Chapter 25

The SuperSmart Grid – paving the way for a completely renewable power system

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Note: Photos and biographies of co-authors can be found in the appendix.

Renewable energy resources are abundant in all of Europe and neighbouring countries. Nonetheless, the current share of modern renewable energy sources in the European energy mix is very low, due to past political and technological decisions. If we are to prevent dangerous climate change, the political decisions that have shaped the current energy mix need to be revised to fully recognize the role of renewables in the immediate future, and to create a suitable environment for a sustainable energy system.

The idea of using solar energy for mechanical operations is very old, and its 'development across the centuries has given birth to various curious devices', as Augustin Mouchot stated as early as 1878 at the Universal Exposition in Paris. In 1861 Mouchot developed a steam engine powered entirely by the sun. But its high cost, coupled with the falling price of coal, doomed his invention to become a footnote in energy history. Since then, due to strong belief in the overarching advantages of fossil energy sources, investment and research in renewable energy technologies have comprised a negligible fraction of the funds provided for fossil and nuclear energy sources. Things slowly began to change during the energy crises in the 1970s, and gained momentum in recent years due to high energy prices and price volatility, and due to the threats posed by climate change.

It is the common view that the long-term climate target for Europe is an 80% reduction of greenhouse gas emissions by 2050 (see, for example, 2009/29/EC, 2009, p. 8). Reducing EU emissions by 80% in 40 years is a huge challenge and will require a transformation of the entire energy system, with great implications for societies and economies. In some sectors – such as the power sector – technological solutions that could enable significant emissions reductions already exist and many new technologies are being developed. Other sectors – such as agriculture or transport – could have a more difficult time reducing emissions at the required magnitude. For these reasons, we believe that the European power sector will have to be the first sector to be fully decarbonized by 2050. This paper discusses the European power sector and how to achieve its decarbonization.

The SuperSmart Grid

There are several options for decarbonizing the power sector. None of them is easy, most require new mental models and political reform, but many are feasible. Among the main options discussed today are energy efficiency, carbon capture and storage (CCS), nuclear power, and renewables (see Bruckner *et al.,* this volume). Demand-side action such as energy efficiency measures will be increasingly important, but this point is not discussed in detail in this paper. On the supply side, the renewable energy option is the only truly sustainable solution, and therefore the less risky option, regardless of whether long-term investment risks, environmental risks, policy risks or other related risks are in focus. This option comprises a variety of technologies, some of them already mature (like hydropower, onshore wind, and biomass) and others in different development phases (offshore wind, photovoltaic (PV), and concentrating solar power (CSP)).

Within the broad field of renewable options, there are two main approaches. The first approach involves centralized, utility-scale power generation spread over a wide area. It requires electricity to be transported over long distances, from generation sites to load and storage areas. This is possible with minimum losses by using high-voltage direct current (HVDC) transmission technologies, which have been in use for decades on all continents. This approach is widely known as *SuperGrid*. The second approach – the virtual power plant – consists of a multitude of scattered generation sources which are aggregated together and managed by intelligent technologies (such as two-way communication between consumers and producers, as well as between producers), and Smart Meters, which enable consumers to manage their load – and thus their electricity cost – automatically. This intelligent operation of decentralized renewable power production, combined with demand-side management measures to better match the volatile supply with the demand are commonly known as *SmartGrid*. These two approaches are often perceived as exclusive alternatives, but it is conceptually necessary and technically possible to merge them. The combination of these two approaches is what we call the *SuperSmart Grid (SSG)*. We strongly believe that by combining them we can not only speed up the decarbonization process, but also open the way to further develop technologies that can address very different energy needs in Europe, in neighbouring countries, and elsewhere in the world.

A first step towards a Northern European SuperSmart Grid was recently taken by the Swedish EU presidency. One of its main objectives is the creation of an interconnected power grid in and around the Baltic sea (known as the Baltic sea power ring) and a joint Baltic power market. A Northern European power market, if successful, could form the nucleus of a pan-European energy market. The Nordic experience with running an international power market could also strongly contribute to the success of the Baltic market. Another example of development towards a SuperSmart Grid is the proposed North Sea grid for integration of wind power – supplying almost 15% of the electricity needs of the seven North Sea countries by 2020 – and, as a positive side-effect, the physical unification of the North Sea power markets (Woyne *et al.,* 2008). Gregor Czisch, a SuperGrid energy expert at Kassel University, states that the potential for offshore wind in the North Sea is 6600 TWh/a, or almost twice the current EU-27 electricity consumption (Czisch, 2005). While this figure may be contested, it nonetheless indicates the potential that can be harnessed by grid expansion projects. A similar approach to the SuperSmart Grid is currently being implemented in the United States, although there it is only called Smart Grid, and is supported by the American stimulus package. Theoretically, the SuperSmart Grid approach could be applied to every power system currently in place.

In Europe, an important first step towards a large-scale, trans-continental SuperGrid for Europe and North Africa was recently taken by the Desertec Industrial Initiative, based on the work of Franz Trieb at the German Aerospace Center and the Desertec Foundation (Club of Rome, 2008; DLR, 2005; DLR, 2006; DLR, 2007). In this initiative, 12 companies – among them Munich Re, Deutsche Bank, E.ON and Siemens – have agreed to 'analyse and develop the technical, economic, political, social and ecological framework for carbon-free power generation in the deserts of North Africa'. The long-term goal of the Desertec consortium is to produce approximately 15 % of European electricity requirements from renewable sources as dispatchable power, mainly from thermal solar power plants, in the Sahara desert, and to transport this electricity into the European power grid (DII, 2009).

Reducing costs through learning effects

The cost of almost any technology starts off high and decreases over time, as increasing cumulative production triggers learning effects (costs are reduced through 'learning by doing') and economies of scale; each piece becomes cheaper as total production increases, since the costs of machines, for example, can be distributed over greater production (Coulomb and Neuhoff, 2006). Today, the costs of CSP are about EUR 0.25 per kWh in Spain and some EUR 0.15 per kWh in southern USA and in the desert of North Africa. These costs are expected to decrease by at least 20–40 % in the next decade if 20 GW of new capacity goes online (Munich Re, 2009; Club of Rome, 2008; DLR, 2006; Ummel and Wheeler, 2008). CSP technology is still far from mass production and it remains to be seen how quickly these learning rates can indeed be achieved or even exceeded.

For wind, the principle is similar, although onshore wind technology has already passed through a large part of its learning curve, limiting the potential for further cost reductions. Nonetheless, onshore wind power can be expected to become some 10 % cheaper per doubling of the cumulated capacity[1] and can at normal sites (see section on quality of sites below) asymptotically reach about EUR 0.06 per kWh in the long run (Krohn *et al.,* 2009; GWEC, 2009; Neij, 2008; Nitsch, 2008). Offshore wind technology is still rather expensive and has only been installed at relatively small scales. The production costs today are about EUR 0.15 per kWh, but are expected to be half of that – EUR 0.075 per kWh – in 2020 (Nitsch, 2008).

[1] In the decade up to 2009, the cumulated global wind capacity has doubled about every three years. This trend is expected to remain the same in the medium-term future.

By comparison, the production costs of new nuclear and coal power based on current world market fuel prices, a carbon dioxide cost of EUR 20 per tonne, and investment costs as provided by the companies constructing new power stations in Europe – excluding costs of all insurances, decommissioning, final storage, interest fees for capital invested during the construction time and all external costs – are between EUR 0.055 and 0.075 per kWh (Olkiluoto 3, nuclear) and EUR 0.045–0.055 per kWh (Neurath 2 and 3, lignite), depending on interest rate and economic lifetime (AFP, 2008; Ernst & Young, 2006; RWE, 2009). A recent meta-study of the costs of new nuclear power stations puts the costs at EUR 0.085–0.145 per kWh (Cooper, 2009). It should be noted that nuclear power is one of the few technologies that is not getting cheaper with time; instead, new nuclear power tends to become more expensive with time (Cooper, 2009; Neij, 2008).

A sustained level of wind and solar power expansion is therefore the key to making renewable technologies competitive, reaching grid parity[2] and eventually becoming the cheapest option for new power stations. Such large cost reductions are not only important for the cost-efficient implementation of renewable electricity in Europe, but also extremely relevant for investments in developing countries where resources are limited and investment competition among different sectors is high. Developing countries today simply cannot invest in the still much more expensive renewable technologies. Today, the upfront investment for electricity generation is substantially lower for old fossil-fuel-based technologies than for renewable energy technologies. That is a major reason why large amounts continue to be invested in old technologies, even in developed countries,[3] despite the threats posed by climate change, the risks of increasing fuel costs, and the risk of an increasing carbon price. Strong European investment in renewable power generation technologies will bring the costs of these technologies down, which will make the renewable option the cheapest and least risky solution to satisfy the rapidly increasing electricity demand in developing countries. Therefore, the impact of European leadership in renewables expansion will extend far beyond the immediate emissions reductions in the European power system since, together with the considerable US efforts in green investments, it can pave the way for even greater reductions globally.

[2] There are numerous definitions of grid parity. Here, we refer to the break-even point of the costs of producing your own electricity and the price of electricity from the grid, including taxes and grid fees.
[3] Between 2007 and 2012 RWE plans to invest EUR 12 billion in power plants, lines and open-pit mines; E.ON even plans to invest EUR 30 billion between 2009 and 2011, mainly in 'renewing and maintaining … and expanding our conventional generation capacity' (E.ON, 2009; RWE, 2007).

Reducing costs by choosing only the best sites

Today, the generation costs of most forms of new renewable electricity are still higher than those of fossil-fuelled electricity, with the possible exception of onshore wind power on good sites (see cost estimates above). The renewables – except for biomass and biogas – have a completely different cost structure to fossil power; investment accounts for by far the greatest share of generation costs, as the fuel costs are zero. Instead of fuel price, the quality of the production site – for example as measured by average wind speed and direct solar insolation[4] – becomes the main variable for determining the production costs. That means that good sites have much lower production costs than marginal sites.

In Europe, the renewable energy potential is high and is probably sufficient to satisfy the current levels of electricity demand (see Fig. 1). However, resources are not evenly distributed and in some countries the renewable potentials exceed the national demand. For example, Sweden and Spain with their extensive renewable resources (biomass, wind and hydro for the former, and solar for the latter) could achieve a 100 % renewable power system if they decided to. Other countries, such as France, Germany, Italy and the Benelux countries, are not as rich in renewable resources, mainly due to high population density and geography. The economic potentials in these countries are much too low for a completely carbon-neutral power system based on renewables and they would have to utilize bad, and thus expensive, production sites in order to achieve very high shares of renewable power.

In the event that European electricity demand should increase significantly in the future, for example by the widespread introduction of electromobility, even the combined and optimally interconnected domestic EU potentials, at reasonable economic cost, may not be large enough.

Enormous potentials for renewable power are found just outside of Europe, for example in the neighbouring North African countries. The solar energy potential is immense all across the Sahara Desert and there is a multitude of very good wind sites, for example along the Red Sea and the coasts of Morocco. The economic solar and wind power potentials of the five countries on the southern Mediterranean rim is two orders of magnitude larger than the combined electricity demand of Europe and North Africa in any realistic scenario (see Fig. 2). Utilizing these resources would allow 'cherry-picking' of production sites. Marginal sites could be completely discarded and only the best ones utilized for electricity production, which would allow for high economic efficiency of the transformed renewable power system by providing dispatchable and controllable capacity (for explanations of these terms, see below). Moreover, if electromobility or other large new

[4] incident solar radiation

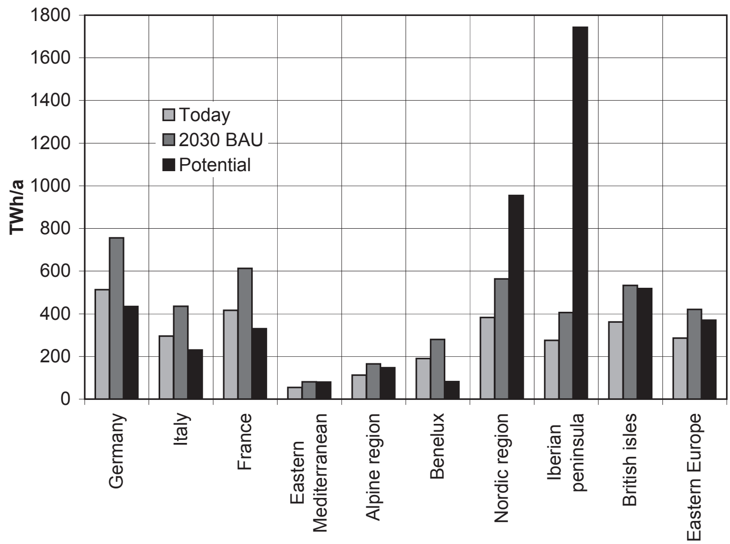

Fig. 1. Electricity consumption today and in 2030 (EU 'business as usual' case) and the economic potentials for all renewable electricity sources in different regions of the EU-27.[5] (*Sources:* DLR, 2005; DLR, 2006; Eurostat, 2009; Resch *et al.,* 2006)

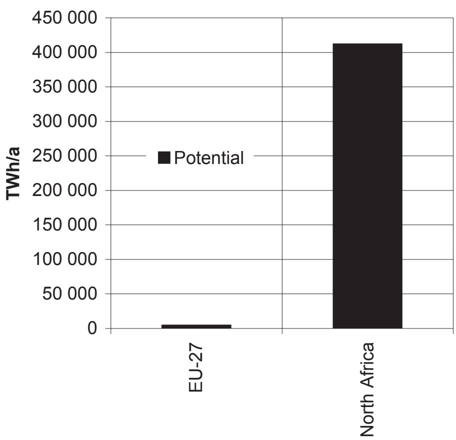

Fig. 2. The economic potential for renewable electricity in the EU-27 and North Africa. Note that this scale is 100 times larger than the scale in Figure 1. Graphically comparing the consumption of Europe (approximately 3000 TWh/a) or North Africa (approximately 200 TWh/a) is not useful, since the potentials are so much larger than any realistic consumption. (*Sources:* DLR, 2005; DLR, 2006)

[5] It should be noted that the potentials in the figure above are averages. As most renewable sources are intermittent, these numbers only indicate that the potentials are, on average, sufficient to decarbonize the power system, but do not indicate that sufficient production will be available at any given time (see section on generation intermittency).

power consuming systems emerge in the future, utilizing the resources in North Africa and other neighbouring regions may be the only way for Europe to sustainably decarbonize its power system at reasonable costs.

Maintaining and improving geopolitical security of supply

The transformation and decarbonization of the power system can only succeed if energy supply is secured at all times. Often, the idea of Europe importing renewable electricity from North Africa is criticized for getting Europe into yet another energy import dependency (see for example Zeller, 2009), adding to Europe's already high import dependency (see Fig. 3) and, as a consequence, jeopardizing European security of supply.

The main option to increase security of supply is to diversify sources, increase the share of domestic fuels and make the power system more flexible.[6] A well developed SmartGrid with a large share of decentralized and distributed renewables generation, linked into a highly flexible grid capable of transporting electricity over vast distances and in all directions, would greatly improve Europe's security of electricity supply (EC, 2006; Jansen *et al.,* 2004; Ocaña and Hariton, 2002; Ötz *et al.,* 2007; Scheepers *et al.,* 2006). Including North Africa in the European power system can lead to further diversification of source countries, fuels and technologies, and reduce import dependency on fossil fuels even in the transition phase to a completely renewable power system, thus improving overall security of electricity supply (Ötz *et al.,* 2007; DII, 2009). In the long run, imports of renewables will be the only imports to the electricity sector, and the total import dependency will be much lower than it is today.

It is a matter of good governance to ensure that these imports are secure and beneficial for both sides. The twin objectives of guaranteeing European electricity supply while avoiding colonial tendencies – real or perceived – and the resource curse[7] for the exporting countries are equally important and should be pursued in tandem. Good governance is not usually addressed in today's world energy market, but it can be. Norway, for example, which today exports large amounts of gas and oil to other European countries (see Fig. 3), is considered at least as secure as any EU member state, it does not suffer from the resource curse, and does not feel colonized or exploited by its energy customers.

An electricity relationship between the EU and its different North African partners

[6] Or, to put it in the almost 100-year-old words of Winston Churchill, 'safety and certainty in oil lie in variety, and variety alone' (Ladoucette, 2002)

[7] The resource curse refers to the paradox that countries with large exports of unrefined natural resources tend to have a slower economic and social development, suffer more corruption and are less democratic than countries with only small exports of natural resources

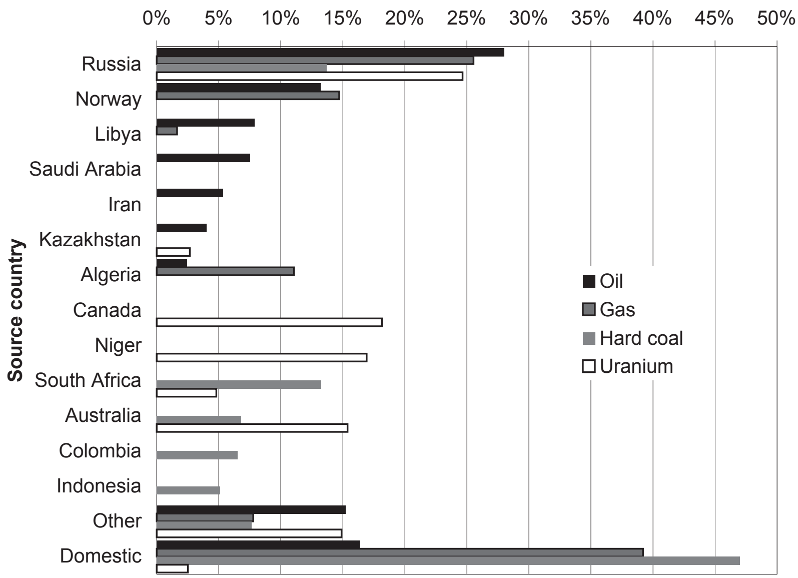

Fig. 3. Import shares to the EU-27 in 2006 from different source countries, as share of total consumption of each fuel. Hard coal imports calculated on the basis the 'solid fuel' category of Eurostat statistics, based on average heating values and with the assumption that all lignite is domestic. (*Sources:* BP, 2008; DG TREN, 2008; Euracoal, 2008 a; Euracoal 2008 b; Euratom, 2008; Eurostat, 2009)

will create interdependency and must be based on clear and stable treaties, as well as the economic and development needs of both sides. A number of specific issues must be explicitly addressed:

- A business model that takes into consideration and satisfies North African power demand and expectations should be developed to guarantee stable and long-lasting cooperation.
- The desert land that, from a European perspective, seems empty and worthless is in fact inhabited by different peoples, such as numerous Bedouin tribes. Although only a small fraction of the Sahara Desert will be exploited, power stations and power lines will be an intrusion into these lands, and the people living there must be included in the planning of CSP and wind capacities.
- If the rights of the desert peoples, as well as local populations in general, are not recognized, European and North African security of supply may be at greater risk and the threat of attacks against power plants and lines may increase. Terrorist attacks against the long power lines through the desert will be a real threat to both North African and European security of supply and measures to minimize this risk will be required. However, a comparison with the gas sector may prove

useful: already today, long pipelines stretching from southern and central Algeria and Libya to the coast exist and are not targets for terrorists, despite their exposed situation. The terrorist threat against energy installations will always be present and must be taken seriously in any location, but should not be exaggerated.

A fair and well thought-out deal between North Africans and Europeans will set the fundaments for a reliable electricity supply and avoid the sort of disruptions or blackmail seen in the Russian-Ukrainian-European gas relationship in recent years.

Handling generation intermittency

The greatest difficulty with renewable energy sources is that they are intermittent and supply-controlled (see Luther, this volume). Fossil-fuelled power plants, on the other hand, are demand-controlled and can be operated whenever there is demand, which is one of their major advantages. A wind power plant can only produce electricity at times when there is wind, and these times may or may not coincide with the times of consumption in the surroundings. CSP production is not necessarily as intermittent as wind, due to the possibility of thermal storage directly in the power station. Some of the heat generated during the day can be stored and used, for example, at night. If the storage and the mirror fields are large enough, a CSP station at a very good site, for example in the desert, can provide firm capacity most of the time (Trieb *et al.,* 2009; DLR, 2006). By adding back-up systems, such as a fossil- or biomass-fuelled combustion chamber to replace or support the solar field during longer periods with little or no sun, firm capacity can be guaranteed at any time. The 'intelligent' operation of CSP plants with intrinsic thermal storage, combined with other, entirely supply-controlled power sources in a broad electricity mix, could be one of the easiest ways – and therefore also one of the cheapest ways – to handle intermittency. In principal, however, all existing renewable power options, except biomass-based ones, are, to different degrees, supply-controlled and intermittent. As electricity has to be consumed instantly, this stochastic behaviour of renewable electricity production has to be managed.

Electricity storage and back-up capacities are often mentioned as necessary tools to maintain stability in power systems with high penetrations of renewables. These options have the advantages that they are easily controllable and fit well into the paradigm of the current system. The main disadvantages are their high costs: long-term storage (on the scale of weeks) and short-term storage ('peak shaving', on the scale of a few hours or up to a day) cost from EUR 0.37 per kWh (long-term pressurized air) – or even EUR 0.5 per kWh for lithium-ion batteries – to EUR

0.1–0.2 per kWh for most short-term technologies, with a singular minimum cost of EUR 0.05 per kWh for short-term pressurized air storage (Leonhard *et al.,* 2008). Even if the costs were to decrease by 50 %, most electricity storage technologies would still be too expensive. They would be uneconomical compared to fossil power and CSP with thermal storage even if the electricity generation were cost-free.[8] The costs of back-up generation vary greatly depending on the power system configuration and electricity mix, but some EUR 0.02–0.04/kWh are realistic wind back-up costs at current wind penetrations. Due to the low load factor[9] of photovoltaic power, the back-up costs can be expected to be higher than this. The back-up costs tend to increase with higher penetrations of intermittent renewables (RAENG, 2004; IEA *et al.,* 2005), and will probably not be viable on a very large scale. Depending on the configuration and size of thermal storage, the need for and costs of back-up and electrical storage for CSP electricity could be significantly lower than for wind; if the thermal storage were large enough, no electrical storage outside of the power plant would be needed.

Another way to deal with intermittency, and the one advocated in the SuperSmart Grid concept, is a mix of different generation technologies in a SmartGrid virtual power plant approach, as well as stochastic smoothing over vast distances. A virtual power plant consists of a number of renewable power stations of different kinds and with different fuels – a broad fuel mix of wind, solar, bio and hydro is the key – that are operated as an aggregate power plant. The combination of supply-controlled technologies (such as wind and PV) and demand-controlled technologies (such as biogas or hydropower with dams, and CSP with thermal storage) makes it possible to operate the aggregate of supply-controlled renewable power stations in a demand-controlled way, offering dispatchable capacity[10] or – in the future – even base-load[11] generation (Mackensen *et al.*, 2008). If the power system is geographically larger than a weather system, which it would be in a SuperGrid Europe, there will always be wind somewhere and sun somewhere else within the area (alternatively, at night electricity from CSP storage plants can be used). If the grid is efficient, densely meshed and flexible, electricity can flow from A (with high production) to B (with low production) at one moment and from B to A in the

[8] This is true only in the current accounting system, which does not include environmental externalities

[9] The load factor is a measurement of the utilization of a power plant and is defined as the quota of the actual yearly production divided by the maximum potential yearly production. Wind power plants typically have load factors of 25–30 %, whereas photovoltaics usually lie around 10–15 %. Baseload power stations, such as lignite and nuclear power plants, typically have load factors between 80 and 90 %. CSP equipped with storage capacity can provide a similar base load to fossil fuels.

[10] The term 'dispatchable capacity' refers to power stations which can provide capacity on demand and when electricity is needed.

[11] Base-load generation involves power plants that operate permanently at full or almost full capacity and are characterized by very high load factors (see above). In the current system design, these power stations provide the base of the supply system, whereas peak-load power plants handle fluctuations and provide electricity during times of high or volatile consumption.

next when the weather system has moved and the production pattern has changed, even if the two points are thousands of kilometres apart.

According to Gregor Czisch (2005), this *correlated* and *stochastic* smoothing[12] over all of Europe as well as North Africa and the Middle East is enough to satisfy power demand at any given time, completely without electric storage and back-up. Even if the power system, for example during the transition phase, does not allow for sufficient smoothing to meet demand at exactly all times, correlated and stochastic smoothing will greatly reduce the need for back-up or storage. The costs of transmitting the renewable electricity to just about any point in Europe, which would be up to about 3000 km, with high-voltage direct current (HVDC, see below) power lines is about EUR 0.01–0.02/kWh (Czisch, 2005; DLR, 2006; Jochem *et al.,* 2008; May, 2005), which makes correlated and stochastic smoothing in combination with dispatchable CSP power by far the cheapest option for handling intermittent renewable energy resources.

Expanding power grids and generation capacities: a policy matter

Today, the power grid is a major bottleneck for a further large-scale expansion of renewable electricity production. Already today, many power lines – especially cross-border interconnectors – are congested and overloaded (Battaglini *et al.,* 2009; DENA, 2005). Long-term strategic planning for a truly European power grid, also recognising the benefits of stochastic smoothing, is urgently required. Currently, expansion plans are made nationally on the basis of 'business as usual' developments and with a time-frame of about ten years. The implementation of such plans generally takes much longer than that, due to bureaucracy and strong opposition by the public. By the time the planned lines are finished, the 2020 renewables targets – and possibly the climate target as well – will no longer be reachable.

The transmission system operators (TSOs) are today neither requested nor paid to have a vision for the future power system. Therefore, they generally do not engage in investigating different development scenarios for future required European transmission capacity. They are not encouraged to have an international, not to mention pan-European, approach to grid expansions, but rather to optimize the national system in the short- to medium term, which is often not the best solution from a long-term perspective. For the integration of electricity produced in North Africa and offshore in the North and Baltic Sea regions into the European power

[12] Correlated smoothing refers to smoothing effects emerging from weather correlations over large distances and among energy generation technologies in a broad technology mix, whereas stochastic smoothing is an effect caused by a random input of wind and solar power (mainly PV) over the wide geographical spread of the power grid.

system, HVDC lines will be required. Such power lines have much lower losses than conventional AC (alternating current) power lines, and are cheaper to build over long distances.[13] On short-distance lines, including almost all national power lines, HVDC is, however, more expensive than AC; the break-even point is about 800–1000 km (DLR, 2006). Therefore, HVDC lines are economically suboptimal in a national, short-term perspective, and TSOs are today de facto not allowed to build these. Thus, the nationally limited grid regulations based on short-term economic efficiency prevent Europe from reaching the longer-term renewables and climate targets in an economically sound way.

Due to these obstacles (national borders, focus on short-term economic efficiency), there is a risk that Europe will build itself into a situation far from a comfortable pathway to the 2050 emission reduction targets. A first step to tackling this problem would be to give the newly created European Network of Transmission System Operators for Electricity (ENTSO-E) the mandate to develop expansion plans for different carbon-neutral electricity mixes until 2050, including different scenarios of entirely renewable power systems, and allowing for imports of electricity from outside the European borders. The short-term and nationally limited perspective on regulation must be abandoned, and long-term, pan-European regulations introduced, which would allow the financing and the construction of the required HVDC lines. The process of restructuring and expanding the transmission grid must be inclusive and involve NGOs and affected communities. The communication and discussions of the grid expansion issue must be far more holistic than is currently the case – especially from the side of green NGOs – and the focus must be expanded to include both generation and transmission. The Renewables Grid Initiative,[14] bringing together NGOs and TSOs, is a first step in this direction.

Moreover, long-term targets and planning are fundamental to building up the supply chains of new renewable generation capacities, which today are not sufficient to realize the required transformation of the electricity system at the required pace. The capacities for the production of new renewable power stations are growing fast, but demand is growing even faster in some regions. Limitations in the renewable power station supply chains already hamper renewables expansion in some areas, especially in the wind power sector, and these supply chain constraints are an important determinant of how fast the transformation of the system can be (see, for example, EWEA, 2009; Krohn *et al.,* 2009). It is the task of policymakers to clearly define the long-term direction and create confidence for investors to channel funds into expanding the supply chains, in order to ensure a faster pace in the

[13] HVDC lines have full load losses of about 2–3% per 1000 km, whereas conventional high-voltage alternating current (HVAC) lines have losses of 7–10% per 1000 km (Battaglini *et al.,* 2009; Czisch, 2005; DLR, 2006).
[14] http://www.renewables-grid.eu

transition towards a renewable power system. It is important to note that serious supply chain bottlenecks are present for new renewable generation technologies and transmission lines, but also for other potential options such as CCS and, most significantly, nuclear energy. Although these technologies are well established, the power plant construction capacity at present is limited and the supply chain would need to be expanded to ensure power supply even in a fossil-fuel-based future power system (DG TREN, 2008).

Conclusion and outlook

The potential for renewables in Europe and North Africa is sufficient to entirely decarbonize the power system. However, this can only be achieved through a co-ordinated pan-European and trans-Mediterranean approach and not by single countries autonomously, as the renewable electricity potentials for most countries are simply not large enough. For some countries costs will be too high and intermittency of supply will cause serious trouble, adding to the cost problem. These problems could be addressed and eased by developing a unified European power market, equipped with smart technologies, and by unifying the European and North African markets into a pan-European, trans-Mediterranean SuperGrid. Such a SuperSmart Grid has the potential to satisfy any electricity needs of the future, to minimize costs by enabling cherry-picking of sites, and manage intermittency problems.

Strong political leadership is required to foster and promote the transition to a largely renewable-based power system. European and American efforts to develop renewable technologies will generate a lot of synergies and accelerate economies of scale. Reduced investment costs and the expected increase in fossil fuel energy prices will provide the economic stimulus to channel investments into renewable technologies, not only in Europe and other developed countries, but also in developing countries. This will contribute greatly to reducing emissions worldwide, and at the same time help guarantee developing countries' right to economic development. It is a difficult process, but achievable nonetheless.

During the second half of the twentieth century, Europe was divided. Most people thought that this division was impossible to overcome, but the vision of reunification was still in the minds of people on both sides. In early 1989, the East German leader Erich Honecker stated that the Berlin Wall would endure for another 100 years. Just a few months later the wall fell. The vision of a power system based entirely on renewable energy sources is not new; it has been discussed for decades, with Desertec in recent years taking the lead in advocating energy cooperation with North Africa to meet Europe's and North Africa's energy needs. The interest among politicians and the business community in the renewable energy option has never been greater than today, and that interest keeps on growing. Nonetheless, the dominance of fossil fuels seems insurmountable. However, sooner or later, just like the Berlin Wall, the fossil-based energy system will crumble, and the time of renewables will come.

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