



The
Energy Situation in
Europe

July 2018

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Energy Dossiers published in this series:

1. The Energy Situation in Europe (2018)

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1. Energy consumption in Europe

1.1. Gross inland energy consumption in the EU

According to Eurostat data, the 2015 gross energy consumption in the EU28 countries was 1,627.5 million⁽¹⁾ tons of oil equivalents (Mtoe). This corresponds to about $68,000 \cdot 10^{15}$ J. To bring this number into perspective, this is also equivalent to $18.9 \cdot 10^{12}$ kWh or approx. 113,000 million times the energy that the average European consumes at home as electricity. The total figure for 2016 is slightly higher (increased by 0.7%) but the energy consumption distribution per sector (see below) is almost equal to 2015. As 2015 data are more detailed, they will be further analysed in this document.

Reported gross energy consumption is not only from the use of energy sources to generate energy (electricity only being one form of energy), but also from non-energy use. This non-energy use mainly includes oil and gas used as raw materials to make products in different sectors (e.g. plastics).

Overall, the gross EU energy consumption consists of three factors:

• Energy consumption	1,084.1 Mtoe	67%
• Non-energy consumption	96.8 Mtoe	6%
• Losses in transformation and distribution	446.6 Mtoe	27%
TOTAL (net energy consumption)	1,627.5 Mtoe	

1.2. Energy consumption of the (petro-)chemical industry

As noted previously, the 2015 EU-28 net energy consumption was equivalent to two-thirds (67 %) of the gross inland consumption, at 1,084 Mtoe, equivalent to $45,385 \cdot 10^{15}$ J.

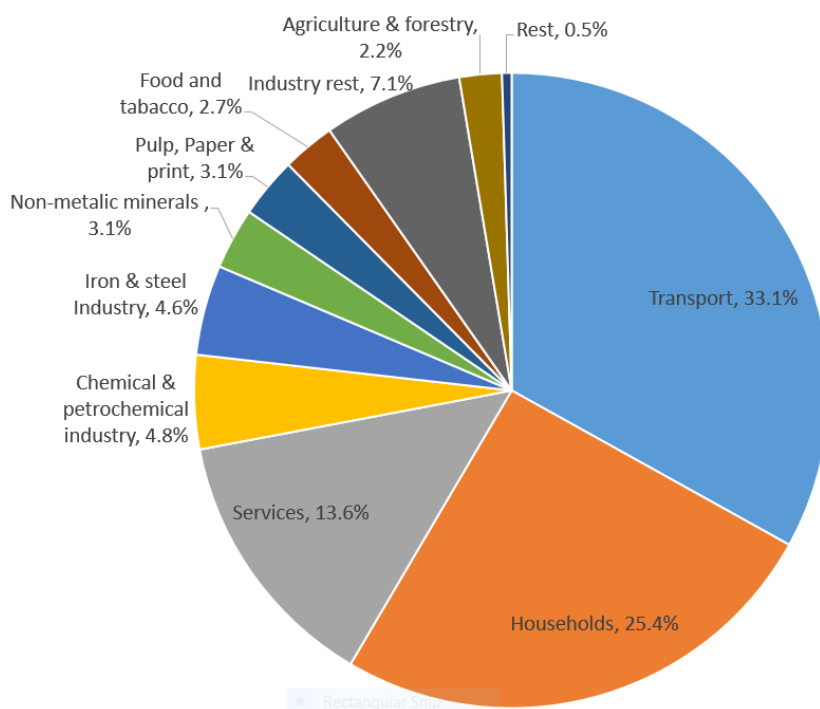


Fig. 1: The energy usage of several sectors (100% equals $45,385 \cdot 10^{15}$ J).



The subdivision of energy use depicted in **Figure 1**, reveals that the major energy users are households and the transport sector. Road transport is the biggest consumer, accounting for 27% of net energy consumption. Aviation is another big consumer at 4.7% of net energy consumption.

The chemical and petrochemical industry accounts for 4.8% of net energy consumption, (6.9 times lower than the energy consumption of the transport sector and 5.3 times lower than the energy consumption of households).

Moving from net to gross energy consumption, the (petro-)chemical industry's contribution is the sum of:

- The sector's net energy consumption, representing 3.1% of the gross energy consumption.
- The non-energy consumption: the chemical and petro-chemical industry accounts for 74.4 Mtoe (3116 PJ) of the total 96.8 Mtoe displayed under 1.1. This is 4.6% of total EU energy consumption.
- The share of losses during transformation and distribution: this mainly occurs via electricity production & use. As we will show later in section 1.4, the (petro-)chemical industry uses about 6.6% of all electricity. That means 6.6% of 27% (or 1.8%) needs to be added to its gross energy consumption share.

Altogether, the total contribution of the chemical and petrochemical industry amounts to 9.6% of gross energy consumption. This means that, in total energy usage terms, the (petro-)chemical industry is far from being the largest consumer.

1.3. Energy sources in the EU

The sources of energy consumed in 2015 by the EU28 are shown in **Figure 2a**. As electricity is merely an indirect source of energy (and should thus be subdivided in several others; see also **Figure 3b**), **Figure 2b** provides a more complete picture of 2015 energy sources. Here, oil and gas clearly dominate.

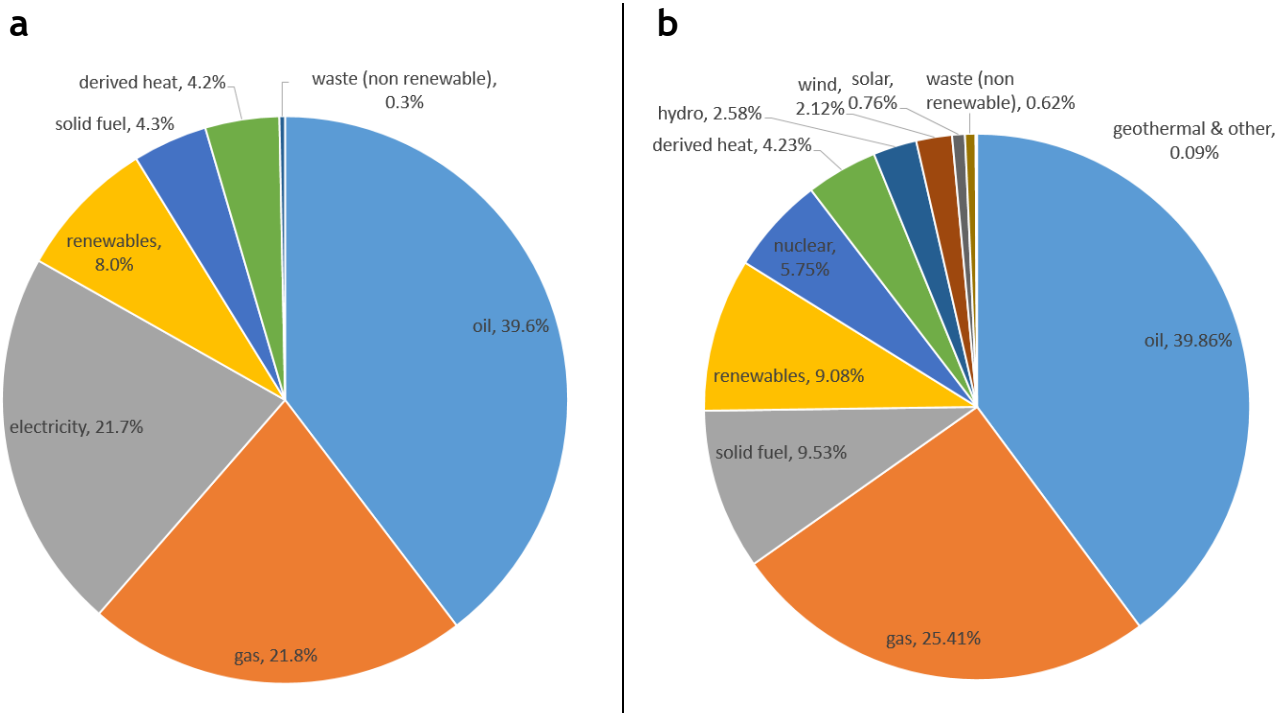


Fig. 2: The sources of the used energy (a) and the same overview when electricity is split into its original energy sources (b).

The EU’s goal is to have a share of 32% of renewable energy by 2030. In 2016, the renewable share in the total energy consumption was 17%.

The graph below depicts the development of renewable energy as part of total energy consumed as well as the contribution of solar and wind in total energy production.

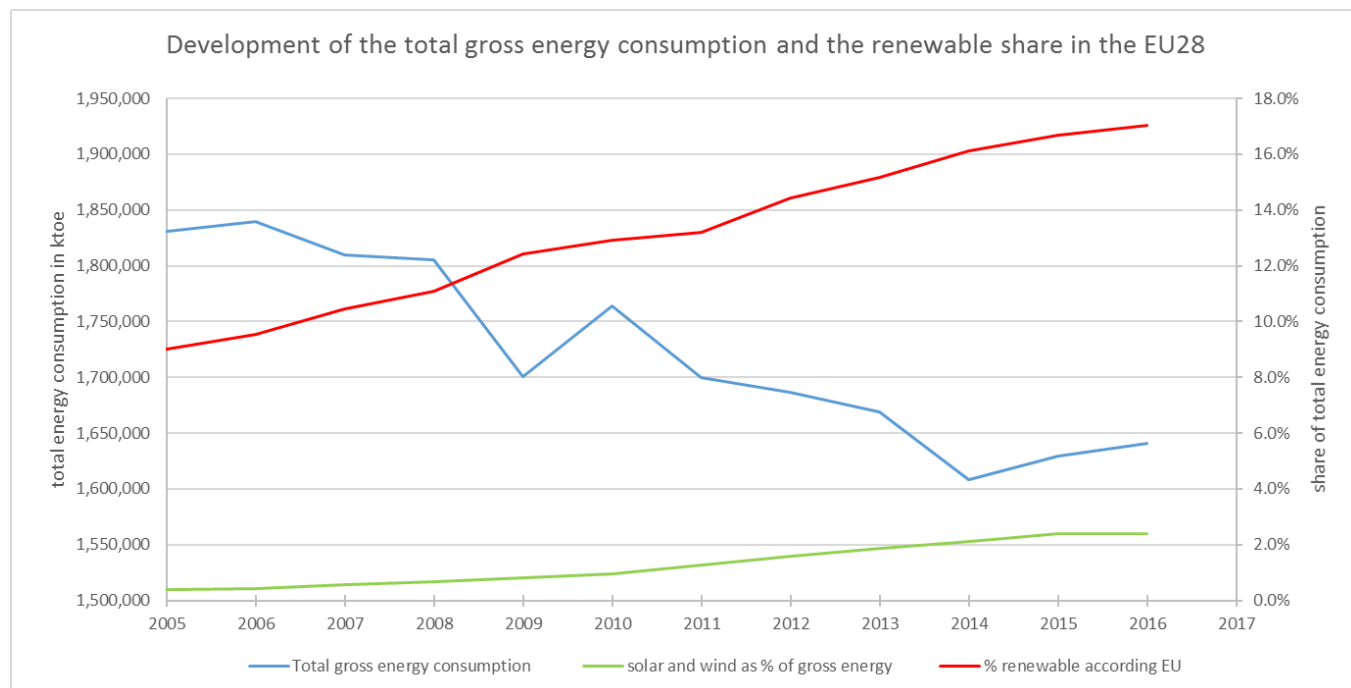


Fig. 3: The development of the total (gross) energy consumption in the EU 28 and the share of renewables and solar & wind in this.

If we consider the development of renewables up to 2016 and project that curve to 2030, this will take the renewables share to approx. 28% by 2030 (the goal being 32%). This is under the assumption that the development of renewable sources will occur at the same rate as for the past 11 years.

It should be noted that the increase of renewables share in the past 11 years was dominated by a growth in biomass, a solution that is currently under heavy political discussion (see also **chapter 3.4.2** in this document). This may further challenge the accomplishment of the 32% goal. Should this biomass solution not work out and we assume that the growth of renewables will only be realised from wind and solar, the extrapolation to 2030 results in a renewable energy share of 20%.

1.4. Electricity singled out as an energy source

About 22% of total gross energy consumption is as electrical energy. 3.07 million GWh⁽²⁾ were used in the EU in 2015. The main users of this ‘electrical energy’ are presented in **Figure 4a**. The sources of the electricity are presented in **Figure 4b**.



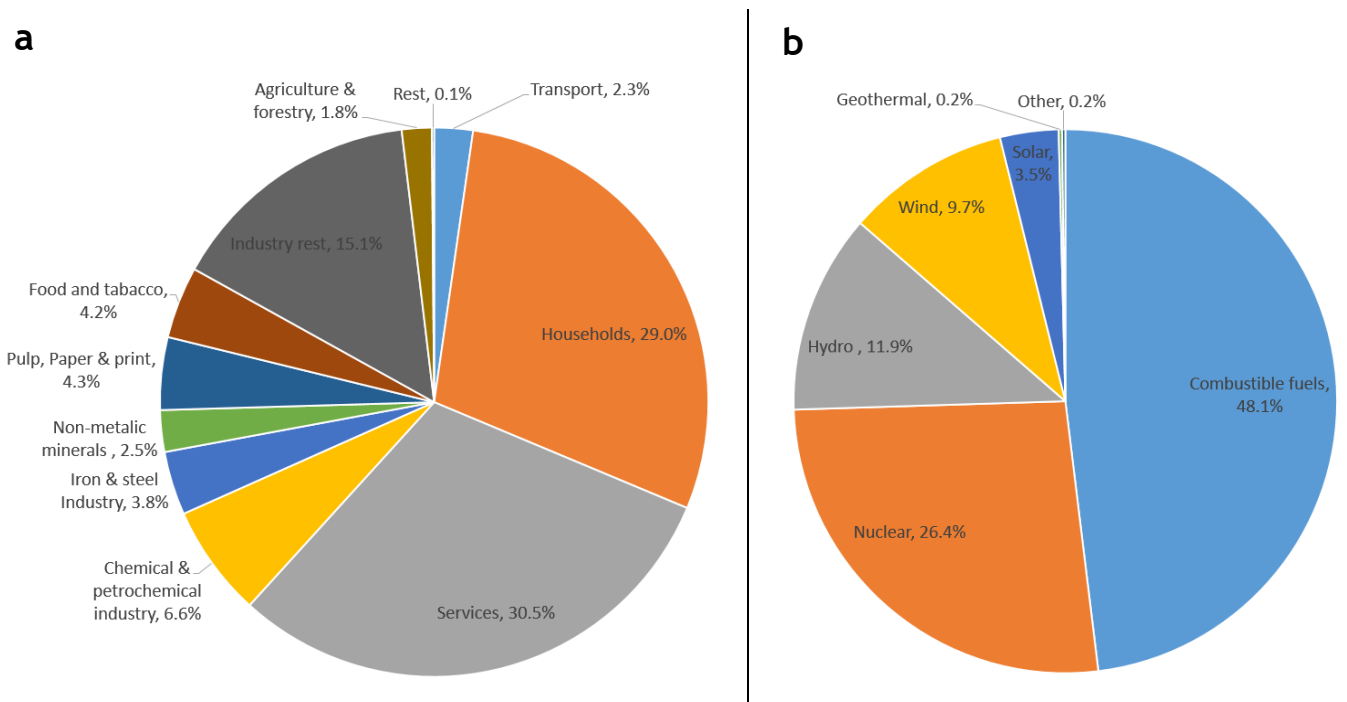


Fig. 4: The 2015 distribution of electrical energy usage across several sectors (a) and the source of the electrical energy used (b).

1.5. The share of the chlor-alkali industry

In 2015, the electricity consumption of the European chlor-alkali industry was 27,446 GWh. In addition, 6.7 million tons of steam were used for heating purposes (mainly in caustic evaporation).

If we transform the electricity and steam into gross energy terms, this would mean that the total energy consumption of the European chlor-alkali industry is approx. 4.1 Mtoe or 0.25% of the gross energy used in the EU28. In reality, it is slightly higher as the salt and water needed for the process will also require some energy during their production. The transport of products and raw materials is excluded as well.

Considering electricity consumption only, the chlor-alkali industry uses 0.73% of the total EU production.

Takeaways

- The chemical industry uses 4.8% of the net energy consumption of the EU28.
- The chlor-alkali industry uses 0.7% of the total electricity in the EU28.
- Europe is aiming for 32% renewables in 2030. With a share of 17% in 2016 a huge challenge is ahead of us, taking into account that the majority of the renewables today are biomass (a further growth is doubtful) and hydro power (also no growth potential).
- Wind and solar are still relative small (2.4%) contributors to the total energy demand.

2. The challenge of obtaining “low-CO₂” energy and raw material supply

2.1. Introduction

People talking about ‘CO₂-free’ or ‘CO₂-neutral’ energy/electricity tend to be talking about renewable sources (hydro, wind, solar, geothermal etc.). The term ‘CO₂-free’ will, however, not be used in this paper anymore, as it can be misleading.

Even for wind energy generation, for instance, one should take into account:

- CO₂ emissions related to wind turbine production (steel, concrete, etc.),
- operation of the power plants,
- transport of the electricity.

In total, this is estimated⁽¹²⁾ to amount to 11.2 g CO₂eq/kWh for a wind power plant (including infrastructure). So electricity from wind is not entirely ‘CO₂-free’.

Nuclear is still not seen as a renewable energy source but on the parameter ‘low-CO₂’ it is as good (or even better) in comparison with wind and solar.

As such, in this document, the term ‘low-CO₂’ will be employed to describe those technologies that significantly reduce the CO₂-emissions/kWh.

Wind and solar are currently considered the most promising contributors. As can be seen in **Fig. 3**, they account for approx. 2.4% of gross energy consumption, whilst 83% of the current energy consumption is “non-renewable”. In order to produce almost all our energy from wind and solar, the existing installations in Europe would need to increase by a factor 40. At first sight, this may seem plausible, but variations in production levels of the wind and solar energy sources hamper their implementation. This will be explained in more detail in **Section 2.3**, by looking at the hourly electricity production⁽³⁾ and consumption data from Denmark, Germany, the Netherlands, Belgium, the United Kingdom and France. These six member states represent 50% of the total electricity demand of the EU28, so will be used as an indicator.

2.2. Electricity consumption

Figure 5 shows the evolution of hourly absolute electricity consumption⁽³⁾ over time. It spans a period of 5 years (2012-2016) and totals the data from the six member states mentioned above. A significant hourly fluctuation can be seen in the electricity consumption pattern with certain cycles dictated by the seasons (higher in winter/autumn and lower in spring/summer as people turn on their lights earlier/ activate their heating etc.).



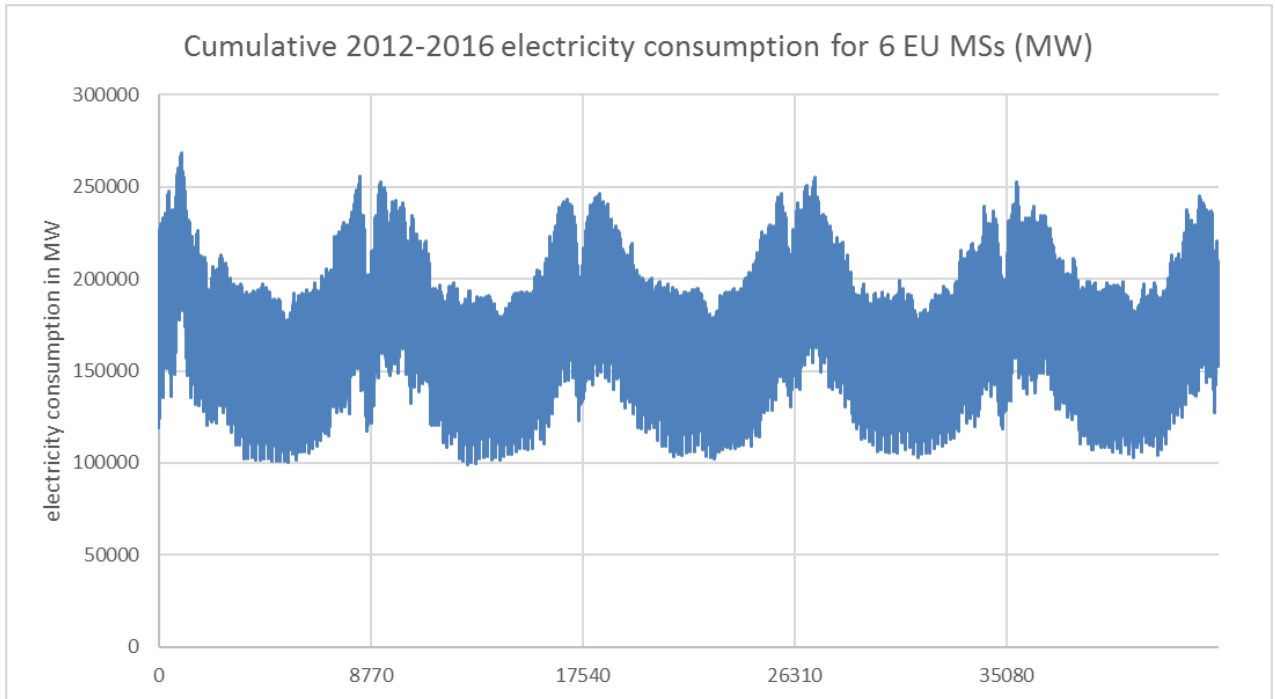


Fig. 5: Total electricity consumption in DK, DE, NL, GB, BE, FR for the period 01-Jan-2012 until 01-Jan-2017 in MW (hourly averaged figures)

2.3. Wind and solar production

As stated before, wind and solar are seen as the most promising/desired CO₂-neutral energy sources, but they have a huge fluctuation in hourly electricity production capacity and some important seasonal changes (see **Figures 6-10**).

The figure below shows the absolute electricity production by wind.

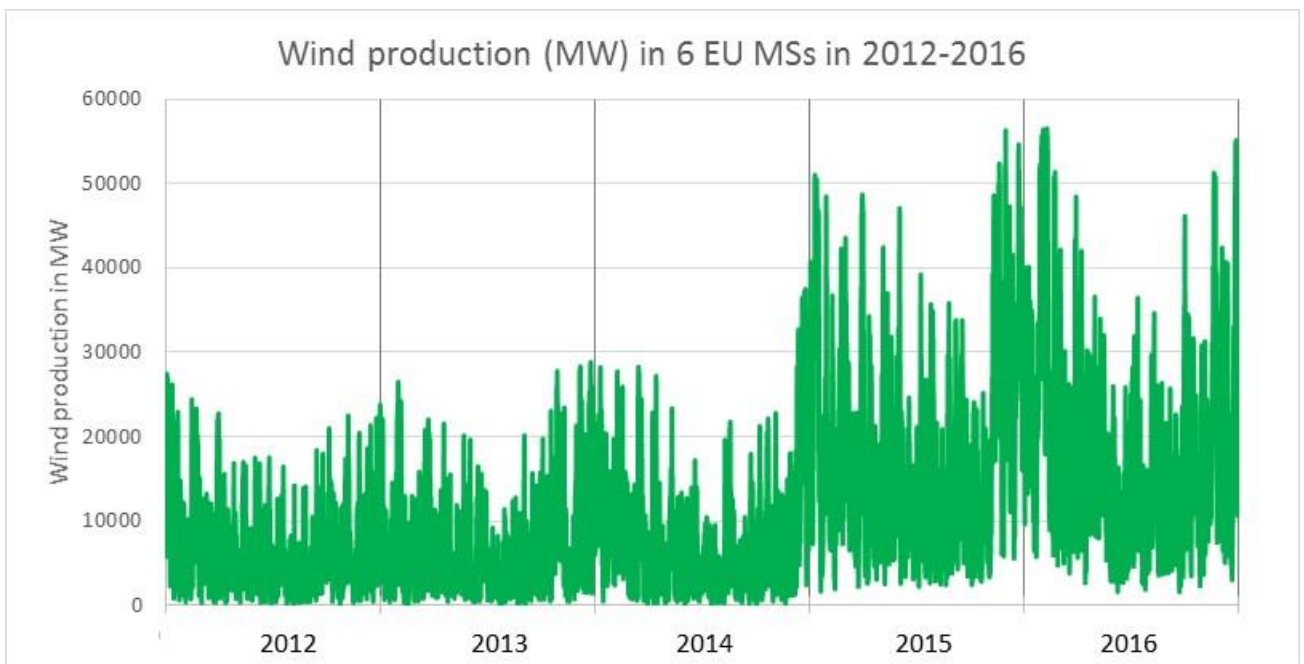


Fig. 6: Absolute wind electricity production in MW (hourly averages) in DK, DE, NL, GB, BE, FR for the period 01-Jan-2012 until 01-Jan-2017

Figure 6 shows that the production of wind energy increased (with a factor of approx. 2.5 from 2012 to 2016) in the period from 2012 to 2016. This was caused mainly by efforts in Germany and Denmark to promote wind and solar by providing significant subsidies. **Figure 6** also clearly demonstrates the huge fluctuation in the hourly production rates (from between 5% and 100%). Compared to the solar electricity consumption pattern shown below in **Figure 7**, wind production has a smaller seasonal effect. Nevertheless, its remaining fluctuations will still cause serious problems in moments of peak demand.

For the production of solar electricity, the seasonal effect is obvious (**Figure 7**). The same applies for the large fluctuation during the day because of the absence of sun during the evening/ night and during more ‘cloudier’ days.

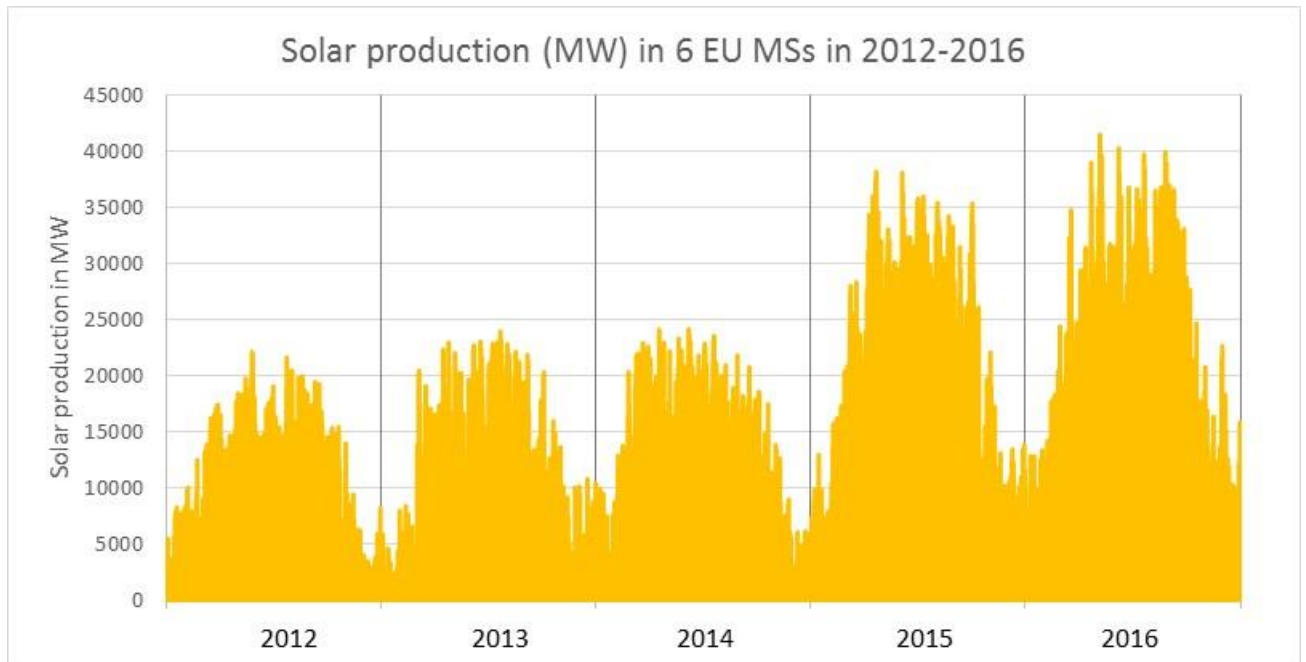


Fig. 7: Solar electricity production in MW (hourly averages) in DK, DE, NL, GB, BE, FR for the period 01-Jan-2012 until 01-Jan-2017

Examples of this can be seen by scrutiny of one month (e.g. June 2016, a ‘sunny’ month in the EU), where the hourly fluctuation of solar energy generation becomes even more apparent (**Figure 8**):

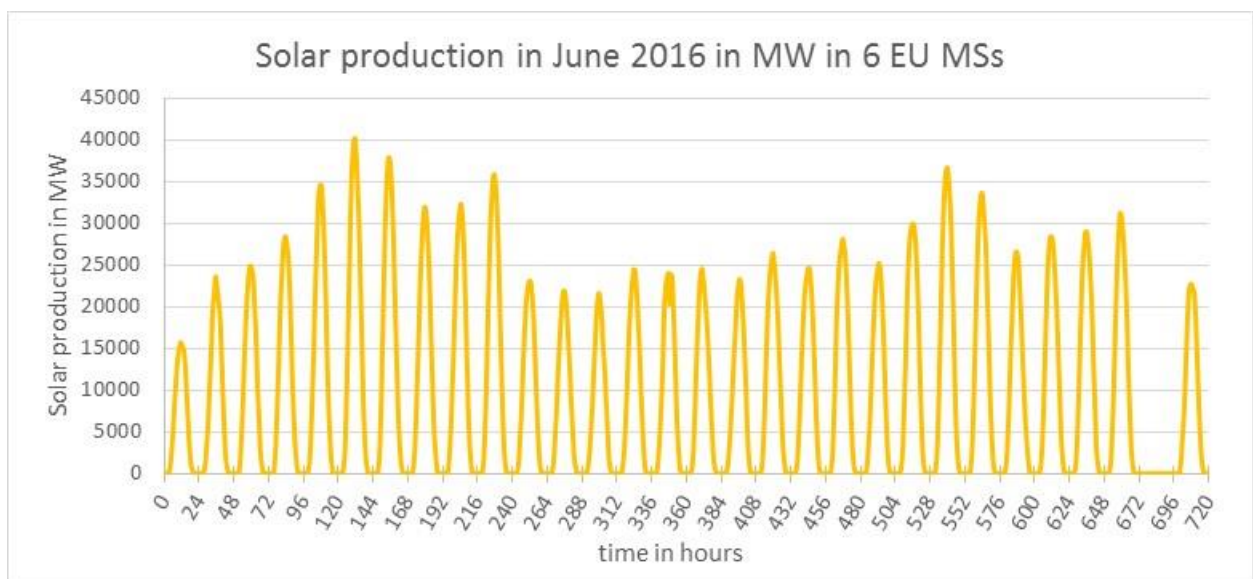


Fig. 8: The total solar production in June 2016 in MW in DK, DE, NL, GB, BE and FR.

The total of wind and solar production together for the entire 2012-2016 period, as a percentage of net electricity consumption, is given in **Figure 9** below. The average contribution in 2012 was 5.6%, increasing to 13.9% in 2016. The overall average contribution over the five years was 9.3%.

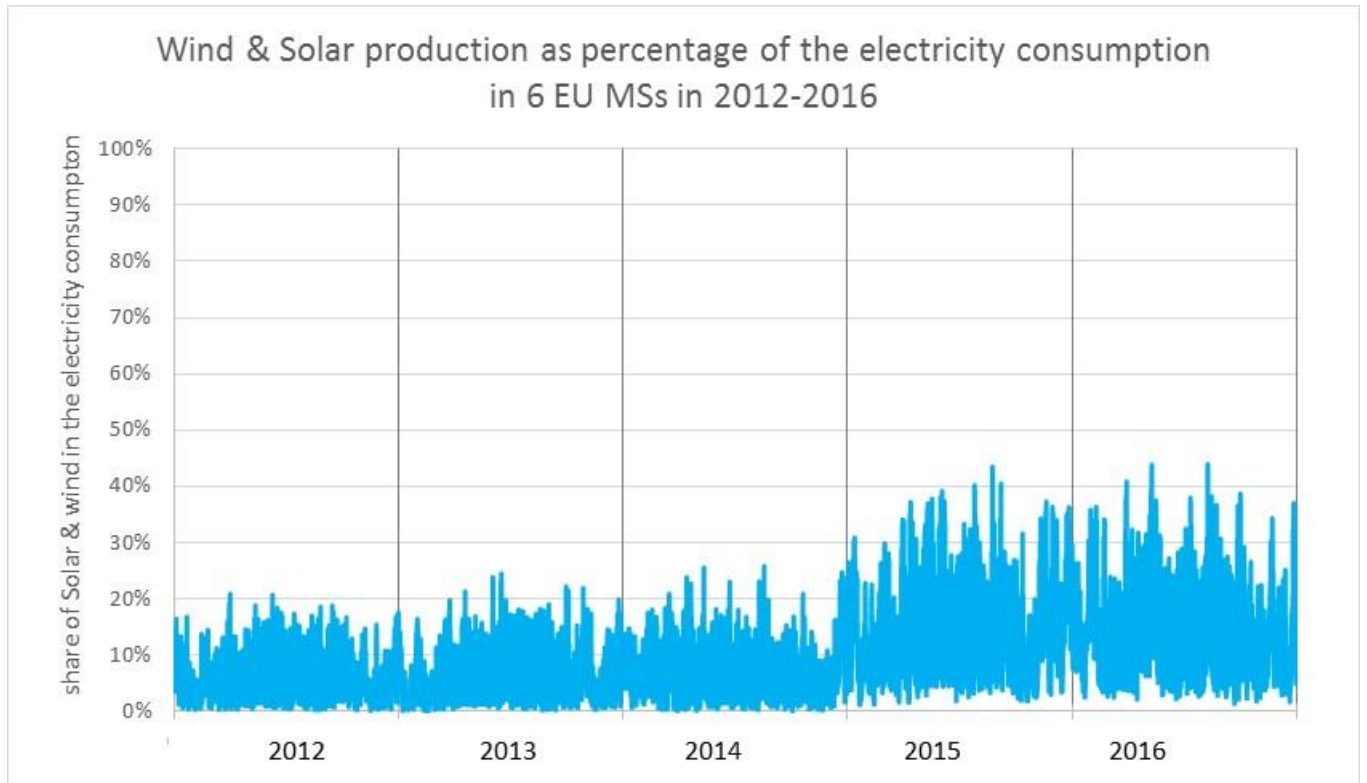
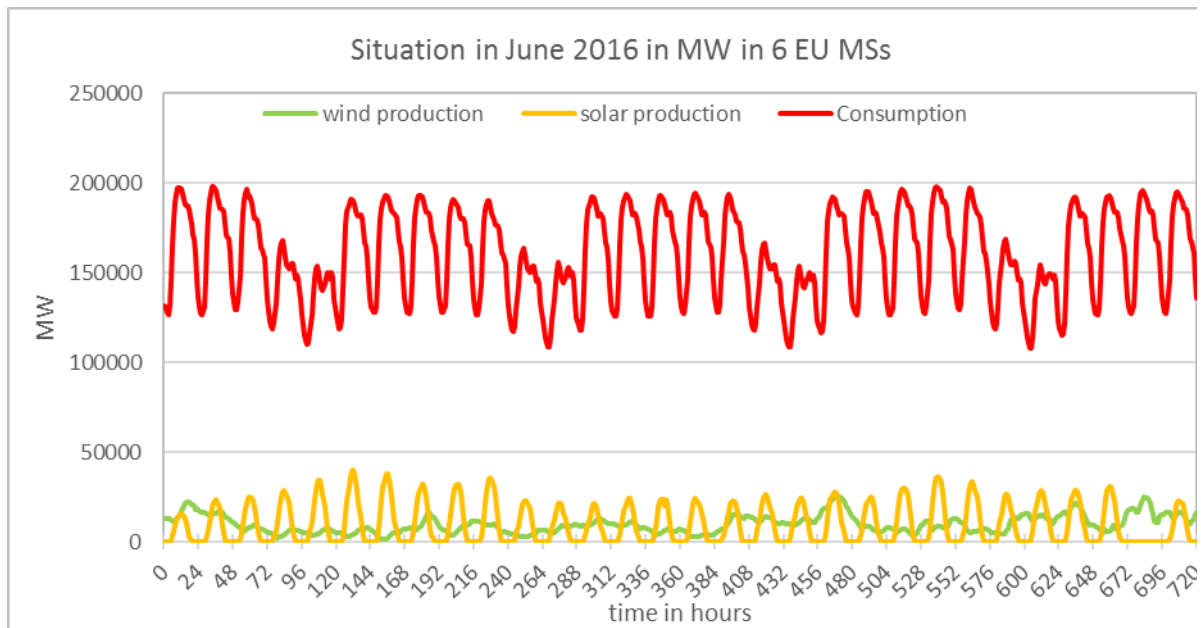


Fig. 9: Total wind and solar production as a percentage of total net electricity consumption in DK, DE, NL, GB, BE, FR for the period 01-Jan-2012 until 01-Jan-2017

To provide a better view on the volatility of the combination of wind and solar compared to the consumption pattern, **Figure 10** provides a more detailed picture for June and December 2016 for which data are particularly rich.

a



b

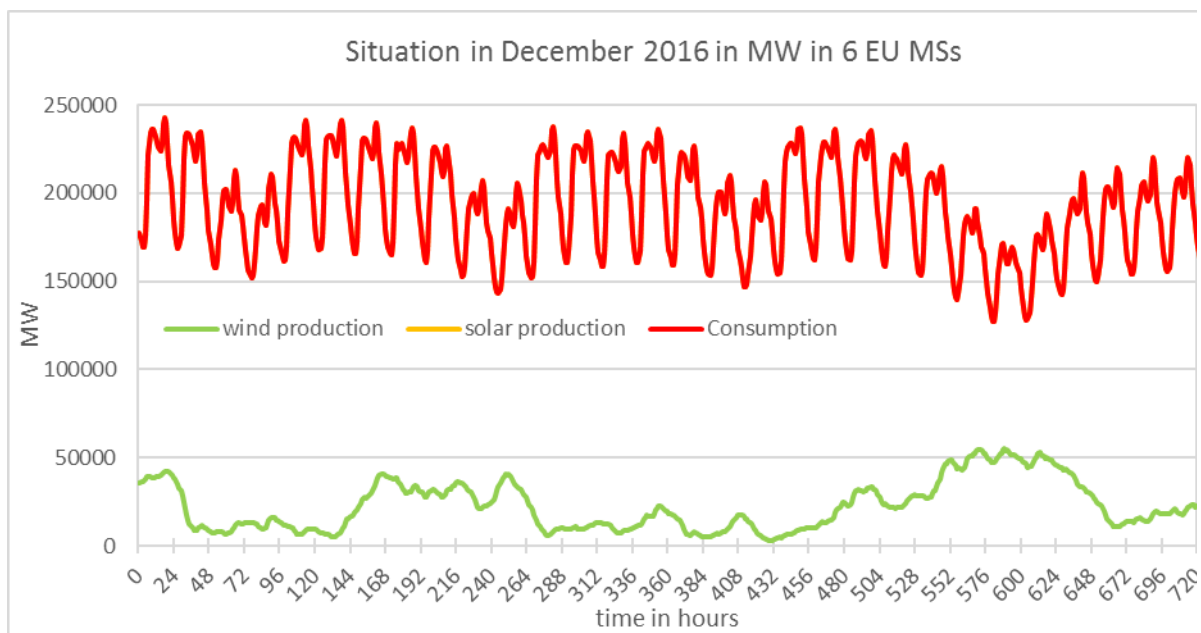


Fig. 10: Total wind and solar production and total electricity consumption for June (a) and December (b) 2016 in 6 European countries.

Note: solar is so low that is not visible in the December graph.

In 2016, the average contribution of wind and solar to electricity consumption was 13.9%, fluctuating between 1.6% and 44.1%. These fluctuations were partly compensated by power generated from other sources such as burning fuels (including gas), nuclear power and hydro-electric power. Pumped water storage was also used as a solution and in some cases the electricity demand could be reduced (or ‘steered’). Steering meant that some activities were put ‘on hold’ until there was more electricity production. This was encouraged by offering lower electricity prices during times of high wind and solar production.



Any overall solution, based on a significant increase in the share of wind and/or solar to create a low-CO₂ electricity production, will increase problems with trying to find ways to compensate for the low electricity generation periods. In addition, energy users which are (currently) not based on electricity may switch to electricity as an energy source, either by directly switching to electricity (e.g. electric cars, heating by heat pumps or electricity), or by producing fuels from electricity (H₂, methanol produced from H₂ and CO₂, etc.). If this happens, currently available technologies will not be sufficient.

Takeaways

- Wind and solar are seen as main technologies to increase the renewable share of European energy demand.
- There is a trend for energy consumption to switch to more electrification.
- Should all our energy need to come from solar and wind, the existing wind and solar installations have to increase by at least a factor of 40.
- The big disadvantage of wind and solar is the enormous fluctuation in the production levels compared to the consumption of electrical energy. This will increase when more electrification takes place.
- When the share of wind and solar increases, there will be moments that there is much more production than required and there will be moments when there is by far insufficient production.
- Therefore, either our electricity demand (energy demand) has to become as flexible as the production of wind and solar, or we have to be able to store energy from wind and solar.

3. Possible solutions

To meet the European climate targets whilst ensuring secure and affordable electricity supply, some challenges need to be overcome. Several options have been identified to solve the problem:

- 1) Sharing between countries. This solution (e.g.) assumes that, when the wind production in (e.g.) Germany is low but wind production in other countries is higher, there is transfer between neighbouring countries to compensate.
- 2) Finding large-scale energy storage solutions. These could include, for example:
 - pumping water to higher altitudes to be released and recaptured later,
 - batteries,
 - hydrogen and/or methanol, which can be ‘burnt’ to produce electricity when production levels are low.
- 3) Influencing consumers to change their behaviour to harmonise with production patterns.
- 4) Developing/ using supplementary low-CO₂ electricity production methods that are contributing to the total demand and are sufficiently flexible to offset the fluctuations in both wind and solar electricity generation and consumption. Options include:
 - power sources based on renewable fuels,
 - traditional nuclear reactors (uranium),
 - innovative nuclear reactors (e.g. molten salt reactors based on thorium).

All of the above will be discussed in the forthcoming sections.

3.1. Sharing energy/electricity between countries

Cross-border sharing of electricity is one of the solutions that has been mentioned many times before. The principle can easily be understood, but when considering its implementation, issues become apparent.

Firstly, transporting electricity over longer distances between member states requires an extensive transport capacity and losses during the transport of electricity have to be taken into account. The losses highly depend on the voltage used for the electricity transport, e.g.:

- when transporting at 350 kV, the losses are approx. 3.5% per 100 km,
- when transporting at 765 kV, the losses reduce to approx. 0.7% per 100 km.

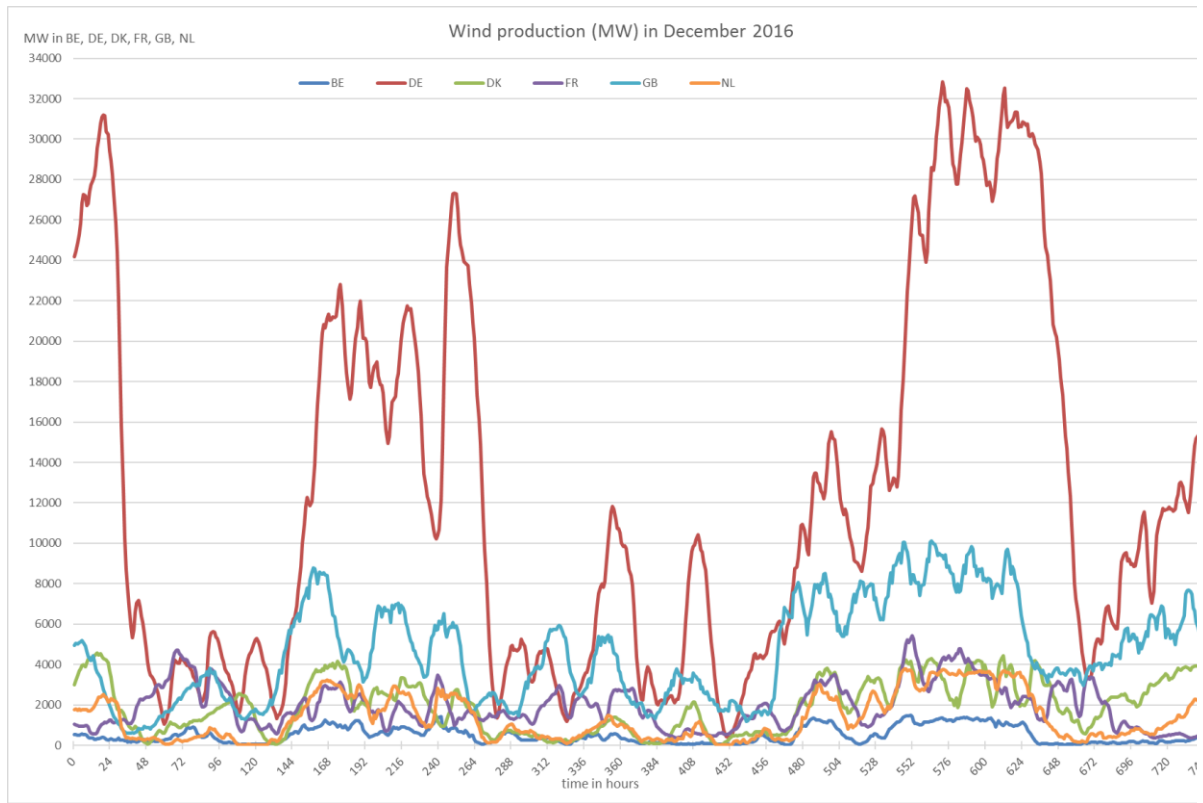
On top of transport losses, transformation losses are observed when increasing to high voltages and back again. Transformation losses are typically in the range of 2-4% of the total energy. As an extended cross-border network currently does not exist, high levels of investment in transport cables and additional infrastructure will be required.

Secondly and most importantly, the basic assumption of the cross-border supply system is that production levels are different among member states at specific moments. In other words, when one area has a very low energy production, another one may have a very high production and is thus able to also supply the low production area. Unfortunately, it cannot always be guaranteed that there will always be a possibility to rely on a region with high production. **Figure 11** depicts the wind production for six member states in December (a) and June (b) 2016 and solar energy production during the month of June (c). As stated before, solar production is negligible in December. Low and high wind production periods tend to frequently coincide across the continent and this significantly hampers the cross-border supply option. Similar examples are available for other months with the same pattern. It should also be considered that wind turbines also have their

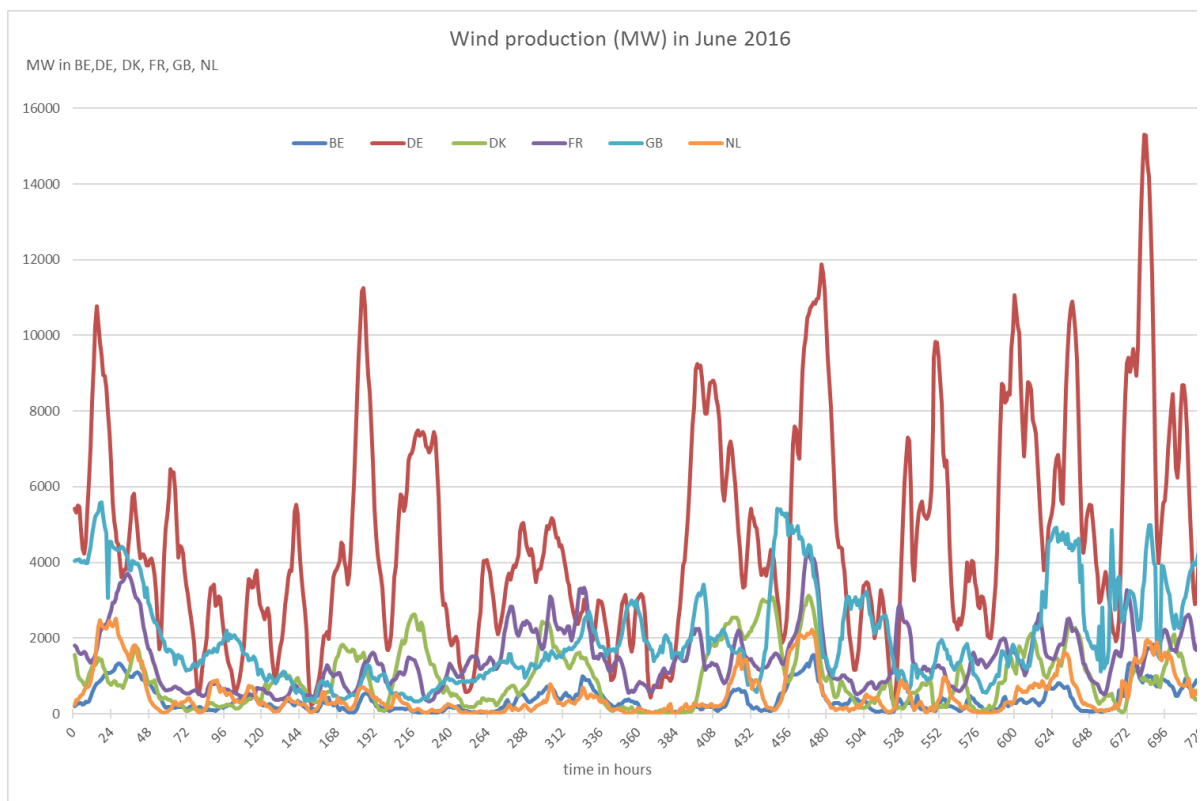


practical and safety limitations. For example, the blades may not turn in case of insufficient or too much wind or when there is ice formation at low temperatures.

a



b



c

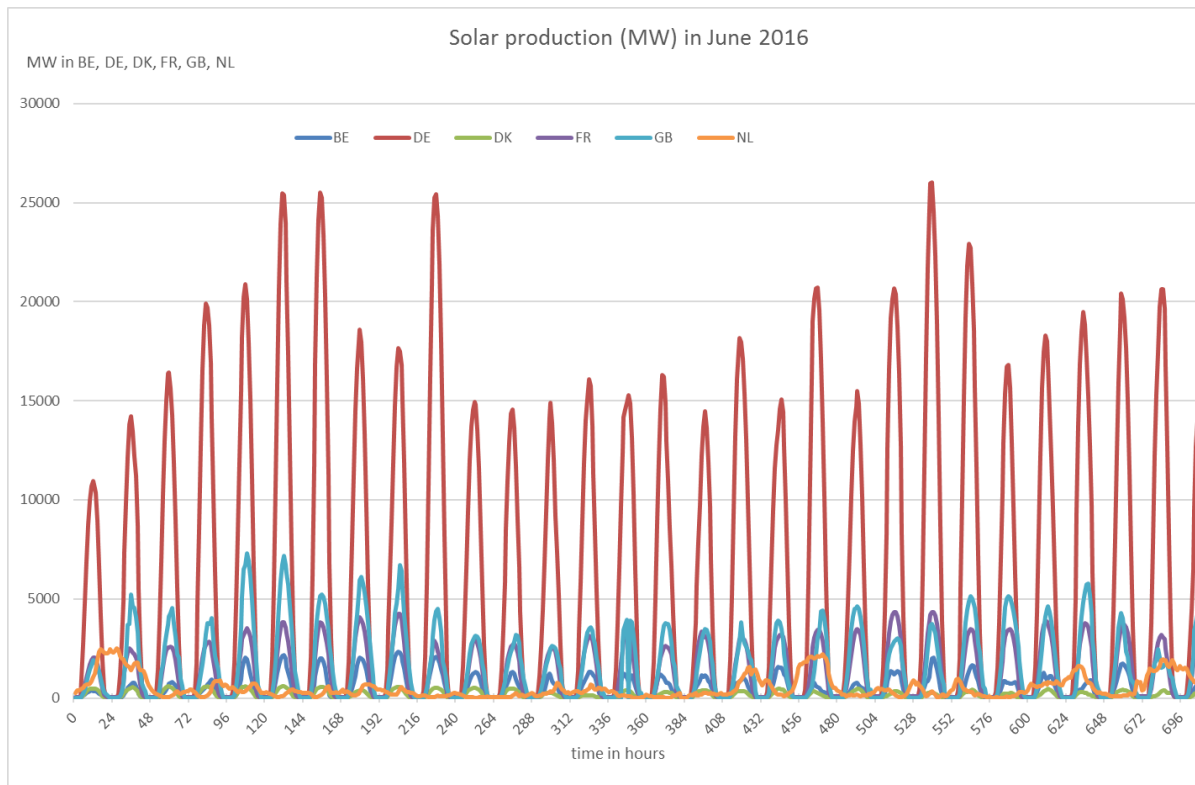


Fig. 11: Wind production in MW for June (a) and December (b) 2016 in the six member states; solar production in MW for the month of June 2016 (c) only.

In **Figure 12**, wind and solar are added for the month of June. It can be clearly seen that solutions, other than cross-border sharing, are needed to satisfy EU electricity needs.

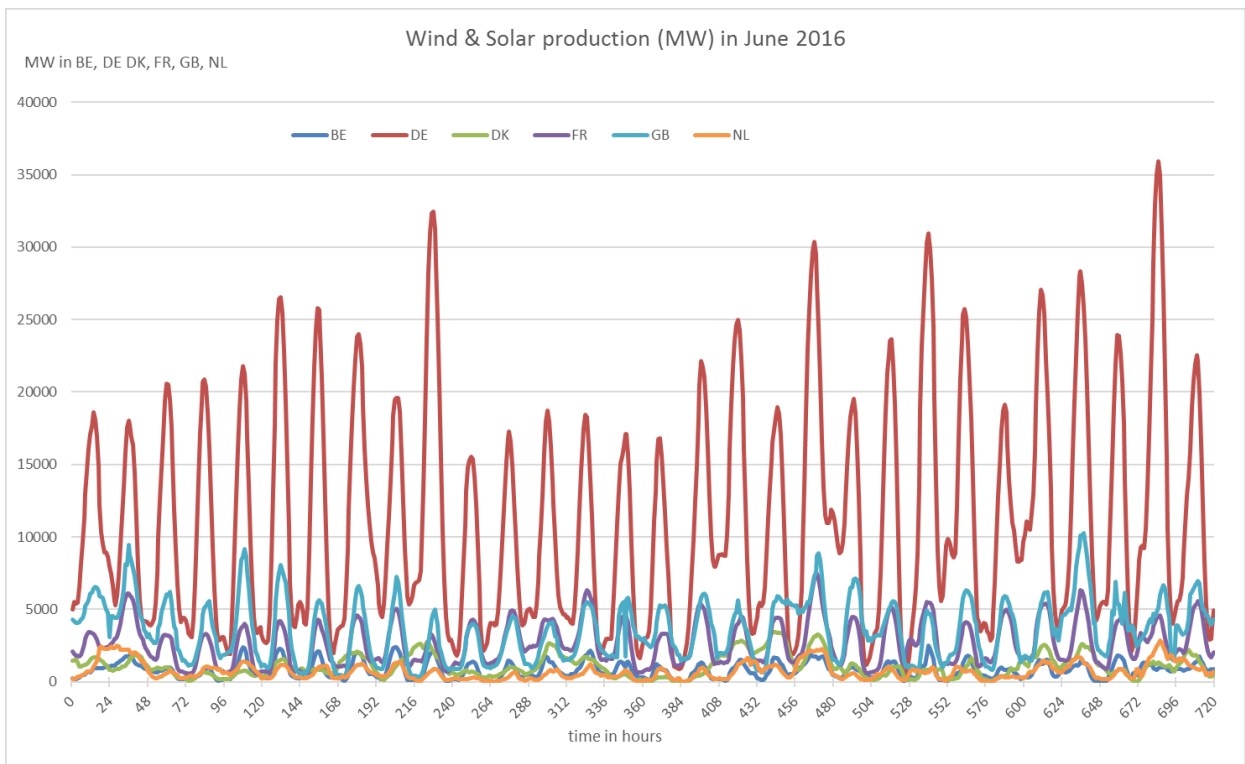


Fig. 12: Cumulative wind and solar production in MW for June 2016 in the six member states



3.2. Energy storage solutions

3.2.1. 'How much' storage do we need?

Wind and solar energy production may exceed electricity demand during peak levels, so perhaps we can simply store that surplus energy to cover any subsequent low wind/ low sun moments. Before we discuss the different storage options, we need to know how much energy that would need to be stored should we only rely on wind and solar in the future. To do this, by using the 2016 hourly wind and solar production data and the hourly net electricity demand during those same hours we can calculate these important figures:

- From the graph of net hourly energy consumption of 2016 (of which the months of June and December can be seen in **Figure 10**) the total net electricity consumption in TWh can be calculated for the year 2016 for the six member states. This amounts to 1538 TWh.
- From the graph with the sum of wind & solar electricity production in the six countries we can extrapolate/calculate the number of required wind turbines and solar panels to generate the required yearly electricity demand, provided that energy/electricity could be stored at peak production levels and released at low production levels. To meet the 2016 net electricity demand, wind and solar production output would need to increase by a factor of 7.2.
- Supposing that there would be sufficient wind and solar electricity generated, the actually required storage in the 2016 situation can be calculated. Therefore assuming that one large, 'perfect' battery was available to store all excess energy at peak moments and 'release' energy at low-wind/low-sun moments, this theoretical battery would have the following features:
 - The battery's content is initially set to zero. When the production exceeds the electricity demand, the battery charges with the amount produced during that hour minus the amount that is consumed during that same hour. The next hour repeats this with electricity being charged onto or released from the battery. This calculation can be performed repeatedly from the 1st of January 2016, 0h00 until the 31st of December, 23h00 (meaning 8,784 hourly values for 2016 for production as well as consumption).
 - Viewing that the battery content started at zero, this battery will regularly drop 'under zero' in the calculations (e.g. if there is no wind or sun during the first hours, it will immediately drop below zero). Therefore, once all numbers are computed for the 8,784 hours, the initial battery's content must be increased until the curve does not drop under zero anymore (to prevent energy shortages over the year). In this way, the required battery capacity can be calculated. For 2016, this amounts to 61.7 TWh.

The evolution of the filling and emptying of the battery for 2016 is shown in **Figure 13**. It gives the picture of the required storage, with every positive slope between two points indicating that the battery is being filled, and every negative slope meaning that wind and solar would need to be supplemented with energy from storage to meet the net electricity demand of that hour. The battery reaches zero twice, meaning that at two moments in 2016, it would have been completely empty.

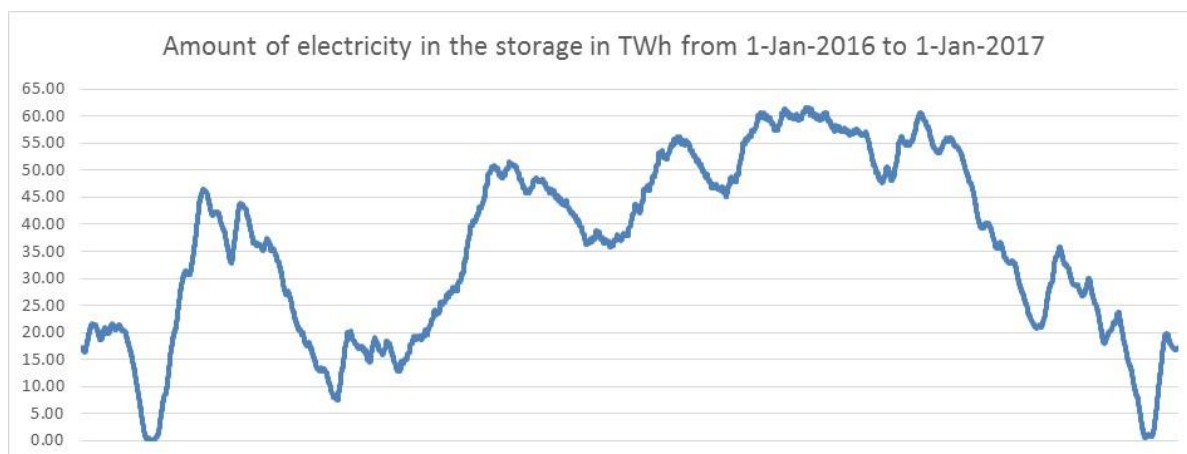


Fig. 13: The hypothetical amount of energy stored (in TWh or 10^9 kWh) assuming that this storage is available and that all electricity in 2016 for DK, DE, NL, GB, BE, FR would have been produced via wind and solar.

The 2016 numbers show that, to avoid power cuts, the required electrical storage capacity for the six member states together would have been 61.7 TWh ($61.7 \cdot 10^9$ kWh). Alongside the required electrical storage capacity, it is also possible to calculate the accumulated amount of electricity that would have needed to come out of the storage systems over a whole year (i.e. the sum of all ‘negative slopes’ in **Figure 13**). For the six countries, this total amount was 323 TWh. This means that, on a yearly basis, approx. 21% of the total electricity demand of these six countries would solely come from stored energy. The yearly amount of electricity to be stored will be a crucial factor in calculating the additional costs per kWh for the storage options discussed below.

One of the major assumptions in this is that the electricity grids have abundant capacity to transport the produced electricity to every corner of the six countries in this evaluation. In reality, this is not true. Therefore, this would require additional investments and there will be additional losses for the transport of the electricity (i.e. even more energy than is projected in **Figure 13** would be needed in addition to cover losses).

In the next chapter it will become clear that 61.7 TWh is a significant storage capacity and that other measures, such as switching off users at the moment of shortage, might be required if solar and wind remain the sole energy sources (with all the social and safety ramifications of such an act included). An additional option would be to build 7.2 times more wind turbines and solar panels. With this amount, there would be enough production at the lowest wind and solar production moments to fulfil the electricity demand. In that case, there will be an overall excess in wind and solar electricity production, meaning that (e.g.) wind turbines would need to be disconnected at certain peak moments. In fact, 89% of the electricity these wind turbines and solar panels could produce would not be produced as there would be no need. The option of over-capacity will be discussed under **3.4.1**.

Finally, it should be noted that this only concerns electricity. The production and storage capacity will further increase dramatically if 1) wind and solar were to provide for the whole energy demand, and 2) electrification fully replaces fossil fuels.

3.2.2. Pumped hydro storage

A pumped storage plant can pump water to a reservoir on a higher altitude when there is excess of power. It releases this water to the lower reservoir when there is shortage of power. Many experts judge pumped storage plants as the cheapest storage option.



Capacity: Typical capacities of pumped hydro storage are 0.32 TWh⁽⁴⁾. With a potential maximum of 2.3 TWh, only 3.7% of the 61.7 TWh needed for the six countries in the above example would be reached. In addition, it is reasonable to assume that the demand for electricity will increase. Therefore, the total available capacity of pumped hydro storage is insufficient to solve the European energy storage problem.

Cost: The maximum electricity production time of pumped storage plant installations is 11 hours on average (3-30 hours). 11 hours corresponds to 29 GW of produced energy with an efficiency of between 75-80%. For the six countries in 2016, the yearly amount that would needed to have been stored was 323 TWh. Taking into account a worst case 75% efficiency rate, about 431 TWh of energy would need to be produced in the plant over the year. The surplus of energy that would need to be generated due to losses by this type of storage (108 TWh) would then become 7% of the total electricity demand. This would mean that the cost of all electricity produced would be increased with 7%, and this is excluding the cost of capital for the investments, the maintenance costs and other operational costs of the storage installations.

Due to the restricted available pumped storage plant capacity, this solution can only marginally contribute to the required solution. Moreover, the geographical features (height and water availability) required for such installations are not present in every region.

3.2.3. Batteries

One of the most common energy storage potentials are batteries. There are several types of batteries⁽⁵⁾ with associated advantages and disadvantages. In this document we will restrict ourselves to the most common ones: Li-ion and vanadium flow batteries.

- Li-ion batteries

Today many electric cars use Li-ion batteries and therefore, an oft- mentioned option is to use the storage capacity of any available (and future) electric cars when they are not on the road. For a battery, it is useful to consider its storage capacity, cycle efficiency (energy loss) and the number of cycles it will be able to run over its lifetime. The cycle efficiency of Li-ion batteries is typically 80-90% and the number of cycles over their lifetime ranges from 400 to 1200. As we have all experienced with our mobile phone batteries, a battery's life is finite and this is a first negative aspect of this type of electricity storage.

Capacity: As mentioned under 3.2, a storage capacity of 61.7 TWh would have been needed in 2016 for the six member states. A battery pack in the largest Tesla electrical car is, at this moment, 100 kWh. This would mean that we would need the storage capacity of 617 million Tesla car batteries, meaning that each person in the EU would require 2.5 Tesla cars to meet such a capacity. It is also worth noting that when batteries have been intensively used for storage and release, electric cars cannot be driven without being fully recharged first. There are also battery packs for the home storage of solar/ wind power with a capacity of 14 kWh. To meet the 2016 needs for the six member states, 4,407 million of these packs would be needed.

Cost: A battery pack of 14 kWh costs 6,300 Euro, so 4,407 million of them would result in an investment of 28,000,000 million Euro, roughly 112,300 Euro per person. Assuming that the investment costs for the batteries would depreciate over 25 years without costs for maintenance and interest, we calculate an additional annual cost of 1,120,000 million Euro/ year. Viewing that the total amount of electricity used in the six countries was 1538 TWh, the storage in Li-ion batteries would add about 728 Euro per MWh to the base electricity price of 40 Euro per MWh. There will also be an additional cost due to the batteries' unavoidable efficiency loss of 10-20%, meaning that 404 TWh has to be stored instead of 323 TWh. This means that 81 TWh needs to be additionally produced

at the base price of 40 Euro per MWh; this will result in an additional efficiency loss cost of 2 Euro per MWh. Overall, the current Li-ion batteries would increase the base electricity price by a factor of 19.

It can be concluded that, to meet the total amount of 323 TWh to be stored in 2016, we would need batteries with much higher capacities and longer lifetimes to allow them to reach the required number of cycles (>200 years). Furthermore, there are maintenance costs to be considered next to the already mentioned efficiency loss. Li-ion batteries may thus contribute to the solution, but will not solve the problem alone.

- Vanadium flow batteries

Vanadium Redox batteries are larger industrial electricity storage options with an efficiency of 60-80%⁽⁶⁾. Their expected lifetime is more than 25 years and the number of full cycles is expected to be > 100,000. Compared to Li-ion batteries, vanadium flow batteries thus have a lower investment cost and longer lifetime. On the other hand, they have a lower efficiency.

Capacity: The capacity of the vanadium flow battery can vary according to the design (electrode area) and storage volume of the electrolytes. Installations of 60 MWh with an output of max 15 MW are considered as large ones. An installation of 800 MWh (output 200 MW) appears to be under construction in China⁽⁷⁾. To match the required capacity of 61.7 TWh, more than 771,000 batteries of 800 MWh would be needed.

Cost: Investment costs are estimated at 340 Euro per kWh⁽⁸⁾, bringing the total for such technologies, if applied on 2016 data to 20,978,000 million Euro. Taking into account the investment needed to install such batteries on a large scale and a depreciation period of 25 years, the yearly cost would reduce to 839,000 million Euro or 545 Euro per MWh overall electricity consumption. The battery has to supply 323 TWh per year and the overall efficiency is 60%. This means that 538 TWh has to be produced and stored. If we assume a base price for the wind and solar electricity of 40 Euro/MWh the loss of efficiency will cost approx. 6 additional Euro for any produced electricity. This brings the total to 591 Euro per MWh or 15 times the base price of electricity.

On a global level, there are already some larger scale installations in operation (Japan) or under construction (China)⁽⁷⁾.

3.2.4. Energy storage as hydrogen and/or methanol

Excess wind and solar energy can also be stored by producing hydrogen, which can later be used as an energy source. Because hydrogen is not easy to store, it is opportune to further convert it into methanol (CH₃OH, reaction with CO₂) or into ammonia (NH₃, reaction with nitrogen). At first sight, this appears to be a very promising option, but efficiency losses need to be overcome.

- Production of hydrogen

Hydrogen is produced through electrolysis of water:



This is a proven technology⁽⁹⁾ with a typical electricity demand of approx. 50 kWh per kg H₂. The produced hydrogen 'energy content' is 35 kWh. This brings the efficiency of the electrolysis to 70%. Storage of hydrogen makes it possible to transfer it back into electricity (and heat) when required. This is commonly performed via fuel cells, which release about 50% of the energy content back as electricity, whereas the other part of the energy content is released as heat at ± 60°C. By preference, this heat could serve for the heating of houses or it can be upgraded to a higher level (≥ 100°C) via heat pumps (additional energy required). Considering the 70% efficiency of the electrolysis and the 50% efficiency for electricity generation, the overall efficiency for converting



to H₂ and back to electricity is 35%, potentially increasing to 70% depending on the extent to which the produced heat of the fuel cells is re-utilised.

Whereas a fully loaded battery has a certain capacity to deliver electricity, hydrogen needs to be produced, stored and released again in subsequent cycles. Therefore, it is useful to compare (from **Figure 13**) the highest production peak (largest increase noted between two points on the figure) and the highest release value (the largest difference between a 'peak value' and the subsequent lower value to which it drops). The highest 'production peak' is 340,000 MW and a maximum of 200,000 MW needs to be released in one go. These numbers are simply read from the figure but do not take into account efficiency losses.

The investment costs for the hydrogen system are subdivided into two parts, namely the investment related to the hydrogen production and the investment related to its storage:

- 1) The investment costs for hydrogen production amount to about 800 Euro per kW for the generation of the hydrogen and approx. 800 Euro per kW for converting the hydrogen back to electricity. The required investment costs, excluding H₂ storage, would be approx. 433,000 million Euro. In order to make this comparable with the battery options this requires an investment of approx. 7 Euro per kWh storage capacity (excluding the costs of the H₂ storage).
- 2) The required storage capacity of "electricity" (as hydrogen) that has to be stored over the year is approx. 61.7 TWh. The electrolysis cells can produce hydrogen with a pressure between 30 and 100 bar. Under 100 bar hydrogen pressure, 1 m³ will contain 8 kg H₂. This can generate 158 kWh. The required H₂ storage would thus approx. amount to 390 million m³. With an investment of 9 kEuro/m³ ⁽¹⁰⁾, this results in 3,510,000 million Euro or 57 Euro per kWh storage capacity. The total would be 64 Euro per kWh.

If we assume that the investment costs will be depreciated over 25 years and that there is no interest and maintenance costs, the cost becomes 103 Euro per MWh electricity.

The overall efficiency from producing hydrogen and converting it back is 35%. Per year 323 TWh has to be produced for the stored hydrogen. This means that we need 922 TWh per year to produce the hydrogen that is required to deliver that 323 TWh. With a base price of 40 Euro/MWh the efficiency loss is counting for approx. 24 Euro/MWh for all electricity required. The overall electricity price would be 167 Euro/MWh.

The disadvantage of energy storage in hydrogen compared to batteries is the lower overall efficiency (35% *versus* 60%-80%). It will thus involve higher electricity production costs.

- Further conversion of hydrogen into methanol

Because methanol is easier to store than hydrogen, it is considered a plausible energy storage solution. However, the additional conversion from hydrogen to methanol will require more energy and more investments in processing equipment. This means that overall efficiency will decrease. On the other hand, it should be noted that 1 m³ methanol can generate 2020 kWh, whereas 1 m³ H₂ (at 100 bar) can generate 158 kWh via fuel cells. The same volume of methanol therefore generates 13 times more electricity than hydrogen. This means that the required storage volume would be a 13 times less. It is also cheaper as atmospheric storage tanks would suffice, as opposed to pressurized H₂ storage tanks. Methanol storage tanks would require an investment of approx. 250 Euro per m³ or for the total required energy storage (30.5 million m³ required) 7,600 million Euro.

Based on industry data ⁽⁹⁾, considering 3000 operating hours per year and an electricity price of 40 Euro per MWh, the production costs of methanol would be approx. 725 Euro per ton. To match the 2016 figures for the six countries, the unit would need to operate approx. 3800 hours per year.

To balance the energy requirement, about 117 million tons of methanol would have to be produced yearly (today the global production of methanol is approx. 80 million tons). This would cost about

84,000 million Euro per year or 55.5 Euro per required MWh nett electricity consumption. Including cost due to the storage depreciating over 25 years, without interest and maintenance, the cost would be 56 Euro per MWh.

The investment for the conversion of methanol to electricity is also based on fuel cell data. This would require an investment of approx. 126,000 million Euro. With a depreciation over 25 years and no interest and maintenance cost, this results in an annual cost of 5,000 million Euro per year or approx. 3 Euro per MWh of total electricity consumption.

The efficiency loss of the hydrogen production is already included in the methanol price. Therefore, we only have to compensate for the loss of efficiency for the transfer of methanol into electricity.

The total electricity price based on a base production price of 40 Euro/MWh becomes approx. 116 Euro per MWh.

3.2.5. Cost summary for the storage options

Table 1 details the costs of the storage options. It assumes that the base production costs of electricity by wind and solar is 40 Euro/MWh and that investments are converted to yearly costs by depreciation in 25 years without costs of interest. It is also assumed that there are no other maintenance and/or operational costs. This is very optimistic but at least provides an idea on the costs of storage on the overall electricity price.

Table 1: Summary of costs of energy storage options

Storage type	Investment cost In 10 ⁹ Euro	Annual storage costs in Euro/MWh	Cost of efficiency losses for the storage Euro/MWh	Price of electricity incl. storage costs and efficiency losses in Euro/MWh	Factor of additional cost on today's current energy cost
Li-ion Batteries	1120	728	2	770	19
Vanadium Flow batteries	839	545	6	591	15
H2 storage	158	103	24	167	4
Methanol		59	17	116	3

3.3. Adapting consumption to wind & solar production

This option would allow us to avoid all the complex and expensive storage options described above. Nevertheless, it would have a huge societal impact. European citizens need to be willing to adapt their energy/ electricity usage according to the wind and solar production. In practical terms, all users should be able to switch between approx. 3% and 100% at any moment of the day. For households, this may mean delaying charging cars and other batteries, usage of domestic appliances (e.g. washing machines), heating/ cooling the houses (with good insulation maintaining the temperature as long as possible afterwards) etc. until there is sufficient energy being produced for the public to run these activities. Consideration would also be needed on emergency power requirements. For larger consumers (e.g. industry), this means developing a complete plan that would allow for minimal energy consumption (of those installations that cannot be turned off) and optimal use of energy at peak production levels.



Should all electricity required in the six countries have been produced with solar and wind in 2016, the average production would have been 33% of the total demand. This means that spare capacities of installations at least would have needed to be increased with a factor 3 to keep installations operative. This would require large investments, resulting in increased consumer prices.

3.4. Further developing/ using low-CO₂ energy sources

3.4.1. Creating wind and solar ‘over-capacity’

If society does not wish to or cannot change lifestyle, another option could be to install more wind and solar than is needed beyond the 100% coverage. In this scenario, production would be switched off when it exceeds the consumption and no complex storage options would be needed. Considering that, at the lowest production moments, the accumulated wind and solar production is only 1.6% of actual consumption, wind and solar capacity would need to be increased by a factor of 64 compared to 2016. This would result in extreme increases in electricity prices and it is doubtful that sufficient infrastructure could even be built from a practical point of view (enough space, materials, etc.).

Having considered this ‘100% coverage’, there may also be a possibility to look at intermediate solutions. That is to say when (e.g.) wind and solar capacity could be increased to twice the amount required for 100% coverage over the year (so 14.5 times more wind turbines and solar panels compared to today), the required storage capacity would drop to approx. 10% of the one indicated above. With this, the cost of storage capacity would decrease but also 100% of the produced wind and solar capacity would not be utilised, already resulting in an increase of the base price for solar and wind with a factor 2.

This clearly shows that a solution could consist of wind and solar to some extent, with some storage capacity and (by preference) energy sources that can compensate during moments of shortage. Some examples of these are given below.

3.4.2. Power sources based on renewable fuels

The use of bio-based fuels such as natural and processed wood, crops, animal, fat, waste, etc. is possible to cover the moments of shortage. The basic principle is that the amount of CO₂ that is released into the atmosphere after combusting these biomass fuels equals the amount of CO₂ absorbed from the atmosphere during its lifetime. The question is whether sufficient biomass could be grown to generate the required amount of energy.

Answers to this are shown in a report⁽¹³⁾ from the “Koninklijke Nederlandse Akademie van Wetenschappen” (Royal Dutch Academy of Sciences), which contains the following statements based on external literature:

- It requires 20-100 years for a tree to capture the amount of CO₂ that is emitted when the tree is burned;
- If the total area of the Netherlands (4.15 million hectares) was used to grow rapeseed on its entire surface, this would enable energy production equivalent to approx. 22% of the total gasoline consumption of the Dutch transport.

3.4.3. Traditional nuclear reactors (uranium)

Nuclear options have been abandoned due to genuine concerns that arose after serious incidents (Harrisburg, Chernobyl and Fukushima). In addition, there are concerns over the risks and security associated with nuclear waste.

Looking objectively at the nuclear option, comparisons of the mortality rate associated with each hour or energy produced indicates that nuclear is favourable (see Table 2). However, this is not the

only criterion as the waste generated by uranium nuclear plants needs to be kept in safe storage for such a long time, and that the technology may introduce too many risks and costs for society.

Table 2: Mortality rates of different energy sources⁽¹⁴⁾

Energy source	Mortality rate (deaths per TWh)
Coal (global)	100
Oil	36
Biofuel/biomass	24
Natural gas	4
Hydro	1,4
Solar	0,44
Wind	0,15
Nuclear	0,09

3.4.4. Innovative nuclear reactors: the thorium molten salt reactor (MSR)

There might however be alternatives based on Thorium (Molten Salt Reactors, MSR). This type of reactor creates less radioactive waste. For example, a nuclear reactor, fuelled by uranium producing 1000 MW of electricity, will require 680 kg/day of natural uranium to create 3.2 kg fission fuel. An equivalent thorium MSR would require, for the same amount of electricity production, 3.2 kg of thorium⁽¹¹⁾. The technology has problems though that stem from the fact that some uranium reactors have given ‘nuclear’ solutions a bad image and that a lot of work is still required to come to commercial scale installations. This is unfortunate, given that the principles of the technology had already been demonstrated in the mid-20th century.

One of the advantages of MSR is that it can react very fast to changes in demand, thanks to the reservoir of molten salt. This heat can be kept stored within the salt to be released upon requirement. Therefore, it could supplement wind and solar to keep the price of the produced electricity at an acceptable level.

It is anticipated that the price of the produced energy can be in the order of 40 Euro per MWh when the installation is run on full load. A large part (80%) of this price comes from the costs associated with capital, maintenance and operation.

If we consider the example discussed previously, where we would need to generate about 7.2 times more wind and solar electricity than in 2016, we would be able to abandon more expensive storage options and compensate supply deficiencies via thorium MSR electricity. Not storing could also mean switching off solar and wind supply at peak moments. As we have calculated earlier, this would have been required for 21% of the solar and wind production, or for 323 TWh over one year. This will need to be produced by the MSR, which has a maximum of 200,000 MW. For the MSR reactor(s), this would entail running for 3800 hours (43% of the time), and only utilizing 18.5% of the installed yearly capacity.

The price of solar and wind energy would increase because of the lower production levels and the costs of the electricity of the MSR. Assuming that in both cases the costs are dominated by yearly fixed costs, this would mean that the electricity price would increase by approx. 27%. Therefore, the assumed 40 Euro/MWh would become approx. 78 Euro/MWh.

This solution would allow the installation of less wind and solar as the MSR reactor could maintain a certain base load. It provides flexibility given the MSR ability to adjust in load. The wind and solar



capacity could be further reduced by using already available capacities for storage as e.g. pumped hydroelectric. By employing available cheaper storage options and adapting MSR capacities, an optimal situation could be found. Unfortunately, the exact electricity price of MSR is not yet known

Takeaways

- An increasing contribution of wind and solar requires solving the high production fluctuation of wind and solar.
- Sharing electricity between regions with high/ low production can only partly contribute as, on a regular basis, the low and high production moments coincide. Additionally a large network of electricity transport cables is needed and consideration is needed for the considerable 'losses' during transport.
- To cover existing electricity consumption in the six members states with solar and wind, these installations need to increase by a factor of 7.2. Such installations would also require between 61.7 TWh and 323 TWh to be stored over the year.
- Current storage options can contribute but may not be economical. They include:
 - Pumped hydro (cheapest option but limited capacity; 3.7% of the required storage capacity).
 - Batteries (expensive at present meaning overall electricity costs would increase with a factor 15-19 if batteries were the only storage solution).
 - H₂ or methanol storage (expensive and would increase electricity costs by a factor 3-4. May also conflict with EU drive to improve overall energy efficiency).
- Adapting the consumption to the production volatility of wind and solar is unrealistic for a modern society.
- Wind and solar production capacity could be increased to cover moments of low production to cover demand, with subsequent switching off of the extra capacity during times of high production. To cover current consumption, wind and solar need to increase by a factor of 64 (or a factor 7.2 if storage was of sufficient capacity). This would require significant investment and would require significant additional areas of land or sea.
- Alternative low CO₂ electricity/ energy generation may be a better solution. Biomass may not be enough but nuclear (new generations e.g. Thorium) could deliver promising options.

and time is required to develop the system to be able to install real production units. Nevertheless, even if MSR would be 2 times more expensive than wind and solar, it would still be a better alternative than the storage options presented above.

4. Main takeaways

- The chemical and petrochemical industry is a relatively small user of the total energy usage in Europe (4.8%); the main consumers are transport (33.1%) and households (25.4%).
- Chlor-alkali production uses only 0.26% of the total energy demand and 0.7% of the EU28 electricity demand
- The contribution of solar and wind to the total energy demand was 2.4% in 2016; nuclear delivered approx. 6% of the total energy demand in Europe. The vast majority (75%) is still based on fossil fuels.
- Increasing the share of wind and solar will increase the volatility of energy supply and this volatility does not match with the variations in demand.
- Increased wind and solar will trigger the need for solutions to their volatility. Storage options are either not sufficiently available (pumped hydro) or extremely expensive. Moving to over-capacity of wind and solar may be an option, but it will increase costs dramatically, there needs to be sufficient space and materials to build all the installations.
- Transferring electricity into H₂ and/or methanol, followed by storage and their transference back to electricity seems the least costly storage option of all. However, it requires extensive storage tanks, so the space needs to be (made) available.
- Balancing electricity consumption (of industry, households, etc.) to cover the full imbalance with electricity production from wind and solar is not a realistic solution for a modern society. Nonetheless, it can contribute.
- Innovative nuclear energy technologies, such as Molten Salt Reactors based on thorium, could be a very useful addition to the energy mix. Because they are low-carbon solutions and loads are easily adjusted, they may be effective at levelling out the fluctuations of wind and solar.



ASSUMPTIONS IN OUR STORAGE AND ALTERNATIVE ENERGY SOURCES CALCULATIONS:

- Cross-border supply is an accomplished fact, meaning that electricity distribution across the member states runs easily and smoothly (from East-DE to West-UK and from North-DK to South-FR). This assumption is a major one though as presently, the infrastructure is not ready and there will be transport losses.
- All players/ consumers pay the same amount for their electricity and contribute to generation and storage of electricity in the same way. There is full equality. This assumption is a major one though as presently, if one player invests less in storage, another one will receive an increased bill. We did not take the latter into account.
- When storage capacity was calculated, assumptions were made that the 2016 wind and solar capacity would be increased by a factor of 7.2. Therefore, the calculations assume a situation with 7.2 times more wind turbines and solar panels than the actual 2016 situation.
- We have not taken into account maintenance costs for storage options and we have considered life cycles of 25 years for the batteries.
- We have only considered electricity demand. Should all energy uses be electrified, 5-7 times more electricity would need to be produced and stored. The consumption patterns will then take a new (yet unknown) shape compared to the 2016 ones.
- When considering wind, the building of the wind turbines and infrastructure costs are included in the 40 Euro/kWh.
- Waste and disposal costs have not been considered (e.g. used batteries).

Conversions and units

1 ton of oil equivalent is equal to 41.868 gigajoules

k = kilo = 10^3 or 1,000

M = Mega = 10^6 or 1000,000

G = Giga = 10^9 or 1000,000,000

T = Tera = 10^{12} or 1000,000,000,000

P = Peta = 10^{15} or 1000,000,000,000,000

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The Energy Dossiers produced by Euro Chlor's Working Groups aim to improve the understanding of key topics related to the chlor-alkali industry

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