Solving the fluctuation problems in a land with 100% of renewable energy

Prof. Damien Ernst – University of Liège
Email: dernst@ulg.ac.be

January 2013

Incentives for getting off fossil fuels and denuclearizing countries

The fossil fuel problem:

1. Fossils fuels are a finite resource (we will run out of cheap gas and oil in our lifetime) that should be used for better purposes than simply being burnt.

2. Even if fossil fuels are still available around the world, we perhaps do not want to depend on untrustworthy foreigners.

3. The climate change motivation: burning fossil-fuel contributes significantly to climate change through the release of carbon dioxide emissions (CO_2).

The nuclear problem: Safety is incompatible with greed.

Chernobyl nuclear power plant

Fukushima nuclear power plant

Note: It is well-known that renewable energy is safe.

The **Banqiao Reservoir Dam** failed catastrophically in 1975. The dam failure killed an estimated 171,000 people and 11 million people lost their homes.

A world with one hundred percent of renewables? You must be kidding... NO

The red stack represents the consumption of a typically affluent person in the UK (in kWh/d - note 40 W ≃ 1 kWh/d). The green stack represents the amount of renewable energy that could realistically be generated in the UK alone (expressed in kWh/d per person). If you remove from the red stack the energy embedded in imported goods (≃ 40 kWh/d per person), you have $size\_green\_stack > size\_red\_stack \Rightarrow$ the UK could live on its own renewables.

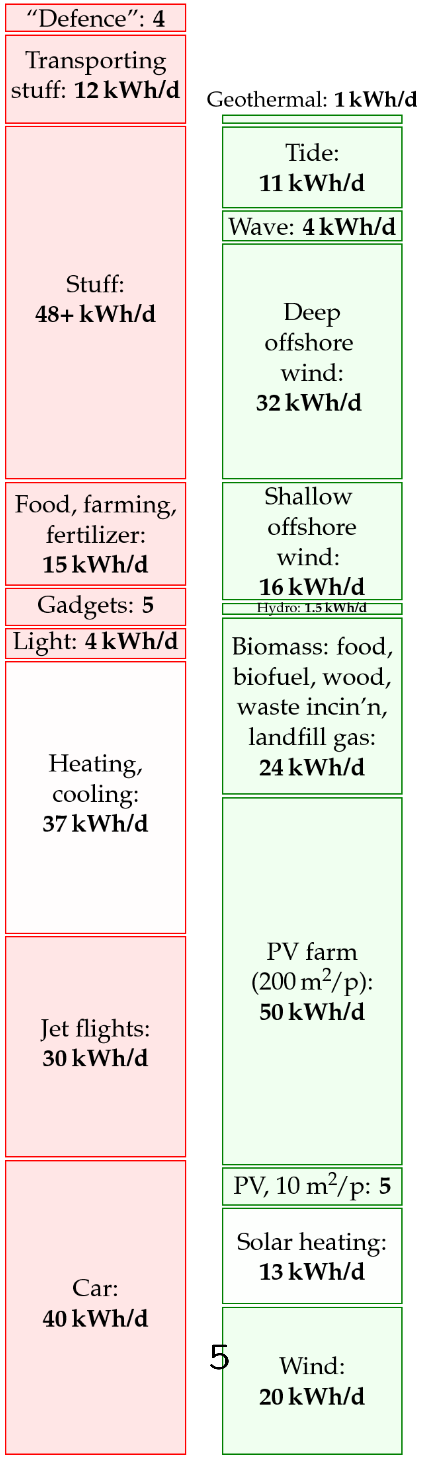
Note that the *realistic assumptions* suppose that people won't say NO to:

wind farms because they are ugly, noisy and kill bats;

solar panels on roofs because they are ugly and too expensive;

hydroelectricity because it ruins the environment and kills fish;

etc.



"Defence": **4**

Transporting stuff: **12 kWh/d**

Stuff: **48+ kWh/d**

Food, farming, fertilizer: **15 kWh/d**

Gadgets: **5**

Light: **4 kWh/d**

Heating, cooling: **37 kWh/d**

Jet flights: **30 kWh/d**

Car: **40 kWh/d**

Geothermal: **1 kWh/d**

Tide: **11 kWh/d**

Wave: **4 kWh/d**

Deep offshore wind: **32 kWh/d**

Shallow offshore wind: **16 kWh/d**

Hydro: **1.5 kWh/d**

Biomass: food, biofuel, wood, waste incin'n, landfill gas: **24 kWh/d**

PV farm ($200\,m^2/p$): **50 kWh/d**

PV, $10\,m^2/p$: **5**

Solar heating: **13 kWh/d**

Wind: **20 kWh/d**

Renewables are diffuse, so **nation-wide facilities** will be needed to generate energy only from renewables.

Power per unit land or water area	
Wind	2 W/m^2
Offshore wind	3 W/m^2
Tidal pools	3 W/m^2
Tidal stream	6 W/m^2
Solar PV panels	5-20 W/m^2
Plants	0.5 W/m^2
Rainwater (highlands)	0.24 W/m^2
Hydroelectric facilities	11 W/m^2
Geothermal	0.017 W/m^2

Example: Let us assume that we want to generate 50 kWh/day per person using PV panels and that solar panels generate on average 20 W/m^2. That would be $\frac{50\times10^3}{24\times20} \simeq 100$ m^2 of pannels per person. Since there are around 60 million people living in the UK, that would mean covering $\frac{60\times10^6\times100}{1000\times1000} = 6000$ km^2 with solar panels. Note that this is only 2.5% of the land in the UK.

What would a country with 100% renewable energy look like?

1. Electricity would be the main vector for energy. Fuels such as hydrogen or biofuels would be limited to transport applications where a high energy per unit mass is required (e.g., air transport).

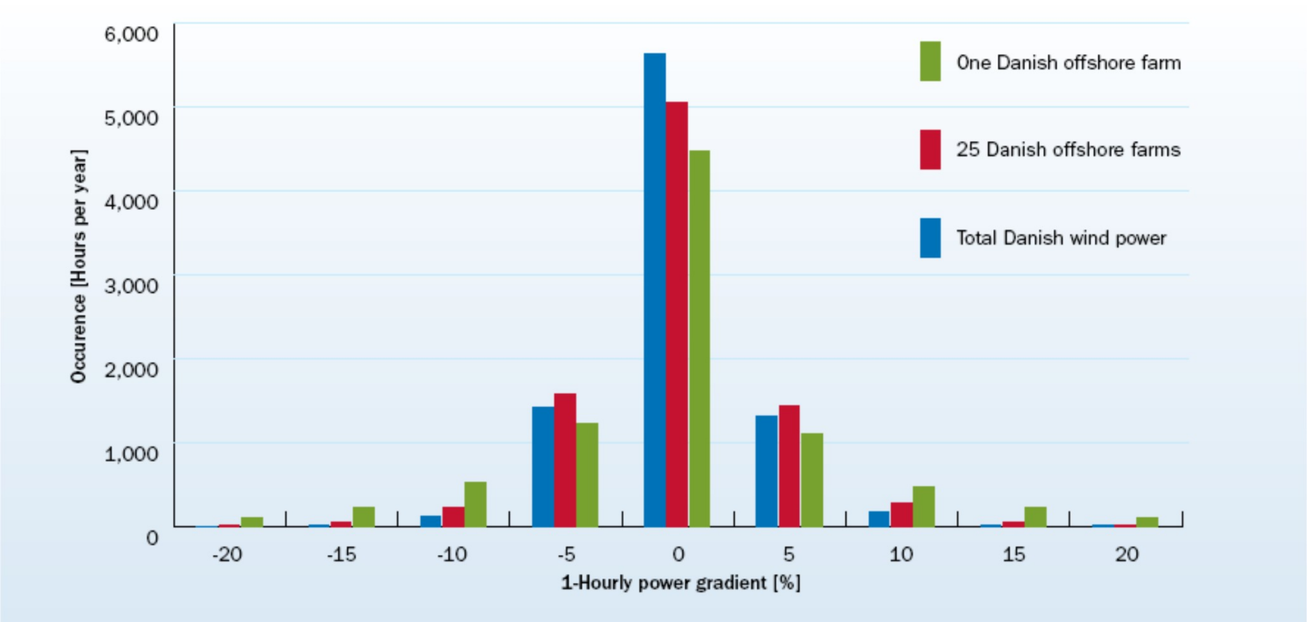
2. Electrification of surface transportation.

3. Electrification of heating systems.

4. The energy needs of a typically affluent person would probably be less than today, mainly due to more energy-efficient transportation and better insulation of buildings.

The intermittency of renewable sources of energy

Wind



A positive value reflects an increase in power and a negative value a decrease.

Figure: frequency of relative power changes in 1 hour intervals from (i) a single offshore wind farm in the Danish North Sea, (ii) all expected Danish offshore wind farms in 2030 (3.8 GW) and (iii) all expected wind farms (onshore & offshore) in Denmark in 2030 (8.1 GW).

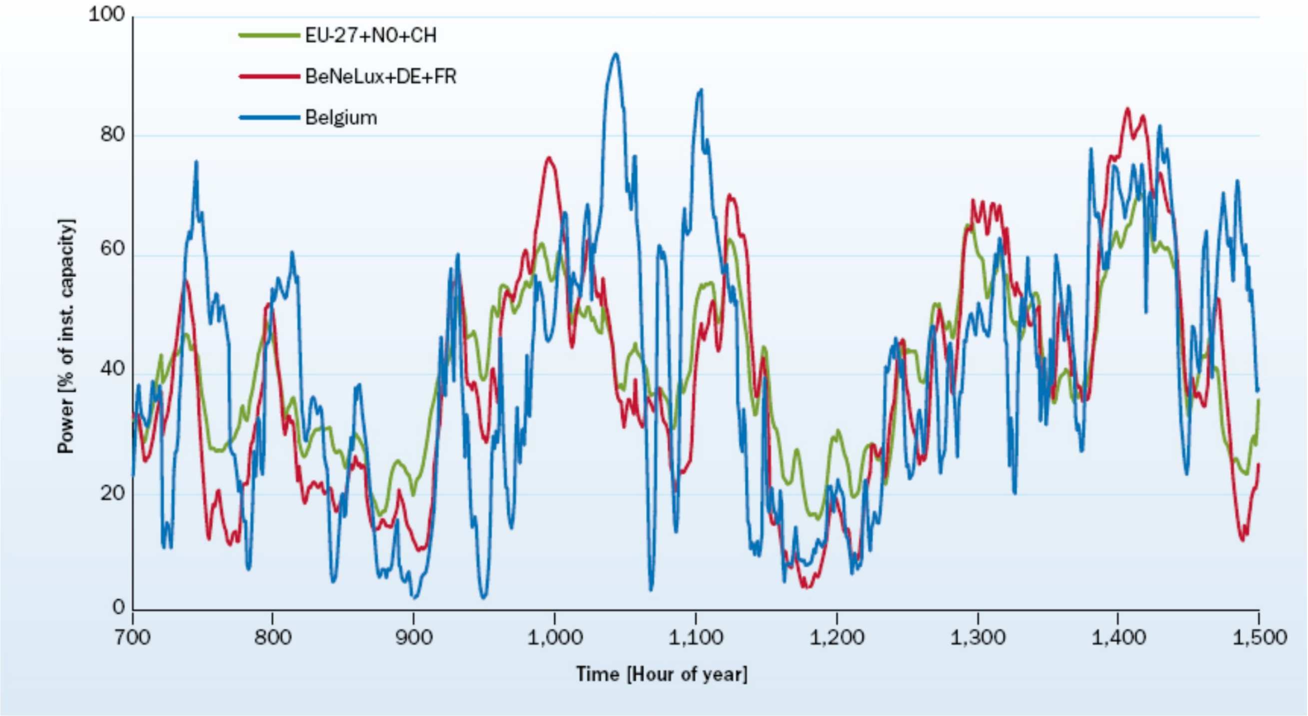


Figure: The figure compares the hourly output of wind power capacity in three areas, including all expected onshore and offshore wind power plants in the year 2030. This is calculated with wind speed data from February 2007.

What can be concluded from these figures? (i) Rapid changes in wind production at a country level are possible within one to several hours. (ii) The larger the area, the smaller the variations. (iii) In a few days and at the European level, wind production may easily vary by a factor of three. (iv) It is possible to have slumps in wind energy production at the European level that can last several days.

Solar thermal and solar photovoltaic

Energy fluctuations come from three main effects: (i) daily fluctuations due to the rotation of the earth, **(ii)** fluctuations due to weather conditions and **(iii)** seasonal fluctuations.

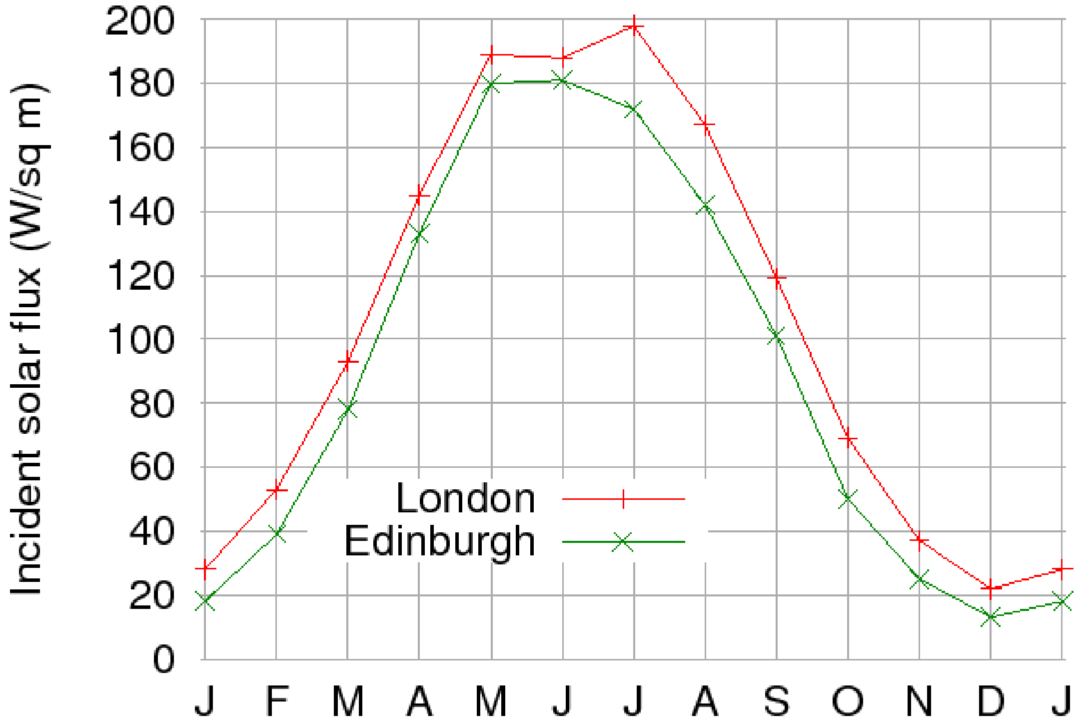


Figure: Average solar intensity in London and Edinburgh as a function of time of the year. The average intensity per unit of land area is 100 W/m^2.

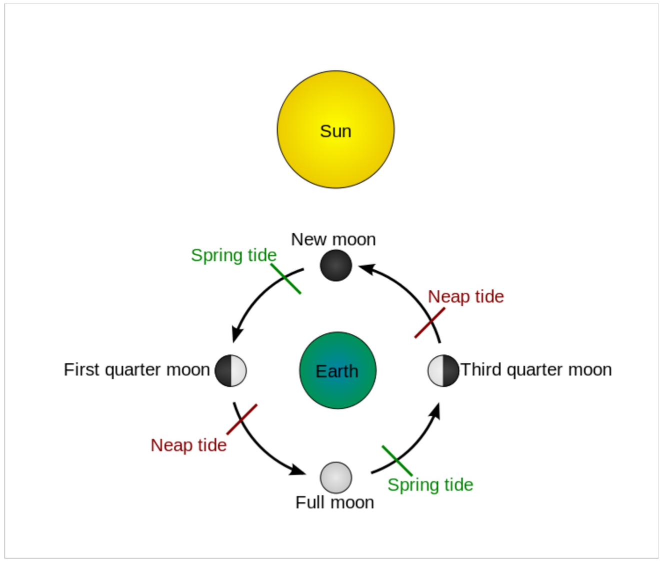
Hydroelectricity. Mostly seasonal fluctuations at the European level.

Waves. Not well studied. Waves form with wind, therefore the power generated from waves will be correlated with the power generated by off-shore wind farms. Note that since it takes time for waves to form with wind, the power collected from waves will fluctuate less rapidly than the power collected directly from wind farms.

Biomass. Seasonal fluctuations of biomass production. However, biomass can be stored before being used.

Geothermal. No fluctuations.

Tides. Power will oscillate with a period of a little more than twelve hours. Monthly variations occur also (e.g., large tides at Spring tide). Energy production is predictable.



Fluctuations of power and demand: the overall problem

On the one hand, power (that can be) generated by renewable sources of energy fluctuates significantly, even at the continental level, on a daily, weekly, monthly and seasonal basis. On the other hand we have a load that also fluctuates with different time constants (hourly, weekly, monthly and seasonally). There may also be periods of the year (cold weather, no wind, cloudy weather) where demand for energy is particularly high and production of energy is particularly low.

Question: How can we ensure that the power generated is equal to the power consumed at all times?

Three generic solutions: **(i)** storing energy and releasing it at the right time; **(ii)** controlling the power generated and **(iii)** controlling demand for energy (energy demand management).

First solution: storing energy and releasing it at the right time

Different types of technology for storing electricity: compressed air energy storage, pumped storage, batteries and fuels.

We are going to:

1. give a very brief description of these technologies;

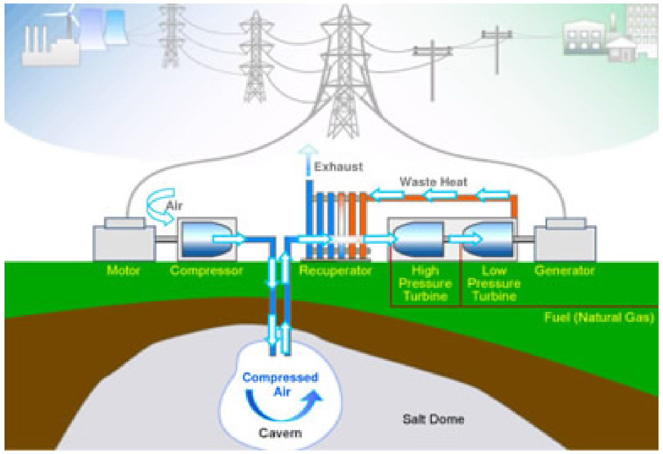
2. make simple computations to get an idea of the storage needs;

3. discuss in which storage technology we should invest in to meet these storage needs.

1. give a very brief description of these technologies

Compressed air energy storage

The energy is stored in the form of compressed air. The tank for storing air can be either a plain steel or a fiber-wound container or a huge (man-made) cavern that has been sealed off. The air is compressed at 200 bars or more. Efficiency is around 0.2.

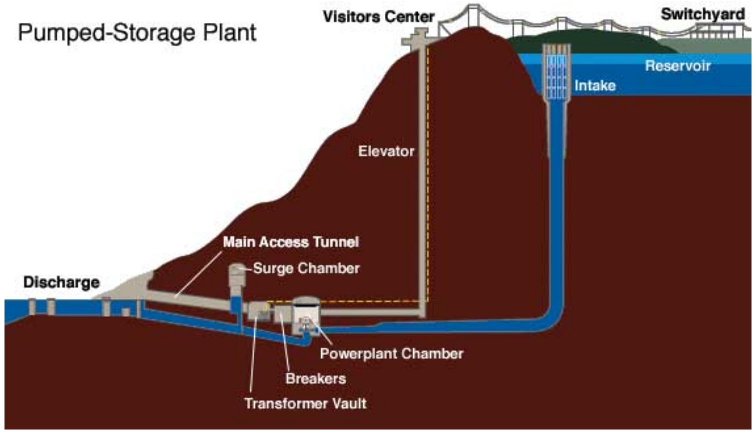


By burning gas to warm up the air during the decompression phase, significantly higher (overall) efficiency rates can be achieved (much higher than those that could be achieved by burning gas in a classic power station to produce electricity). Possibility also to store heat generated by the compression phase to warm up the air before the decompression phase so as to improve efficiency.

Note that if the air is compressed to 200 bars, 1 m^3 of air weighs around 260 kg and has a potential energy of around 106 MJ or $\frac{106\times10^6}{3600\times1000} \simeq 29.5$ kWh $\Rightarrow$ Air has an energy density of $\frac{29.5}{260} = 0.11$ kWh/kg and a volumetric energy density of 29.5 kWh/m^3.

Plants with a power of more than 100 MW and a capacity of 24 hours have been built. Note that 100 MW over 24 hours is equivalent to $\frac{100\times10^6\times24}{1000} = 2.4$ M kWh. Given that the average **primary energy consumption** in the EU is around 125 kWh/d per person, it is the equivalent of the daily power consumption of 19,200 people. Such a plant would require a reservoir of $\frac{2.4\times10^6}{29.5} \simeq 81353$ m^3. That's a cube of side length equal to $(81356)^{\frac{1}{3}} = 43.3$ m.

Pumped storage



This method stores energy in the form of potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Efficiency is between 0.7 and 0.8.

Question: What is the energy (in kWh) that can be stored in a pumped storage station knowing that **(i)** the area covered by the upper reservoir is 1 km^2, **(ii)** the depth of the elevation reservoir is 50 m, **(iii)** the lower reservoir height is constant, **(iv)** the difference of altitude between the lower reservoir and the bottom of the upper reservoir is 400 m, **(v)** we assume an efficiency of 1.

Parameters: Density of water is equal to 1000 kg/m^2, gravity g is $\simeq$ 10 m/s^2.

Well-known result: Potential energy of a mass standing at height h: mgh.

Average height of the water in the upper reservoir: $400 + \frac{50}{2} = 425$ m. Mass of water in the upper reservoir:
$1000 \times 1000 \times 50 \times 1000 = 5 \times 10^{10}$ kg$\Rightarrow$ potential energy in the upper reservoir $5 \times 10^{10} \times 10 \times 425 = 2.125 \times 10^{14}$ J.

That's $\frac{2.125 \times 10^{14}}{1000 \times 3600} \simeq 5.9 \times 10^7$ kWh. With a primary energy consumption of around 125 kWh/d per person, it is **equivalent to the daily power consumption of 472,222 people.**

Batteries

Batteries are devices consisting of one or more electrochemical cells that convert stored chemical energy into electrical energy and vice versa. Efficiency is above 0.8. The energy density of a battery (the amount of energy that can be stored per kg of battery) depends greatly on the technology used.

battery type	energy density (Wh/kg)
nickel-cadmium	45-80
lead-acid	30-50
lithium-ion	110-160
reusable alkaline	80

Question: [A] How many kilograms of lithium-ion batteries would be needed to cover the daily primary energy needs of 1 million people assuming an efficiency of 1? [B] What would be a rough estimation of the cost of such an installation? [C] In terms of energy per kg, how do lithium-ion batteries compare with water in the pumped storage station example given previously?

Additional data: Electrical cars are powered by lithium-ion batteries. Typically, these batteries store 20 kWh of energy and cost 10,000 euros.

[A] Daily consumption of 1 million people: 125×10^6 kWh. Assuming an energy density of lithium-ion batteries of 0.16 kWh/kg, $\frac{125\times10^6}{0.16} \simeq 8 \times 10^8$ kg of batteries are needed. Note that the weight of the Charles de Gaulle aircraft carrier is 42,000 tons ⇒ that corresponds to the weight of $\frac{8\times10^8}{42000\times1000} \simeq 18.6$ aircraft carriers.

[B] Cost would be $\frac{125\times10^6\times10000}{20} \simeq 62.5$ billion euros.

[C] Pumped storage station was storing 2.125×10^{14} J when filled with 5×10^{10} kg of water ⇒ Energy density for water $\frac{2.125\times10^{14}}{5\times10^{10}\times3600} \simeq$ 1.2 Wh/kg. In terms of energy per kg, lithium-ion batteries are therefore 133 times more efficient.

Fuels

The main idea is to use electricity to transform low-energy material into a fuel with high-energy density from which electricity could be generated when needed. The fuel can be either burned to generate this electricity or used in a fuel cell device that converts the chemical energy of the fuel into electricity through a chemical reaction with oxygen or another oxidizing agent.

Main advantage of this technology: the fuels have a **high-energy density**. They also have a high volumetric energy density. However, efficiency may be low. For example, producing hydrogen from water is 50% energy efficient in commercial solutions and fuel cells are generally 40-60% energy efficient.

Stor. device.	energy density (kWh/kg)	vol. energy density (kWh/m^3)
Pumped station	0.0012	1.2
Lithium Ion batt.	0.160	
Hydrogen (350 bars)	39.0	390
Natural gas	14.85	
Air (200 bars)	0.11	29.5

Remark: Hydrogen compressed at 350 bars a density of only 0.010 kg/L or 10 kg/m^3. Its volumetric energy density is computed by multiplying its density by its energy density. Therefore, we get as volumetric energy density for the hydrogen compressed at 350 bars: $10 \times 39.0 = 390$ kWh/m^3.

Question: Compare the weight of water, lithium-ion batteries and hydrogen that would be needed to generate enough electricity to cover the daily primary energy needs of 1 million people.

Additional data. Efficiency for transforming the stored energy into electricity is assumed to be $\sqrt{0.7}$ for a pumped storage station, $\sqrt{0.8}$ for lithium-ion batteries and 0.5 for fuel cells.

Daily primary energy consumed by 1 million of people: 125×10^6 kWh.

Weight of water: $\frac{125\times10^6}{0.0012\times\sqrt{0.7}} = 124.5$ million t. That's the weight of **2964.35** aircraft carriers.

Weight of lithium-ion batteries: $\frac{125\times10^6}{0.160\times\sqrt{0.8}} = 0.873$ million t. That's the weight of **20.8** aircraft carriers.

Weight of hydrogen: $\frac{125\times10^6}{39.0\times0.5} = 0.0064$ million t. That's the weight of **0.15** aircraft carrier. A cube of side length $\left(\frac{125\times10^6}{390\times0.5}\right)^{\frac{1}{3}} \simeq$ 86.2 m would be needed to store such an amount of hydrogen.

2. make simple computations to get an idea of the storage needs.

We first compute the storage needs caused by daily fluctuations of PV installations in an EU with 100% renewable energy. We make the following assumptions:

1. The EU wants to be able to cover all its energy needs at all times.

2. The load and the production of electricity by other sources of renewable energy than PVs are assumed to be constant.

3. PV sources generate a constant power from 7 am till 7 pm and no power outside those hours.

4. PV sources generate 50 kWh/day per person of energy.

5. Efficiency of 1 is assumed for storage.

6. The annual production of energy in the EU is equal to its annual consumption.

Data: There are 550 million people living in the EU.

For the twelve hours during which PV sources generate energy, 25 kWh per person need to be stored ⇒ That's a total of $25 \times 550 \times 10^6 \simeq 1.38 \times 10^{10}$ kWh of energy.

Note that storing this energy would require:

- $\frac{1.38\times10^{10}}{5.9\times10^{7}} \simeq 233$ pumped storage stations of our previous example

or,

- lithium-ion batteries that would weigh the same as $\frac{1.38\times10^{10}}{0.16\times42000\times1000} \simeq 2054$ aircraft carriers or,
- a cube of side length $\left(\frac{1.38\times10^{10}}{390}\right)^{\frac{1}{3}} \simeq 328$ m filled with hydrogen compressed at 350 bars.

We now compute the storage needs caused by seasonal fluctuations of PV installations in an EU with 100% renewable energy. We make the following assumptions:

1. The EU wants to be able to cover all its energy needs at all times.

2. The load and the production of electricity by other sources of renewable energy than PVs are assumed to be constant.

3. PV sources generate 80 kWh/day per person during the sunny period that starts beginning of May and finishes end of October. They generate 20 kWh/day per person the rest of the year.

4. Efficiency of 1 is assumed for storage.

5. The annual production of energy in the EU is equal to its annual consumption.

During the sunny period, we have to store $80 - 50 = 30$ kWh/day per person. That's $30 \times \frac{365}{2} \times 550 \times 10^6 \simeq 3.01 \times 10^{12}$ kWh of energy.

Note that storing this energy would require:

- $\frac{3.01 \times 10^{12}}{5.9 \times 10^7} \simeq 51016.94$ pumped storage stations or,
- lithium-ion batteries that would weigh the same as $\frac{3.01 \times 10^{12}}{0.16 \times 42000 \times 1000} \simeq 447{,}919$ aircraft carriers or,
- a cube of side length $\left(\frac{3.01 \times 10^{12}}{390}\right)^{\frac{1}{3}} \simeq$ 1979 m filled with hydrogen compressed at 350 bars.

This is how big this cube may be.

3. discuss in which storage technology we should invest in to meet these storage needs.

Four main criteria can be used to select the right storage technology to invest in:

1. Investments needed to build the storage system; except for batteries investment costs can be splitted into two parts: (I) the cost of the reservoir for storing the energy storage vector and (II) the cost of the system for “transforming” electricity into the energy storage vector and vice versa. The cost of the first part grows with the capacity of the reservoir. The cost of the second part grows with the rates at which energy is stored and is sent back to the power grid.
2. Lifetime expressed in number of cycles the energy system can deliver before it needs refurbishing.
3. Environmental impact.
4. Efficiency and other “running costs”.

Compressed air energy storage

1. It is very difficult to know what the investment costs are. We may guess that the cost of compressors and generators is at least 1000 euros per kW or 1 euro per W. For intraday fluctuations, we have to store 1.38×10^{10} kWh in 12 hours. That would lead to a cost of $\frac{\text{energy to be stored}}{\text{time for storing}} \times (\text{cost per W}) = \frac{1.38 \times 10^{10} \times 3600 \times 1000}{12 \times 3600} \simeq$ 1150 billion euros. Huge costs are expected for the reservoirs but no clear data are available.

2. At least 10,000 cycles.

3. Environmental impact is low because the reservoirs would be underground. May be much higher if gas were to be burned to warm up the air during the decompression phase.

4. Efficiency is low.

Pumped storage

1. Investment costs in classic hydro projects are in between 2000 and 4000 euros per kW. If we take 2000 euros, that would be an investment cost of 2300 billion euros for the case of our intraday fluctuations. But much larger reservoirs may be needed than in classic hydro projects and this may significantly increase the costs, especially if people have to be displaced to build the reservoirs.

2. 50,000 cycles or more.

3. Environmental impact may be huge. Reservoirs would have to cover hundreds of kilometres just to cope with intraday fluctuations and perhaps thousands of square kilometers or more to cope with seasonal fluctuations.

4. Efficiency is high and running costs are low.

Batteries

1. Technology is evolving to build low-cost batteries using iron or vanadium. They are much cheaper than lithium-ion batteries but have a much lower energy density (e.g., 20 Wh/kg). A 1500 kWh vanadium system costs around 300,000 euros. For the case of our intraday fluctuations, 1.38×10^{10} kWh need to be stored. That would lead to a cost of $\frac{1.38 \times 10^{10}}{1500} \times 300,000 \simeq$ 2760 billion euros. In order to meet the storage needs caused by seasonal fluctuations, it would cost $\frac{3.01 \times 10^{12}}{1500} \times 300,000 \simeq=$ 602,000 billion euros.

2. 10,000 cycles or more.

3. Environmental impact may be low if batteries are properly recycled.

4. Efficiency is high (around 0.75 for vanadium batteries).

Fuels

1. Difficult to know the costs. For example, no large-scale production of hydrogen from electricity exists at the present time. It may be reasonable to suppose that due to the high-energy density of fuels, this technology would be interesting for the storage of high quantities of energy.

2. Based on the performances of existing fuel cells, the number of cycles may be less than 10,000.

3. Environmental impact may be low since hydrogen and other fuels have a high volumetric energy density.

4. Efficiency is low but may significantly improve with technology.

Storing electricity - what I would do

1. I would develop pumped storage sites where they can be developed in an environmentally friendly way due to the high efficiency and the cheap cost of this technology.
2. I would invest in batteries to store the imbalances between production of energy and consumption of electricity for short periods of time (intraday fluctuations). It seems to me that this technology would be too expensive to tackle the problem of long-term imbalances between production and consumption.
3. I would not invest in compressed air storage due to its low efficiency.
4. I would invest in technologies that transform electricity into fuels but I would not transform fuels back into electricity for the grid. I would rather use the fuel for applications where high-energy density is required. The fuel would be made when supply of energy is high and used all year long. This would offer a way to compensate for long-term imbalances between production and consumption.

Second solution: controlling the power generated

Three possibilities for controlling the power generated:

1. exploiting storage capabilities of renewable sources of energy;

2. downwards modulation by throwing away renewable energy;

3. upwards modulation which is possible if renewable sources of energy are not operated at full power.

1. exploiting storage capabilities of renewable sources of energy

Many renewable energy sources have (or can be built so as to have) storage capabilities. These storage capabilities can be used to adapt their power production to demand.

Plant type	Energy storage vector
Hydro	water in the reservoir
Tidal	water in the reservoir
Geothermal	heat in the ground
Thermal solar	heat in pressurized steam, concrete, molten salts
Wind	blades that store kinetic energy
Biofuel	fuel

2. downwards modulation by throwing away renewable energy.

When production of electricity is higher than demand for electricity, renewable sources of energy such as wind farms or PV installations could be turned off.

3. upwards modulation which is possible if renewable sources of energy are not operated at full power.

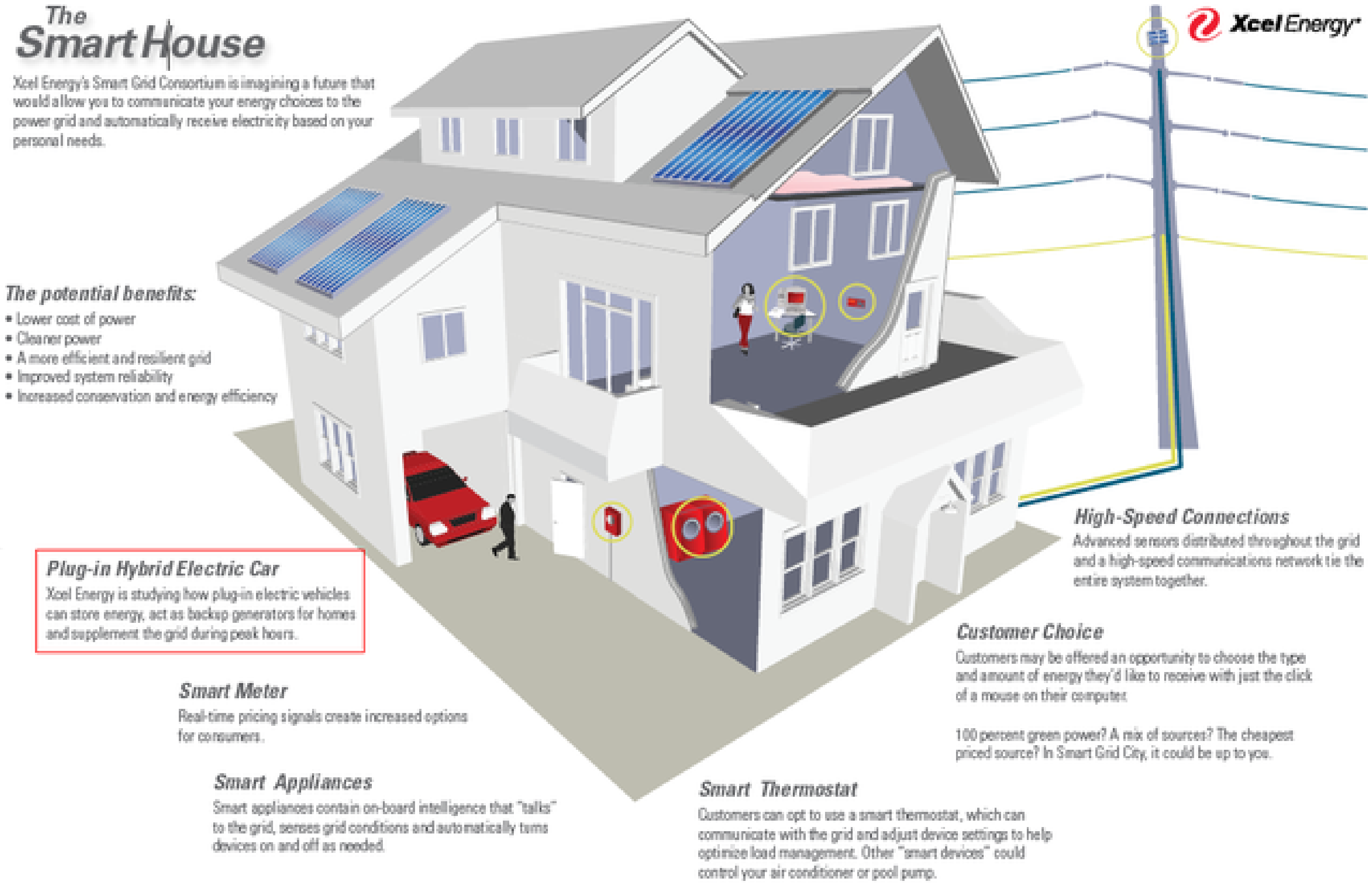
We could invest in renewable energy sources so as to ensure that there is - most of the time - a surplus of capacity. In such a context, when the demand for electricity increases, renewable energy sources could potentially be modulated upwards.

Third solution: controlling demand for energy (Demand side management)

Demand side management modifies the demand for energy so as to move consumption from hours where electricity is a scarce commodity to hours where there is a surplus of electricity.

Examples of electrical loads that could be shifted: fridges, washing machines, electrical cars, heating/cooling devices.

Demand side management is an old concept in power systems for ensuring a balance between production and consumption of electricity. It has long been applied to industrial loads. Day and night metering of electricity has also been used in households to transfer portions of daytime consumption to nighttime consumption.



The Smart House

Xcel Energy's Smart Grid Consortium is imagining a future that would allow you to communicate your energy choices to the power grid and automatically receive electricity based on your personal needs.

The potential benefits:

- Lower cost of power
- Cleaner power
- A more efficient and resilient grid
- Improved system reliability
- Increased conservation and energy efficiency

Plug-in Hybrid Electric Car

Xcel Energy is studying how plug-in electric vehicles can store energy, act as backup generators for homes and supplement the grid during peak hours.

Smart Meter

Real-time pricing signals create increased options for consumers.

Smart Appliances

Smart appliances contain on-board intelligence that "talks" to the grid, senses grid conditions and automatically turns devices on and off as needed.

High-Speed Connections

Advanced sensors distributed throughout the grid and a high-speed communications network tie the entire system together.

Customer Choice

Customers may be offered an opportunity to choose the type and amount of energy they'd like to receive with just the click of a mouse on their computer.

100 percent green power? A mix of sources? The cheapest priced source? In Smart Grid City, it could be up to you.

Smart Thermostat

Customers can opt to use a smart thermostat, which can communicate with the grid and adjust device settings to help optimize load management. Other "smart devices" could control your air conditioner or pool pump.

The smart house. A "new concept" relying on information technology for shifting/managing domestic loads in real-time.

Demand side management using electrical vehicles

In a future with 100% renewable energy, surface transport will be electrified.

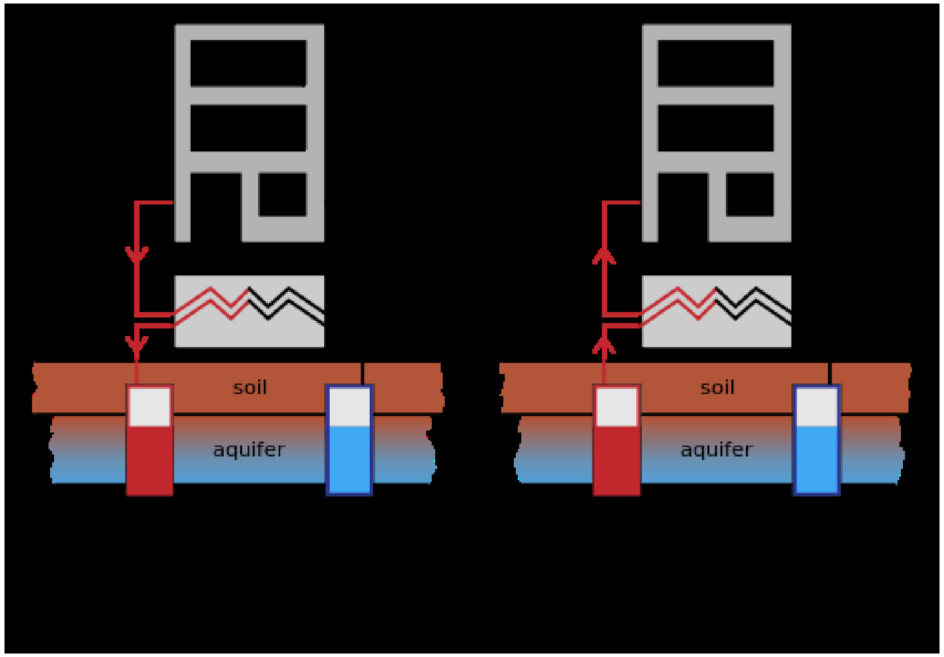
There are more than 250 million vehicles on the European roads. If we assume **(i)** that all vehicles will be electrified and **(ii)** that the vehicles batteries will have on average a capacity of 20 kWh $\Rightarrow$ the total storage capacity of these vehicles will be $20 \times 250^6 = 5 \times 10^9$ kWh. This represents a fraction $\frac{5 \times 10^9}{1.38 \times 10^{10}} \simeq 0.36$ of the energy that needs to be stored to cope with the intraday fluctuations of our previous example.

Demand side management schemes exploiting this storage capacity would be worth developing. If too much power was generated by renewable sources of energy, cars connected to the power grid would store the energy. If there was not enough power generated, they would send power back to the power grid.

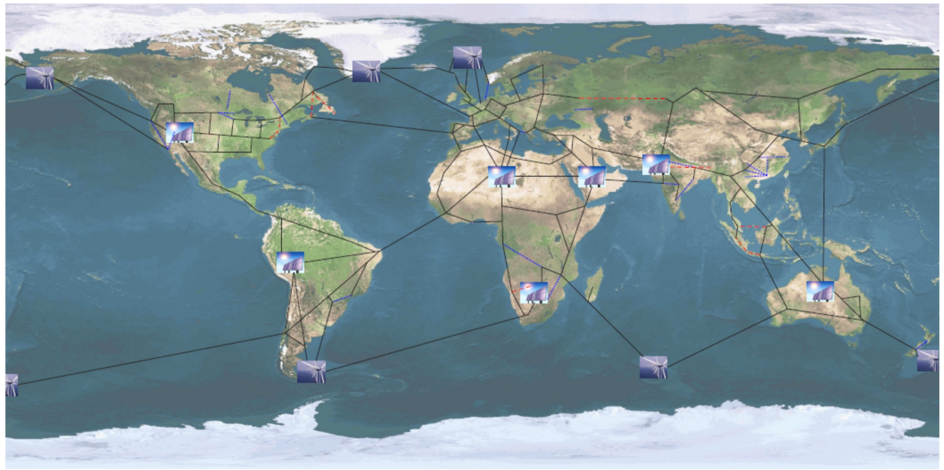
Long-term thermal storage: a demand side management approach for long-term imbalances

Typical demand side management schemes could help to cope with short-term imbalances between generation and consumption. For long-term imbalances, e.g. seasonal imbalances, a useful technology would surely be **long-term thermal storage**.

With long-term thermal storage, heat pumps in buildings would work in a reverse way in the summer: they would send heat to the ground. This heat would be delivered to the buildings in the winter so as to decrease their electrical power consumption during this season.

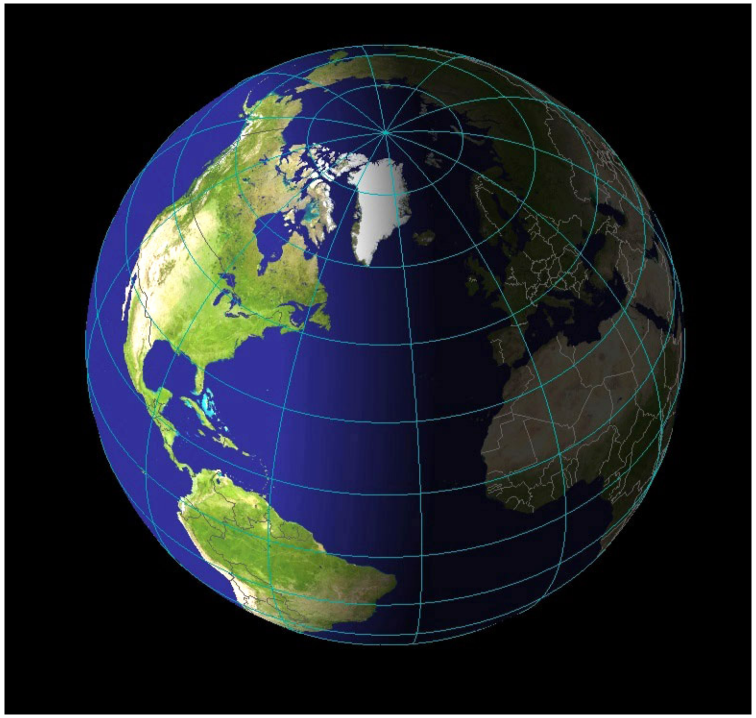


The out of the box solution: the Global Grid



The **Global Grid** refers to an electricity network spanning the whole planet and connecting most of the power plants in the world. Its key infrastructure element would be its high capacity long transmission lines. Such a network is technologically feasible and could be economically competitive (see research paper “The Global Grid” from Spyros Chatzivasileiadis, Damien Ernst and Göran Andersson).

Pictures that show why the Global Grid could bring a solution to the intraday and seasonal imbalance problems



The Global Grid versus batteries for coping with intraday fluctuations

Remember that for coping with the daily fluctuations of our example we needed to store 1.38×10^{10} kWh of energy in 12 hours. We computed that with vanadium batteries, this would cost 2760 billion euros.

Question: What would be the cost of the transmission infrastructure for sending this energy to the American continent in 12 hours and sending it back over the next 12 hours? We assume **(i)** a cost of 1,5 billion euros per 1000 km for a submarine cable able to transfer 5000 MW of power **(ii)** that 5500 km of cables would be needed to connect the European with the North American grid **(iii)** that the transmission losses could be ignored.

Transmitting 1.38×10^{10} kWh of energy in 12 hours would require a transmission power of $\frac{1.38 \times 10^{10} \times 1000 \times 3600}{12 \times 3600 \times 10^{6}} \simeq 1,150,000$ MW.

A 5000 MW cable between Europe and North America would have a cost of $1.5 \times 5.5 = 8.75$ billion euros. The number of cables needed to transmit 1,150,000 MW would be $\frac{1150000}{5000} = 230 \Rightarrow$ The cost of the transmission infrastructure is 2012.5 billion euros, slightly less than the vanadium batteries solution.

Note that since the cost of the transmission infrastructure does not grow with the integral of the energy imbalances but with the maximum instantaneous imbalance, the Global Grid solution could be much more interesting than a storage solution to deal with seasonal fluctuations.

Concluding remarks

Many possibilities exist for solving load and generation fluctuation problems in a land with 100% of renewable energy. The real challenge is deciding where and in which type of technology to invest for generation, storage and demand side management to ensure a safe supply of energy at the lowest cost.

In the real world, **governments** will not invest directly in generation, storage and demand side management schemes but will set up incentive mechanisms, regulations and market structures that define the rules for the different stakeholders of an energy system. A key question for governments is how to define these rules so as to have greedy stakeholders (consumers, prosumers, producers) driving - at small cost - the energy system towards being near-optimal.

List of documents used for preparing this talk

"Sustainable energy - without the hot air". David JC MacKay. UIT Cambridge, England, 2009.
"The Global Grid". Spyros Chatzivasileiadis, Damien Ernst and Göran Andersson. Renewable Energy, Volume 57, September 2013, Pages 372-383.
"Powering Europe: wind energy and the electricity grid". A report by the European Wind Energy Association. November 2010.
Wikipedia for the different storage technologies.
Google images for many of the pictures.