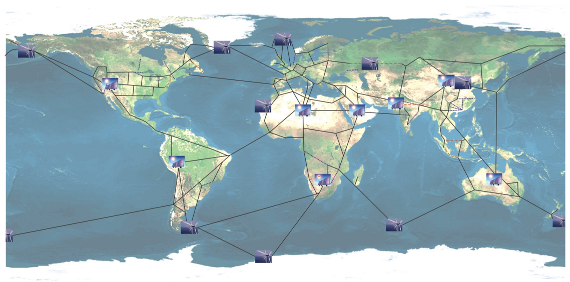

The Global Grid

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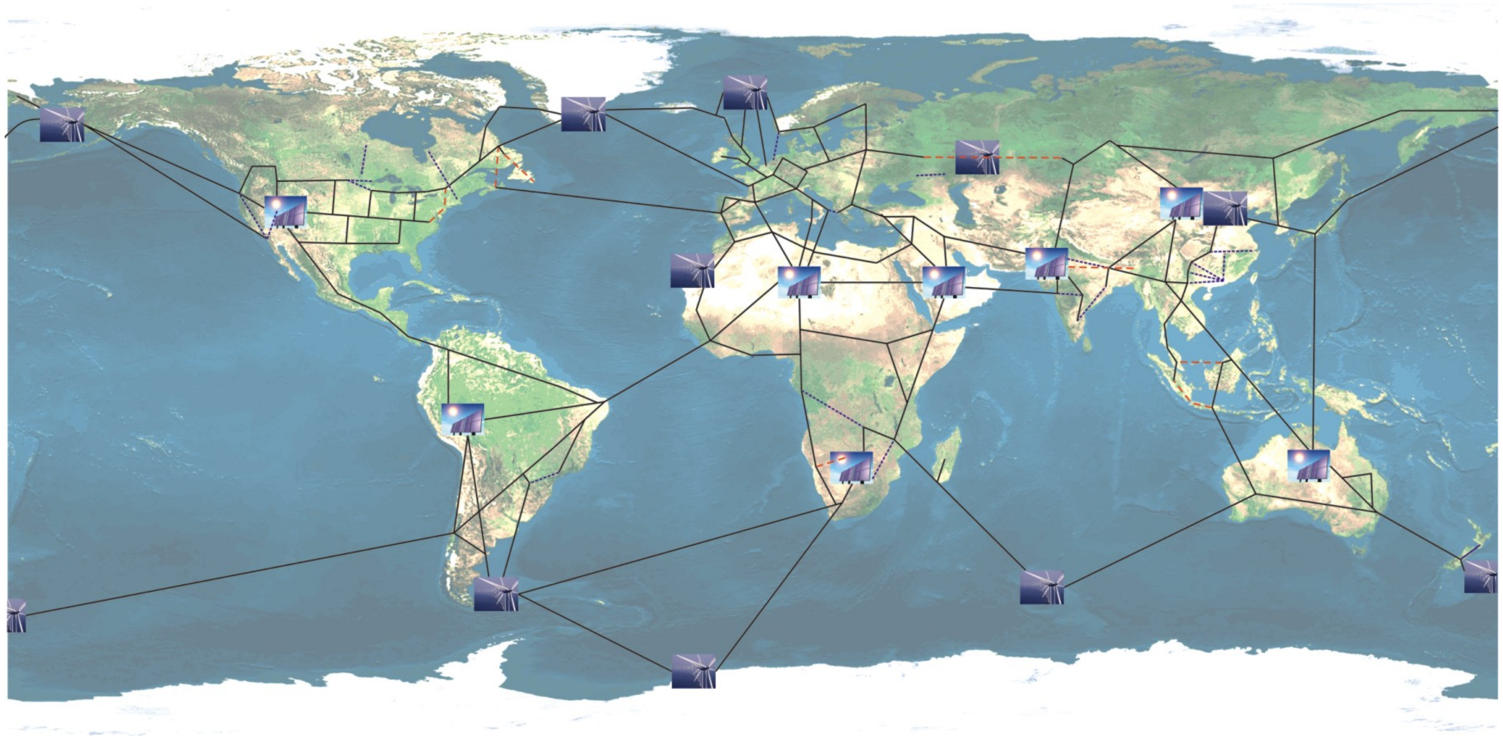
The Global Grid: what is it?



Global Grid: Refers to an electrical grid spanning the whole planet and connecting most of the large power plants in the world. Envisaged to be a natural future stage for the electricity network. May be reached in a few ten years.

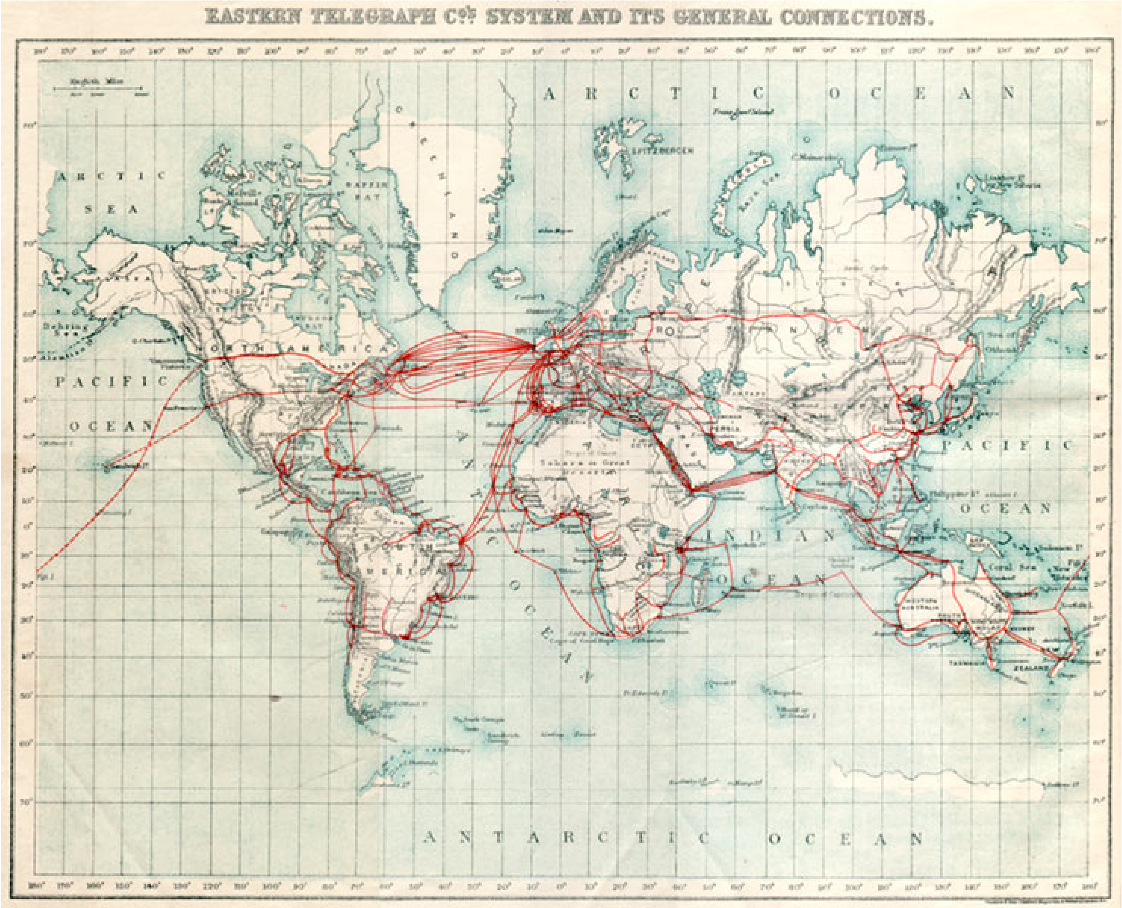
Key infrastructure element: Long High Voltage Direct Current (HVDC) transmission lines.

Main driving force behind the global grid: Harvesting of remote renewable sources of energy, mostly wind and sun.

With the global grid, electricity will become a global commodity, such as petrol and coal are.

Technological feasibility arguments

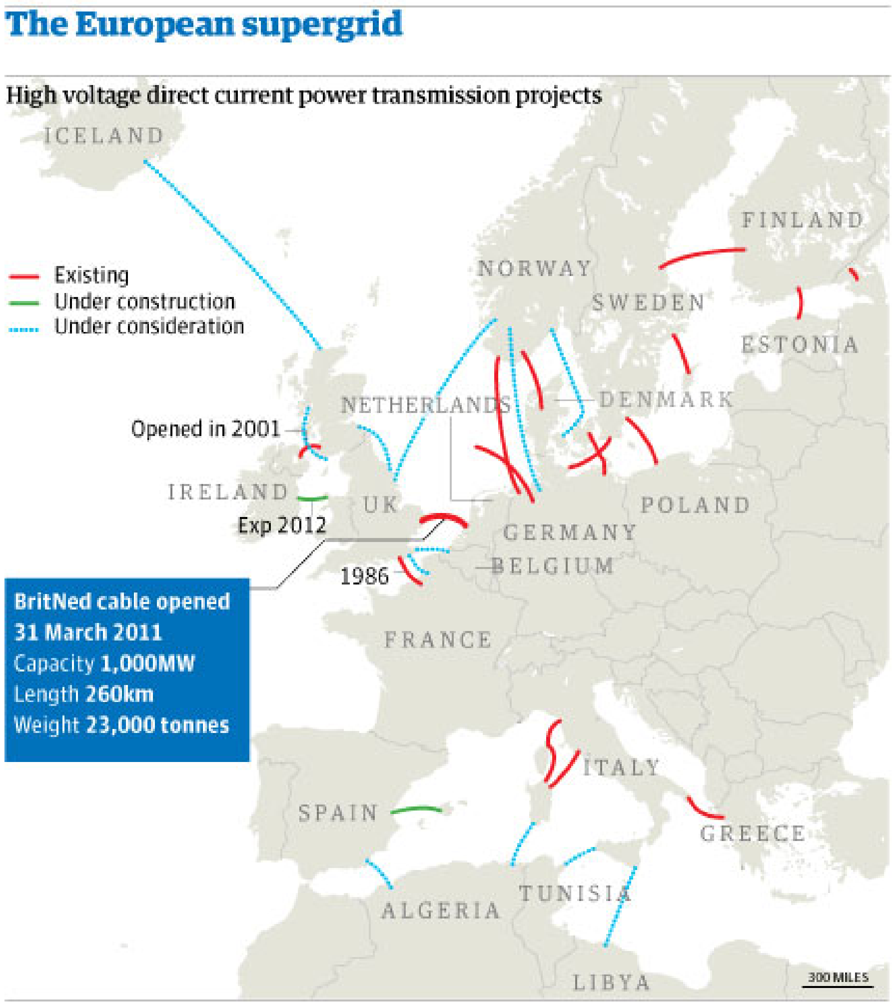
Global cable networks exist for a long time already. Sketch of the telegraph network in 1901:



Many undersea DC cables already in operation.

Longest one in 2012: 580 km (the Eernshaving-Feda link)

Undersea cables already installed up to a depth of 1500 m.



No technological problems for building on land very long DC lines or cables.

Technological hurdles on the way

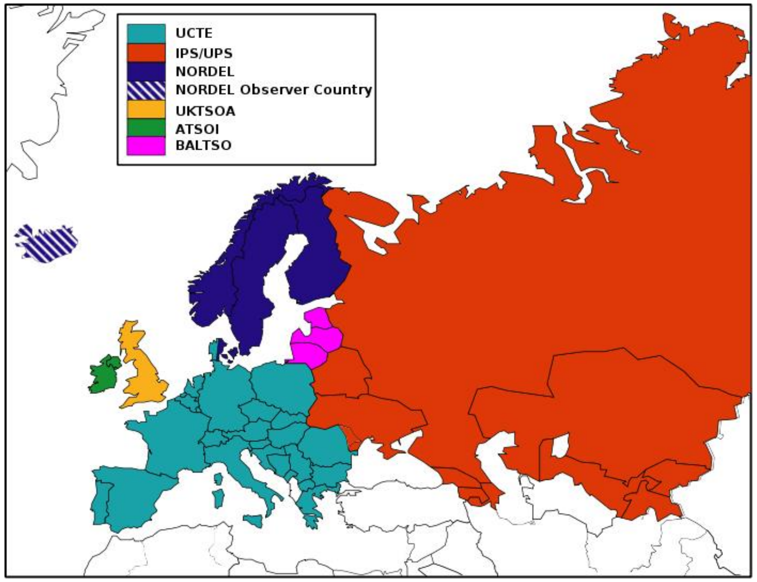
Mechanical constraints that go with installing the cables at very large water depth ($>$ 1500 m)

DC breakers technology not yet fully mature. Very important component to start building High-Voltage Direct Current (HVDC) grids.

Control/decision making issues for the combined operation of a DC network with an AC one.

Why a DC technology and not an Alternative Current (AC) one for the links?

Much easier to connect non-synchronous power systems with DC technology (act as a firewall between the AC zones - decoupling of the dynamics).



Synchronous areas in Europe.

For a same voltage level less losses in DC links than in AC ones.

Control over the power transferred in the HVDC lines (eases the operation of the power system - may foster merchant investment).

Main force behind the creation of the global grid: the quest for renewable energy

The quest for renewable energy has really started in Europe at the beginning of the years 2000, mainly for getting off fossil fuels (climate change motivation) and denuclearizing countries (safety issues).

First phase of this quest was driven by subsidies. Costs of renewable energies (mostly wind and sun) have significantly dropped during this first phase.

A second phase driven by the cheap costs of renewables is progressively starting. Renewable energy (in good locations) is indeed becoming competitive with fossil fuel (except coal) and nuclear energy.

A few numbers for the year 2013

Off-shore wind farms installed in the North Sea produce energy at a cost below 130€/MWh. Cost computed as follow: $\frac{investment\_costs+maintenance\_costs\_during\_20\_years}{number\_of\_MWh\_produced\_during\_20\_years}$

On-shore wind farms in windy Texas produce energy at a cost below 60€/MWh.

Large PV installations in good locations: prices have fallen well-below 100€/MWh.

Deal between the UK government and EDF for building two new nuclear power plants in Hinkley is worth 110€/MWh.

Average cost of gas in Belgium: around 30€/MWh. Price of gas for generating 1 MWh of electricity in power plant with an efficiency 58%: $\frac{30}{0.58} \simeq$ 52€/MWh.

Average cost of coal in Belgium around $\frac{65\text{€/ton}}{8.14\text{MWh/ton}} \simeq$ 8€/MWh. Price of coal for generating 1 MWh of electricity in power plant with an efficiency of 35%: $\frac{8}{0.35} \simeq$ 23€/MWh.

Average price of electricity in Belgium: around **45€/MWh**.

Statement:

(Almost) Subsidy-free development of renewable energy will come with a geographical extension of existing electrical networks. At one point, disconnected electrical systems will meet and the global grid will form.

First reason behind this statement: Not enough good locations available for collecting renewable energy which is (almost) competitive with fossil fuels and nuclear energy in places "covered" by existing electrical networks.

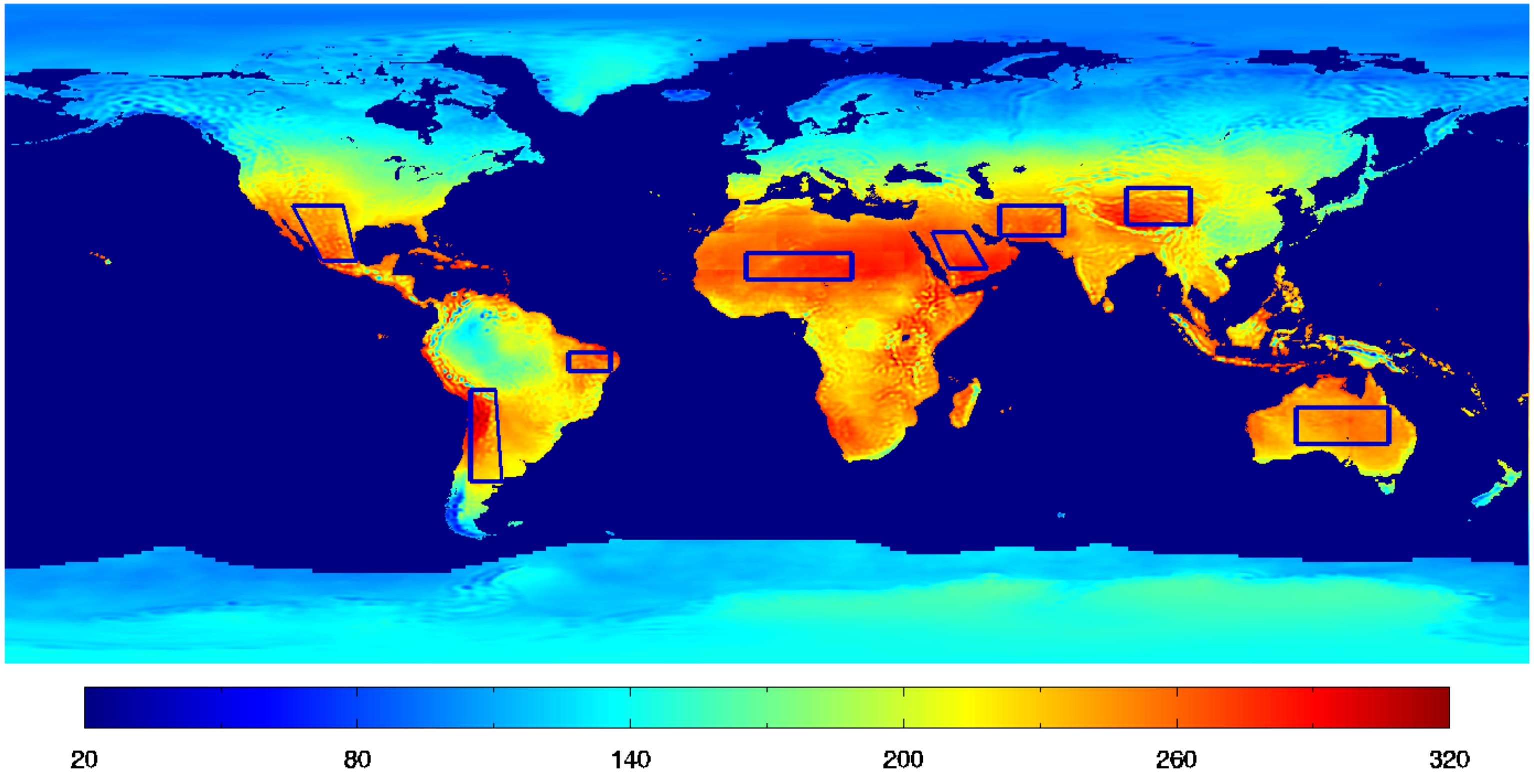
Let us take the case of **wind energy** in Belgium, a country which is very well covered by its electrical network. In 2010, the annual consumption of electricity in Belgium was 91 TWh (1 T $= 10^{12}$). In a good location, a wind farm will produce at best 3 W/m^2 $\Rightarrow$ $\frac{91\times10^{12}}{3\times8760\times10^6} \simeq 3462$ km^2 (11% of the country) of windy land need to be covered by wind farms to cover Belgian electricity needs. Belgium does not have 11% of its land where (almost) cost-competitive (with gas and nuclear power) wind farms could be built.

Not In My BackYard (NIMBY) driven opposition to wind farms also significantly shrinks the size of the well-exposed areas on which wind energy could be collected.

On-shore wind power in Spain: The increase in technological performances and installed capacity per turbine did not compensate in these recent years for the decrease in resource quality and availability.

Second reason behind this statement: The vast majority of the best locations for collecting renewable energy are located far from existing networks. This may be a push for extending the existing networks, even if there still exist in areas closer to load centres, renewable sources of energy that can be exploited in a cost competitive way with conventional sources of energy (fossil fuel and nuclear).

Average solar radiation map (W/m^2):



A simple **cost of energy based decision making process** for deciding whether to develop renewables locally or in well-exposed remote locations:

Let:

$cost_{loc.}$ be the cost per MWh of producing renewable energy locally;

$cost_{rem.}$ be the cost per MWh of producing renewable energy in a remote location;

$cost_{trans.}$ be the cost of transport of electricity per MWh of electricity delivered;

$losses$ be the ratio of power lost during transport.

If $cost_{loc.} > \frac{cost_{rem.}}{1-losses} + cost_{trans.}$, import the energy. Otherwise, produce locally.

Example: Assume that the cost of electricity from PV sources in Belgium is the same as the cost of electricity produced by (new) nuclear power stations. What is the most cost efficient solution: (i) To invest in 5 GW of PV panels in Belgium (i) To install the same capacity in North Africa and bring this power back to Belgium with a 5 GW cable?

Data: (i) Period of analysis: 20 years (lifetime of the PV panels) (ii) Cost of electricity produced by a nuclear power plant: 110€/MWh (iii) Load factor of PV panels in Belgium: 0.1; load factor of PV panels in North Africa: 0.25 (average solar radiation around 250 W/m^2 in Africa and around 100 W/m^2 in Belgium) (iv) Cost of a 5 GW cable: €2 billion/1000 km; cost per converter: €350 million (v) Length of the cable between North Africa and Belgium: 4000 km (vi) Losses in the cable: 3% per 1000 km.

Solution:

$cost_{loc.} = 110$€/MWh

$cost_{rem.} = \frac{110}{2.5} = 44$€/MWh

Energy produced in Africa by the PV panels over 20 years:

$5 \times 10^3 \times 0.25 \times 8670 \times 20 \simeq 216 \times 10^6$ MWh

Energy delivered: $0.88 \times 216 \times 10^6 = 190 \times 10^6$MWh

Cost transmission infrastructure: $4 \times 2 \times 10^9 + 2 \times 350 \times 10^6 =$ €8.7 billion.

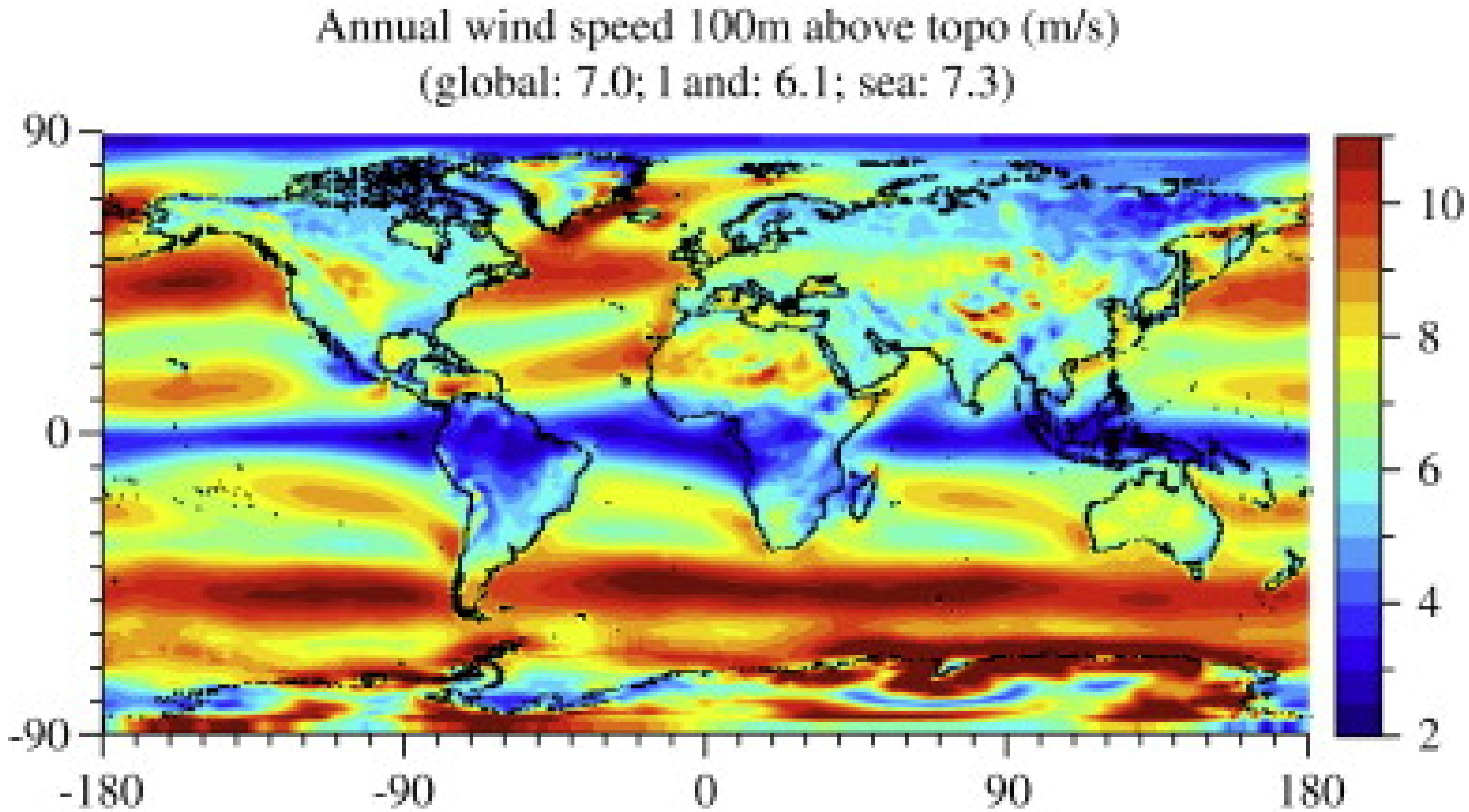
$cost_{trans.} = \frac{8.7 \times 10^9}{190 \times 10^6} = 45.7$€/MWh.

$losses = 0.12$

$\frac{cost_{rem.}}{1-losses} + cost_{trans.} = 95.7$€/MWh.

$\Rightarrow$ Importing electricity produced with PV panels in Africa would cost

14.3€/MWh less than producing this electricity with PV panels in Belgium.



In the best on-shore locations in continental Europe, the wind speed is around 7 m/s. On the East coast of Greenland, it is around 11 m/s. The length of the Greenland coastline exposed to these high winds is around 1500 km.

The power outputted by a windmill - that operates within its limits - grows as a cubic function of the wind speed $\Rightarrow$ if the wind speed doubles, its power outputs is multiplied by a factor 8.

Since the wind power generated by a well-placed wind farm in continental Europe is around 3 W/m^2, we assume that a wind farm in Greenland could produce $3 \times (\frac{11}{7})^3 \simeq 12$ W/m^2. That corresponds to an amount of energy equal to $12 \times 8760 \simeq 105 \times 10^3$ MWh/km^2 per year.

The total consumption of electricity in the EU-27 was 3.18 billion MWh $\Rightarrow$ $\frac{3.18 \times 10^9}{105 \times 10^3} = 30{,}285$ km^2 of wind farms in Greenland would cover the entire EU-27 consumption. This surface corresponds to a strip of land (mixed land/sea) of around 20 km wide along the coastline of Greenland well exposed to winds.

There will be no NIMBY opposition to wind farms on the East coast of Greenland because no one is living there. Wildlife may however be impacted.

Snow-white Ivory Gull

What about the costs?

Cost per MWh produced in Greenland: Difficult to know. Probably somewhere in the interval $[30, 60]$€/MWh. Cost will depend on (i) the technology that will be developed for wind turbines adapted to the weather conditions of Greenland (ii) the economy of scale (very large wind projects could be developed).

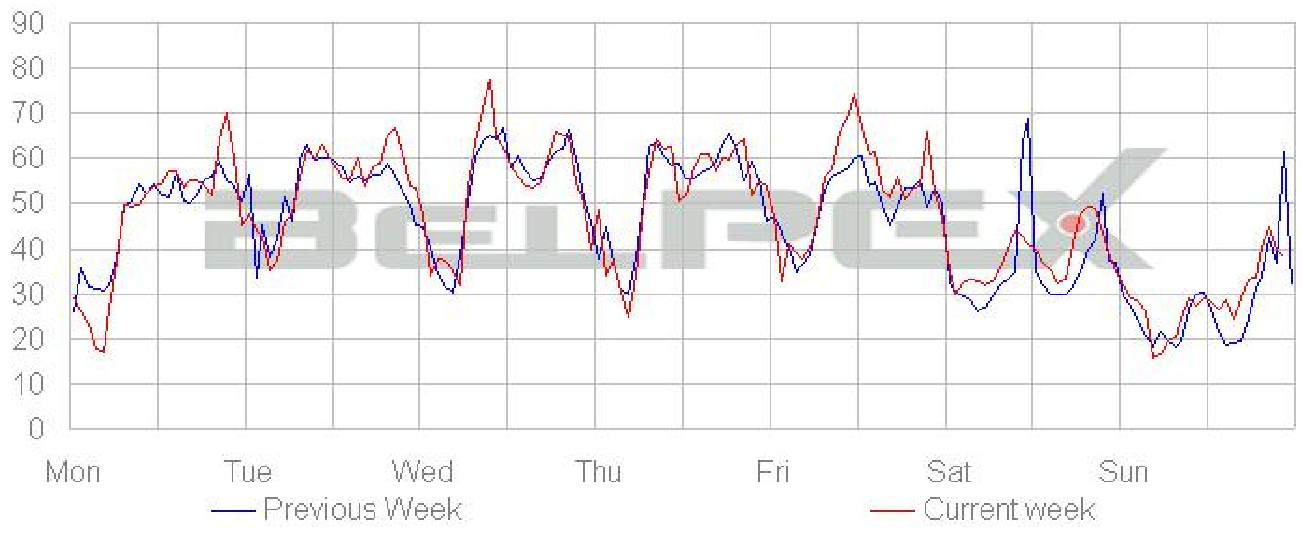
Transport costs per MWh delivered: Around 4000 km from Greenland to mainland Europe. Same distance as in the PV example where the costs of transport where around 45€/MWh. Due to the higher load factor of wind farms (25% for the PV panels in North Africa against 50% for wind farms in Greenland installed over a large location), the utilization factor of the transmission infrastructure would increase. Costs will drop to less than 23€/MWh.

Losses: Around 12%

$\Rightarrow$ **Total costs in €/MWh in the interval $[53, 83]$. Note:** Only the lower end of the interval is competitive with the Texas wind farms.

Other force behind the creation of the global grid: electricity price fluctuations

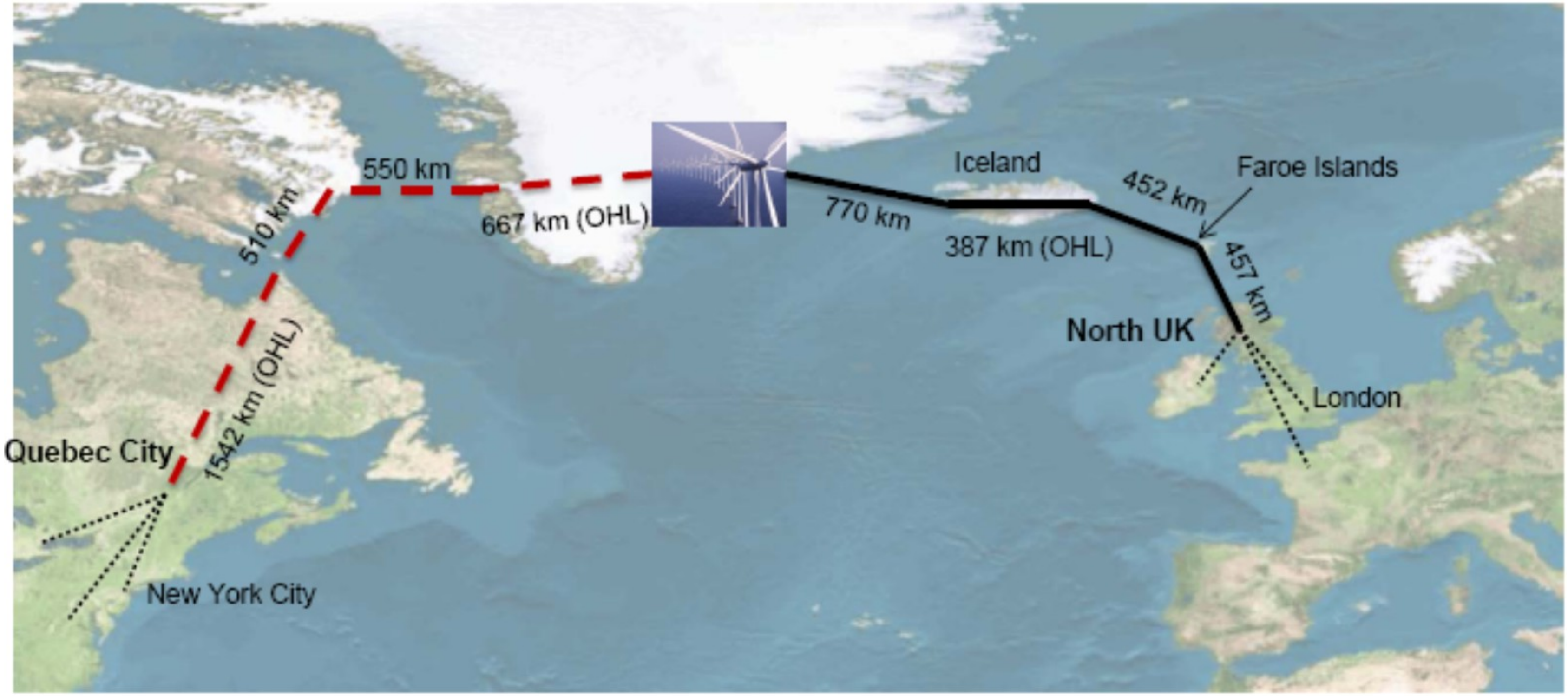
Electricity prices vary during the day. Typical price evolution (in €/MWh) on Belpex:



Prices are usually high during the day (high-demand for electricity) and low during the night (low-demand for electricity).

Countries in significantly different time zones are therefore likely to experience high instantaneous price differences ⇒ That creates business cases for building new electrical connections, such as for example between North America and Europe.

An example: Suppose that there are plans for investing in a new 5 GW wind farm in Greenland and that the grid infrastructure for bringing this power back to Europe already exists. Would it be profitable to build also at the same time a 5 GW connection to North America?



Two cases are analyzed:

First case: The new connection is only used for selling the wind power produced by the wind farm at the highest price.

Second case: Since the wind farm will not always produce 5 GW, we also analyze the possibility to valorise the remaining capacity of the cable by trading electricity between Europe and North America.

Data: (i) Cost of the grid infrastructure for transmitting power to North America: €4 billion. (ii) Cost of the wind farm per MW installed: €1.5 million. (iii) Load factor of the wind farm: 50%. (iv) Losses for transporting electricity from Greenland to North America or mainland Europe are the same and equal to 12%. Losses equal to 24% for transporting electricity from North America to Europe and vice versa. (v) Two prices for electricity in Europe and North America: the *peak price* and the *off-peak price*. Ratio between peak price and off-peak price is equal to 2. When there is a peak price for electricity in North America, there is an off-peak price in Europe, and vice-versa. Peak price period is lasting 12 hours per day. (vi) No limits on the amount of electricity that can be transported from Greenland to mainland Europe.

Results:

Yearly revenue without the connection to North America (base case): Let $peak\_price$ be the peak price for electricity expressed in €/MWh. The wind farm will sell its electricity at an average price of $0.75 \times peak\_price$. The yearly revenue of the wind farm is: $8760 \times 0.5 \times 5000 \times 0.88 \times 0.75 \times peak\_price \simeq 14{,}454{,}000 \times peak\_price$.

Increase in investments: $\frac{4.\times 10^9}{1.5\times 10^6 \times 5000} \times 100 = 53\%$.

Increase in revenue for the first case: The wind farm will always be able to sell its electricity at $peak\_price$. The increase in revenue is: $\frac{1-0.75}{0.75} \times 100 = 33\%$.

Yearly revenue made by valorizing the remaining capacity of the cable by trading: When the wind farm is exporting power to Europe (4380 hours per year), 5 GW of electricity can be traded from America to Europe. When the wind farm is exporting power to North America, an average of 2.5 GW of electricity can be traded from Europe to America. That leads to a yearly revenue of: $(4380 \times (5000 + 2500) \times 0.76) \times peak\_price - (4380 \times (5000 + 2500)) \times \frac{peak\_price}{2} = 8{,}541{,}000 \times peak\_price$. This is a revenue which is equal to 59% of the base case one.

Increase in revenue for the second case: $33\% + 59\% = 92\%$.

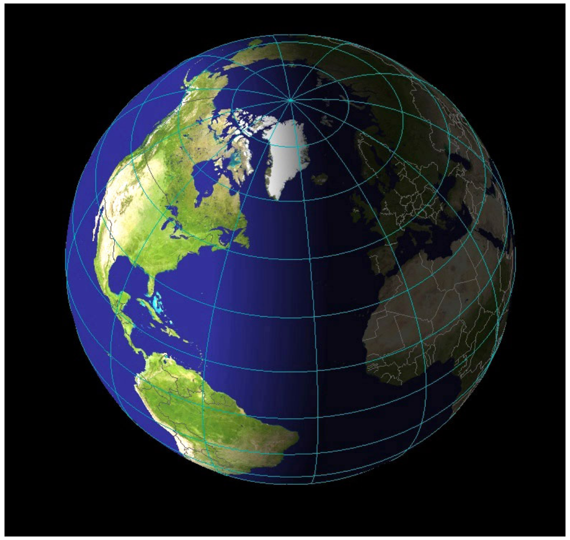
Fluctuation of the demand and the production in a Global Grid environment

The power injected into the Global Grid has always to be equal to the power taken off the grid plus losses.

If we assume that most of the energy in a Global Grid environment will be produced by renewables - mostly wind and sun - whose power output cannot follow the load, wouldn't it be a problem? Would it require to invest massively into bulk storage electricity (e.g., under the form of hydrogen) or in back-up gas power stations?

Indeed, the load in a specific location fluctuates a lot with the hour of the day and the seasons. And so does the power produced by renewable energy.

But since:



⇒ It seems reasonable to assume that the load at the Earth level (and the energy produced by renewables) are (would be) more or less constant.

Additionally:

Wind power and sun power can always be modulated downwards.

The load can be modulated using demand side management schemes.

The Global Grid will allow to tap into new hydro power resources which offer flexibility without throwing away energy. As way of example, the hydro power potential of Greenland is equal to 8×10^8 MWh/year, that is $\frac{8\times10^8}{3.18\times10^9} \times 100 = 2.5\%$ of the EU-27 consumption of electricity.

Vandkraftværk hydro installation.
Capacity: 3×15 MW.

$\Rightarrow$ I do not expect the needs for bulk storage of electricity or back-up gas power stations to be high in a Global Grid environment.

Electricity generation in a country and the global grid: the cost of energy perspective

In a global grid environment, the power plants of a country will have to compete with plants of any other countries.

It may happen that when only costs of production and transport are taken into account, power production may not be profitable anymore in many countries that do not possess highly profitable sources of renewable energy.

Question: What should countries that do not have such sources of energy do?

Answer: They should compute the benefits of producing electricity locally, both in terms of security of supply and of creation of local economic activities. If these benefits are higher that the additional costs of producing electricity locally, they should subsidize the local production of electricity. Otherwise not.

The dangers of the global grid

We cannot exclude the fact that a global grid may lead to **global blackouts.** Even if a global blackout is a worst-case scenario, countries relying on imports for their electricity will very likely experience country-wide blackouts if there is an important failure in the global grid infrastructure.

In a global grid environment, countries may be tempted to rely too much on imports for their electricity supply. That may lead them (even if the grid infrastructure is working perfectly well) (i) with no control over the electricity prices, (ii) to being dependent on untrustworthy foreign countries, (iii) to being particularly exposed to a global shortage of supply.

Note: Even if we are still tens of years of having a global grid, Belgium is already taking this dangerous path of relying (too much) on imports for its electricity supply.

Final words

The transition towards a global grid will happen, sooner or later.

Globalisation of the electricity commodity will seriously challenge the power industries of many countries.

Countries relying too much on the global grid for their electricity supply may experience very adverse effects.

"*The global grid*". S. Chatzivasileiadis, D. Ernst and G. Andersson. Renewable Energy, Volume 57, September 2013, pages 372-383.