CHAPTER

Global Power Grids for Harnessing World Renewable Energy

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1. Introduction

Increased environmental awareness has led to concrete actions in the energy sector in recent years. Examples are the European Commission's target of 20% participation of renewable energy sources (RESs) in the EU energy mix by 2020 [1] and California's decision to increase renewable energy in the state's electricity mix to 33% of retail sales, again by 2020 [2]. At the same time, several studies have been carried out investigating the possibilities of a higher share of RESs in the energy supply system of the future. For instance, the German Energy Agency assumes 39% RES participation by 2020 [3], whereas a detailed study from the National Renewable Energy Laboratory suggests that meeting the US electricity demand in 2050 with 80% RES supply is a feasible option [4]. Czisch [5] discusses a 100% renewable energy supply system in Europe with interconnections in North Africa and West Asia. Jacobson and Delucchi [6] more recently investigated "the feasibility of providing worldwide energy for all purposes (electric power, transportation, heating/cooling, etc.) from wind, water, and sunlight." The authors made a detailed analysis and proposed a plan for implementation. They found that the barriers to the deployment of this plan are not technological or economic but rather social and political.

All these studies suggest that the development of the electricity network will play a crucial role in the efficient integration of increasing shares of RESs. Two reasons are most often mentioned. First, interconnecting RESs increases the reliability of their supply. Second, long transmission lines can help harvest renewable energy from remote locations with abundant potential and very low production costs. To exploit the benefits of such interconnections, concrete actions have been taken that will lead to the creation of regional supergrids. EU guidelines already encourage transmission projects, such as the Baltic Ring [7]. Projects such as Medgrid (www.medgrid-psm.com) and OffshoreGrid (www.offshoregrid.eu/) have been launched to interconnect Mediterranean states with Europe and transfer renewable energy to the major load centers. At the same time, initiatives such as Gobitec (www.gobitec.org/) in Asia and Atlantic Wind Connection (www.atlanticwindconnection.com) in the USA aim to interconnect the Asian power grids or transmit offshore wind energy to the east coast of the USA.

In Ref. [8] we suggested the next natural step of the electricity network: the Global Grid. With growing electricity demand, the need for green energy resources also will increase. The electricity networks will expand to harvest the renewable potential abundant in remote locations, forming supergrids of increasing size. The Global Grid aims at interconnecting the regional supergrids into one global

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electricity network. High-capacity long transmission lines will interconnect wind farms and solar power plants, supplying load centers with green power over long distances. Besides introducing the concept, in Ref. [8] we further highlighted the multiple opportunities emerging from it. We supported our analysis with studies of the economic feasibility of such a concept, and we further discussed possible investment mechanisms and operating schemes.

In this chapter, we introduce and elaborate on four possible stages that could gradually lead to the development of a globally interconnected power network. We extend our analysis with additional studies of the economic competitiveness of long transmission lines in different world regions, and we show that substantial profits can arise from intercontinental electricity trade.

Section 2 introduces the four possible development stages followed a brief illustration of the concept as we have envisioned it in Section 3. Sections 4–6 describe in detail all four development stages and provide examples, with quantitative analyses for each stage. In Section 7 we briefly discuss the additional opportunities emerging from a Global Grid. We conclude this chapter with Section 8.

2. Stages toward a global power grid

We expect that three main reasons will act as the major incentives toward the creation of a globally interconnected network. First, the need to harvest remote renewable energy resources–located either further off-shore or in deserts–will lead to continuously expanding regional supergrids. Second, taking advantage of the shift in peak demand periods between continents, remote RES plants located at similar distances from two regions can connect and sell their power always at peak price. Third, the time zone diversity between continents creates opportunities for electricity arbitrage, which can lead to a profitable electricity trade. Based on these reasons, in this section we present the four main stages we envision as leading to the development of a Global Grid environment.

The main driving force behind a Global Grid will be the harvesting of remote renewable resources. In the search for green electricity, new sites located even further away from the existing load centers and the current power grids, will be exploited. Deserts such as the Sahara or the Gobi serve as examples for solar power plants, and on-shore or off-shore locations with high winds such as the shores of Greenland or the Indian Ocean serve as examples for wind farms. This constitutes the first stage toward a Global Grid. Our cost–benefit analysis in this chapter will focus on the wind potential of such remote locations.

By building wind farms and solar parks in remote locations, a point will be reached at which an RES power plant will be equidistant from two power systems on different continents. A wind farm in Greenland, for instance, would be a realistic example of such a situation. Our analysis in Ref. [8] showed that connecting such a wind farm to both Europe and North America is a profitable solution. In this second development stage of the Global Grid, remote RES power plants can take advantage of the time difference between the continents to sell their power always at peak prices. For example, the wind farm in Greenland can sell its produced power 50% of the time during the peak demand in Europe and 50% of the time during the peak demand in North America. From there, an interconnected global power grid can start to form.

With an electrical connection between two continents, opportunities for electricity trade emerge, signaling the progression to the third stage. Wind (and solar) production is intermittent and most of the time does not use the total cable capacity. In addition, peak demand between the continents is shifted in time, which leaves room for electricity arbitrage. Therefore, electricity can be bought at lower prices in one area and sold at higher prices during peak demand in other areas. In Section 5.2 we explore the electricity trade potential for the Europe–North America connection over Greenland, using the remaining cable capacity.

As we will see in Section 5.2, the transmission corridor enabling electricity trade between the continents can result in substantial profits. Based on that, in the fourth stage of the development towards a Global Grid, direct interconnections between countries or continents can start to be built, independent of their connection to remote areas with high RES potential. Such an analysis for a cable between Europe and North America has already been carried out in Ref. [8], showing that, except for the most expensive RES generators, it would be more economical for the USA to import RES power from Europe than operate its own fossil fuel power plants. Here, we extend this analysis by considering real electricity prices in Germany and the USA and by examining the amortization period of such an investment.

Introducing the four development stages helps create a path leading to a Global Grid environment. It does not imply, nevertheless, that global interconnections will move through the four stages in a sequential manner. For example, the direct interconnections in the fourth stage can directly occur after the first stage; or the second and third development stage can occur simultaneously, for example, as we will see in Section 5, an off-shore wind farm can connect to both continents in order to sell at peak prices and, at the same time, benefit from the electricity trade.

3. The global grid: an illustration

The current section is devoted to a brief description of the Global Grid as we envision it. We hope this will produce a better understanding of this concept, first proposed in Ref. [8]. Figure 1 illustrates a possible global grid. We envision that the power supply of the Global Grid will depend on RESs. Large

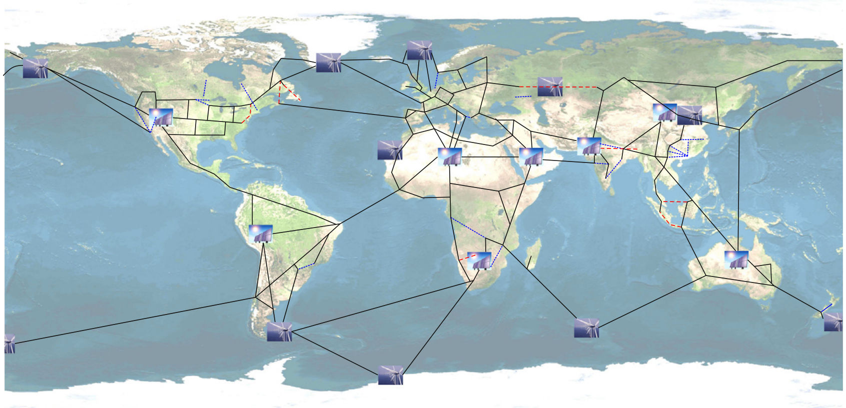

FIGURE 1 Illustration of a possible Global Grid.

The dotted lines indicate the high-voltage direct current (HVDC) lines with a length of more than 500 km that are already in operation; the lines currently in the building/planning phase are indicated by dashed lines (the list of the illustrated HVDC lines is not exhaustive). The locations of the renewable energy source power plants are based on solar radiation maps, average wind speeds, and sea depths [8].

renewable potential exists in remote locations, such as in deserts or offshore. Long high-voltage direct current (HVDC) lines will constitute the main arteries in a Global Grid environment, transmitting bulk quantities of power over long distances. HVDC lines are superior to alternating current technologies for long-distance transmission because they exhibit lower losses, provide active and reactive power support, and can connect nonsynchronous grids. Issues pertaining to the power generation and transmission by the Global Grid are described in more detail in Ref. [8].

4. Harvesting RESs from remote locations

Tapping the renewable potential in Greenland, as mentioned in Section 2, would be a realistic example of how we could progress to global interconnections. Greenland was selected in Ref. [8] as a representative example for three reasons. First, it has a significant wind and hydro potential [6,9]. Second, it is close to Iceland; Ref. [10] has already shown that the Iceland–UK interconnection is a viable option, and the two governments are currently discussing its possible realization [11]. Third, all interconnecting sections along this route have lengths or sea depths that are comparable to currently existing projects (see Ref. [8] for more details). Also important is that Greenland lies at an equal distance from both Europe and North America. Later in this chapter we extend our analysis of Greenland by exploring the possibilities for intercontinental trade.

In this section, we move to the southern hemisphere and study in more detail a wind farm on the Kerguelen Islands. These are a group of islands in the southern Indian Ocean that belong to France. Their climate is similar to that of Iceland and the Falkland Islands, with an average temperature between 0 and 10 °C [12]. The Kerguelen Islands are characterized by high continuous winds, with an average speed of about 9.7 m/s. For about 312.9 days a year they experience wind gusts above 16 m/s, and during 68.1 days the gusts exceed a speed of 28 m/s [13]. This is expected to have a substantial effect on the wind farm capacity factor, which is estimated at 60–70%.[1]

The Kerguelen Islands are located approximately an equal distance between South Africa and Australia (about 4000 km to South Africa and about 4150 km to Western Australia). In this analysis we assume a cable length of 4150 km and we focus on the connection to South Africa. Based on our calculations, detailed in Appendix A, the cable costs for a 4150-km route from the Kerguelen Islands to South Africa would lie between 0.019 and 0.054 USD per delivered kilowatt hour, depending on the capacity factor of the wind farm. The cost for wind generation for 2020 and beyond has been projected in Ref. [14]. Onshore wind costs are estimated to start from less than 0.04 USD per delivered kilowatt hour, whereas offshore wind is projected to cost between 0.08 and 0.13 USD per delivered kilowatt hour. All cost projections in Ref. [14], assumed a wind capacity factor of 40%. Given the strong winds that the Kerguelen Islands receive, the wind capacity factor in that region is likely be around 60%. Furthermore, with an area of more than 7000 km^2 and only 100 residents, there is plenty of space available for onshore wind farms. As a result, we expect that wind production costs can start from as low as 0.02 USD per kilowatt hour for onshore and should not exceed 0.09 USD per kilowatt hour for offshore wind farms.[2]

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[1] Wind turbines are typically designed to reach their rated output power for wind speeds in the range between 14 and 25 m/s. Because of a lack of additional wind data for the Kerguelen Islands, we can assume that the wind turbines to be installed there will be designed such that the cut-out speed will be around 28 m/s.

[2] Kerguelen islands have resulted from volcanic formations. In such cases the sea depth increases quickly a few miles off the coast. Therefore, we expect that the majority of the wind farms installed on the Kerguelen islands would be onshore.

Figure 2 presents the total cost per delivered kilowatt hour, including both production and transmission to South Africa, plotted against varying wind production costs. In the graph we account for three different capacity factors of the wind farm—40%, 50%, and 60%—as well two cable cost projections: a high-cost cable and a low-cost cable. Each colored area represents a different capacity factor, with the lower costs per delivered kilowatt hour corresponding to a capacity factor of 60% and the higher costs corresponding to a capacity factor of 40%. The bottom border of each colored area represents the low-cost cable projections, whereas the top border stands for the high-cost cable projections. As a result, the total wind production and transmission costs will lie somewhere within a colored area, depending on the wind energy production costs and the cable costs. Besides the total costs for wind, in Figure 2 we also plot the expected revenues per kilowatt hour for wind energy production as determined by the South African government in 2011. In August 2011, South Africa launched a competitive bidding process for RESs. Two rounds of bids took place. The selected projects are expected to be commissioned by June 2014 (June 2015 for concentrated solar power plants) [15]. The average indexed bid prices for wind, expressed in US dollars, were 0.11 USD/kWh in the first round and 0.09 USD/kWh in the second round. These prices also are plotted as lines in Figure 2.

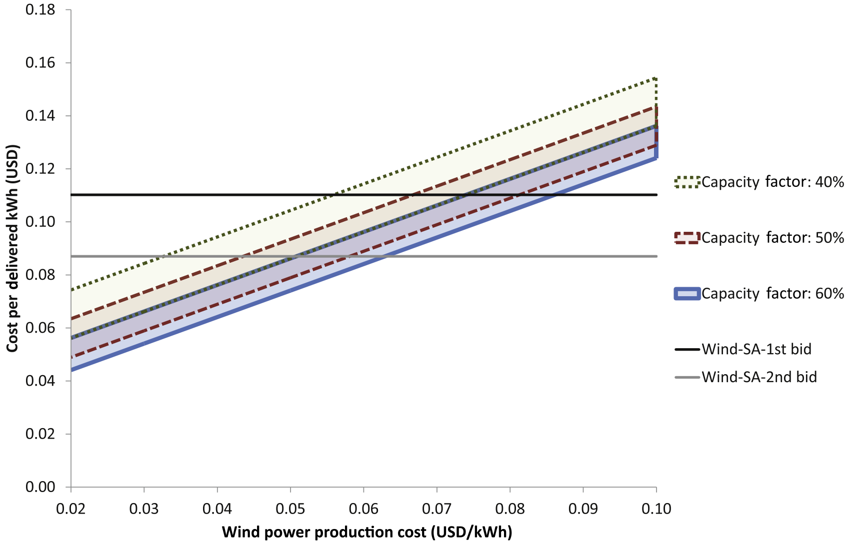

FIGURE 2 Awind farm on the Kerguelen Islands supplying South Africa.

Total cost per delivered kilowatt hour (production and transmission) for varying wind energy production costs, wind capacity factors, and cable costs. Each colored area corresponds to a different capacity factor and presents the cost spectrum depending on varying cost projections for the cable transmission and the wind power production. With Wind-SA-Bid are shown the constant prices per kilowatt hour that wind power producers in South Africa will receive, as determined in two rounds of a competitive bidding process.

As can be observed, for a wind capacity factor of 60%, the wind farm on the Kerguelen Islands can compete with local South African wind farms if the wind energy production costs are less than 0.085 USD/kWh for the low-cost cable projection. In the case of higher cable installation costs, the wind energy production costs should fall below 0.075 USD/kWh. Given the high wind potential of this region, and the fact that wind farms can be built on the island, the wind energy production costs, even by today's standards, are not expected to surpass these values. With decreasing capacity factors, as we observe in Figure 2, the wind energy production costs should decrease so that wind farms can remain competitive with those in South Africa. With a 40% capacity factor, the wind production costs should not exceed 0.033–0.055 USD/kWh in the worst case. Taking into account that Ref. [14] projects the production costs for onshore wind farms to start at less than 0.040 USD/kWh, values such as 0.033 USD/kWh are highly probable by 2020 and beyond.

By being already connected to South Africa, at a later stage the wind farm can also connect to Australia to take advantage of the time zone diversity and facilitate electricity trade. As the distance from the Kerguelen Islands to Australia is similar to the distance from the islands to South Africa, the cost projections, as shown in Figure 2, also are valid for the cable connection to Australia.

5. Interconnecting two continents over remote RES locations

In our analysis in Ref. [8], we assumed that a 3-GW wind farm off the eastern shores of Greenland is feasible; some investors have decided to connect a wind farm with a 3-GW line to Europe through Iceland and the Faroe Islands. We investigated whether a connection to North America would be profitable, taking into account two effects. First, because of the time zone difference, the wind farm will be able to sell its produced power always at peak prices, for example, 50% of the time to Europe and 50% of the time to the USA. Second, by creating a link between Europe and the USA via Greenland, opportunities for electricity trade between the continents emerge. Because the wind farm can produce power for a limited amount of time (we assume a capacity factor of 40%), the cable capacity can be reserved for electricity trade for the remaining hours.

5.1 Offering RES power at peak prices

In our analysis in Ref. [8], we estimated that the cable can deliver about 20 TWh/year after taking into account transmission losses. From this, about 10 TWh are allocated to wind farm production. This means that for about 50% of the time the cable capacity is available for electricity trade.

By building the transmission route from Greenland to the USA, we found that the wind farm's costs per delivered kilowatt hour would increase by 21–25%, assuming production costs of 0.06 USD/kWh.[3] If off-peak prices are half of peak prices, the revenues will increase by 31–33%, which results in additional profits of 7–12% for the wind farm, as shown in Table 1.

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[3] As already mentioned, Ref. [14] projects production costs of less than 0.04 USD/kWh for onshore and 0.08–0.13 USD/kWh for offshore wind farms by 2020. By assuming higher production costs, variations in transmission costs affect the final cost per delivered kilowatt hour less. To account for the less favorable case, we assumed lower production costs, allowing the increase in transmission cost to play a more significant role in the final cost.

Table 1 Wind Farm in Greenland: Summary of the Cost-benefit Analysis Results for Connecting the Wind Farm to the USA

Transmission Route: Europe – USA via Greenland (Total Cable Energy Capacity: 20 TWh)			
	Wind Farm Production	**Electricity Trade**	
Utilization (% of total time)[a]	~10 TWh (40)	~6 TWh (30)	~10 TWh (50)
Profit increase (%)	7–12	24–27	39–42

[a] *The wind farm is located in the middle of the path from Europe to the USA. As a result, it incurs only half of the transmission losses. That means that the same amount of power, e.g. 10 TWh, can be delivered in less time, resulting in a lower utilization factor of the transmission path.*

5.2 Intercontinental electricity trade

In this section, we focus on the electricity trade opportunities that emerge from the connection of the wind farm to both continents. Our analysis is based on real price data for the year 2012. We obtained the hourly spot prices from the European Power Exchange in Germany [16] and the PJM Interconnection in the USA [17]. Because of the time zone difference between the two continents, the two electricity markets experience their peak and lowest prices at different times. Our analysis is detailed in Appendix B.2. We mainly examine two levels of utilization: 30% and 50%. As already mentioned, 50% corresponds to the maximum utilization rate of the cable for electricity trade; the rest is used to transfer the power produced by the wind farm. We also investigate a lower utilization rate of 30% to account for a less favorable case (e.g. reduced availability of the cable or of excess renewable energy). Our investigations show that through the revenues generated from the electricity trade, the route between Greenland and North America can be amortized within 10–12 years with a 50% utilization and within 14–17 years if the cable is used for electricity trade only 30% of the time. Translating these results into profits, we find that by exercising electricity trading 30% of the time, the net profits[4] will increase by 24–27%; this is in comparison with the case where the wind farm sells its wind power only to the UK and earns a *profit* of 0.06 USD for each delivered kilowatt hour.[5] When exercising electricity trade 50% of the time, the profits can increase up to 42%. Table 1 summarizes our results.

To conclude, it seems that being connected to both continents would be a profitable solution for the wind farm in Greenland. In the last two sections, we investigate two possible sources of income created by building a transmission route from Europe to the USA via a wind farm in Greenland: first, selling the produced wind power always at peak prices, either in Europe or in the USA, and second, by trading

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[4] The investment costs of the additional cable have been deducted from the electricity trade revenues.

[5] The profits from the intercontinental electricity trade are positive, that is, the revenues surpass substantially the investment costs for the additional line in all cases. However, the *increase* in the final profit depends on the wind farm profits. Selling wind energy at higher prices to the UK results in lower variation of the total profit from the electricity trade revenues. In accordance with Section 5, profits of 0.06 USD/kWh imply a sell price of 0.12 USD/kWh. Here, we account again for the less favorable case in our calculations, assuming that the wind farm generates substantial profits by selling the produced power at a price twice its marginal cost.

electricity between the continents. Both options independently result in a profitable operation for the wind farm.

6. Intercontinental interconnections by direct lines

In Ref. [8], we analyzed the expected transmission costs per delivered kilowatt hour. We estimated the cost of a 5500-km, 3-GW submarine cable to be in the range between 0.0166 and 0.0251 € per delivered kilowatt hour, and we found that, except for the most expensive RES generators, it seems that it would be more economical for the USA to import RES power from Europe than operate its own fossil fuel power plants.[6]

Here, we extend our analysis to estimate whether the cost for a long submarine cable could be amortized through the revenues arising by the electricity trade between the two continents. Again, we used the hourly spot prices for 2012 provided by PJM Interconnection in the USA and the European Power Exchange in Germany [16,17]. In our calculations we accounted for the transmission losses incurred by an 8000-km-long corridor connecting the USA with Germany. We further assumed that before the realization of a direct submarine cable between the two continents, there will already exist long HVDC lines on land in both Europe and the USA. Therefore, we considered that the investment costs of this project correspond to the direct submarine cable between Europe and the USA, which has a length of 5500 km and a capacity of 3 GW. In our analysis, presented in Appendix B.1, we estimate that for an 80% utilization of the cable (i.e. the cable is used only 80% of the time), the amortization period ranges between 18 and 28 years. For the less favorable case in which the cable utilization is 50%, the amortization period increases to about 23–35 years, depending on the cost projections. Although such amortization periods might not be most attractive for private investors, these results highlight that, from the point of view of social welfare, such a cable is beneficial for society.

7. Discussion

In the previous sections, we saw how intercontinental interconnections can take advantage of the time zone difference and smooth out electricity supply and demand. In this way, excess electricity production will not be irrevocably lost but transmitted to where it is needed most. Besides this, there are several additional opportunities that emerge from such a concept. In the following we provide a brief overview of them. For a more detailed analysis that refers to both the benefits and challenges that arise, the interested reader can refer to Ref. [8].

7.1 Minimizing power reserves

With the increasing penetration of RESs, the necessary control reserve capacity is expected to increase [18]. Global interconnections can offer such services. Taking advantage of time zone diversity, they

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[6] The study is based on electricity generation from conventional sources estimated in Ref. [14] with fuel cost projections based on Ref. [18]. Unconventional sources of oil and gas such as oil sands and natural gas shales are also considered in the projections of Ref. [18].

can reserve control capacity in areas with lower electricity demand and offer it at locations that experience their peak demand at the same time. By offering an additional source of control power that is supplementary to the control reserve options available in each control area, significant cost savings could emerge, as building additional “peaking” gas power plants for balancing renewable energy could be avoided. Aboumahboub et al. [19] investigated this, comparing the necessary conventional power plants in the presence (or not) of interconnecting lines between regions. Their results for both the European and a potential Global Grid showed that through interconnections the need for dispatchable conventional power plants could be reduced by two to eight times.

7.2 Alleviating the storage problem

Bulk quantities of storage will be necessary for absorbing nontransmissible power and relieving congestion (e.g. Ref. [3]). The HVDC links of the Global Grid have the potential to alleviate the storage problem in future power systems by absorbing excess power (i.e. at a low cost) and injecting it into regions where it is needed more. In terms of efficiency, the losses of an ultra-HVDC line (e.g. ±800 kV) amount to about 3% for every 1000 km [20]. This would imply that a 6000-km HVDC line using current technology has better efficiency than pump-hydro or compressed-air energy storage.

7.3 Additional benefits

Global Grid interconnections present additional opportunities that can prove beneficial to power systems. For example, they have the potential to reduce the volatility of electricity prices. They also allow the transmission of bulk quantities of power with less loss of power. Power system security can also be enhanced through such interconnections in two ways. First, they provide additional pathways for the power to flow. Second, because of HVDC technology, they offer independent active and reactive power control and can act as a firewall between the systems they interconnect, not allowing disturbances to spread.

8. Conclusions

The Global Grid advocates the connection of all regional power systems into one electricity transmission system spanning the whole globe [8]. Power systems are currently forming larger and larger interconnections, while ongoing projects plan to supply, for example, Europe with “green power” from the North Sea. Environmental awareness and increased electricity consumption will lead more investments toward RESs, which are abundant in remote locations (offshore or in deserts). The Global Grid will facilitate the transmission of this “green” electricity to the load centers, serving as a backbone.

The Global Grid concept was already introduced in Ref. [8], but this chapter presented four possible stages that could gradually lead to the development of a globally interconnected power network. Building long transmission lines to harvest remote renewable resources will be the main driving force in the first stage of the Global Grid development. From there, a point will be reached where an RES power plant will be equidistant from two power systems on different continents. Connecting the RES power plant to both continents to sell the produced power always at peak prices—taking advantage of the time zone diversity—will mark the second developmental stage of the Global Grid. Because RES power plants usually have a capacity factor below 50%, the remaining cable capacity can be used for intercontinental electricity trade. This signals the progression into the third stage of development. As long as the profits from electricity trade are substantial, in the fourth developmental stage direct interconnections between countries or continents can start to be built. Introducing the four development stages helps to lay out a path leading towards a global grid environment. Nevertheless, the progression into these stages does not need to happen in a sequential manner, e.g. the fourth stage can follow directly the first, or the second and third stage can occur simultaneously.

Quantitative analyses of all four development stages have been provided in this chapter, showing that global interconnections can be both technically feasible and economically competitive. By exploring the possibility of a wind farm in the Kerguelen Islands in the Indian Ocean, we showed that it could provide renewable energy to South Africa at a cost competitive to that charged by local wind farms. At a later stage, this wind farm could connect to Australia, leading to intercontinental interconnections. We further estimated that connecting a wind farm in Greenland to both Europe and North America results in a 7–12% increase in profit. At the same time, the remaining cable capacity leaves room for intercontinental electricity trade. Based on real 2012 prices from Germany and PJM Interconnection in the USA, we found that electricity trade results in additional profits of 24–42%. We concluded our calculations by conducting a cost-benefit analysis for a direct submarine cable between Europe and the USA. The revenues from the intercontinental electricity trade, again based on real prices, result in an amortization period of 18–35 years for the cable investments, depending on the cable utilization factor. This highlights that, from a social welfare point of view, such a cable is beneficial for society. Based on the results detailed in this chapter, additional studies are necessary on a technical, economic, and societal level. The research community and the industry should also be encouraged to actively participate in identifying challenges and developing solutions that could lead to a Global Grid.

Appendix A. Cable cost projections

In Ref. [8], we carried out a detailed analysis on the projected costs of a long HVDC submarine cable. In this work we adopt the same cost considerations. We will assume a 3000-MW, ±800-kV submarine cable. We selected the ±800-kV option because we believe that higher voltage levels will be adopted for long-distance transmission. We distinguish between two cost alternatives for the submarine cables. As a high-cost case, we assume a cost of €1.8 million/km for our 3000-MW line, the same as what was suggested in Ref. [21] for a 5000-MW sea cable. As a low-cost case, we assume the maximum cost of the completed HVDC projects (up to 2012 as presented in Ref. [8]). This is €1.15 million/km. The rest of the cost assumptions are the same for both cases. Concerning the voltage source converters, because of the higher voltage and the large capacity of the line, we assume the cost of each terminal converter to be €300 million. For additional details, the reader can refer to Ref. [8].

Table A.1 Kerguelen Islands to South Africa: Transmission Cost per Delivered Kilowatt Hour (in USD)

	Wind Farm Capacity Factor		
Cable Costs	**40%**	**50%**	**60%**
Low cost	0.036	0.029	0.024
High cost	0.054	0.043	0.036

Kerguelen Islands. For the connection between the Kerguelen Islands and South Africa we assume a 3000-MW, ±800-kV submarine cable with a length of 4150 km. Based on the cost assumptions above and in Ref. [8], Table A.1 presents the transmission costs per delivered kilowatt hour for different wind farm capacity factors.

Europe—North America over Greenland. For the route over Greenland, besides HVDC cables, building HVDC overhead lines will also be necessary. Thus, for HVDC overhead lines, we assume a cost of €600 million/1000 km, as also suggested by Weigt [22] and Delucchi and Jacobson [14]. The detailed cost analysis can be found in Ref. [8].

Europe—North America through a direct submarine cable. We assume a 3000-MW, ±800-kV submarine cable with a length of 5500 km. Note that the distance from Halifax, Canada, to Oporto, Portugal, is 4338 km, whereas the distance from New York City to Oporto is 5334 km.

Appendix B. Electricity trade between Europe and the USA: detailed analysis

Appendix B.1. Direct submarine cable

In this section we detail the analysis we carried out to investigate the possibilities for electricity trade between Europe and the USA. Because of the time zone difference, the peak demand, and thus the peak prices, are shifted in time. Opportunities for electricity trade emerge. Our analysis is based on real hourly price data for the year 2012 obtained from Germany in Europe and the PJM Interconnection in the USA. For Germany we took the hourly spot prices for 2012 from the European Power Exchange [16]. For PJM we took the real-time prices, specifically the system energy price, that is, the price component that is the same over the whole PJM area, ignoring cost of congestion and losses [17]. We assume that the two power systems are connected through an 8000-km line, from which 5500 km correspond to the submarine cable between Oporto and New York and the remaining 2500 km correspond to an HVDC corridor between Oporto and Germany. We further assume that by the time the investment for the intercontinental cable will take place, there will already exist several HVDC interconnections within Europe and the USA. These could be used for the transfer of power between Oporto and Germany. Therefore, as investment costs we assume the cost of the submarine cable between Oporto and New York. Still, our calculations take into account the incurred losses along the total length of the corridor, that is, the 8000 km.

We assume a time difference of 6 h between Germany and the US east coast, where the PJM Interconnection is located. The hourly prices in Euros are transformed to US dollars through average monthly exchange rates for 2012.[7] In our analysis we assume that the investment takes place in 2012, but the revenues are generated during the next 40 years since this is the expected lifetime of a cable [10, 24, 25]. Because data were available only for 2012, we assume that the prices over the next 40 years will be similar to those in 2012, considering a discount rate of 3%, as suggested by the National Renewable Energy Laboratory ([26], p. 9), and an inflation rate of 2.5%. We distinguish between three different utilization rates for the cable: 30%, 50%, and 80%. These rates reflect the equivalent amount of hours per year during which the cable is used. For example, 30% utilization means that the cable transmits power up to its full capacity 30% of the time. For a 30% utilization,

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[7] Source: http://www.x-rates.com/average/?from=EUR&to=USD&amount=1&year=2012.

Table B.1 Amortization Period (in years) for a High-Cost and a Low-Cost Projection of the Cable

	Utilization		
Cable Costs	**30%**	**50%**	**80%**
Low cost	31	23	18
High cost	>40	35	28

electricity is traded when the price difference is more than US$35; for 50% utilization the trade takes place for prices more than US$23, and for 80% utilization the minimum price difference is US$10.

Table B.1 presents the amortization period for the submarine cable. The cable generates revenues by buying electricity with a low marginal price on one continent and selling it at higher system marginal price to the other continent. As can be observed, for 50% and 80% utilization of the cable the payback time is less than the minimum cable lifetime for both the high-cost and the low-cost scenario. For a utilization of about 30%, the cable is amortized only in the low-cost scenario. Here we stress that building a cable between the USA and Europe is not primarily a for-profit investment. The goal is to create an investment that will be beneficial society as a whole. Thus, any amortization period that is less than the lifetime of the project is considered positive because it is expected to benefit society.

Appendix B.2. Connecting Europe with the USA through a wind farm in Greenland

The connection of a wind farm in Greenland to both continents facilitates electricity trade between Europe and the USA. In this appendix we investigate whether the costs for building the line between Greenland and the USA could be covered from the revenues generated from electricity trade. In our analysis of Greenland in Ref. [8], we calculated that over a year, 50% of the cable energy capacity can be used for electricity trade. Two effects should be considered here. First, in reality the wind farm will often operate at capacities lower than its maximum. Therefore, on the one hand, only a part of the transmission capacity often will be available electricity trade; on the other hand, this capacity will be available for more than 50% of the time. Second, it may occur that during periods when there is substantial price difference between the two continents, the wind farm will be producing power at the same time. As a result, the transmission capacity cannot be used for profitable arbitrage. Because of these two effects, we assume that the transmission capacity factor for electricity trade will be about 30%, whereas in the best case it will not exceed 50%. Table B.2 presents the amortization period for

Table B.2 Amortization Period (in years) for the Transmission Path from Tasiilaq to New York for a High-Cost and a Low-Cost Projection of the Cable

	Utilization		
Cable Costs	**30%**	**50%**	**80%**
Low cost	14	10	8
High cost	17	12	10

three utilization levels of the cable: 30%, 50%, and 80%. (The 80% level is presented only for comparison with Table B.1.) As we can observe, for a utilization of 30–50%, the costs of the route from Greenland to North America can be recouped within 10–17 years. It should be noted that the payback period here does not take into account the additional profits the wind farm will make by always selling its produced wind power at peak prices. It is also interesting to point out that the route from Germany to New York via Greenland is a similar distance to that of the route from Germany to New York through a direct submarine cable in Oporto, Portugal.

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