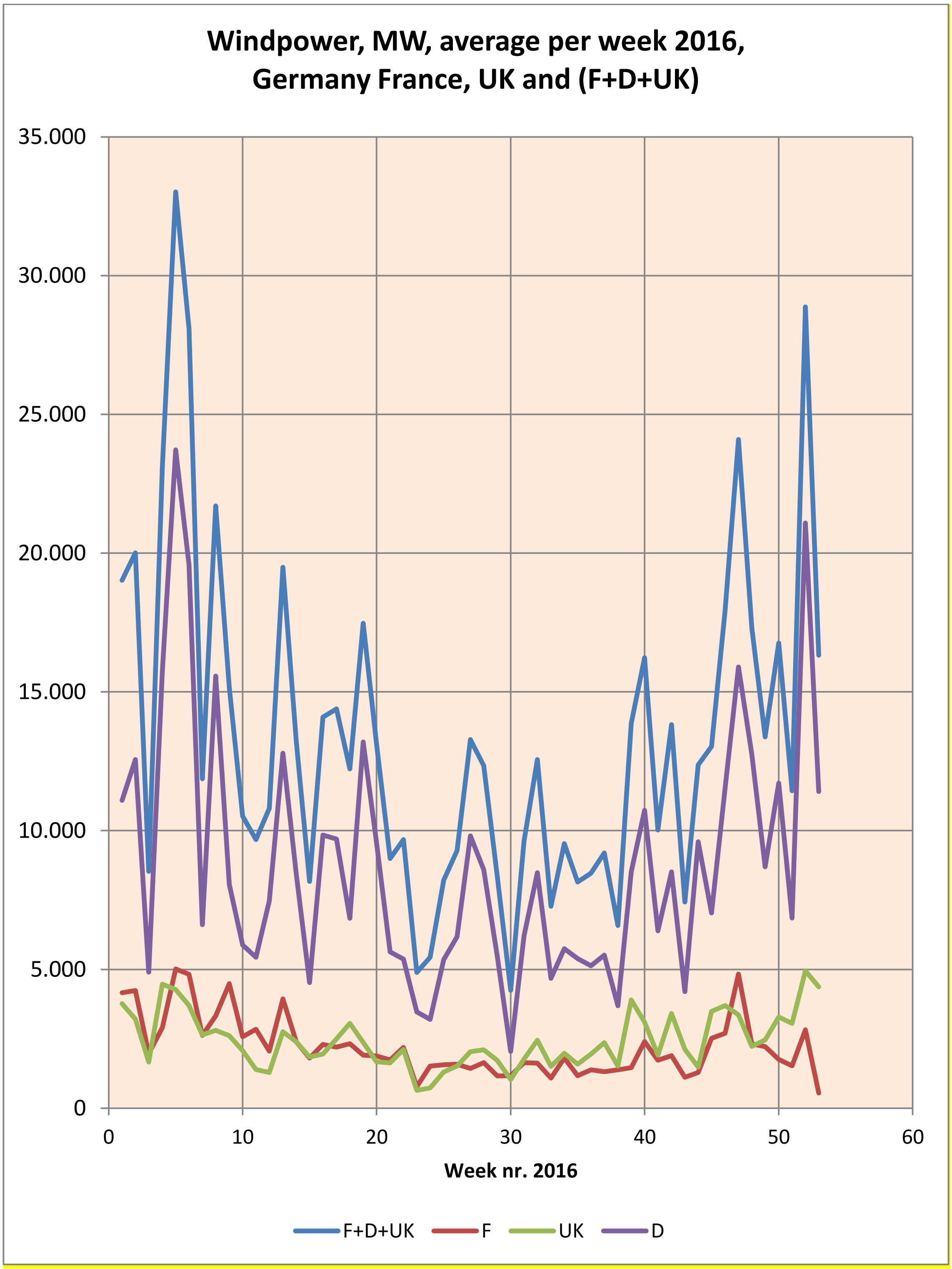
The Necessity of Storing Green Energy



The diagram above showing the weekly averages for wind energy produced in Germany, France and United Kingdom illustrates clearly the necessity to store wind energy if this energy is thought to play an essential role in our future energy supply.

The aim of this report is to describe and quantify what to do to let the ambitions become true.

Contents

Acknowledgements

I wish to express my thanks to
Associate professor, Alan Tarp
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My granddaughter, Student in National Economy, Maria Elisabeth Kjaersgaard-Jensen
For much advice and help with the editing.

Definitions and Units

Notation: The data used in the report are written in Danish or German notation, and consequently this has been used throughout this report.

Comma is used as the decimal sign. I.e. 100,27 means 100+27/100.

The point is used as separator sign. I.e. 100.000 means hundred thousand.

Units: Generally electricity production and consumption (Load) is expressed in Watts. (Joule/second) and the prefixes

K(ilo) = 1000 = 10^3
M(ega) = 1000.000 = 10^6
G(iga) = 1000.000.000 = 10^9
T(era) = 1.000.000.000.000 = 10^12
E(xa) = 1.000.000.000.000.000 = 10^15

Proportions: Many years of experience with long and complicated calculations has taught the author that it is much safer to adhere strictly to **System Internationale** and thus express for instance wind power as the proportion of the load as W/kW and not in per cent.

Load: This means the consumption of electricity measured in W.

PV: Photo Voltaic Power

Standard deviation: stddev

Introduction

It is a well known, but often not recognized matter of fact that green energy – Photo Voltaic and Wind Power are and remain unstable and therefore are of little use unless back up is provided for.

Denmark has been a forerunner for wind power. Some results are shown in

Table 1

Year		2015	2016
Wind Power	**MW**	1612	1452
Load	**MW**	3826	3862
Wind/Load	**%**	42	38
Wind/Load after correction for export	**MW**	1394	1231
	%	36	32

36 % wind in the system may be impressive. However, Denmark is a special case because Denmark is situated between Norway, Sweden and Germany, whose electricity loads are about 15 GW, 15 GW and 55 GW against the Danish ca. 3,8 GW, about 4.5 % of our neighbours' load.

For more than 100 years, Denmark has been electrically connected to Sweden and for more than 50 years Denmark has had strong connections to Norway and Germany too. The circumstance that Norwegians and Swedes normally are willing to buy wind power at a very low price when available and deliver hydro and nuclear power back, when needed, and at a much better price, which made the Danish wind power system possible.

This report deals with the question whether it will be possible for Germany, France and UK to obtain the same proportion of wind energy in their systems.

The Fraunhofer Institute has published the report:

FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME, ISE

100 % ERNEUERBARE ENERGIEN FÜR STROM UND WÄRME IN DEUTSCHLAND

In this report it is proposed to increase the German Wind and Solar Power with a factor 8.

This report deals with the idea of a many fold increase of the wind and solar power, and the following demands to the energy storing and regenerating systems.

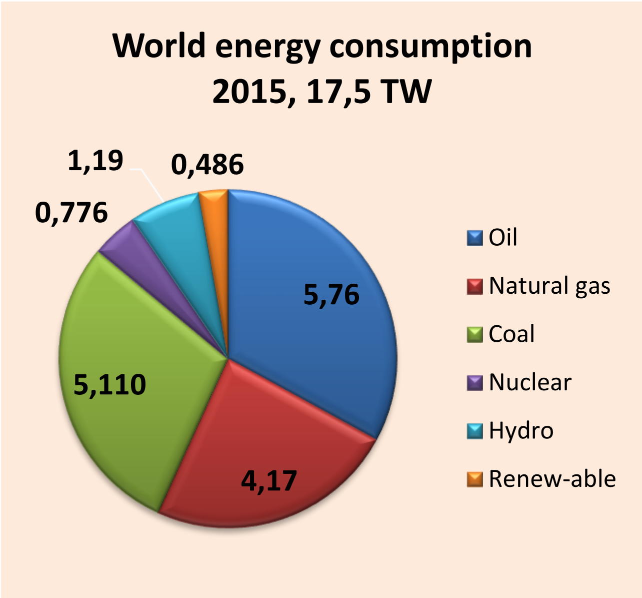
This author has a long experience with operation of complicated chemical plants. It seems evident that the authors of the mentioned Frauenhofer report never have been responsible for operating a complicated process.

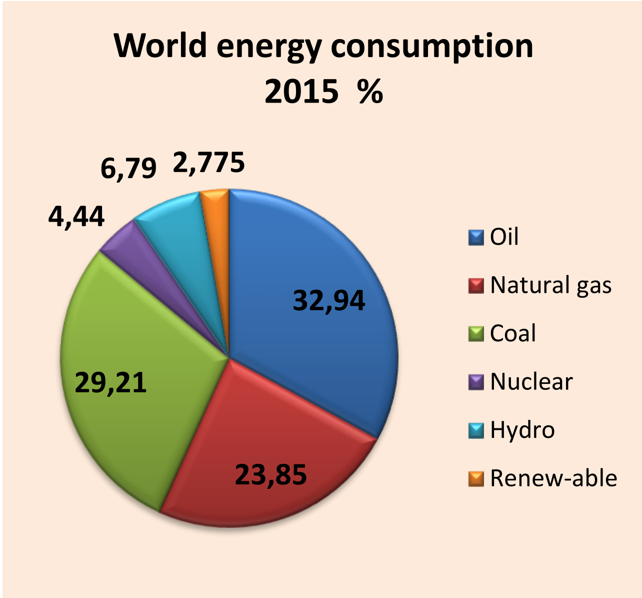
Neither has the German chancellor behind "Die Energiewende" nor the Danish prime minister, Anders Fogh Rasmussen, who at a congress at 16. Nov. 2008 promised the audience "A fossil free Denmark in 2050".

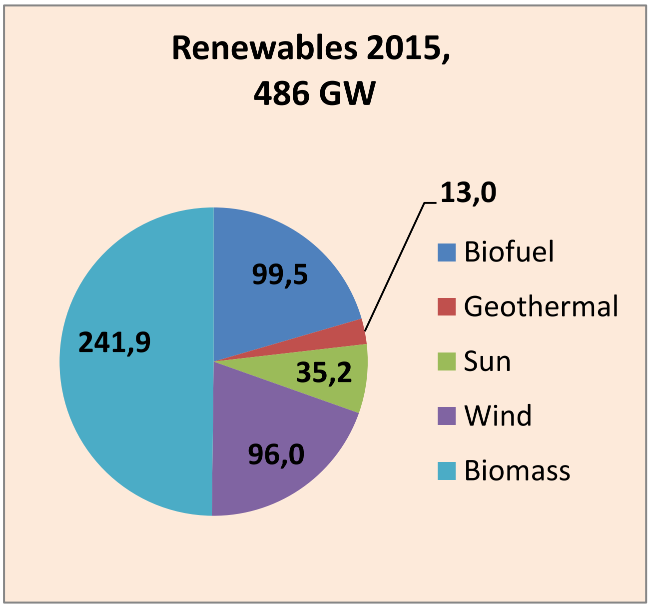
If Denmark has to be "Fossil Free", we must increase the "green energy" with a factor 4-5. The size of the storage for wind and solar will depend of to which degree biomass can supply the wind. Nobody knows. But "fossil free" must mean, that biomass and wind + sun energy supply all our energy needs and raw materials for our chemicals.

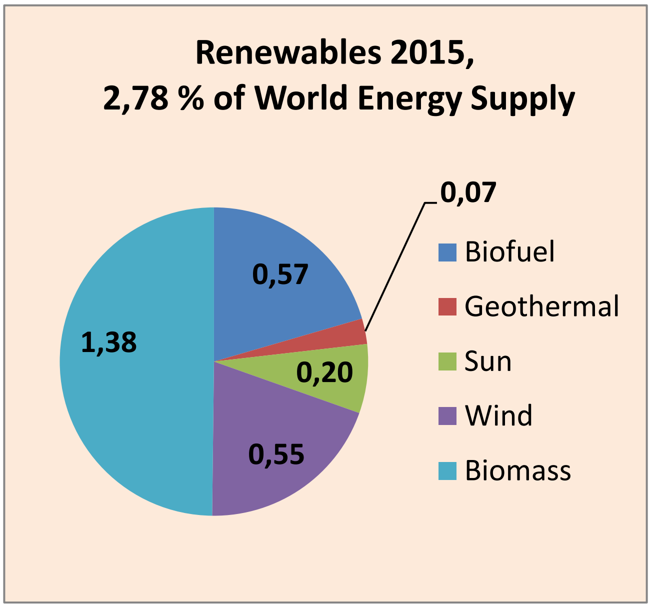
Of course possible in principle, there are trees enough in the World to keep the 5,6 million Danes warm.

The World's energy consumption is about 550 EJ (10^18 J) per year, corresponding to 17,5 TW. A little less than 1000 times the Danish consumption. The following Graphs based on BP's energy statistics[1] illustrate the magnitude of the task to make the World **"Fossil Free".**









The wind power was 96 GW. The wind industry is always very eager to inform about the installed capacity, about 435 GW. They do not very often tell the public that they only yield about 20 % of this. The German wind turbines in Jan-March 2017 yielded 25 % of the installed capacity, varying between 0,5% and 76% of this.

Conclusions

Everybody knows the wind power varies considerably. Therefore we must store some of it when the wind blows and draw from the storage when the wind doesn't blow.

Table 2

Measured data Germany+France+UK		*2015*	*2016*
Average Wind	GW	13.7	13.4
Max Wind		44.9	45.1
Min Wind		1.3	0,9
Average Load		141	141
Max Load		220	209
Min Load		86.	85

Table 2 above shows wind and load in Germany, France and United Kingdom in 2015 and 2016. The data above are based on the data given every hour, 8760 hours in 2015 and 8784 hours in 2016[2].

The sum of the wind power in the 3 countries in the two years varies between 0,9 GW and 45 GW – a factor 50, whereas the load (consumption) varies between 85 GW and 220 GW. The wind power is roughly 10 % of the load. A little lower in 2016 than in 2015.

The Danish premier minister, Anders Fogh Rasmussen promised the audience at a congress at 16. Nov. 2008: "A fossil free Denmark in 2050". And after the Fukushima disaster the German Chancellor, Angela Merkel, decided that Germany should make an "Energiewende".

("Also, in a May 11, 2016 e-mail to CNSNews.com, Jaya Mohan, information officer for the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), said "no deaths directly caused by radiation exposure after the accident at the Fukushima-Daiichi nuclear power plant have been reported.")[3]

We are not informed about what the two leaders thought about how to reach their objectives. So the author has made two different calculations for the necessary capacities for storing the fluctuating wind power.

Since Germany has a considerable photo voltaic (PV) capacity the necessary capacities for storing wind + sun power have been calculated too for Germany.

Two situations have been chosen for the calculations:

1. The output from wind + PV + storage shall be kept constant
2. The output from Wind + PV + storage should equal the load, any time.

Condition1 is not very realistic of course, but anyway the calculations give an idea about what it demands to smoothen out the "green power".

Condition 2 does not seem very realistic either, but nevertheless The Fraunhofer Institute has elaborated a plan for 100 % renewable energy to cover the demands for electricity and heating in Germany implying a 7 fold increase in the wind power capacity and a 6 fold increase of the PV capacity. (Basis 2015)

Table 3 shows the results for the case where the present output from wind power + storage should be kept constant in Germany + France + United Kingdom.

Table 3

Calculation, Constant Output, DE, F, UK		2015	2016
Average Wind	GW	13,8	13,4
Max Wind	GW	45,3	45,1
Min Wind	GW	1,201	0,887
Storage capacity hrs of average production	hrs	1271	1173
Calculated storage capacity	TWh	17.5	15.7
Max input to storage	GW	32,2	32,4
Max output from storage	GW	11,8	11,8
Loss	MW	726	705

It may be difficult to imagine a storage capacity of 17 TWh, and besides the unit is not very well suited to compare systems of different magnitude.
So we have introduced the unit **hours of average production.** We find this to be 1271 in 2015 and 1173 in 2016. That means that the storage should be large enough to store the average production of 1271 hours (2015) and 1173 hours (2016). That corresponds to the average production in about 7 weeks.
The combined Scandinavian storage capacity is 115-120 TWh. This might be sufficient to give back-up to Germany, France and UK as long as the wind power is only about 10% of the load.
However it is calculated that the storages should be able to receive an effect of 32 GW, corresponding to the average Swedish + Norwegian load. That is unimaginable, but you could with an acceptable loss reduce the receiving capacity to for instance 20 GW. As long as the wind power is only 10% of the load.
The only practicable way to cooperate with the Scandinavian hydropower is to ask the Scandinavians to reduce the water flow to the turbines when it blows on the continent and then ask them to use continental wind power instead. It might be possible to draw cables to Norway and Sweden with a capacity of 20 GW.
But you must also be sure, that you can get up to 12 GW in return. I.e. The Scandinavians should be asked to install a new hydro power generation capacity of 12 GW. And considerably more, if the Swedes should choose to follow the German Chancellor and close their nuclear power stations which in this winter with a surprising regularity have produced 9 GW.

The Danish wind energy is based on this cooperation with Norway and Sweden. But you should not forget, that the Danish electricity load on average is a little lower than **4 GW** whereas the Swedish, Norwegian, German French and British is **170-175 GW**

Table 4

Calculated Wind = Load. DE, F, UK		2015	2016
Average Wind	***GW***	***13,7***	***13,4***
Average Load		***141***	***141***
Calculated Storage Capacity	TWh	173	127
Storage Average production	Hrs	1.159	852
Max input to Storage	GW	338	358
Max output from storage		181	169
Loss by storing		7,9	7,6
Relation Load/(Wind+PV)		10,27	10,55
Calculated Factor		10,84	11,12

Table 4 shows first average wind power and load in 2015 and 2016 and then the calculated results under the condition that the **wind power + output from storage any time should equal the load.**

The figures show that this condition is wildly unrealistic.

Never the less the well esteemed Fraunhofer Institute has as mentioned above elaborated a plan to cover the German needs for electric power and heating by use of only wind, PV and biomass, comprising a 7 fold increase of the wind power and a 6 fold increase of the PV capacity.

Germany produced on average 8,8 GW wind power in 2016, France 2,2 GW and UK 2,4 GW.

Table 4 shows that on average for the 3 countries the load was 10,3 and 10,6 times the wind power in 2015 and 2016. The Fraunhofer institute proposes to increase the wind power to 75 GW for Germany alone, thus a 10 fold increase in the wind power to 135 GW for the 3 countries is within the limits of ideas developed for German tax payers' money. And the author has just tried to calculate some of the consequences.

The calculated input to the storage of 338-358 GW corresponding to 2,5 times the average load is of course unrealistic. The losses by putting an upper limit to the input capacity will be shown below.

The next line shows the size of the storage expressed in TWh and thereafter in hours of average production, if we decide that wind power should deliver the entire electric load.

The magnitude of this storage varies according to the calculations from 172 TWh in 2015 to 127 TWh in 2016. For comparison the Norwegian + Swedish hydropower storing capacity is 117 TWh[4], Europe's largest pumped storage in Vianden in Luxembourg has a capacity of 0,005 TWh and Geesthacht by Hamburg has a storing capacity of 0,0005 TWh.

The demands for the power regeneration are lower. It should just be possible to regenerate the power with an effect slightly larger than the average load. 181 GW and 168 GW respectively.

It must be admitted that a combination of solar and wind power reduces the demands for the storing capacity to about the half. But then you must add, that if you wish to be fossil free you must increase the electricity consumption several times. Already today the per capita consumption in Sweden is about 1,7 kW of electricity against the German 0,7 kW. Among other because the most houses in Sweden are heated by electricity.

A storage system larger than the Scandinavian hydropower storages of 115-120 TWh is unthinkable.

Sometimes you hear that the future belongs to the electric car, and that the cars can store power during the nights. A VW Golf-e, January 2017, has a battery capacity of 36 kWh. One third of the Scandinavian storages is 36 TWh. A **billion times** the storage capacity of a VW Golf-e. Just now, April 5, 2017 at 15,43 o'clock the Danish wind turbines produce 3985 MW, and the export is 1751 MW. So in just one hour 1 751 000/36= 48 639 Golf-e's could be charged. Considerably more than there are electro cars in Denmark. [5]

That is a pity for the electricity in Western Denmark at this moment is only 0,02

€/MWh.[6]

The Author

I have a Master's Degree in chemical engineering and graduated from the technical university in Copenhagen in 1960.

In my career, I have worked with the production of polystyrene, soap and detergents, fine organic chemicals for the pharmaceutical industry where I worked with practically all the nastiest chemicals in the industry. I have experience with productions in the scale a few kgs/year to several tonnes per day.

I have worked with oil and gas production from the off-shore fields in the North Sea, and with the production of cellulose from straw.

After the carbon dioxide tax was introduced in 1992 energy became an essential part of my job, until the taxation got the production transferred to Asia.

I ended my career in the energy department at Cowi Consulting Engineers in Aarhus. Since my retirement I have worked as an independent consultant. And until recently I was Scandinavian agent for Perry Process Equipment Ltd. A large part of my occupation was to find equipment from chemical plants which because of energy- and other detrimental taxation were forced to transfer their operations to other continents.

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The necessity of back up

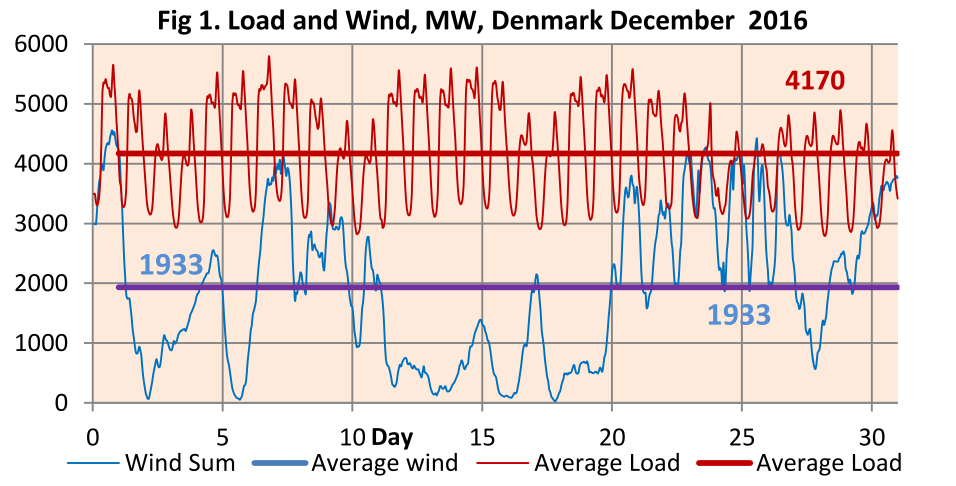


Fig 1 illustrates the necessity of back-up for wind power.

"Wind Sum". The term is used because the Danish Wind statistic gives separate data for Denmark East and Denmark West, because the Big Belt separates the systems in East and West.

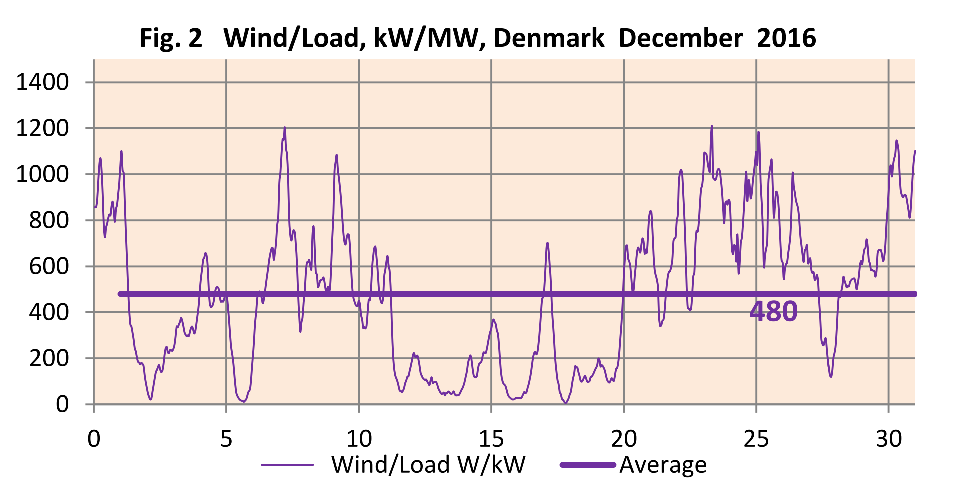


Fig. 2 illustrates the part of wind power relative to the load measured in the unit kWW/M

The load varies between 3000 Mw and 6000 MW after a foreseeable pattern.

In a very short part of the time the wind power is higher than the demand and in a considerable part of the time, it is very far from the demand.

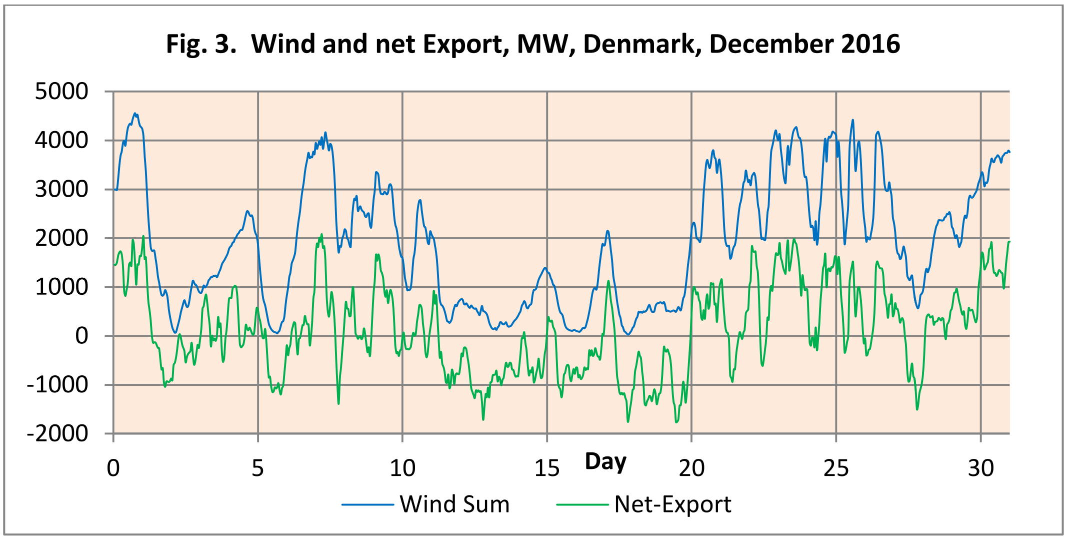
In the ideal case the value would be 1000 at all times, because then you would get exactly 1000 kW = 1 MW of wind power when you need 1 MW power.

The average 480 kW wind power per 1 MW Load is probably higher than you could find anywhere else.

The variation is less impressing. When the Wind power/Load larger than1000, you produce more wind power than is used, and when the figure is close to zero you do not produce any wind power at all.

So fig.2 illustrates clearly that you must either be able to store wind energy, have a complete back-up system either as power plants functioning inefficiently because of the large variations in the demand or you must be able to exchange a large part of your electricity production and load with your neighbours. For Denmark it is Norway, Sweden and Germany.

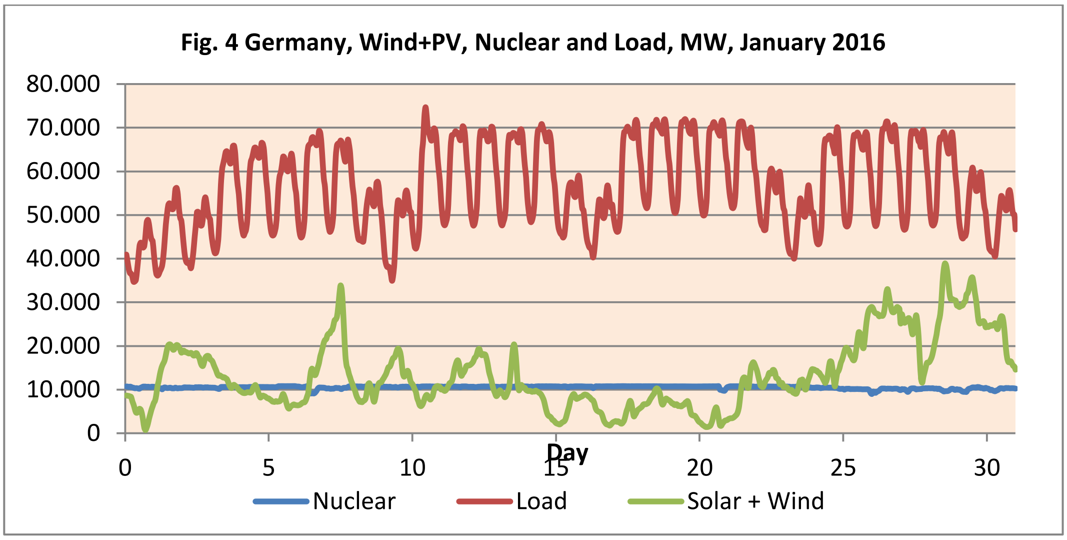
Figure 3 illustrates how Denmark has been able to solve the problem of the the fluctuating wind power. By importing power when it doesn't blow and by exporting when it blows.

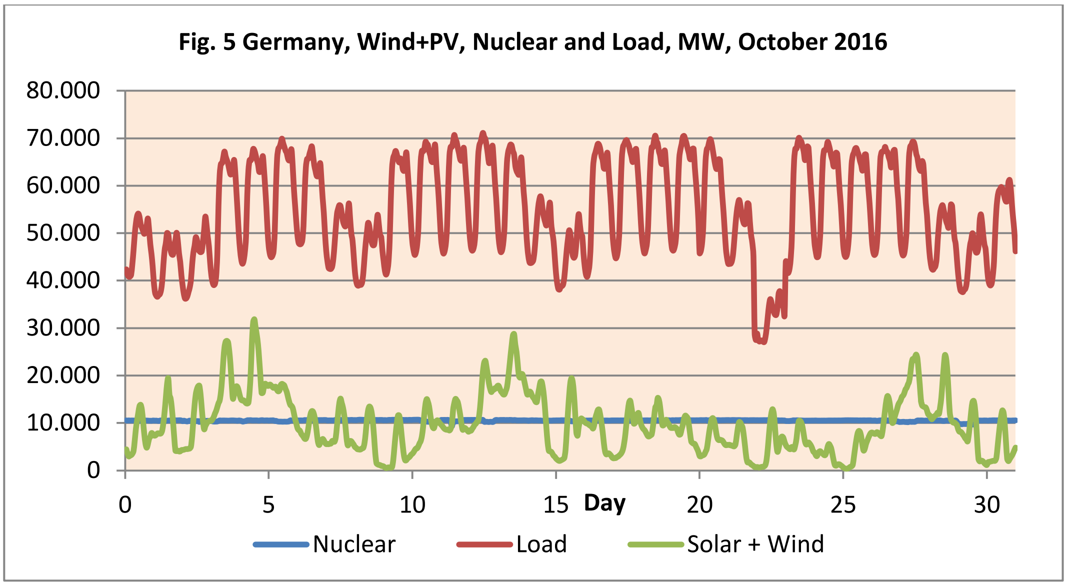


That has hitherto been possible, because Denmark is a small country with an average load about 4 GW, whereas the Norwegian, Swedish and German load on average is about 85 GW.

The average Danish load in 2016 was 3862 MW. Maximum import and export were 2890 and 2028 MW. 75% and 52% of the average load. You may wonder how Germany after having obtained the same proportion of wind power would be able to export more than 40 GW of electricity. The Poles already have said: “Nein Danke.”

Fig 4 and Fig 5 illustrate the German Load, Nuclear and (Wind +Solar) power in January and October 2016.





It is seen clearly, that on work days the load increases by 20-30 GW within a couple of hours. In the summer solar energy may provide for a part of this variation, but not in the winter. And although we can calculate the climate 100 years in advance, we are unable to tell, how much wind there will be in a week from now.

The idea with Die Energiewende is to get rid of fossil fuels and nuclear power. So there remains only Wind-, Solar-, Geo thermal- and Hydro power + burning of Biomass.

Geothermal, Hydro and Biomass are insufficient so Wind and Solar power must be very much expanded, and it will be necessary to build storages to compensate for the uncontrolled variation of wind and sun, as long as nuclear power is rejected as a possibility.

Creative fantasies with deep disrespect for realities are abundant. The Danish periodical Ingeniören recently had an article about a Tesla Storage in California, the largest in the World. The photo was impressive, and the capacity 80 MWh. The following calculations show that batteries are hopelessly insufficient to create back-up, although they may be useful for special local demands.

Wind and solar energy reached 3,0 % of the German energy consumption in 2015, and 7,3 % of the Danish consumption in 2015. The Danish wind power yielded about 10% less in 2016 than in 2015. 1,45 GW against 1,61GW on average. The corresponding German figures were roughly 10 times higher for wind + solar: 12,8 GW and 12,7 GW although billions of euros have been spent on new wind turbines in Germany in 2015 and 2016.

3% sun and wind power in the energy supply is very far from the objects of “Die Energiewende”, and the “Fossil free Society” as the Danish Prime Minister, Anders Fogh Rasmussen expressed it in November 2008. And one may ask, how Germany will get the remaining 97% of her energy. If it should be by more wind- and solar energy, the back-up demands will grow proportionately.

Storage Calculations

The author has tried to calculate the necessary capacities for a back-up and storage system. It is not enough to cover the variations from day to day or from week to week. When one considers the whole year one finds much larger numbers than one would expect.

Two different conditions have been considered:

1. The output from existing wind and solar systems should be constant.
2. The wind, solar and storage systems should equal the load.

Calculation of the needed storage to keep the output constant

We have chosen to calculate the back up demand under the condition that the combined yield from wind turbines (+ PV) and the storage shall be constant. We know of course that the reality will differ from this assumption.

Table 5

Wind DK 2015	Wind	To Storage	To storage after losses	From Storage	Regene-rated Power	Resul-ting Power	Storage content
	MW						GWh
Average	*1612*	551	495	495	446	1507	930
Max	*4450*	2943	2649	1673	1506	1507	1476
Min	*1*	0	0	0	0	1507	0
Stddev	*1171*	781	703	578	520	0	424
Observations	*8760*	8760	8760	8760	8760	8760	8760

The necessary data to make the calculations are the hourly production data for the wind power production (8760 hours per year)[7] and the losses by storing and by regenerating the wind power.

The calculated average, max, min and standard deviation (stddev) are shown in the first column of table 5. The other columns are calculated by means of the conditions:

1. Sum of Input to and Output from the storage must be equal to each other.
2. The contents of the storage may not be under zero. This is obtained by adjusting the initial storage to fulfil this condition.
3. The loss by storing and regeneration must be considered.
4. The Vianden pumped storage plant in Luxembourg operates with a loss a little more than 10% by pumping and 10% by regenerating power. In total 19%. We have used the same figures.

The result is shown in table 6:

Table 6

Wind DK 2015		Vianden	Future storage	Future/ Vianden
Capacity	GWh	**5**	**1476**	**295**
	hrs of average production	**3,1**	**916**	**295**
	Max input MW	1040	**2943**	**3**
	Max Output MW	1290	**1506**	**1**

The Vianden Pumped Storage plant in Luxemburg is the largest in Europe with an input capacity of 1040 MW, and a generation capacity of 1290 MW. It is located close to very large consumers and is important for smoothening the daily electricity consumption and production. It is mentioned here because it is easy to google “Vianden” and thus become an impression of, what we talk about.

The storage capacity, 5 GWh, is very limited. If the Danish wind power production in 2015 should be smoothed out, you would according to the result found in table 4 need a storage capacity of 1476 GWh, **295 times the Vianden capacity**. This capacity can impossibly be created in Denmark.

It might be possible to establish the necessary capacities for filling and emptying the storage, 2943 MW and 1506 MW respectively, however the capacities are very large compared to the average Danish load about 4 GW.

Description of the calculation method

The calculations are made for a period of a year. By means of “if statements” it is possible to handle the conditions described below:

1. **”To storage”:**
   (If wind power > (average for the period)*faktor:(wind power – average*faktor); 0)

2. **”To storage after losses”:**
   It will always cost something to transfer electricity/energy to storage.
   This loss is subtracted from **”To storage”** to become
   ”To storage after losses”

3. **”Regenerated Power”:**
   (If wind power < average*factor;**(**average *faktor – Wind power);0).

4. **”From Storage”:**
   This is **”Regenerated Power” divided with** the efficiency obtained when transferring the stored energy to electricity.
   In the case of a pumped storage you can obtain an efficiency of about 0,9. If you will burn stored hydrogen in a gas turbine to generate electricity you may obtain an efficiency of about 0,6. If you are lucky.

5. **”Resulting Power”:**
   Sum of (**Wind - To Storage + Regenerated Power)**

6. **”Storage contents”:**
   Accumulated sum of **(To Storage after losses - From Storage),**
   plus a starting value large enough to obtain a minimum value of 0.
   This value is added manually..

”To storage after losses” must equal to **”From storage”,** when the year is gone.

Faktor is calculated by an iteration process, which the Excel program performs in about a second to fulfil the condition: **From storage = To Storage**.

If there were no losses from storing and regeneration the **Faktor** would be 1.

The calculations to increase the wind power so that it equals the load are performed in a similar way. Instead of keeping the output constant, the output any time must equal the load.

Production Statistics 2015

The **wind power** is given for Sweden, Denmark, Germany, France and United Kingdom and photovoltaics (**PV**) for Denmark and Germany.

Table 7

Production statistics 2015											
	PV DK	Wind DK	Wind S	Wind F	Wind UK	Wind Onsho-re DE	Wind Offsho-re D	Wind D	PV D	Wind + PV D	Wind, DK, S, D, F, UK
	MW										
Average	69	1612	1918	2237	2669	7972	883	8855	3947	12802	17291
Max	496	4450	4967	7450	6584	31162	2947	32607	25812	43524	51614
Min	0	1	74	262	70	0	0	58	0	231	1992
Stddev	112	1171	1094	1516	1641	6698	811	7082	6010	8508	10169
Observations	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760
Stddev kW/MW average	1629	727	570	678	615	840	918	800	1523	665	588

Storage calculations for Sweden, Denmark, Germany, France and United Kingdom:

Table 8

Calculated storages to provide a constant power from wind (and PV). Data 2015										
		Storing Efficiency	Production			To Storage		Regenerated Power	
			Ave-rage	Max	Min	Ave-rage	Max	Ave-rage	Max
		J/kJ	MW						
Germany 2015	Wind	810	8855	32607	**58**	3059	24333	2478	8216
	PV		3947	25812	**0**	2553	22350	2068	3462
	Wind+PV		12802	43524	**231**	3859	31455	3126	11838
		540	12802	43524	**231**	4522	32802	2442	**10491**
Denmark 2015	Wind	810	1612	4450	**1**	551	2943	446	1506
	PV		69	496	**0**	46	436	37	60
	Wind+PV		1681	4650	**2**	549	3073	444	1574
		540	1681	4650	**2**	643	3265	347	1383
Sweden 2015	Wind	810	1918	4967	**74**	452	2830	407	1748
France 2015	Wind		2237	7450	**262**	588	4804	529	1851
UK 2015	Wind		2669	6584	**70**	700	3656	630	2451
S+DK+D+F+UK	**Wind**	**810**	**17291**	**51614**	**1992**	**3962**	**31644**	**3565**	**14462**

There is made a calculation for a storage efficiency of **0,81** as described for the Vianden Pumped Storage. The calculation is made for wind, PV, and (wind + PV) for Germany and Denmark.

A recent futile idea of heating granite stones to 600°C when the wind blows and then cooling the stones with air to produce steam to produce electric power, has been debated even in serious journals. The overall efficiency is estimated (by the author) to a not very realistic **0,54.** The calculation assuming an efficiency of 0,54 is made for **Germany** and **Denmark**

The sum of wind power in Sweden, France and United Kingdom combined varies between 51614 MW and 1992 MW.

Resulting Power output S, DK, S, F, UK

Table 9

		Storing Efficiency	Resulting Power	Loss	Calculated storage capacity		Times Vianden capacities		
			Average		Energy	Average Production	To storage	From storage	Storage
		J/kJ	MW		GWh	hrs			
Germany 2015	Wind	810	8274	581	12088	1365	23	6	2418
	PV		3462	485	8461	2143	21	3	1692
	Wind+PV		12069	733	7691	601	30	9	1538
		540	10722	2080	9034	706	32	8	1807
Denmark 2015	Wind	810	1507	105	1476	916	3	1	295
	PV		60	9	175	2534	0	0	35
	Wind+PV		1577	104	1340	798	3	1	268
	Wind+PV	540	1385	296	1548	921	5	3	310
Sweden 2015	Wind	810	1823	96	1937	1010	3	1	387
France 2015	Wind		2113	124	2184	976	5	1	437
UK 2015	Wind		2521	148	3461	1297	4	2	692
S+DK+D+F+UK	**Wind**	**810**	**16454**	**836**	**20547**	**1188**	**34**	**11**	**4109**

The resulting power after having accounted for the losses by storing and regeneration is shown in column 4. In the case of Germany you find 8274 MW. In the foregoing table you see that the average German wind yield was 8855 MW. So on average it costs 581 MW (column 5) to operate the storage under the given conditions. 581 MW corresponds to 5089 GWh/year at an estimated price of 6 € cents/kWh i.e. abt. 300 million € per year.

In 2015, the German wind turbines operated with an average efficiency of 0,206. If we estimate a building price of 1,3 million € per nominal MW, you should build new wind turbines with a nameplate capacity of 581/0,206 = 2820 MW at a cost of 3,77 billion € to compensate for the loss by storing. That is 12 times the cost of the yearly loss of electricity. And you could easily get 581 MW nuclear capacity for 3,77 billion €.

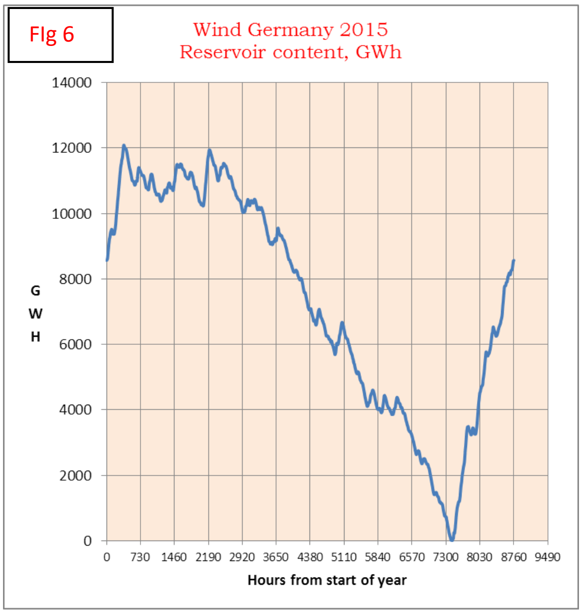
Calculation of the storage needed to keep German wind power constant

Table 10

Wind Germany 2015		To Storage	To storage after losses	From storage	Regene-rated Power	Resulting Wind Power	Storage content
	MW						GWh
Average	8855	3059	2753	2753	2478	8274	7316
Max	32607	24333	21900	9129	8216	8274	12088
Min	58	0	0	0	0	8274	0
Stddev	7082	8855	4771	2916	2625	0	3425
Observations	8760	32607	8760	8760	8760	8760	8760

Loss by storing	Joule/kJ	***100***	Loss	MW	581
Loss by reproduction	Joule/kJ	***100***		%	6,6
Loss totally	Joule/kJ	190		GWh/år	5092
Storage Efficiency	kWh/kWh	810			

		Future storage	Vianden in Luxembourg	Future/ Vianden
Capacity	GWh	**12088**	**5**	**2418**
	hrs of average production	**1365**	**0,6**	
	Max input MW	24333	1040	**23**
	Max Output MW	8216	1290	**6**



The graph illustrates that if we wish a constant output of 8274 MW from wind turbines + the storage you must have a very large sorage because there must be drawn from the storage from April to November, and you can begin to fill op again from November to January.

The storage demand is huge - 12 TWh, correspondimg to ca. 35% of the total Swedish capacity. Or 2418 times the Storage capacity of Vianden.

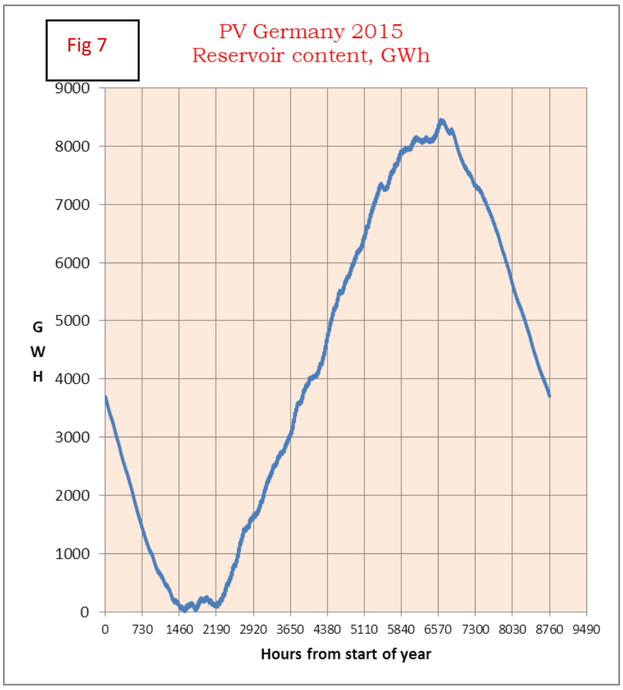
The storage capacity corresponds to 1365 hours of average production.

And you must be able to fill the storage with pumps with a capacity of 24 GW. For comparison the german average load is about 55 GW.

Calculation of the storage needed to keep German sun power constant

Table 11

PV Germany 2015		To Storage	To storage after losses	From Storage	Regene-rated Power	Resulting Wind Power	Storage content
	MW						GWh
Average	3947	2553	2298	2298	2068	3462	4224
Max	25812	22350	20115	3847	3462	3462	8461
Min	0	0	0	0	0	3462	0
Stddev	6010	4798	4318	1774	1596	0	2818
Observations	8760	8760	8760	8760	8760	8760	8760
Loss by storing		Joule/kJ	***100***		MW	485	
Loss by reproduction		Joule/kJ	***100***	**Loss**	%	12,3	
Loss totally		Joule/kJ	190		GWh/år	4249	
Storage Efficiency		kWh/kWh	810				
			Future storage	Vianden in Luxem-bourg	Future/ Vianden		
Capacity	GWh		**8461**	**5**	**1692**		
	hrs of average production		**2143**	**1,3**			
	Max input MW		22350	1040	**21**		
	Max Output MW		3462	1290	**3**		
Efficiency	kWh/MWh		810	800			



The graph for storage of Wind and PV are quite different. The PV production in 2015 was on average 3947 MW against the wind pover 8855 MW.

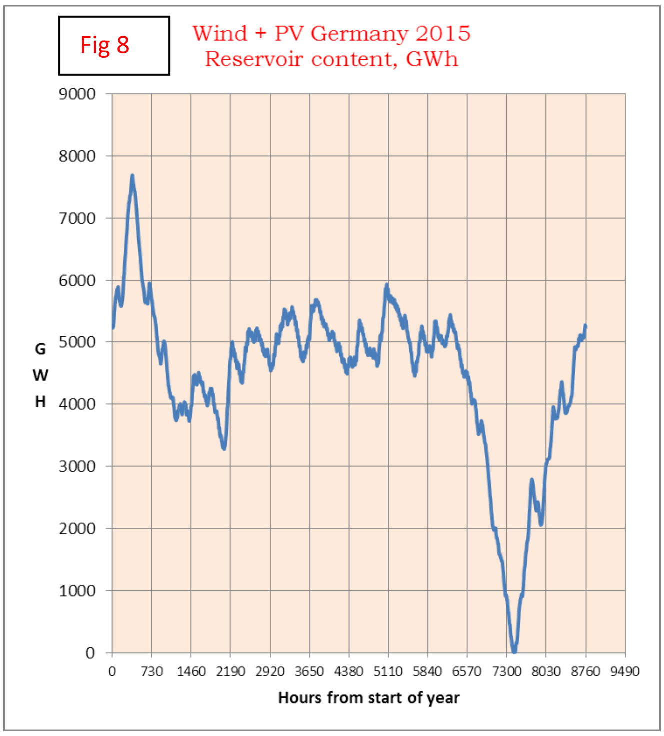
So the needed storage capacity is less, but where you should store 1365 hrs of averege wind power you need to store 2143 hrs of solar power.

So let us consider sun and wind power combined.

Calculation of the storage needed to keep German sun+wind power constant

Table 12

Wind + PV D 2015		To Storage	To storage after losses	From Storage	Regene-rated Power	Resulting Power	Storage content
	MW						**GWh**
Average	12802	3859	3473	3473	3126	12069	4450
Max	43524	31455	28309	13154	11838	12069	7691
Min	231	0	0	0	0	12069	0
Stddev	8508	5884	5296	4104	3694	0	1330
Observations	8760	8760	8760	8760	8760	8760	8760
Loss by storing		Joule/kJ	***100***	**Loss**	MW	733	
Loss by reproduction		Joule/kJ	***100***		%	5,7	
Loss totally		Joule/kJ	190		GWh/år	6423	
Storage Efficiency		W/kWh	810				
			Future storage	Vianden in Luxem-bourg	Future/ Vianden		
Capacity	GWh		**7691**	**5**	**1538**		
	hrs of average production		**601**	**0,4**			
	Max input MW		**31455**	1040	**30**		



The graph for Wind and PV combined is very different from the graphs for Wind and solar.

Table 13

Storages by constant output Germany 2015				
		Wind	PV	W+PV
Av. Production	MW	8855	3947	12802
Storage	GWh	12088	8461	7691
Input capacity	GW	24,3	22,3	31,5
Output capacity	GW	8,2	3,5	11,8
Hrs. of average production		1365	2143	706
Times Vianden		2418	1692	1807

The data talk for themselves. The German average load for 2015 was 54554 MW and wind + solar supplied 23% of this.

That corresponds to 3,03 % of the German energy consumption, so there remains a huge task to supply Germany with energy without using nuclear or fossil energy.

The input capacities - 24-32 GW - to the storage can impossibly be realized, since they correspond to about 50% of the German electricity load.

The author is not a specialist in electricity trade, but thinks that it would not be so easy to draw up to 10 GW from the Scandinavian storages, not to speak about sending 15 GW the other way. Just as a beginning. According to plans, northern Europe will have much more sun and wind energy in the near future.

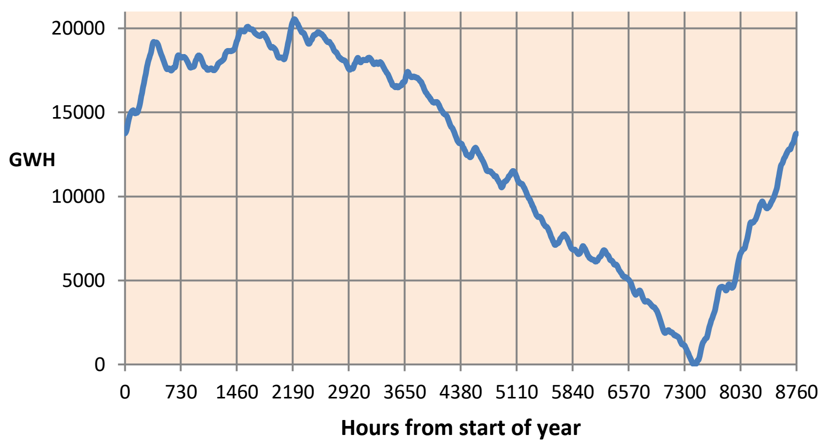
Combined wind power in Sweden, Denmark, Germany, France and UK 2015

Table 14

Wind, DK, S, D, F, UK 2015		To Storage	To storage after losses	From Storage	Regene-rated Power	Resulting Power	Storage content
	MW						**GWh**
Average	17291	4402	3962	3962	3565	16454	12441
Max	51614	35160	31644	16069	14462	16454	20547
Min	1992	0	0	0	0	16454	0
Stddev	10169	7457	6711	4502	4052	0	6072
Observations	8760	8760	8760	8760	8760	8760	8760
Loss by storing		Joule/kJ	***100***	**Loss**	MW	836	
Loss by reproduction		Joule/kJ	***100***		%	4,8	
Loss totally		Joule/kJ	190		GWh/år	7326	
Storage Efficiency		kWh/kWh	810				

		Future storage	Vianden in Luxembourg	Future/ Vianden
Capacity	GWh	**20547**	**5**	**4109**
	hrs of average production	**1188**	**0,3**	
	Max input MW	**35160**	1040	**34**
	Max Output MW	**14462**	1290	**11**

Fig 9 Wind S+DK+D+F+UK 2015 Reservoir content, GWh

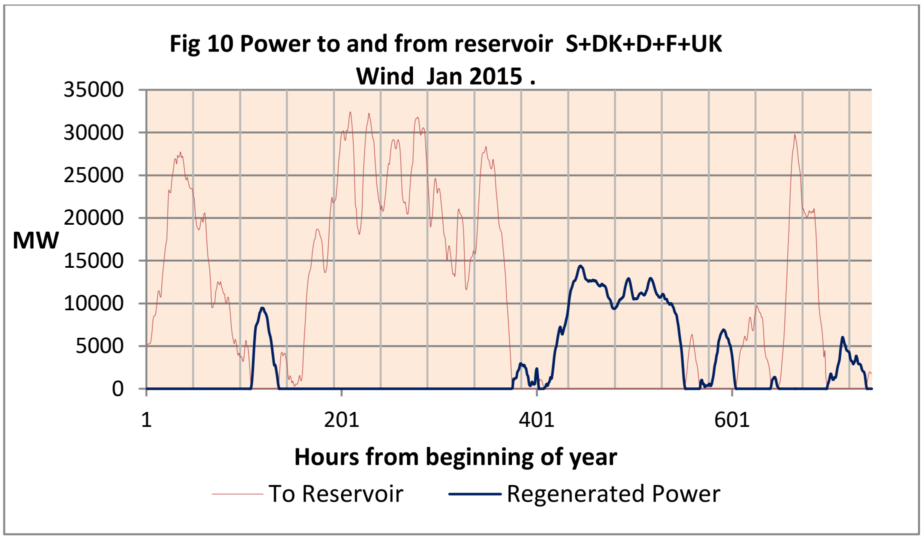


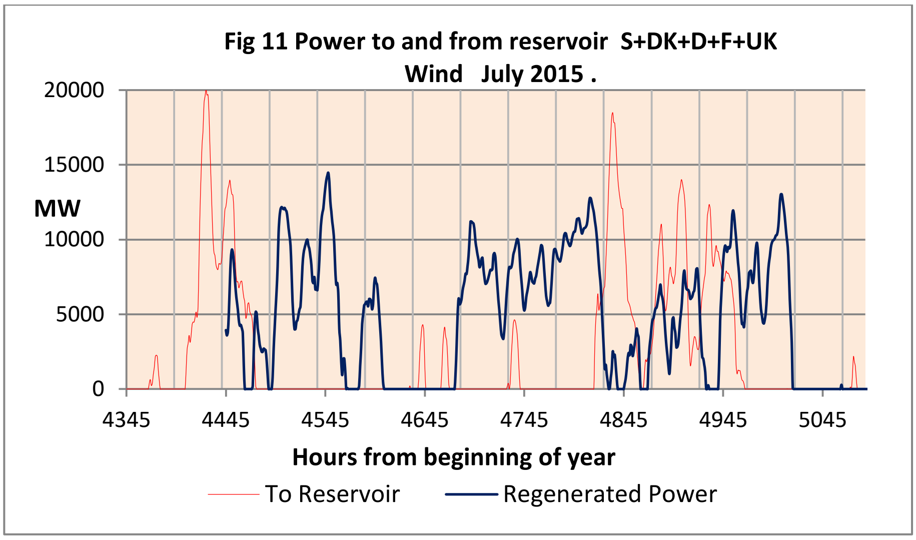
We see exactly the same form of graph by adding several countries spread over a huge area. And the same enormous demands to input and output capacity.

Table 15

Storages by constant output					
		Germany			S,DK,DE,UK
		Wind	PV	W+PV	Wind
Average Production	MW	8855	3947	12802	17291
Storage	GWh	12088	8461	9034	20457
Input capacity	GW	24,3	22,4	32,8	35,1
Output capacity	GW	8,2	3,5	11,8	14,5
Hrs. of average production		1365	2143	706	1188
Times Vianden		2418	1692	1807	4109

It is evident, that a large European smart grid would not do much to stabilize the wind power. For Germany alone you would need a storage capacity of 1365 hrs of average wind production and one would need a storage of 1188 hrs of average production for the 5 countries combined. But you could reduce the storage demand by introducing PV as in Germany.





For Germany and for the 5 countries combined you see the same demand for drawing on the storage in January from hour nr. 410 to hour nr. 500, i.e. from January 17 to January 23.

In July you among other dates would be forced to draw on the storage from hr. nr. 4570 to 4730 and again in the hours nr. 4836 to 4915 i.e. July 10 at 15,00 o'clock to July 17 at 02 o'clock and July 21 at 10 o'cloc to July 24 at 19 o'clock.

Wind + PV = Load

It can never be an ideal to provide a constant yield from (wind + PV – input + output). **So we have calculated the situation for Wind+PV +/- Storage = Load.**

That is far from the present situation but at the same time the ideal for a future electricity supply, so it makes sense to investigate the idea. As mentioned, above the idea is promoted by the **Fraunhofer Institut**.

Germany 2016, Wind + PV = Load

Table 16

Germany 2016 Wind + PV	**Wind +PV Germany 2016**	**Load Germany 2016**	**Calcu-lated Wind**	**To Storage**	**To storage after losses**	**From storage**	**Regene-rated Power**	**Resul-ting Power**	**Storage content GWh**
	MW								**GWh**
Average	12687	54766	57824	16095	14485	14485	13037	54766	15407
Max	43860	75377	199902	148229	133407	73303	65973	75377	26320
Min	374	31455	1702	0	0	0	0	31455	0
Stddev	8379	9796	38189	25850	23265	17592	15833	9796	
Stddev % of average	66	18	66	161	161	121	121	18	
Observations	8784	8784	8784	8784	8784	8784	8784	8784	8784
Loss by storing		***100***			MW	3058	*Mio €/TWh*		*70*
Loss by reproduction		***100***			%	5,3			
Loss totally		190	J/kJ	**Loss**	TWh/Year	27			
Storage Efficiency		810			Mio €/year	1875			

	Future Storage	Vianden	Future/ Vianden
Capacity GWh	**26320**	**5**	**5264**
hrs of average production	**455**	**0,0002**	
Max input MW	**148229**	1040	**143**
Max output	**65973**	1290	**51**
Relation Load/(Wind+PV)	4,317		
Calculated Factor	4,558		

In this example the present Wind + PV for Germany are multiplied by a factor 4,558 to equal the load. That is a little more than the present relation between average wind + PV and average load, 4,317. The difference is due to the loss by storing and regenerating. Even if wind and PV are added, there remains a very large need for both storage capacity and for the capacity to receive wind- and solar power when is blows and the sun shines. But still considerably lower, than for wind alone. See table 14 page 23.

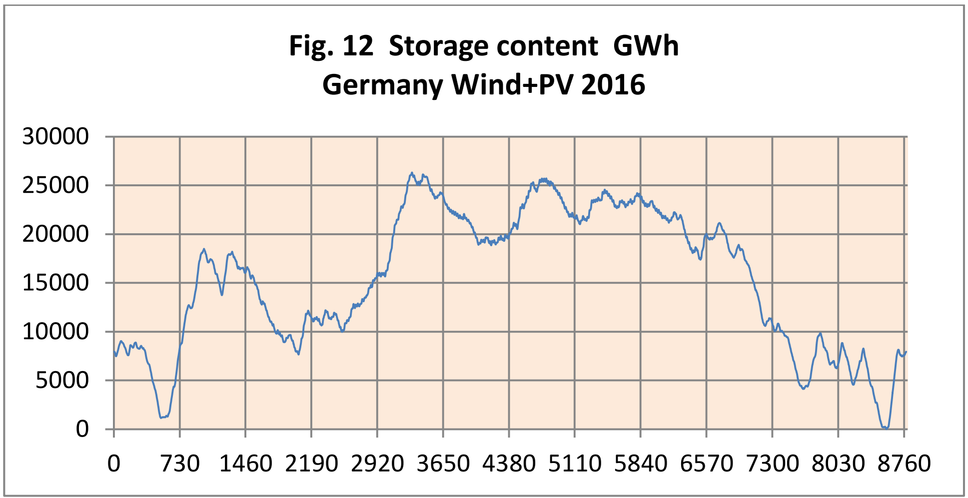
The needed storage 26 TWh should be compared with the Swedish storage capacity of 34 TWh.

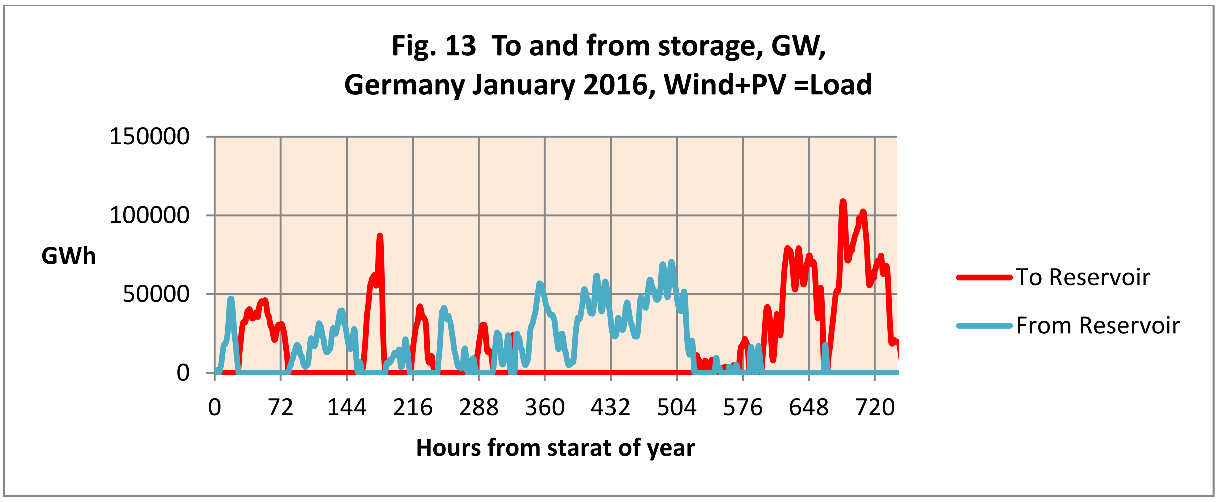
The capacity of the pumps needed to fill a pumped storage is calculated to 148 GW, Nearly three times the German average electric load. This is clearly impossible. The loss by limiting the input capacity will be calculated in the following.

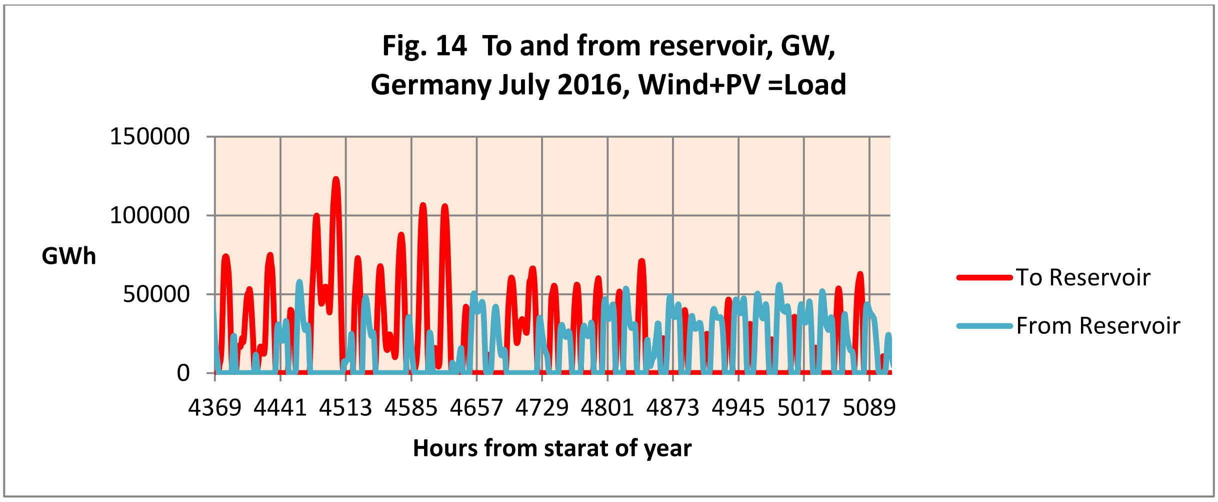
The Fraunhofer Institute proposes to produce double as much wind and solar power as calculated in the above table. So even if the calculations in this report seem unrealistic, they are not beyond the propositions from esteemed institutes.

Fig 12, 13 and 14 below illustrate the storage content and the effects needed to fill and draw from the storages.

You may discuss which type of storages you would need. The Frauenhofer idea operates among other with a methane storage with a capacity for handling 298 TWh electricity and 50 TWh biomass per year, (30,6 GW and 5,7 GW). This will be commented later.







Germany, France and United Kingdom Combined

An European Super Grid is a hot topic at the moment, so let us consider the combined Wind Power and Load from Germany, France and UK.

Table 17

F,D,UK 2015	Wind F, D, UK, 2015	Load F ,D, UK 2015	Calcu-lated Wind	To storage	To storage after losses	From storage	Regene-rated Power	Resul-ting Power	Storage content
	MW								GWh
Average	13754	141232	149147	41657	37492	37492	33743	141232	93187
Max	44879	219835	486660	338173	304355	201448	181303	219835	172831
Min	1342	86435	14553	0	0	0	0	86435	0
Stddev	9052	25155	98154	71248	64124	44492	40043	25155	
Stddev % of average	66	18	66	171	171	119	119	18	
Observations	8760	8760	8760	8760	8760	8760	8760	8760	8760

We operate with a storage efficiency of 81%

The calculations for 2016 are shown below.

Table 18

F,D,UK 2016	Wind F, D, UK, 2016	Load F ,D, UK 2016	Calcu-lated Wind	To storage	To storage after losses	From storage	Regene-rated Power	Resul-ting Power	Storage content
	MW								GWh
Average	13407	141495	149122	40141	36127	36127	32514	141495	65731
Max	45053	209487	501097	357528	321775	187256	168530	209487	126989
Min	887	85074	9869	0	0	0	0	85074	0
Stddev	8680	25142	96544	70307	63276	44030	39627	25142	
Stddev % of average	65	18	65	175	175	122	122	18	
Observations	8784	8784	8784	8784	8784	8784	8784	8784	8784

Table 19

Storage and production		**2015**	**2016**
Average Wind	**MW**	13.754	13.407
Average Load		141.232	141.495
Capacity	**GWh**	**172.831**	**126.989**
Storage Average production	**Hrs**	**1.159**	**852**
Max input MW	MW	**338.173**	**357.528**
Max output		**181.303**	**168.530**
Loss by storing		**7.915**	**7.627**
Relation Load/(Wind+PV)		**10,27**	**10,55**
Calculated Factor		**10,84**	**11,12**

The future storage is calculated to 172 TWh based on the 2015 statistics and 126 TWh for the 2016 calculations. The Scandinavian hydropower storing capacity is 117 TWh and the total West European capacity is 220 TWh. It is a surprise that the figures are so different.

You might argue that the calculations are nonsense. But if you want a fossil free future and reject nuclear power, the electricity production must be vastly increased, surely beyond what can be provided for by bio fuels. I.e. wind and sun must be very much expanded.

European Super Grid ?

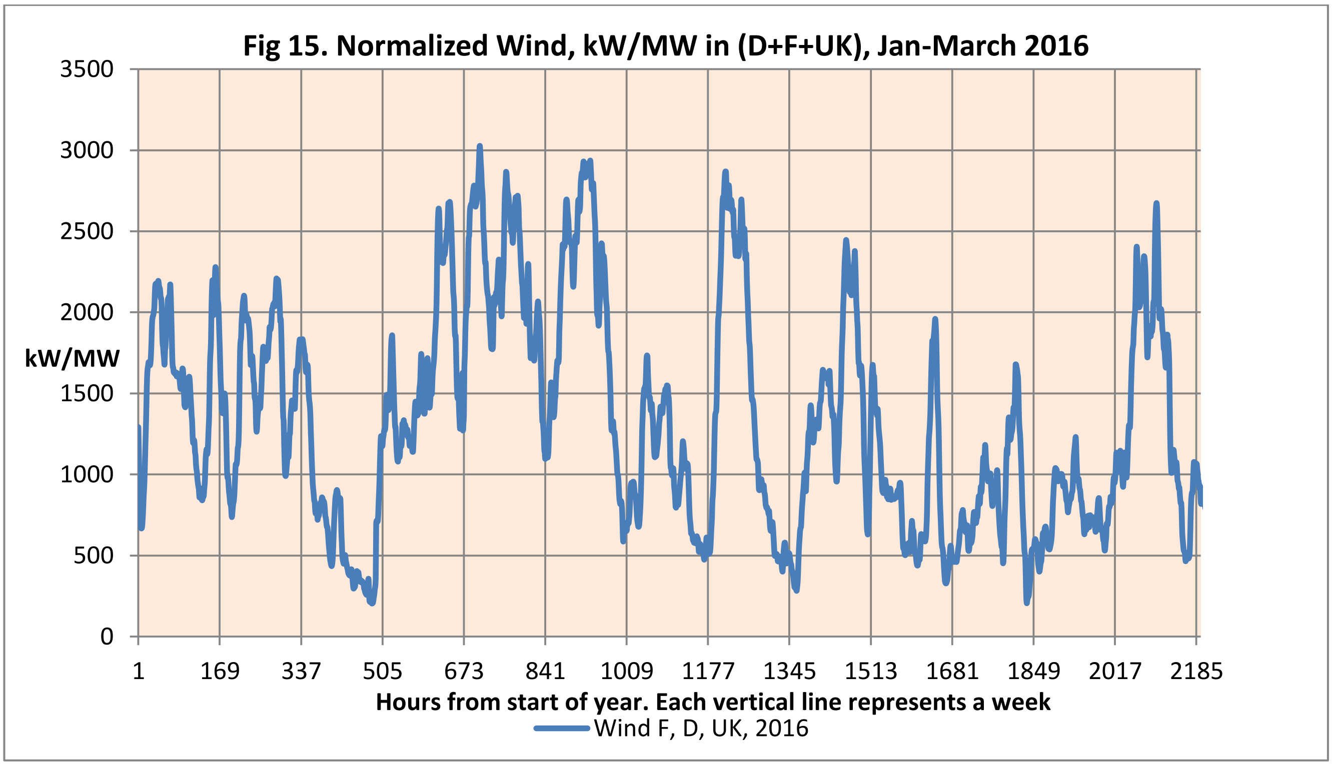
Table 20

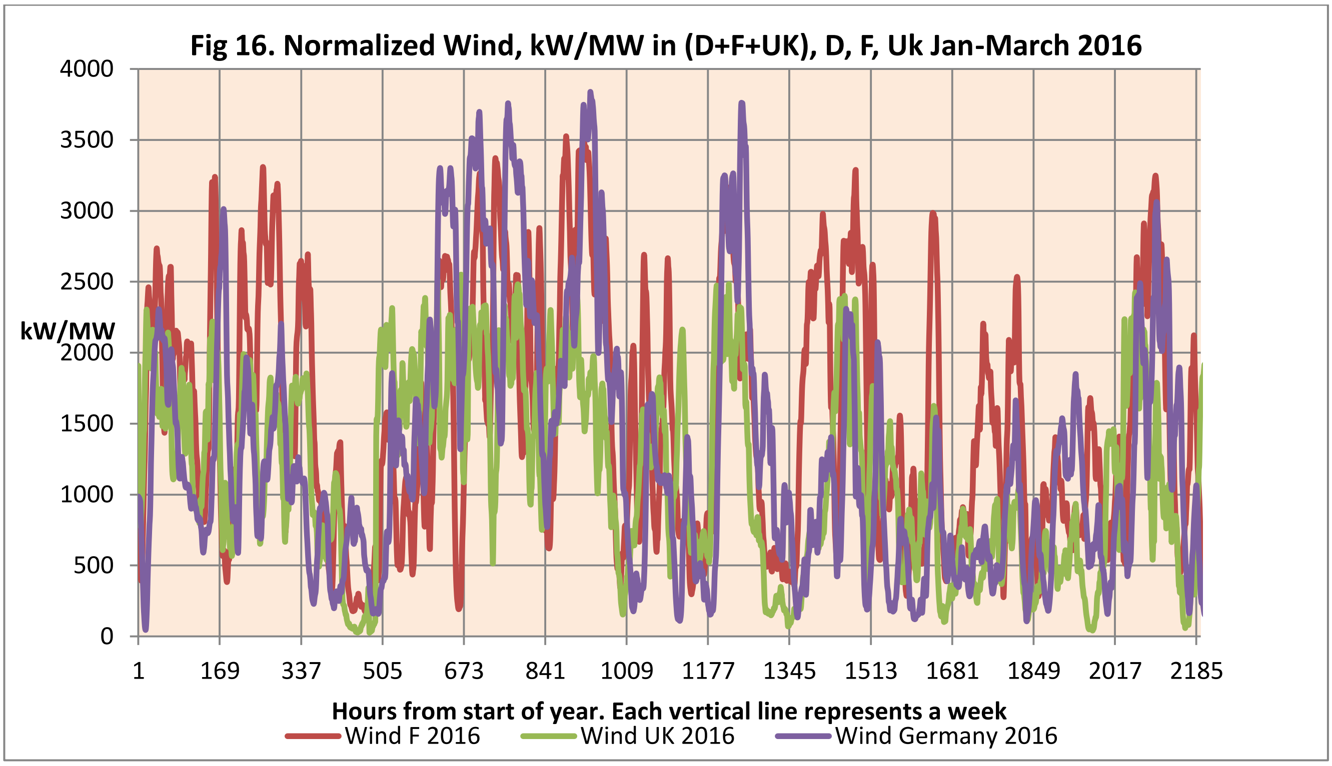
Wind Power in Germany, Franc and United Kingdom in 2016					
		D+F+UK	D	F	UK
Average	MW	13407	8765	2232	2411
Max		45053	33626	8050	7833
Min		887	135	330	0
Standard Deviation		8680	6865	1583	1578
Standard Deviation/average	%	65	78	71	65
Normalized Wind Power in Germany, Franc and United Kingdom in 2016					
		D+F+UK	D	F	UK
Average	kW/MW	1000	1000	1000	1000
Max		3027	3837	3607	3248
Min		101	15	148	27
Standard Deviation/Average	%	57	78	71	65

The German Wind Power system is much larger than the French and the British. Therefore it is impossible to compare directly. But if you divide every single value for each country with the average of the year and multiply by 1000 you get the dimensionless **normalized unit kW/MW,** which enables you to compare the variations in systems of different size.

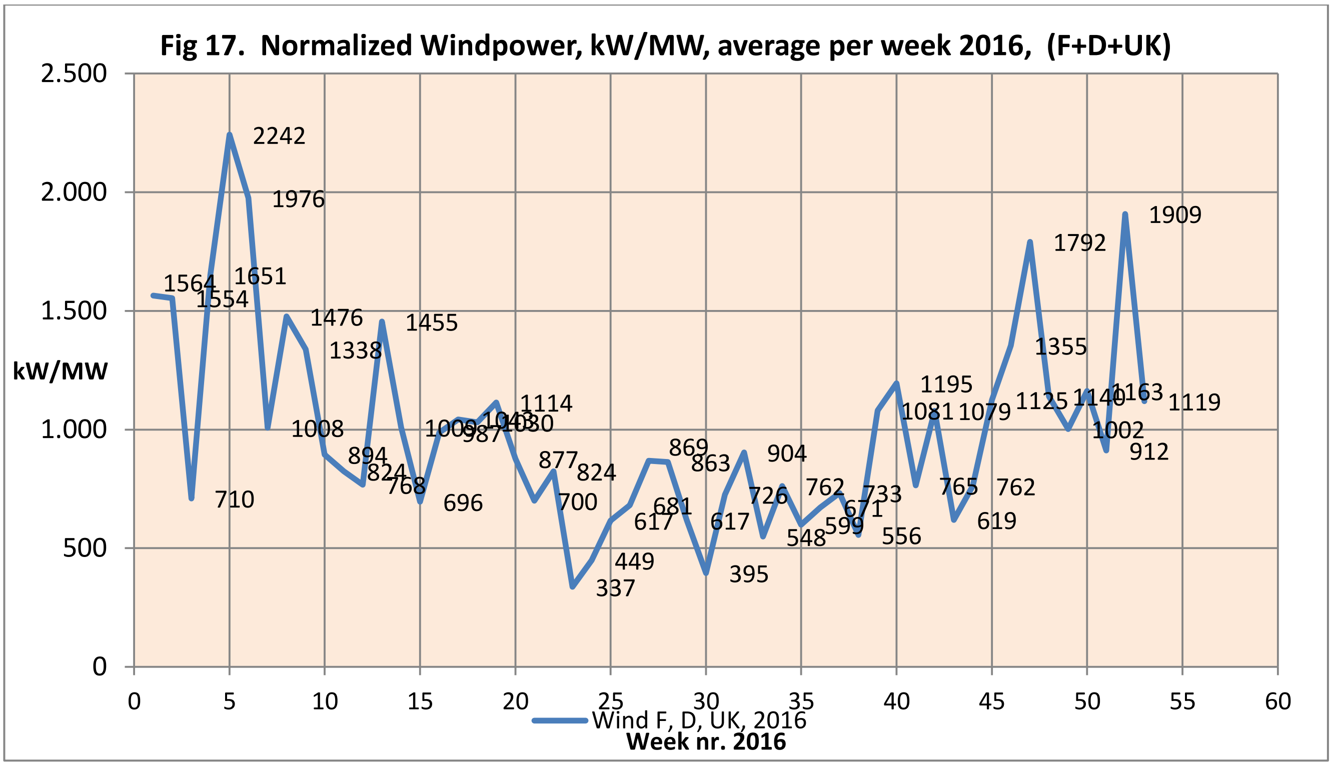
If you add the normalized values for the 3 countries, divide by 3 and calculate the standard deviation you see that this is slightly lower than the standard deviation calculated for the added data. 57% against 65%.

The following graphs fig 15 and 16 illustrate this:





The graph fig 17 illustrates too and may be more clearly that a smart grid will not at all secure a reliable energy supply. We must either have alternatives to the wind power or huge storage systems.



Graphs for Germany, France and UK provided that the average Wind power equals the Load

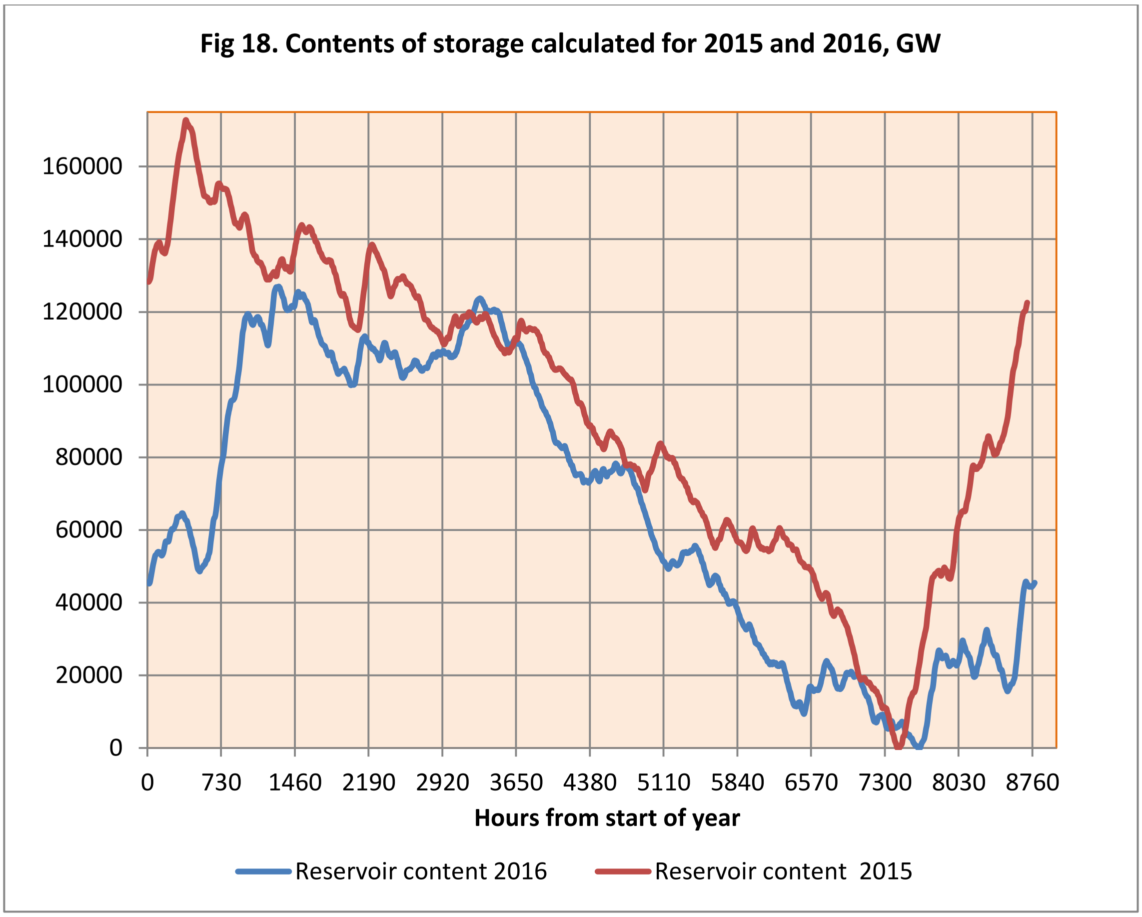
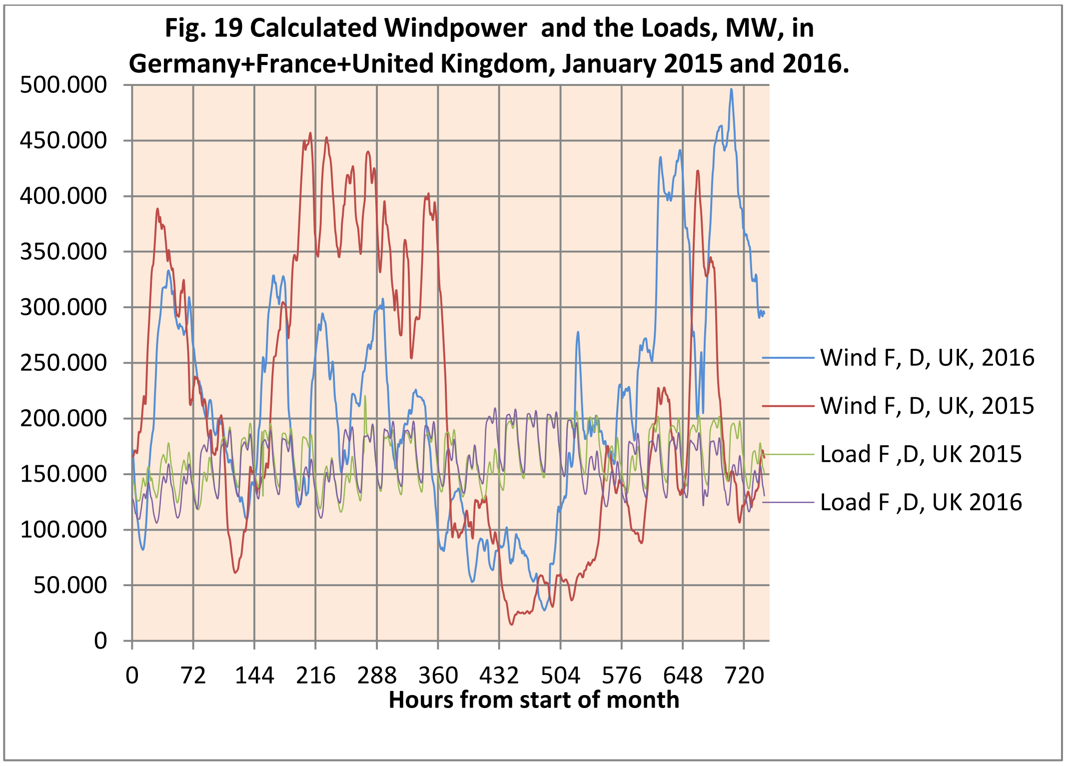
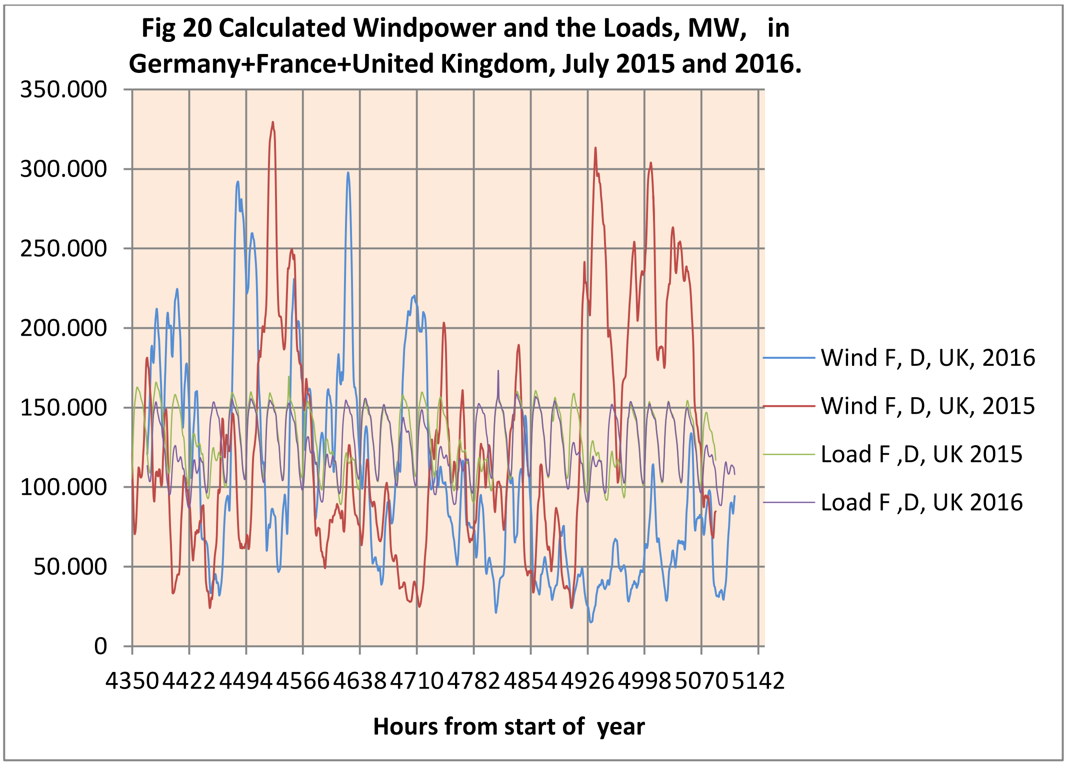


Fig. 18 illustrates the contents of the storage calculated for 2015 and 2016 under the condition that the wind power equals the load in Germany, France and United Kingdom. You observe the same pattern but with substantial differences from year to year.



It is clearly seen that there are enormous differences between the calculated wind power and the loads in 2015 and 2016.

If it is decided to have a substantial increase of the wind power, it will be necessary either to solve the problems abut storing of this or accept that a large part of the wind power will be wasted.



The variations in July are much smaller than in January.

Limiting the storage input capacity

From table 19 above we see that the input storage capacity is calculated to max 357 GW. More than double the average load in Germany+ France + United Kingdom. This is not realistic of course.

However, the Fraunhofer Institute proposes to produce 657 TWh wind power per year corresponding to 75 GW and 246 TWh PV corresponding to 28 GW. Totally 103 GW corresponding to the proposed future average load.

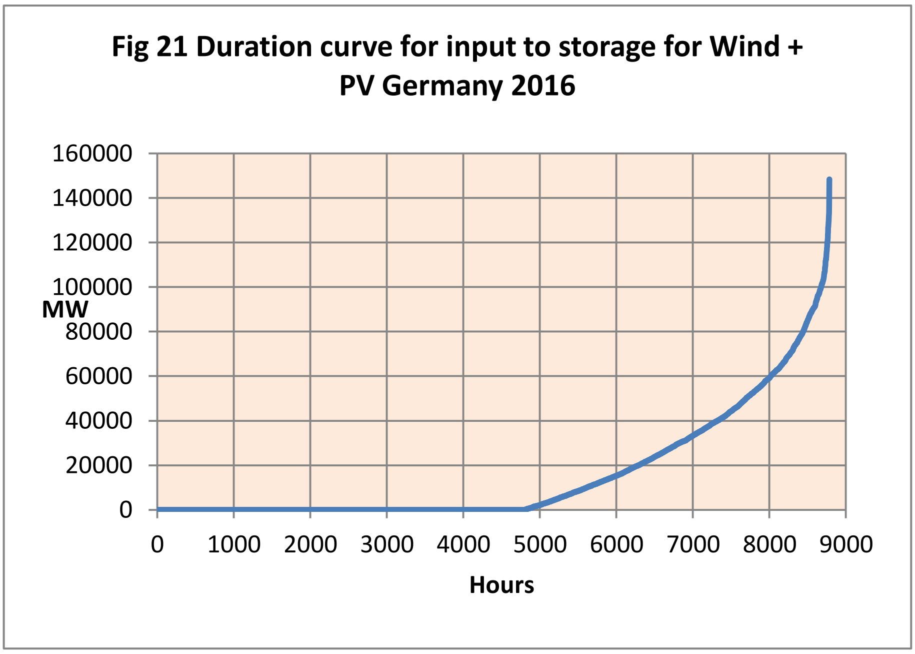
The relation between max/average for (Wind + PV) was 3,5 in Germany in 2016. So it is not meaningless to consider how to handle an electric effect several times the average load. But it is necessary to investigate the cost of reducing the storage effect

Table 21

Future storage calculated for Germany		Wind + PV 2016
Storage capacity	TWh	26
Max input	GW	148
Max output	GW	66

Table 21 shows (ref. table 16 above) the storage data calculated for Germany based on data from 2016, in the case that the entire green electricity supply is provided for by wind power and PV in the same proportion between Wind and PV as in 2016.

The duration curve for the input to storage for the Wind + PV is show in the diagram fig. 21



It is seen that the storage shall receive elctricity in about 4000 hours per year, and that only a small part of the electricity should be delivered with an effect of more than 80000 MW.

The cost of reducing the input capacity is shown in table 22 below.

Table 22

Loss by reducing the input capacity to storage, provided that German Wind + PV should have supplied the entire electric load in Germany in 2016				
Upper limit for input GW	Loss % of produced wind + PV	Loss GW	LossTwh per year	Loss Million € per year
20	15,3	8,8	77	3871
30	10,9	6,3	55	2761
40	7,5	4,3	38	1910
50	5,0	2,9	26	1280
60	3,2	1,9	16	820
70	2,0	1,1	10	504
80	1,1	0,7	6	290
90	0,6	0,3	3	148
100	0,3	0,2	1	69

The losses are calculated based on an electricity price of 50€/MWh.

As long as we know nothing about the cost of establishing a storage, we can't calculate the optimal input limit, but it is evident, that it must be considerable lover than 100 GW

A similar calculation for wind Power alone supplying the electricity in Germany, France and United Kingdom in 2016 is shown in table 21 below.

Table 23

Loss by reducing the input capacity to storage, provided that the Wind Power in D, F and UK have supplied the entire load in 2016				
Upper limit for input GW	Loss % of produced wind power	Loss GW	LossTwh per year	Loss Billion € per year
20	21,4	31,9	280	14,0
30	19,1	28,4	250	12,5
40	17,0	25,3	222	11,1
50	15,1	22,6	198	9,9
60	13,5	20,1	177	8,8
70	12,0	17,9	157	7,9
80	10,7	15,9	140	7,0
90	9,5	14,2	125	6,2
100	8,5	12,7	111	5,6

By comparing the data in table 22 and table 23 it must be observed, that table 22 shows the conditions when wind and PV supply the entire load in Germany.

Table 23 shows the conditions when wind power alone supplies the entire load in Germany, France and United Kingdom.

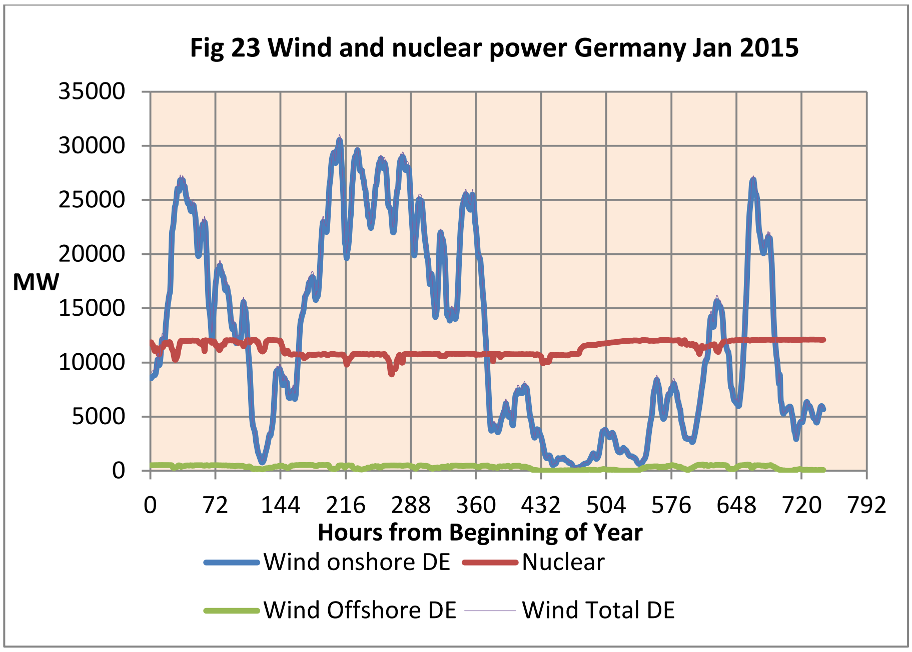
It should be observed that in 2016 the German load was **54,8 GW** on average and the load in Germany+France +United Kingdom was **141 GW.**

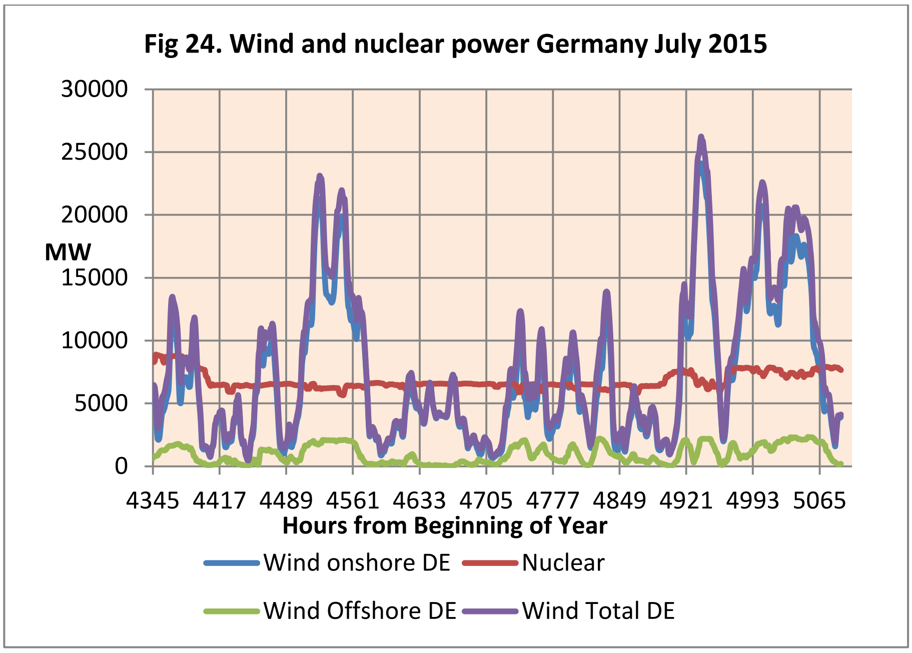
Table 24

Future storage for Germany, France and United Kingdom, when wind power alone should provide the electric load. Based on data from 2016.	
Capacity TWh	127
Max input GW	358
Max output GW	168

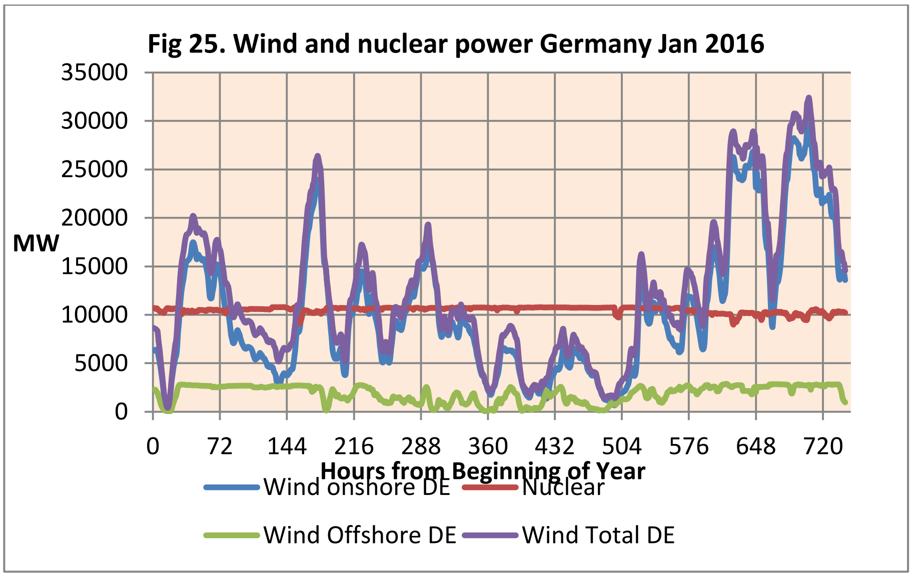
Table 24 shows the calculated capacity data for the needed storage if wind power alone should have supplied the loads in Germany, France and United Kingdom.

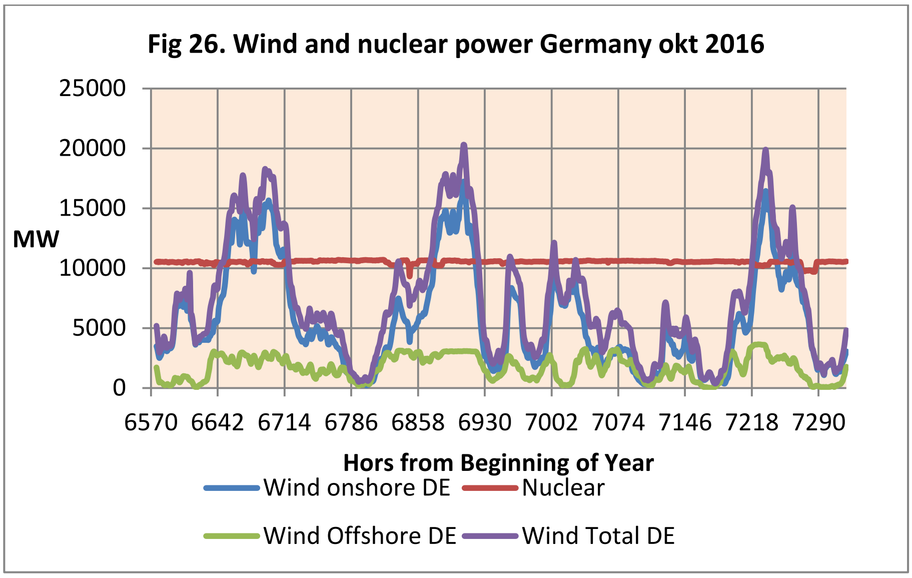
Some German Graphs. Wind and nuclear Power





There are 72 hours between the vertical lines, so each of the, represent 3 days..





There has been a substantial increase in installed off shore wind power during 2015 and 2016.

The off shore capacities should be

990 MW in 2014,

3430 MW in 2015 and

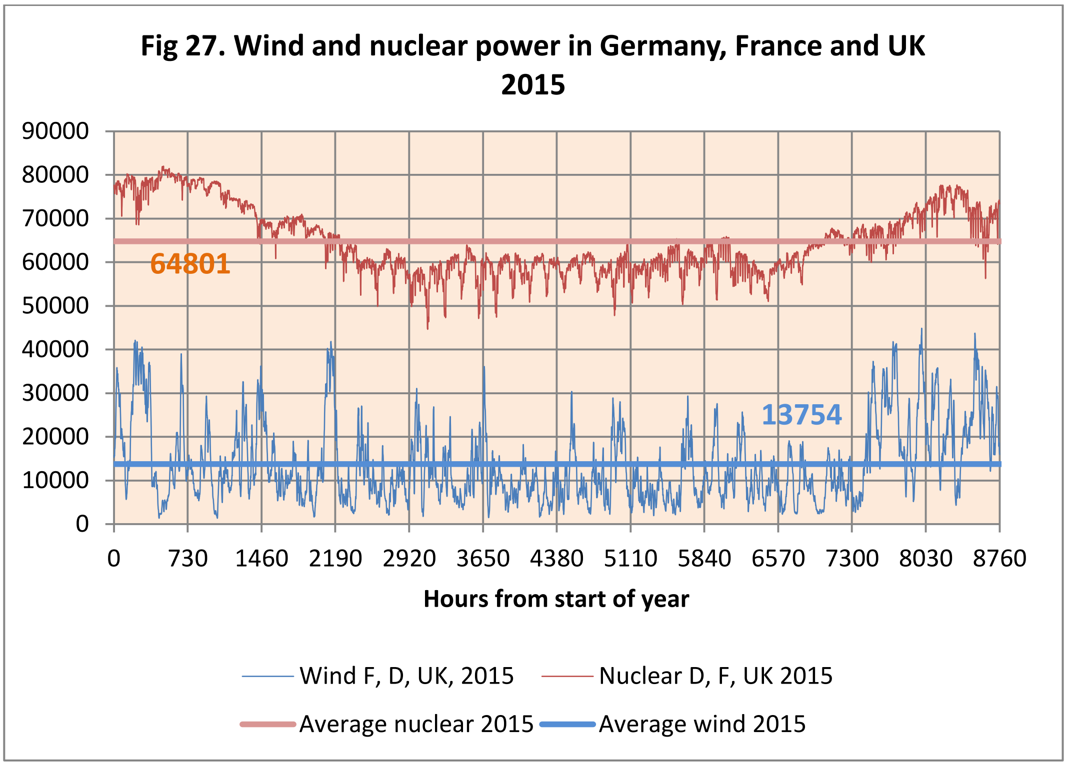
4130 MW in 2016.

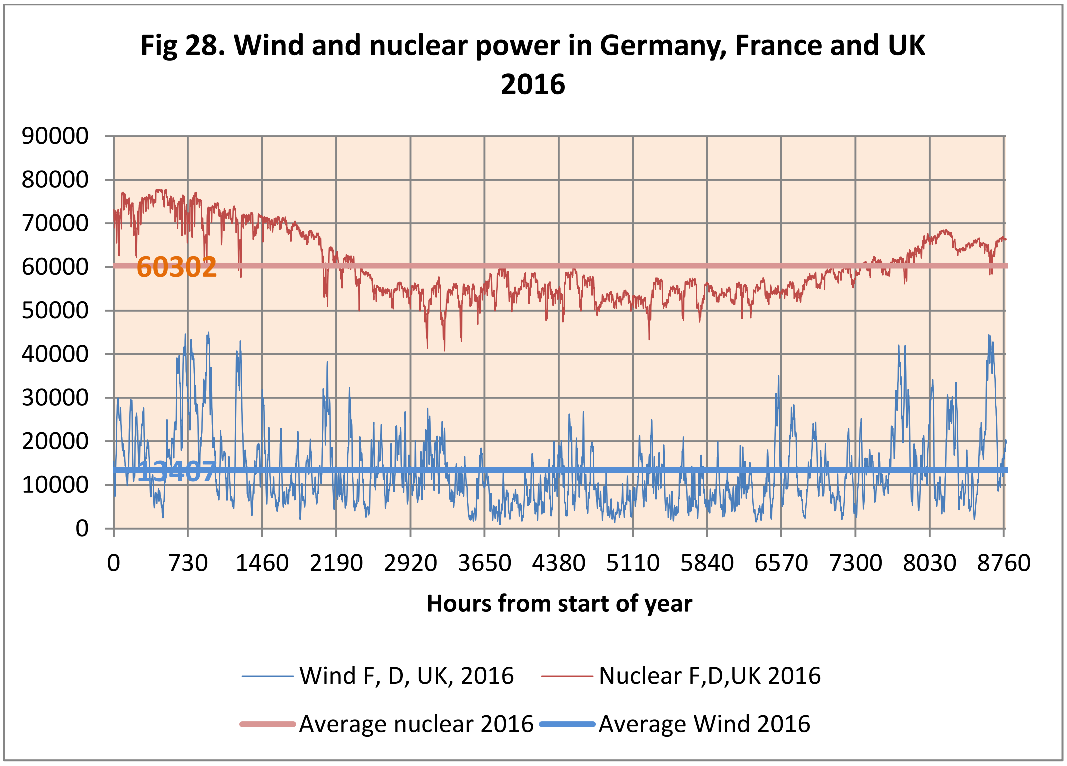
The average of shore yield in 2015 and 2016 were 883 MW and 1361 MW.

25,7 % and 33,0 % of the installed capacity. If we find the output relative to the capacity in the previous year we find 89% and 40% respectively. The 89 % does not make any sense, and the 40 % are far from impressing, but comparable with the Danish average off shore yield of 42%.

The German off shore wind power yielded on average 328 MW in January 2015 and 2336 MW in January 2016. However, the total German wind production was lower in in 2016 (8751 MW) than in 2015 (8854 MW).

Diagrams Wind and Nuclear Power in Germany, France and UK in 2015 and 2016





Each of the vertical lines represents 730 hours ≈ one month

Nuclear power can be controlled according to demand. All the minima are in the week-ends. The wind power does not need any comment.

A few facts about Nuclear Power

The table below shows the production and capital cost for the Swedish Nuclear Power Plant, Forsmark in 2016.[8]

Table 25

Forsmark Sweden 2016			
Production	GWh	21.128	
	MW	2.412	
Nominal capacity	MW	3.294	
Efficiency	**kW/MW**	**732**	
Total cost	**SEK/MWh**	**301**	**32**
	%	**SEK/MWh**	**€/MWh**
Reactor fuel	16	48	5,1
Interest and depreciation	15	45	4,8
Funding for future costs	14	42	4,5
Operation	28	84	8,9
Other	4	12	1,3
Effect tax	23	69	7,3
Sum	**100**	**301**	**32**
Minus effect tax		**232**	**24**
Minus effect tax and capital		**187**	**20**

You might say that the plant has been paid and therefore is the power so cheap.

That is not quite true. A lot of money has been spent in the foregoing years to upgrade the power plant built about 1980. And the capital costs are 100 Mio €/year

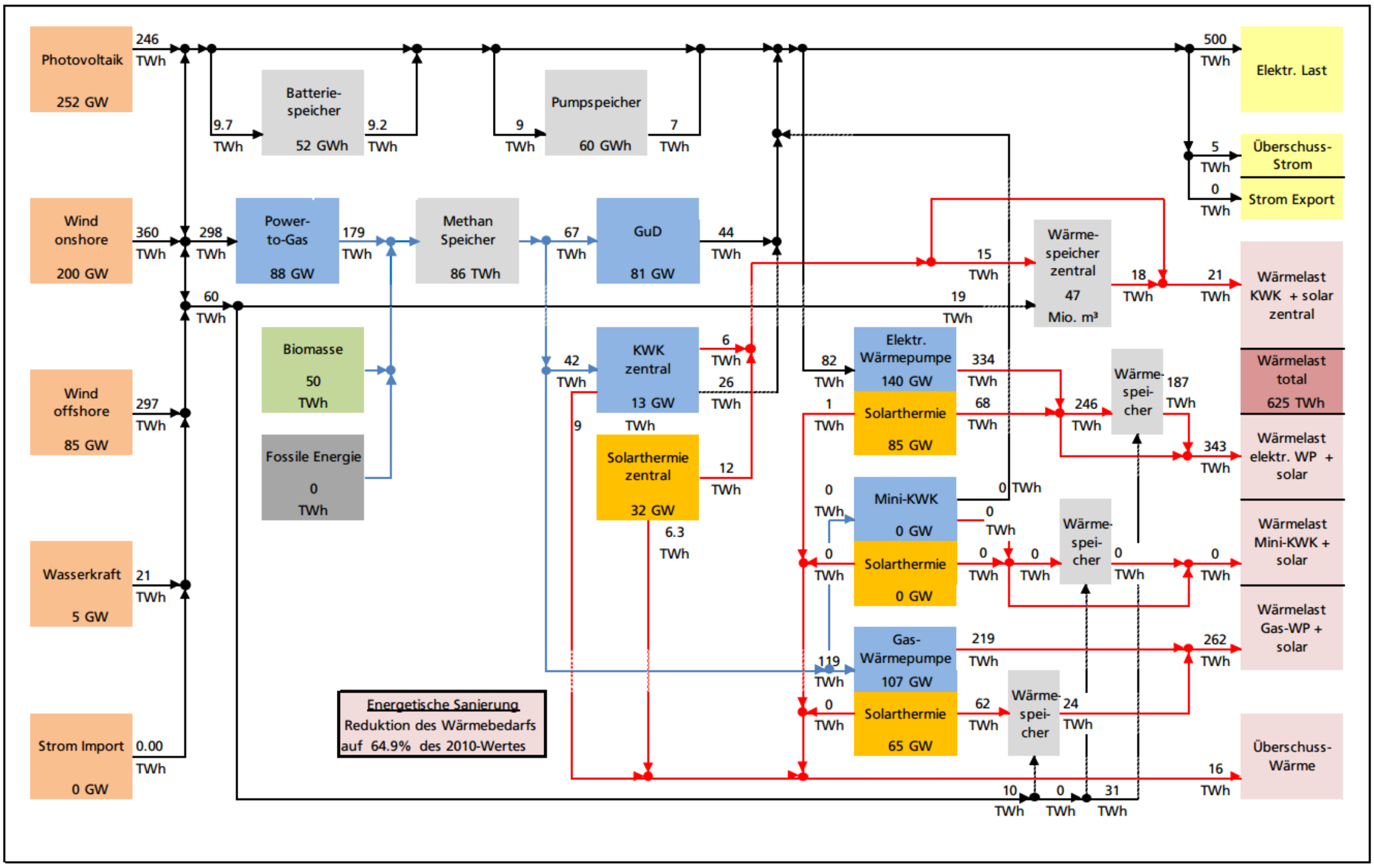
According to data published about an ordered Turkish nuclear power plant[9] we find capital cost of 33 €/MWh by assuming an overall efficiency of 90%, interest rate 4% p.a., 30 years of operation and a building period at 8 years for a modern power plant. If we add the Swedish cost for fuel, funding for future costs, operation and other costs we find a total cost of **53 €/MWh**.

Absolutely competitive with wind power – not to speak of the cost for wind power + back up.

A German Dream

100 % ERNEUERBARE ENERGIEN FÜR STROM UND WÄRME IN DEUTSCHLAND[10]

The fig. 26 below illustrates an idea for this elaborated by The Fraunhofer institute.



The average German (wind power + PV) was 12,687 GW in 2016. (See table 14 above)

The diagram above represents indicates a Wind and Photo Voltaic productin of 903 TWh/year corresponding to 103 GW or 3,25 E(xa)J. The present German average load is about 55 GW.

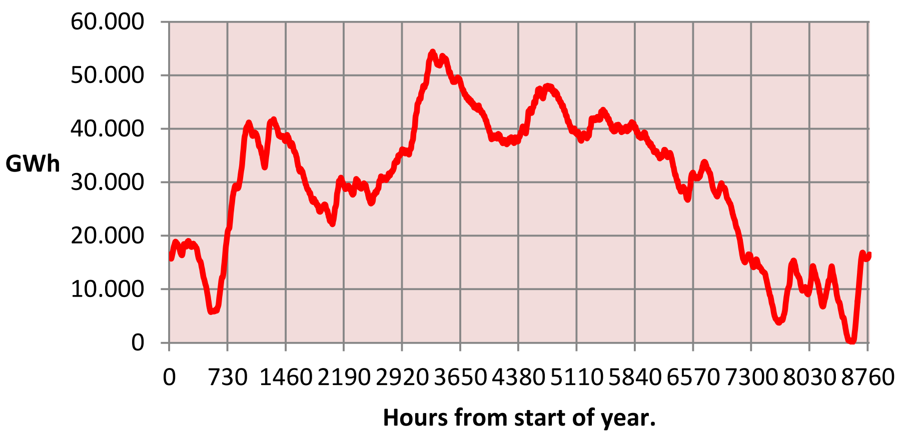
The German energy consumption in 2015 was 305 Mio tons oil equivalent[11] corresponding to 405 GW corresponding to 12,8 EJ. **So there is still missing 302 GW or 9,2 EJ/year to complete "Die Energiewende"**. And the ideas illustrated above about how to store fluctuating electric energy production are neither cheap nor easy to realize.

We will try to analyse the Fraunhofer ideas as described above by assuming:

The average output from wind and PV will be	103 GW
The future wind power will be	75 GW
The future PV power will be	28 GW
The future load will be	103 GW

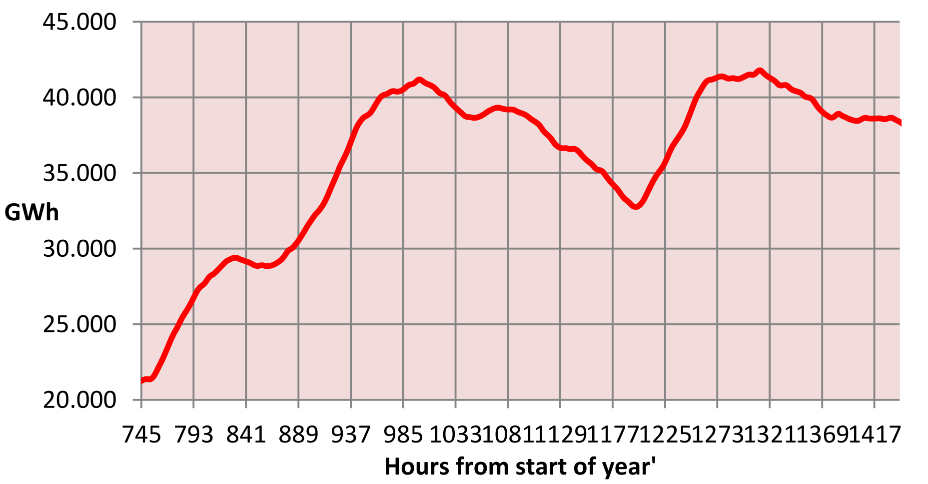
The average load in 2016 was 54,8 GW, and the future load, 103 GW, is = output from wind + PV. That is a simplified assumption of course, because input to and output from the storage will entail a loss. It is assumed too that both Wind, PV and load follows the same pattern as in 2016.
It will be necessary to store Wind and PV when they together yield more than the load and vice versa.
Based on the data from 2016 we can make a graph showing the storage contents any time and a graph showing the input to and the output from the storage for every hour. Other periods would give other results.

Fig 29 Reservoir content GWh according to the Fraunhofer project



During the year input to and output from the storage must be equal, and the storage content can't have a minimum less than zero. Each of the vertical lines represent 730 hours ≈ one month.

Fig 28 Reservoir content, GWh, according to the Fraunhofer project, February



Each of the vertical lines represent 48 hours.

In the first 10 days the contents of the storage must be increased by 20 TWh.

Considering that the Swedish hydro storage capacity is 34 TWh, it is obvious that it will be a gigantic task to build the storage. The next 8 days the storage shall deliver 9 TWh ≈ 47 GW on average.

One of the elements in the proposed storage system is hydrogen production followed by a unit to transform hydrogen + biomass to methane. In principle possible – the process has been known in 90 years – but in 5052 of the 8784 hours in 2016 the production of wind power + PV would be lower than the load. I.e. in 57% of the time there would be no electricity to operate the hydrogen production units. Unless electric energy stored in batteries or in pumped storages will be used.

Until now that kind of plant operation has only been possible in a Soviet type of economy. One might suspect that this is the purpose of the whole green economy.

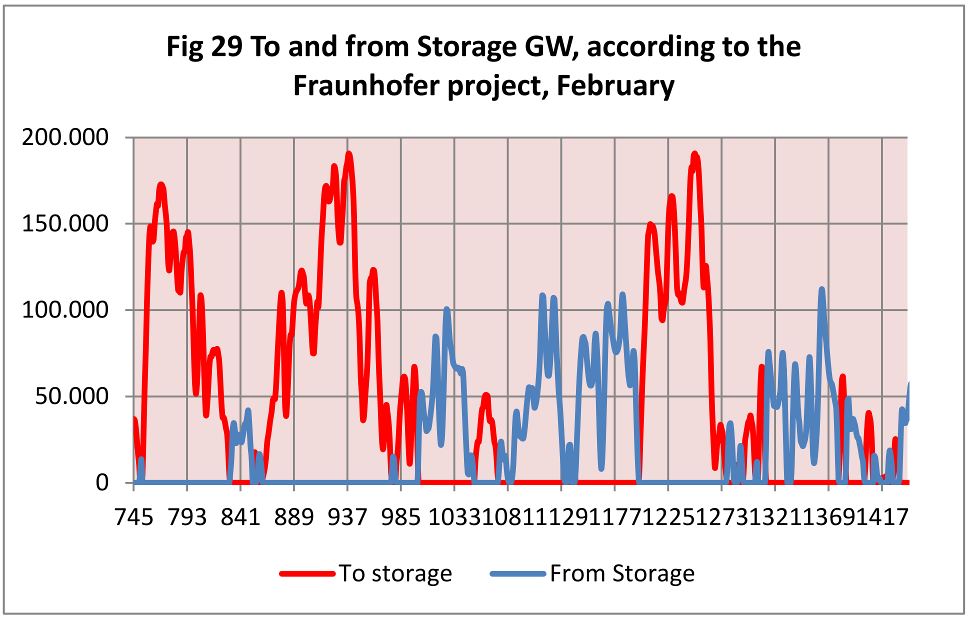


Fig 29 to the left illustrates the difference between (Wind+PV) and load.

The read curve illustrates that Wind + PV is larger than the load and the blue curve illustrates the opposite.

I.e. the curves illustrates when effect must be transferred to and from the storage, and how much.

The author has 35 years of experience with the operation of large chemical plants, and is happy that he never was forced to operate a plant according to fig 29.

The author hopes to have convinced his readers, that we need completely new ideas to obtain "Die Energiewende".

Grenaa, Denmark

April 2017

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