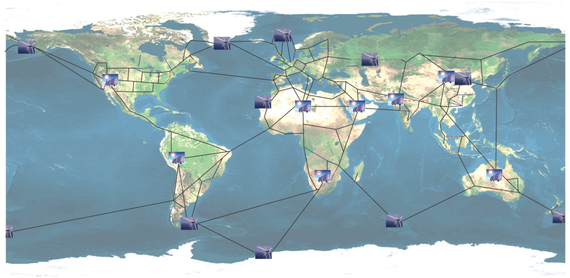

An economic case for transnational and international transmission

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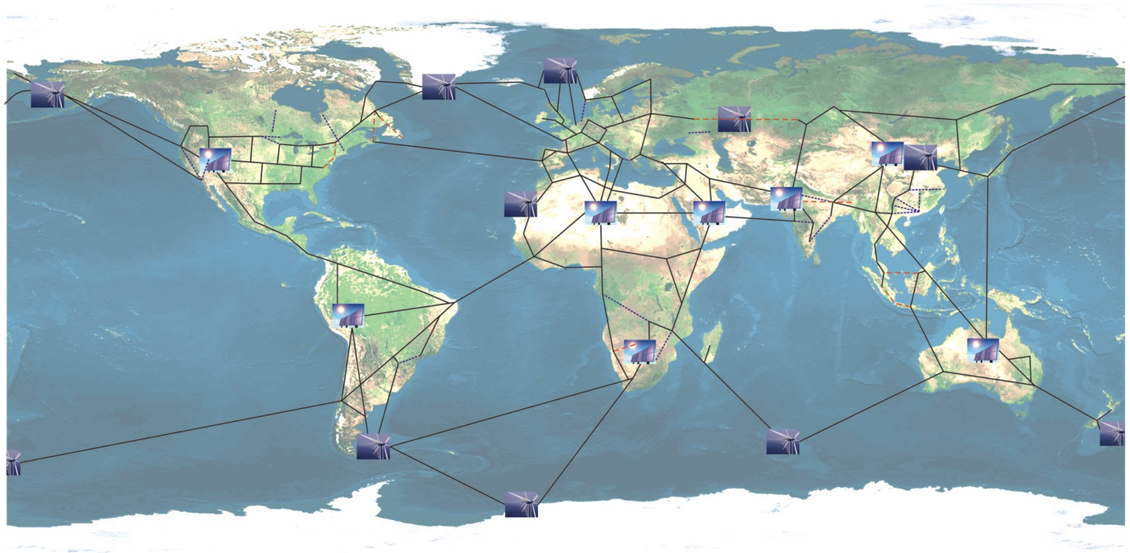
Is this the landscape of tomorrow's energy sector?



1. A global grid which is an electrical network spanning the whole planet and connecting together of the world's power plants. Key infrastructure elements: lenghty (HVDC) electrical interconnections

2. A multitude of renewable energy sources, especially in parts of the world where there is ample wind or plenty of sunshine.

The economic case for transnational and international interconnections

Three reasons for building interconnections for obtaining cheap green energy:

1. In many countries, you have only a limited number of prime locations for harvesting renewable energy.

2. Tapping into rich veins of renewable energy sources.

3. Market prices that fluctuate throughout the day and intermittency of renewable energy sources.

Limited number of locations for harvesting renewable energy

Let us take the case of **wind energy** in the country of Belgium. In 2010, its annual consumption of electricity in Belgium was 91 TWh ($1 \text{ T} = 10^{12}$). In a good location, a wind farm will produce at best $3 \text{ W/m}^2 \Rightarrow \frac{91 \times 10^{12}}{3 \times 8760 \times 10^6} \simeq 3462 \text{ km}^2$ (meaning that 11% of the country would need to be used for wind farms to meet Belgium's electricity requirements). But currently Belgium has, at most, 1-2% of its land that would be suitable as sites where cost-competitive wind farms could be built.

Not In My BackYard (NIMBY) driven opposition to wind farms also significantly reduces the number of appropriate locations where wind energy could be harvested.

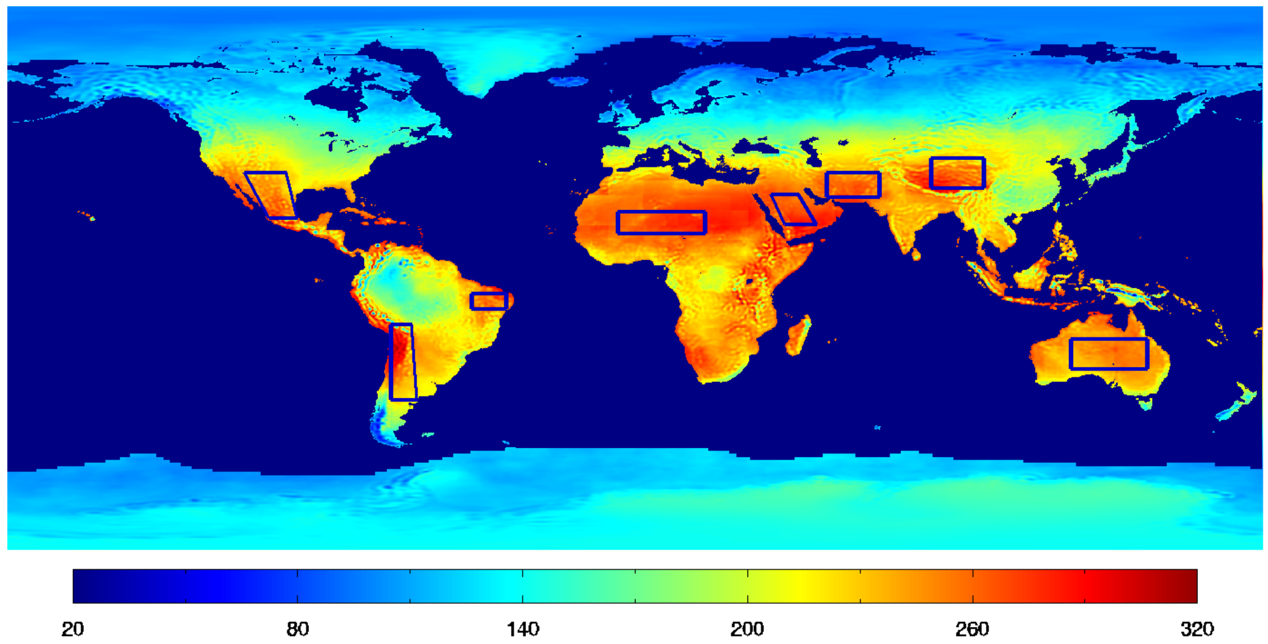
On-shore wind power in Spain: The increase in technological performances and installed capacity per turbine has not compensated in recent years for the decrease in resource quality and availability.

$\Rightarrow$ Those countries with a limited number of prime locations for harvesting renewable energy will have to rely on interconnections for accessing cheap renewable energy sources.

Tapping into rich renewable energy sources

The vast majority of the most suitable locations for harvesting renewable energy are located far from existing networks. This may require a push for investment in the creation of long-distance cables/lines, even if there still exists 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 to build interconnections to harvest renewable energy sources:

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 $cost_{loc.} > \frac{cost_{rem.}}{1-losses} + cost_{trans.}$, energy should be imported. Otherwise, produce locally.

Example: Assume that the cost of electricity from PV sources in Belgium is 110€/MWh. 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.

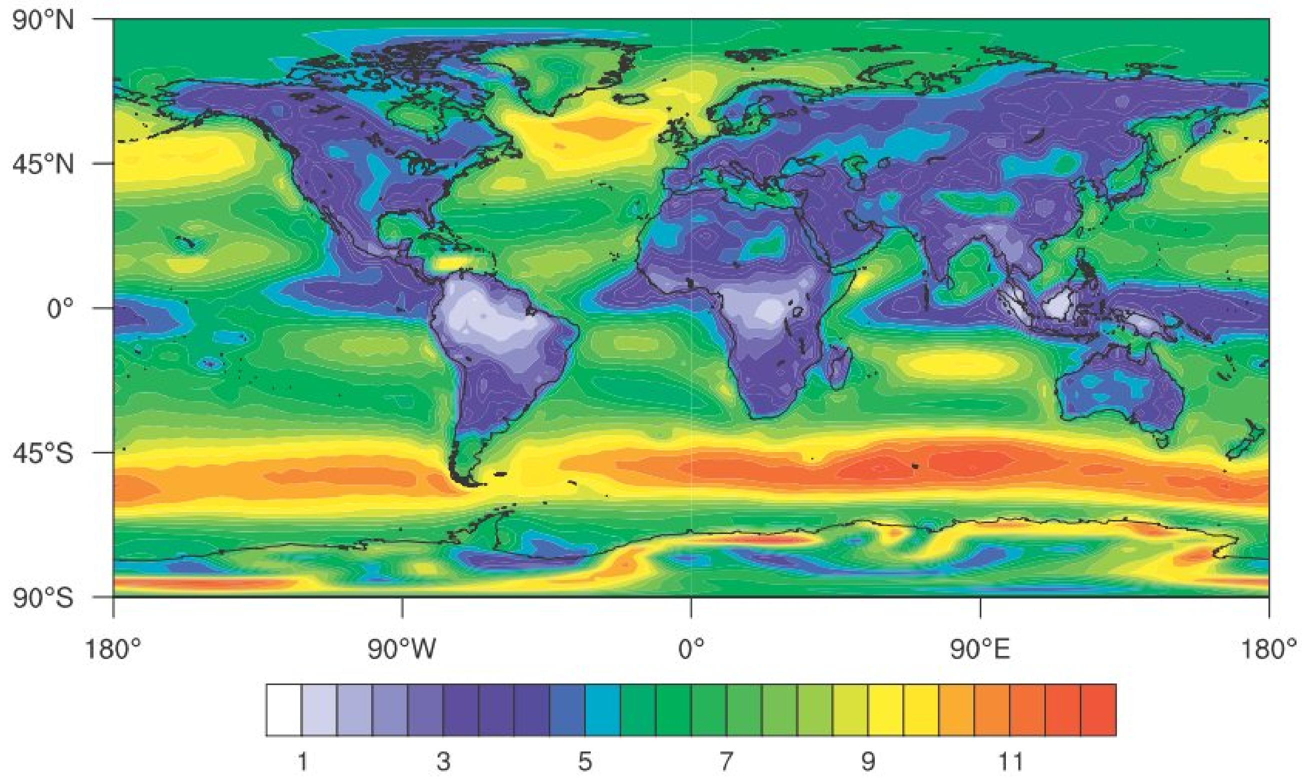
$cost_{trans.} = \frac{8.7 \times 10^9}{190 \times 10^6}$ = 45.7€/MWh.

$losses = 0.12$

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

⇒ Importing electricity produced with PV panels in Africa would cost

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



The southern part of South America has among the best on-shore wind resources in the world, with average winds around 10 m/s.

Gigantic wind farms could be built there to power the whole of South America!

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

With a wind around 6 m/s, a wind farm generates around 3 W/m^2. We can therefore assume that a wind farm in southern part of south America could produce $3 \times (\frac{10}{6})^3 \simeq 13$ W/m^2. That corresponds to an amount of energy equal to $13 \times 8760 \simeq 119 \times 10^3$ MWh/km^2 per year. The total consumption of electricity in Brazil is around 500 TWh $\Rightarrow \frac{500 \times 10^6}{119 \times 10^3} = 4201$ km^2 of wind farms in the southern part of South America to cover the entire consumption of Brazil.

Covering the red area with wind mills would generate enough electricity to power the whole of Brazil.

What about the costs?

Cost per MWh for electricity produced in the southern part of South America: Difficult to know. Probably somewhere between $[20, 50]$€/MWh. Cost will depend on (i) the technology that will be developed for wind turbines adapted to these extreme weather conditions (ii) the economies of scale (very large wind projects could be developed).

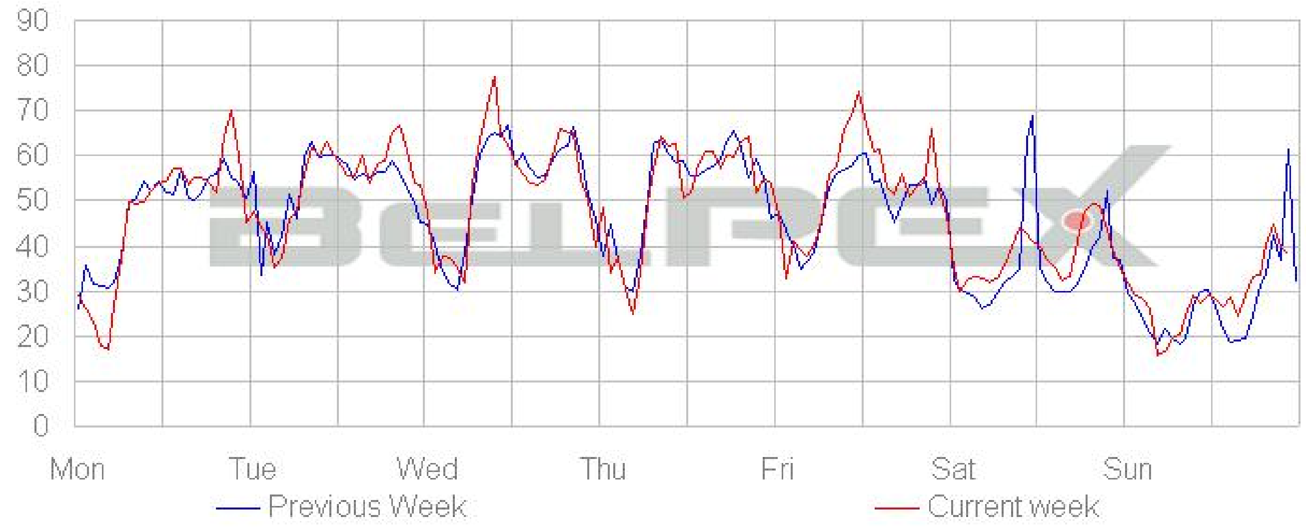
Transport costs per MWh delivered: Around 4000 km from the southern part of South America to its "middle". Assuming the same distance as in the PV example where the costs of transport where around 45€/MWh. Due to the higher load factor of wind farms (25% for the PV panels in North Africa against 50% for wind farms 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 between $[45, 80]$.**

Electricity price fluctuations

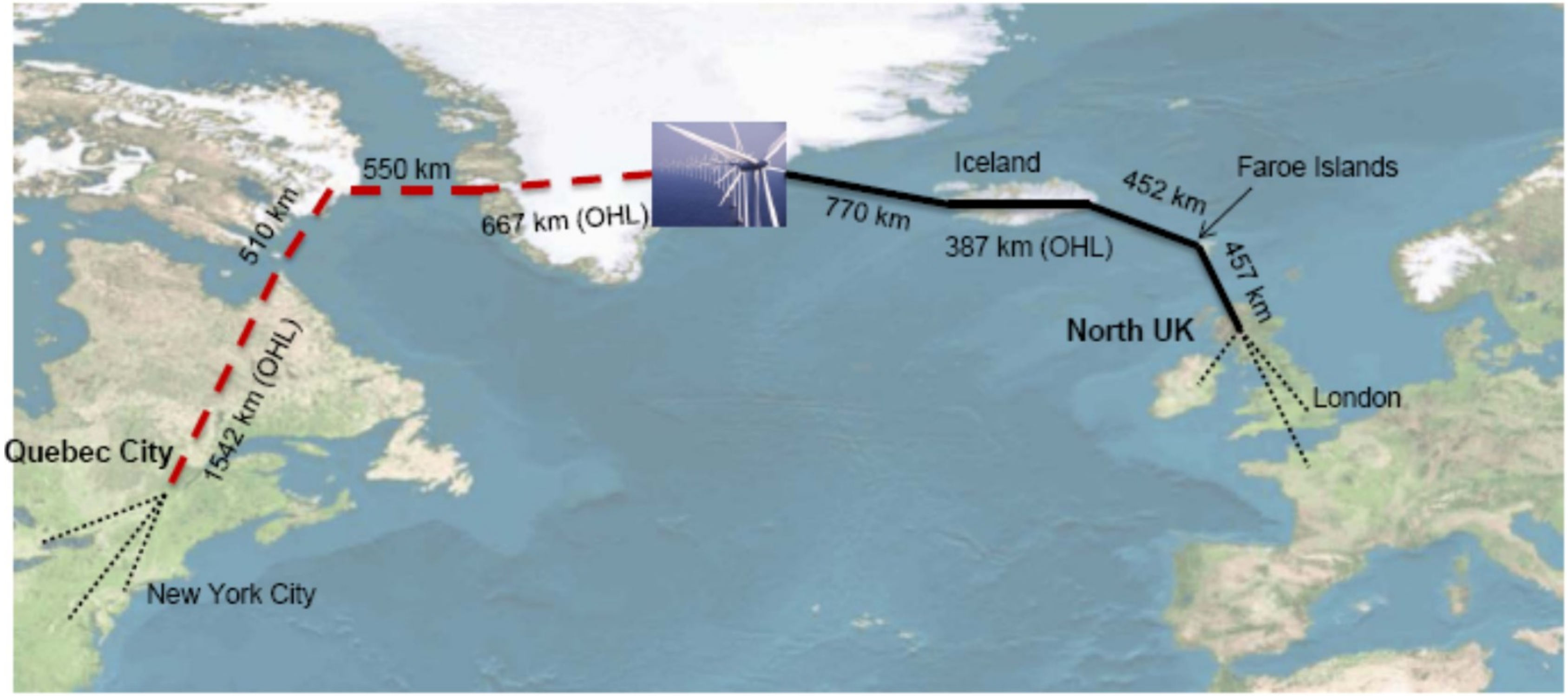
Electricity prices vary during the day. Typical price evolution (in €/MWh) in Europe:



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 one between North America and Europe.

An example: Suppose that there were 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 simultaneously build a 5 GW connection to North America?



Two cases are analysed:

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

Second case: Since the wind farm will not always produce 5 GW, we also analyse the possibility to capitalize on 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 lasts 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 valorising 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 revenue which is equal to 59% of the base case revenue.

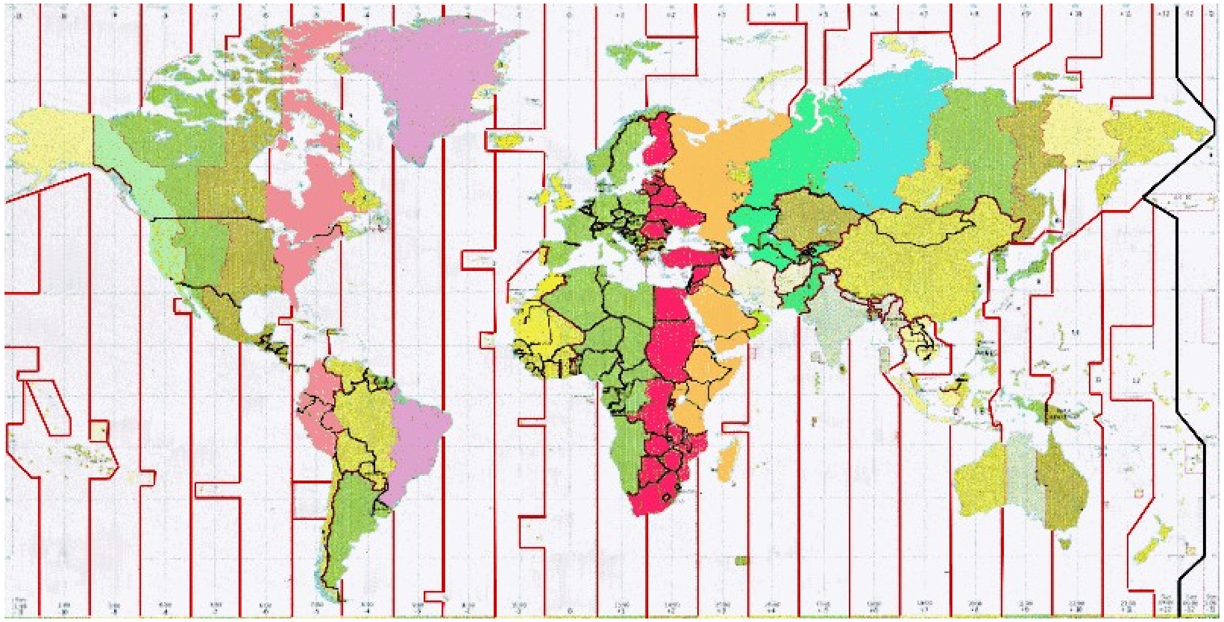
Increase in revenue for the second case: $33\% + 59\% = 92\%$.

Fluctuations of renewable energy

The larger the area over which you collect renewable energy, the less the total amount of energy collected will vary over time. So, with lengthy electrical interconnections, you can expect to make the problems of fluctutations of renewable energy sources virtually disappear.

Question: Assume that electrical interconnections exist between the Middle East and East China and that both East China and the Middle East have invested massively in PV panels. How could these interconnections be used to smooth out the fluctuations in electricity production and consumption?

Five time zones between the Middle East and East China.



[A] Around midday, the Middle East could start sending its excess of solar production to East China, where the evening had begun.

[B] East China would send its excess of solar energy to the Middle Eastern morning surge in demand.

Building a global grid is more than likely the best solution for the most cost-effective provision of renewable energy.

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

“*Global power grids for harnessing world renewable energy*. S. Chatzivasileiadis, D. Ernst, G. Andersson. In Jones, Lawrence (Ed.) Renewable Energy Integration: Practical Management of Variability, Uncertainty and Flexibility in Power Grids, 2014, pp. 175-188