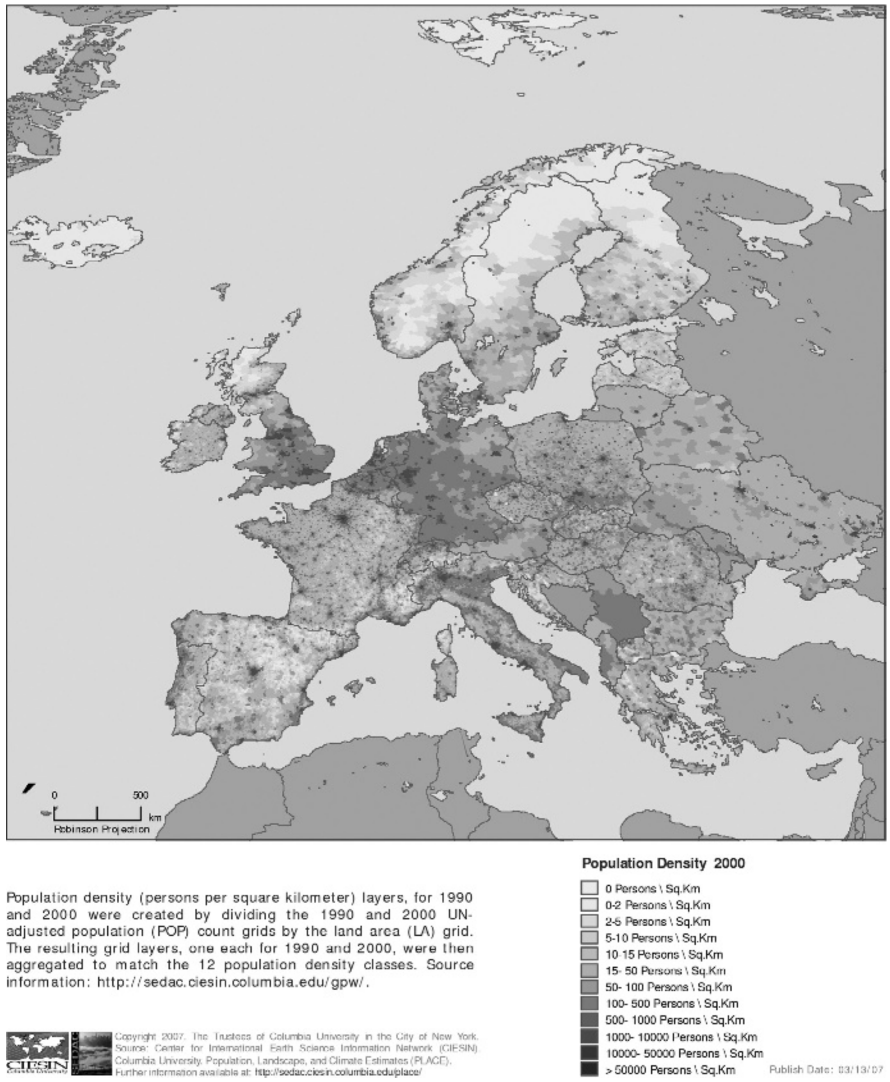

Figure 1.3 Population density in Europe. (*Source*: Columbia University.)

1.4 INVESTMENTS IN THE GRID

1.4.1 Why Investments Are Needed in the Transmission System

After the introduction of more renewables and liberalization, system operation has become more challenging due to more variable energy flows through the power system, which is furthermore less controllable due to a reduced number of control options available to the system operator. At the same time, renewables integration and the new market environment not only increase the flows on the international transmission system, but also make those flows more variable in time. Add to these facts that the demand for electric power keeps increasing, although at a reduced pace in industrial countries, and that there is increased transmission distance between generation and load; it is obvious that the system is used closer to its operational and security limits while uncertainty increases. Investments in new transmission lines form a clear and necessary solution to overcome the aforementioned problems. The correct investments can alleviate the flows in the system and remove congestion. The safety margin increases, and higher transmission capacity becomes available to the market. Additional transmission capacity between zones is needed to remove bottlenecks in the transmission system. Doing so, prices converge, when all bottlenecks are removed, a so-called *copper plate* system is reached, without congestion and a single price zone. In such a system, each user has access to the cheapest energy source. However, it is important to note that the formation of a copper plate transmission system is in fact an overinvestment, and an economic balance between investments, reliability, and congestion costs results in the most cost-effective energy system.

Not only new grid requirements drive the need for new investments. The existing transmission system is aging and slowly reaching its design life. The current system was largely constructed in the 1960s, 1970s and 1980s. As such, a considerable part of the current system is approaching the end of life and requires a fundamental refurbishment in the decades to come.

Grid interconnection capacity is also a fundamental contributor to security of supply, allowing exchange of energy over a larger system—for example, by reducing local effects of renewables through spatial balancing. With this in mind, the European Commission proposed to set a target for the interconnection capacity between member states to 15% by 2030 (where it currently stands at an average of 8%) [19].

The advantages to increased interconnection capacity include [20]:

- Improved reliability and increased capacity reserve
- Improved load factor and increased load diversity, leading to reduced investments in generation capacity
- Economies of scale in new generation units
- Diversified generation mix and supply security
- Increasing market potential
- Environmental dispatch and new plant siting
- Coordination of maintenance schedules

1.4.2 Difficulties with New Transmission Lines

Even when the reasons for additional transmission capacity are clear, in practice these investments are not straightforward. Several obstructions can cause severe delays or even cancellation of projects. These obstructions can be divided into social, environmental, political, legal, and economic [20].

Although new interconnections often improve overall social welfare in the corresponding regions, public resistance is common in industrialized regions.

Transmission lines are considered non-aesthetic and suffer from the *not in my backyard* (NIMBY) concepts and related syndromes.

Environmental concerns exist on the effects of electromagnetic fields on human health (although scientific consensus supporting these concerns is not available), or bird population. Acoustic noise is also a concern. Natural reserves are considered off limit for a transmission corridor. Oil-filled cables exhibit potentially dangerous or hazardous leakages, as do Gas Insulated Lines (utilizing the SF_6 gas). This makes it difficult to obtain permits for crossing natural reserves or residential areas, even when undergrounding parts of the corridor.

Legally and politically seen, several entities are involved in the process of permitting a new interconnection: international, national, and local authorities, ministries, and other public bodies, each with their own requirements, rules, and agendas [21]. The companies involved include not only transmission system owners, but also generator companies. The latter experience a different market situation after the construction of new capacity. Furthermore, several institutions or pressure groups at different hierarchical levels get involved. The result is a difficult and a complex permitting process with several facets that intertwine:

- Policy makers are greatly influenced by public concerns and tend to postpone any decision making as they could have a negative effect on forthcoming elections.
- Transmission investments are subject to a plethora of regulations and requirements, with possibly different and even conflicting requirements and time frames of handling. The fact that requirements are often linked does not help either (e.g., when the trajectory has to be altered because of problems obtaining an environmental permit, reapplication for a new building permit and afterwards an environmental permit can be required).

As such, obtaining a permit for an overhead transmission line takes normally about 7–10 years, but can take significantly longer [22]. In the power industry, there is a broad consensus that complex processes and unpredictable timetables for authorization and building of new lines are major issues in terms of building necessary transmission infrastructure.

Economically, not all players necessarily benefit from extra interconnections. Zones that expect a higher degree of export after the additional capacity may expect prices in their region to rise. In the importing region, the existing generator firms may see increased competition. For those players, a perfectly competitive market can potentially lead to lower profits. For system developers, the development of additional transmission infrastructure is governed by the regulatory framework and the remuneration of transmission investments. Financing and risk of such investments plays an important role (see also Chapter 9).

For international connections, finding new transmission paths requires the involvement of even more stakeholders, generally operating in a different framework. In references 21 and 22, different requirements for the application for new lines in different member states are given.

It becomes even more problematic when the most optimal investment in the transmission system for a certain TSO is not located within its own control area.

There is no incentive for a foreign party to invest in transmission capacity within its own zone that would mainly benefit an other party. This is a so-called *regulatory gap*, where there is currently no incentive for member state regulators to consider issues outside the borders of their country.

1.4.3 Available Investments Technologies

Several technologies exist to expand the available transmission capacity. A short overview is given here; a more in-depth coverage of this topic can be found in reference 23.

1.4.3.1 New Overhead Lines The traditional approach in transmission system enforcement is three-phase overhead AC transmission lines (OHL). This solution is very cost effective and robust. It uses technology that is known and used for decades. There are currently no technologies that can compete with OHL on a purely economic basis, especially not in rural areas [23]. Although OHL often experience short outages—for instance, due to lightning strikes—they can be restored with a simple line reclosure, making this a non-issue in meshed transmission systems. However, OHL have a high visual impact and are considered not appealing and possibly hazardous by public opinion. New tower types are available which are more visually appealing than lattice towers, but the towers can still be seen from a distance. This results in tough siting opposition and long permitting processes. The construction of a new transmission system demands a new transmission path, which requires a significant right-of-way (a corridor of up to hundreds of meters wide).

1.4.3.2 Uprating or Upgrading Existing Circuits A first option to add capacity to existing transmission paths is by making optimal use of the existing capacity through the use of dynamic line rating. A second option is to add capacity by adding an additional circuit to existing pylons or by increasing the voltage when possible. This is only possible when this upgrade was already conceived at the planning stage. Alternatively, the existing conductors may be replaced by new conductor types able to carry higher currents. New materials are constantly developed, which allow higher temperatures and, consequently, higher permissible currents for equal cross sections. These approaches can lead to significantly shorter permitting procedures as the right-of-way remains the same, and the visual impact of the transmission line is not greatly affected. Changing a double circuit three-phase AC system (6-wires) to an HVDC system can increase the capacity of a transmission corridor by a factor of 2 up to 3.5 [24, 25]. The German system operators consider using such conversion from AC to DC for the upgrade of the German transmission system [26].

1.4.3.3 Underground Cable Connections In order to avoid most of the visual impact, undergrounding transmission assets are considered the ideal solution. However, technically and economically, this is not necessarily the case. Next to being several times more expensive than OHL, high-voltage cables for transmission systems act as capacitors, requiring large compensation units, and hinder system operations. Cable systems for transmission system voltages are limited in length due to the charging current. A special type of cables are gas insulated lines (GILs) which allow longer lengths, higher transmission voltages, and higher power ratings. At this moment there are no long-distance connections using GIL installed. GIL is more expensive than underground cables. Serious advances are being made in the field of high-temperature superconducting (HTS) cables, which promise high ratings under low losses. At this moment though, the high-temperature supercondicting technology is not yet ready for use in the transmission system.

Underground connections are several times more expensive than overhead lines, while less troublesome concerning permitting and social requirements. Therefore, often a compromise solution is found, where part of the connection is overhead and part underground. The combined solution requires a substation at each transition. Each transition also comes with a change in the characteristic impedance, requiring additional equipment to protect it from voltage surges in the transmission system.

1.4.3.4 Grid Flexibility Through Power Flow Control The solutions proposed above all add capacity by adding new paths or strengthening existing paths. In the case of international connections, permits at both sides of the border are needed to achieve this incremental capacity. Power-flow-controlling devices (PFCs) such as phase-shifting transformers and HVDC connections offer a completely different approach as they consist of devices placed at one specific point. As such, they can be placed in existing interconnectors, influencing the flow through that path. The additional space required by devices such as the PST is normally limited to the device itself, which can be placed in an existing substation. When used as a reinforcement of an interconnector, only the investing zone/system owner is involved. This makes the permitting process much easier. The devices themselves allow the control of the power flowing through the devices. As such, they can redistribute the line flows in the system, alleviating stress on the heavily loaded lines and thus increasing the overall transfer capabilities of the grid. As this technology presents a single investment in a single device, the solution is in relatively cheap compared to other ones. PFCs receive lots of attention of TSOs that need increased transmission capacity for a short time. A more in depth coverage of the principles and the technologies is presented in reference 27. With respect to the applicability for grid investments, the power-flow-controlling devices are being categorized into two types: flexible AC transmission systems (FACTSs) [28] including phase-shifting transformers (PST) and high-voltage DC (HVDC) solutions. The HVDC solution combines the power flow control aspect and the additional transmission capacity.

1.4.4 HVDC Technology

Next to providing additional flexibility to the system through flow control, HVDC provides additional transmission capacity in itself. HVDC transmission systems transmit electric power at zero frequency and use power electronic converters to interface between the AC grid and the DC grid. Traditional applications of HVDC are:

- Bulk transmission of energy over long distances
- Interconnection of asynchronous systems (possibly back-to-back)
- Undersea connections

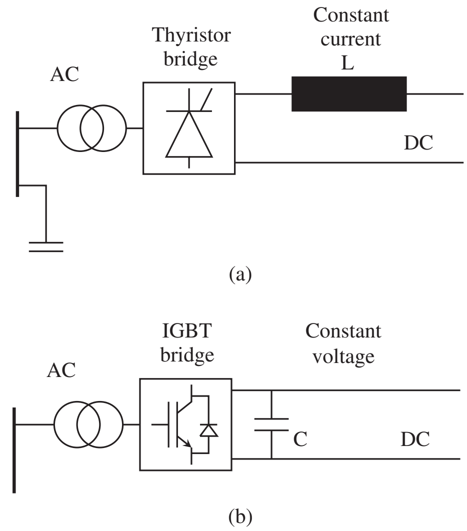

Figure 1.4 LCC- and VSC-HVDC one-line diagrams. (a) Current source converter. (b) Voltage source converter.

The most common and oldest technology is called line-commutated converter (LCC) HVDC, sometimes also referred to as current source converter (CSC) HVDC. It uses thyristors as switches and operates using a constant DC current characteristic. The DC voltage is controlled to alter the power flow.

Voltage source converter (VSC) HVDC was developed in the mid-1990s and uses IGBTs. The voltage source converters have a number of advantages over LCC technology. The VSC converter delivers a constant DC voltage, and the current is controlled to alter the power flow. This allows the use of the easier and cheaper XLPE cables instead of mass-impregnated oil-filled cables. Furthermore, the VSC converter can build an independent rotating field at the AC side. This allows the connection to weak islanded grids and offers black-start capability. An example is the connection to offshore wind power plants, which is virtually impossible when using LCC HVDC. Figure 1.4 shows the one-line schematics of the two technologies.

HVDC technology is briefly introduced in the following section and is discussed in far greater detail in the remainder of the book, more specifically in Chapters 3 and 4.

1.5 TOWARDS HVDC GRIDS

For many, VSC-HVDC technology is seen as an enabler for the future power system, and more specifically a technology that allows the massive integration of renewable energy sources in the system [29]. This is especially so for Europe, where large amounts of renewable energy are available on remote locations, often offshore or near the sea. The long-distance transmission of energy from source to load, but also for balancing, puts extra pressure on the already heavily loaded transmission system. Because of the variability of the renewable energy sources, more transmission lines are needed for the same amount of energy delivered when compared to classic energy sources [30, 31]. The lack of support for new transmission lines, especially overhead ones, require solutions other than the traditional AC overhead line [32]. An additional problem is the location of offshore resources, which are increasingly difficult to realize with AC technology.

HVDC lines, and by extension an HVDC grid, has the potential to address the aforementioned problems.

1.5.1 Transmission Technology

New grid investments are required for, on the one hand, fundamental upgrade of the existing transmission system, possibly evolving into a backbone or overlay grid. Such a system is also referred to as a supergrid. A second type of new investments is specific for connection of offshore generation and load, eventually leading to an offshore grid.

A new backbone transmission system can be built using traditional alternating current (AC) or direct current (DC) technology. AC systems are a well-known technology, offering a cheap and reliable solution for high power transmission using classic overhead lines. DC systems, on the other hand, experience much fewer problems with long-distance power transmission, especially when cables are used. As such, a DC overlay grid seems to be the most appropriate solution when cables are needed.

VSC HVDC is the most appropriate technology for multi-terminal applications as it uses a common DC voltage, making parallel connections easy to build and control. LCC HVDC is much more troublesome to control in a parallel multi-terminal configuration, and especially changing the power direction in a single converter without interruption is problematic. Operating a multi-terminal LCC-HVDC system with many terminals with constantly changing power flows might result in an unreliable system. The possibility to connect islanded grids to a VSC-HVDC converter is another important advantage.

Two LCC-HVDC systems are in operation which are used in a multi-terminal HVDC configuration, namely the system between Hydro-Quebec to New England and the connection between Italy, Corsica, and Sardinia. Both have three terminals (although the first system actually has five terminals, only three are in operation). At the time of their construction, VSC-HVDC technology was not yet developed.

New multi-terminal systems using VSC-HVDC are built in a pilot phase (e.g., the system connecting Nanao island to the mainland Guangdong power grid and the Zhoushan 5-terminal system in China) and several projects are under study (e.g., the Moray Firth Offshore HVDC hub in Scotland, the Cobra cable between the Netherlands and Denmark with an offshore wind farm connected and the Atlanic Wind Interconnector in the USA).

1.5.2 Why Not AC?

The use of AC is disregarded as a potential option for a future supergrid in Europe. However, AC systems are capable of carrying large quantities of electric power over large distances when ultrahigh voltage (UHV, 1000 kV AC or higher) is used. AC systems using UHV voltages were developed in the 1970s, and they are currently planned and installed in China. The technical reasons why UHV AC is not seen as a potential technology for the supergrid are as follows:

- DC line losses are lower (no skin effect, no proximity effect).
- AC cable solutions for the needed high voltages are not yet available.
- AC cables experience a high charging current which limits their length. Long AC cables at very high voltages are difficult to construct and expensive.
- Offshore resources, as well as connections outside the main continent, are virtually inaccessible when using AC.
- HVDC offers an inherent active power control, making it more flexible in use and easier to limit overloads in the system.

There are also nontechnical reasons which are in favor of DC over AC technology. By using cables which cause no visual pollution and emit no varying electromagnetic fields, much less opposition and problems with licencing and construction are expected. Overhead lines are very difficult to construct because of nontechnical issues. Furthermore, using sea cables allows a fast and relatively cheap cabling because less joints are needed [32].

Figure 1.5 shows a graphic representation of the relative costs of HVDC and HVAC systems. The difference in cost price for an installation in systems without constraints (easier permitting process and the lower amount of "special" considerations to be taken into account such as deviations from the ideal path, sound protection, etc.) and in systems that experience significant constraints cannot be underestimated.

In short, AC overhead lines can be an option from a technical point of view, but constructing them is often an issue because of political and environmental concerns and AC cables are not suited for long-distance bulk power transfer. In case these disadvantages are deemed less important, AC overhead lines remain a valid option. This is also the case for regions with relatively seen more open space to place the transmission lines and where fewer offshore connections are needed. Both northern America and China might benefit more from additional AC reinforcements, combined

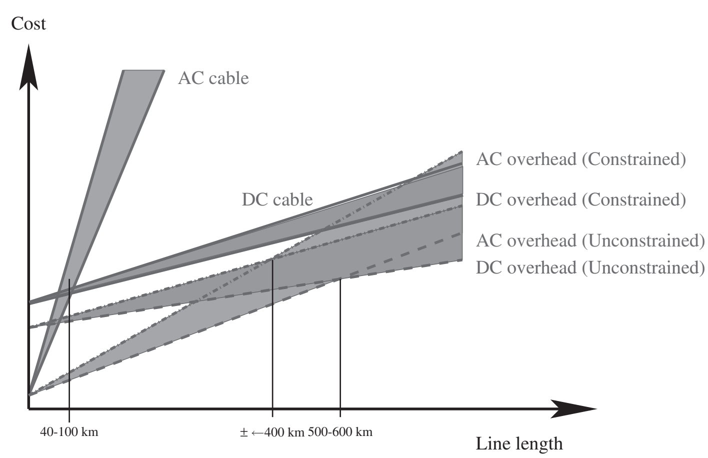

Figure 1.5 Cost breakdown for AC and DC systems [33].

with specific HVDC installations, than from a DC supergrid. Even in continental Europe, this would be possible if the opposition against new lines would cease. Offshore and other remote resources would still require cable connections, which makes AC no longer possible. A future “supergrid” which uses a mix of AC and DC technology is a realistic option.

HVDC is discussed in further detail in the remainder of the book, and more specifically in Chapters 3 and 4 on the comparison between AC and DC.

1.5.3 HVDC Grids as a Supergrid

A new overlay grid should allow an increased integration of all resources, including renewables. The variability of the renewable energy sources can be reduced because of the limited correlation of different weather system through connection of different energy sources such as wind, hydro, and solar, at different locations. Wind energy from the north of Europe can be partially balanced with wind from Spain or solar energy from the Sahara dessert. The remainder can be balanced by hydro energy, possibly from Scandinavia or the Alps. It could even allow the connection to the vast geothermal energy resources of Iceland.

Definition. A supergrid can be defined as a transmission solution which allows the massive integration of renewable energy sources in the European power system. It connects the different remote energy sources to the existing grid while offering additional control, it offers balancing through geographic spread, and allows a more diversified energy portfolio. In the meanwhile it increases the security of supply [33].

Many supergrid topologies have been proposed by different organizations [34, 35] and also by environmental organizations [36]; this is considered to be one of the most important options to reach a cleaner energy provision. These projects and ideas have received widespread attention from both politics and the press. The developments in Europe [33] have received most attention because of their leading role in renewable integration and their specific concerns with respect to transmission expansion. However, also in other regions we see the necessity to expand the power system. In China, long-distance energy transmission is vital to bring the energy resources from the west to the main load centers at the coast, most importantly the regions of Beijing and Shanghai. The transmission system in China is therefore playing a key role in the rapid growth in the country [37] and can be considered to be new overlay grid. India is in the process of connecting its different subsystems and reinforcing the interconnection in between with the focus on achieving a energy system which is more reliable. The Japan Renewable Energy Foundation [38] has proposed to interconnect the Japanese islands with mainland Asia (with China, India, South Korea, and Thailand) as well as Indonesia and Taiwan (Figure 1.6). In the United States, the energy system is up to a fundamental upgrade with a considerable need for new invesments at the highest transmission level [39]. In the eastern parts of the United States, the Atlantic Wind Connection consortium was formed to develop an offshore system which should strengthen the aging infrastructure, alleviate congestion, and lower energy prices and improve the reliability of the region [40] (Figure 1.7).

Figure 1.6 Plans for an Asian super grid [41].

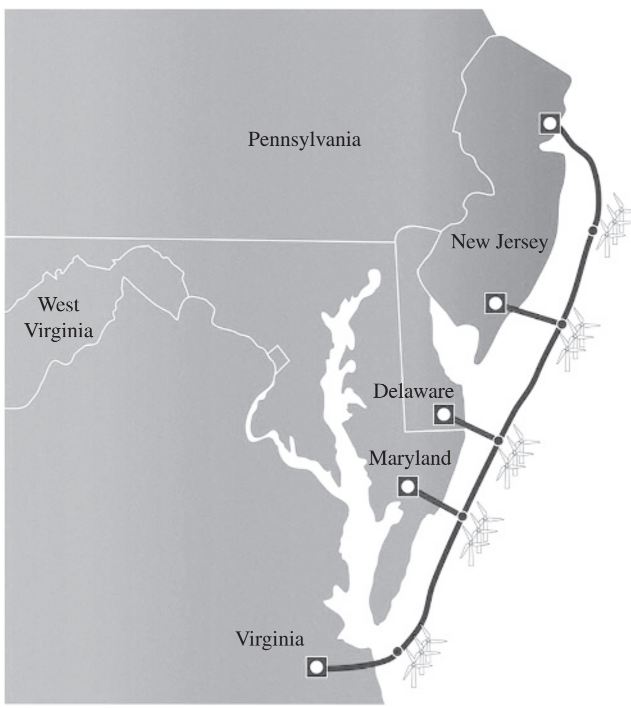

Figure 1.7 Schematic overview of the announced Atlantic Wind Interconnection offshore system connecting the east of the United States (*Source*: www.atlanticwindconnection.com.)

However, within the technical community, a lot of skepticism exist with respect to the development of HVDC grids. These visions do not contain sufficient detail in either technological, economic, or power systems engineering to allow full-scale development on a very short time frame. Nevertheless, research and technological innovations are quickly bridging the gap between vision and reality.

1.6 CONCLUSIONS

The efforts towards a sustainable, competitive, and secure energy supply have changed the requirements for the grid of the future. This has led to more flows on the transmission system which are furthermore increasingly variable. This has caused the power system to become increasingly congested. At the same time, structural investments in transmission capacity have been lacking over the past few decades. The foreseen changes in generation and load will only increase the need for transmission, especially if the massively available offshore energy resources are to be connected in the next decades.

Different technologies already exist to reinforce the transmission system. Most common technologies are AC overhead lines and cables, system uprating, power flow controlling devices, and HVDC connections. Of these technologies, HVDC is seen as very promising as it allows structural upgrades using cable technology. More specifically, the evolution of a DC grid is seen as the most promising option which can cause a paradigm shift and act as an enabler for the grid of the future with a high share of renewables.

REFERENCES

1. UCTE, “Articles of Association,” Union for the Co-ordination of Transmission of Electricity (UCTE), Technical Report, June 12, 2005.
2. Single market for gas & electricity: Third package for electricity & gas markets. European Union [online]. Available: http://ec.europa.eu/energy/gas_electricity/legislation/third_legislative_package_en.htm
3. D. S. Kirschen and S. Goran, *Fundamentals of Power System Economics*. Chichester, UK: Wiley, 2004.
4. T. Jamasb and M. Pollitt, “Electricity market reform in the European Union: Review of progress toward liberalization & integration,” Center for Energy and Environmental Policy Research, Technical Report, 2005, doc: 05-003 WP.
5. IEA, *Lessons from Liberalised Electricity Markets*, series Energy Market Experience. Paris: International Energy Agency, 2005.
6. P. Joskow, “Lessons learned from electricity market liberalization,” *The Energy Journal*, vol. 29, no. 2, pp. 9–42, 2008.
7. “Directive 96/92/ec of the European Parliament and the counsel of 19 December 1996, concerning common rules of the internal market in electricity,” European Union, 1996 [online]. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31996L0092:EN:HTML
8. L. Meeus, K. Purchala, and R. Belmans, “Development of the internal electricity market in Europe,” *Electricity Journal*, vol. 18, no. 6, pp. 25–35, July 2005 [Online]. Available: http://www.esat.kuleuven.be/electa/publications/fulltexts/pub_1467.pdf

9. European Commission, "Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market," *Official Journal of the European Union*, pp. 33–40, Oct. 2001 [Online]. Available: http://eur-lex.europa.eu/pri/en/oj/dat/2001/l_283/l_28320011027en00330040.pdf
10. The 2020 climate and energy package. European Union [online]. Available: http://ec.europa.eu/clima/policies/package/index_en.htm
11. European Commission. (April 2014) 2030 framework for climate and energy policies. Brussels, Belgium [Online]. Available: http://ec.europa.eu/clima/policies/2030/index_en.htm
12. European Wind Energy Agency (EWEA), "Wind in power—2013 European statistics," EWEA, Technical Report, 2014 [Online]. Available: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA_Annual_Statistics_2013.pdf
13. Renewable Energy Policy Network for the 21st century (REN21), "Renewables 2014—global status report," REN21, Technical Report, 2014 [Online]. Available: http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf
14. German Energy Agency, "Dena grid study II—Integration of renewable energy sources in the German power supply system from 2015–2020 with an outlook to 2025," Technical Report, Nov. 2010.
15. J. De Decker and P. Kreutzkamp, "Offshore electricity grid infrastructure in Europe—Final Report," Technical Report, Oct. 2011.
16. European Comission, DG energy in collaboration DC climate action DG and DG mobility and transport, "EU Energy Trends to 2030," Technical Report, 2009.
17. European Wind Energy Association (2010), Factsheet: Statistics & targets [Online]. Available: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/factsheets/Factsheets.pdf
18. European Energy Agency (EEA), "Europe's onshore and offshore wind energy potential: *An assessment of environmental and economic constraints*," EEA, Technical Report ISSN 1725–2237, 2009.
19. European Commission, "Communication from the commission to the European parliament and the council—*European Energy Security Strategy*," European Commission, Technical Report, 2014. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0330&from=EN
20. United Nations: Economic & Social Affairs, "Multi dimensional issues in international electric power grid interconnections," United Nations, Technical Report, 2006.
21. ETSO, "Overview of the administrative procedures for constructing 110 kV to 400 kV overhead lines," European Transmission System Operators, Technical Report, Dec. 5, 2006.
22. Nascimento Baptista (Ed.), "Public acceptance for new transmission overhead lines and substations," Eurelectric, Technical Report, 2003.
23. S. Cole, D. Van Hertem, L. Meeus, and R. Belmans, "Technical developments for the future transmission grid," in *International Conference on Future Power Systems, ISBN 90-78205-01-6*, Amsterdam, the Netherlands, 16–18 Nov. 2005, p. 6 [Online]. Available: www.esat.kuleuven.be/electa/publications/fulltexts/pub_1503.pdf
24. J. Lundquist, L. Barthold, A. Beutel, A. Britten, D. Douglass, J. Iglesias, V. Jankov, J. Jardini, D. Muftic, and S. Steevens, "Guide to the conversion of existing ac lines to dc operation," Cigré, Technical Brochure 583, May 2014, wG B2.41.
25. J. Lundkvist, I. Gutman, and L. Weimers, "Feasibility study for converting 380 kV lines to hybrid AC/DC lines," in *High-Voltage Direct Current & Flexible AC Transmission Systems*. EPRI, Nov. 5–6 2009, p. 25.
26. P. Fairley, "Germany jump-starts the supergrid," *Spectrum, IEEE*, vol. 50, no. 5, pp. 36–41, May 2013.
27. D. Van Hertem, "The use of power flow controlling devices in the liberalized market," Ph.D. dissertation, KU Leuven, Jan. 2009.
28. N. G. Hingorani and L. Gyugyi, *Understanding FACTS*. New York: IEEE Press, 2000, iSBN 0-7803-3455-8.
29. S. Gordon, "Supergrid to the rescue," *Power Engineer*, vol. 20, no. 5, pp. 30–33, Oct.–Nov. 2006.
30. ETSO, "European wind integration study (EWIS)—*Towards a Successful integration of Wind Power into European Electricity Grids*," Project report, Jan. 2007 [Online]. Available: http://www.wind-integration.eu/downloads/library/EWIS-phase-I-final-report.pdf

31. P. Buijs, D. Bekaert, D. Van Hertem, and R. Belmans, "Needed investments in the power system to bring wind energy to shore in Belgium," in *IEEE PowerTech 2009*, Bucharest, Romania, June 28–July 2, 2009, p. 6 [Online]. Available: www.esat.kuleuven.be/electa/publications/fulltexts/pub_1884.pdf
32. P. Buijs, D. Bekaert, S. Cole, D. Van Hertem, and R. Belmans, "Transmission investment problems in Europe: Going beyond standard solutions," *Energy Policy*, vol. 39, no. 3, pp. 1794–1801, 2011 [Online]. Available: http://www.sciencedirect.com/science/article/pii/S030142151100022X
33. D. Van Hertem and M. Ghandhari, "Multi-terminal vsc hvdc for the european supergrid: Obstacles," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3156–3163, 2010 [Online]. Available: http://www.sciencedirect.com/science/article/B6VMY-50PJ72B-8/2/83156f1dd30bf5615ce11bf4ab2e99dc
34. Desertec Foundation, "Clean power from deserts—*The DESERTEC concept for energy, water and climate security*," Trans-Mediterranean Renewable Energy Cooperation (TREC), Whitebook, 2007 [Online]. Available: http://www.desertec.org/fileadmin/downloads/DESERTEC-WhiteBook_en_small.pdf
35. J. De Decker, A. Woyte, B. Schödwell, J. Völker, and C. Srikandam, "Directory of offshore grid initiatives, studies & organisations," OffshoreGrid, Technical Report, Sep. 2009.
36. A. Woyte, J. De Decker, and T. Vu Van, *A North Sea electricity grid [R]evolution—Electricity output of interconnected offshore wind power: A vision of offshore wind power integration*. Greenpeace—3E, 2008 [Online]. Available: http://www.greenpeace.org/raw/content/eu-unit/press-centre/reports/A-North-Sea-electricity-grid-(r)evolution.pdf
37. Stage Grid Corporation China, "Sgcc framework and roadmap for strong & smart grid standards," SGCC, Technical Report, 2009.
38. T. Kåberger, "Asian super grid—vision for Mongolia and Asia," in *Mongolian Renewable Energy—International Conference*, Ulaanbaatar, Mongolia, May 2012.
39. J. Lawhorn, D. Osborn, J. Caspary, B. Nickell, D. Larson, W. Lasher, and M. Rahman, "The view from the top," *Power and Energy Magazine, IEEE*, vol. 7, no. 6, pp. 76–88, 2009.
40. The Chertoff Group, "Grid resiliency, its economic and security impacts, and the implications of AWC," The Chertoff Group, Technical Report, Oct. 2012.
41. S. Mano, B. Ovgor, Z. Samadov, M. Pudlik, V. Jülch, D. Sokolov, and J. Yong Yoon, "Gobitec and Asian super grid for renewable energies in northeast Asia," Energy Charter, Technical Report ISBN 978-905948-143-5, 2014.