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USING WIND ENERGY TO SAVE FUEL AND REDUCE CO₂ EMISSIONS

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ABSTRACT

The official Dutch green energy policy aims at increasing the total wind turbine capacity in the Netherlands to 10.5 Gigawatts. This paper analyses the possible fossil fuel savings due to the resulting contribution of 25% wind to the national power grid. The planned wind contribution amounts to 3.25% of the country's total energy consumption, as 13% of the total energy need in the Netherlands is used in the form of electricity. The effects of curtailment, grid accommodation losses and self-energy are discussed. It is shown from performance data that these three factors reduce the fuel saving due to wind energy to less than 31% of the nominal saving. The three factors effectively reduce the total fuel saving due to wind from 3.25 to one percent.

1. INTRODUCTION

In a former paper¹ we enumerated 9 factors that influence the saving of fossil fuel due to large-scale implementation of wind energy.

These factors are:

1. Conventional units are forced to operate at less than optimal power due to supply of wind electricity. As a consequence, they have a lower thermal efficiency. They consume more fuel per kWh compared to the consumption without wind.
2. Cycling conventional units – ramping up or down – in response to fluctuating wind contribution uses more fuel than running at constant power.
3. Idling of conventional generators synchronous with the grid but not delivering electric power costs 6 – 8% of the fuel required for running at design capacity.
4. Extra cold starts of conventional units easily require more fuel than wind developments produce.
5. Construction and installation of wind turbines require a quantity of energy equivalent to about 10% of their life-time production.
6. Capital costs and energy involved in connecting wind turbine parks to the grid, including adaption and transforming, have to be added to the wind park costs and subtracted from yields.
7. Self-consumption of electric energy by wind turbines and their electronics while idling and at rest, *i.e.* heating during cold periods and electricity consumed by the power electronics for grid adaption.
8. Increased use of inefficient, fast ramping OCGTs (Open Cycle Gas Turbines) instead of twice as efficient CCGTs to meet sudden wind variations.
9. Energy costs related to extra wear and tear of conventional units due to frequent forced ramping in response to the wind variations.

Existing literature uses only model data to calculate this fossil fuel saving. The reason is, that fuel input data for power production required to measure the conversion efficiency of conventional generators are not made public. This paper uses among others data that recently became available in Ireland and Spain.

(In first approximation fuel savings and CO₂ emission reduction go in parallel. Gas and coal differ in the amount of CO₂ emitted per unit of heat produced. This difference is taken into account where needed.)

Following EU- agreements, the Dutch government assumes that every kWh of wind-generated electricity saves the fuel necessary to generate 1 kWh of fossil fuel generated electricity. This is only true when the contribution of wind energy is very small. It certainly does not hold when the wind penetration reaches the goal of 25%.

The government stated to Parliament in 2013 that the saving might be approximately 3% lower because of losses², although in an earlier discussion it was admitted to parliament that 5.1 % of the saving was lost³. The KEMA, the research institute founded by the Dutch electricity industry, did a study of such losses. The study⁴ concluded:

“The loss is possibly 10% of the amount of CO₂ emission you hope to save”.

The difference between the official EU figure of 0% loss, the 3 to 5% loss quoted by the Dutch government, the 10% quoted by the experts of KEMA and the 100% loss calculated by one of us (CleP⁵) is certainly a reason for grave concern.

This paper aims to provide more information on this subject.

2. WIND ENERGY, A SUPPLY DRIVEN COMMODITY.

Wind turbines can be added to the existing system of electricity production, but they cannot substitute fossil fuelled generators.

The following examples serve to illustrate this statement.

A. During several weeks a year all wind turbines in West Europe together produce only a few percent of their nameplate capacity. This fact has been neglected so far in the public debate, because conventional fossil or nuclear units fill the gap. On the other hand, a black out anywhere is front-page news. Wind power cannot deliver electricity on demand, so it requires large-scale storage or back up. Large-scale energy storage is not available to the Netherlands, so a 100% back up system remains essential to guarantee equilibrium between supply and demand at all times.

B. By law, renewable energy has absolute priority in the merit order on the electricity market. This has some unintended consequences. As soon as wind supplies on average more than a few percent of the electricity demand, a high wind speed causes the electricity price to fall significantly. In 2010 the Dutch ‘Central Planning Bureau’ coined the word “profile effect” for this phenomenon. This profile effect is significant already in the North-West European electricity market. Wind energy disturbs the operation of the market and it affects the necessary investments in conventional production capacity⁶.

In September 2013 forty (!) organisations in the Netherlands signed a so-called Energy Agreement, which when fully implemented will allow the country to comply with the EU requirement to supply 16% of the Dutch energy consumption from renewable sources by 2023. In the EU definition hydro, solar, wind, wood pellets (!) and other biofuels qualify as such. This Energy Agreement forces the government to supply € 18 billion in exploitation subsidies for future offshore wind turbines. The amount does not include the € 5.5 billion already committed for the exploitation of previously planned and existing offshore wind farms. The € 23.5 billion subsidy will be generated by a levy on the price to be paid by the electricity consumers during 15 years.

When so much money is at stake, it is essential to know to what extent the stated goal of reduction in fossil fuel consumption and CO₂ emission is actually achieved.

We also note that the societal impact of building thousands of turbines on land and off shore is nowhere mentioned in the Energy Agreement.

3. THE TOTAL AMOUNT OF WIND ENERGY PRODUCED.

Table 1 shows the energy balance for the Netherlands⁷.

Table 1, The energy balance for the Netherlands in 2011.

Present situation (2011)⁷.	<i>1 PJ = 10¹⁵ Joule</i>
Converted + consumed in the Netherlands	13443 PJ ⁸
Dutch energy consumption	3245 PJ
Dutch electricity use	422 PJ
Wind electricity production in 2023 ^{a)}	104 PJ
The wind contribution in 2023 is (assuming the same energy consumption as in 2011):	
Of the electricity consumption	25%
Of Dutch energy consumption	3,2%
Of all energy converted and used	0,8%

The wind electricity production in 2023 is calculated for 6 GW on land with a capacity factor (CF) of 25% and 4,5 GW off shore (CF 40%).

If the turbines would perform as the government expects, they will contribute 3.2% of all energy used in the Netherlands, but only 0.8% of the energy we use and process.

Data has become available about three factors, which decrease the savings expected by the addition of wind energy. These effects will be discussed in sectors 4, 5 and 6 on the basis of real performance data, rather than *model predictions*.

4. OVERSUPPLY OF WIND ELECTRICITY.

The Netherlands is in an unfavourable situation, as it lacks the relief required for hydroelectric generation and storage. This technology is at present the only economical large-scale storage and buffering option for (excess) wind electricity. Alternative ideas for wind energy storage, such as the plan to build a large artificial reservoir in the IJsselmeer (inland lake), or a giant hole surrounded by dikes in the North Sea, both with windmills on the dikes and hydro driven generators in the dikes, have never left the drawing board because of the excessive costs for these systems. The second option, export of the excess electricity, will be blocked in the coming years as all surrounding nations are also investing heavily in wind energy. The wind strength in NW Europe is strongly correlated, so an oversupply in Holland will more often than not coincide with oversupply in Germany, Belgium, Denmark and Great Britain. Therefore, when a 10.5 GW wind capacity is placed in Holland, the country must solve its own problems. KEMA came to this conclusion already in 2010 in a study⁹ requested by the General Energy council AER and the power companies Delta, Essent, Eneco and Nuon.

The composition of the Dutch fossil fuel mix is 54% gas and 31% coal. The gas is used in the CCGT units, some OCGT units and cogenerator plants. Both the CCGT's and coal fired units have limited balancing capabilities due to low turn up and turn down rates (4-5 %/min) and relatively high minimum loads. The OCGT units and the CCGT units are the principal balancing elements.

The issue of wind oversupply has been recognised some time ago. The Delft University Wind Energy Study Team has looked at it in 2008. In 2009 the magazine “De Ingenieur” gave a review¹⁰ of Dr Ummels’ thesis, and noted that large-scale fitting-in of wind energy in the Dutch grid would present no problem. This is not correct according to the data presented below.

The ‘power duration curves’ in figure 1 are taken from the thesis of Ummels, with an additional horizontal line at the 10 GW power level.

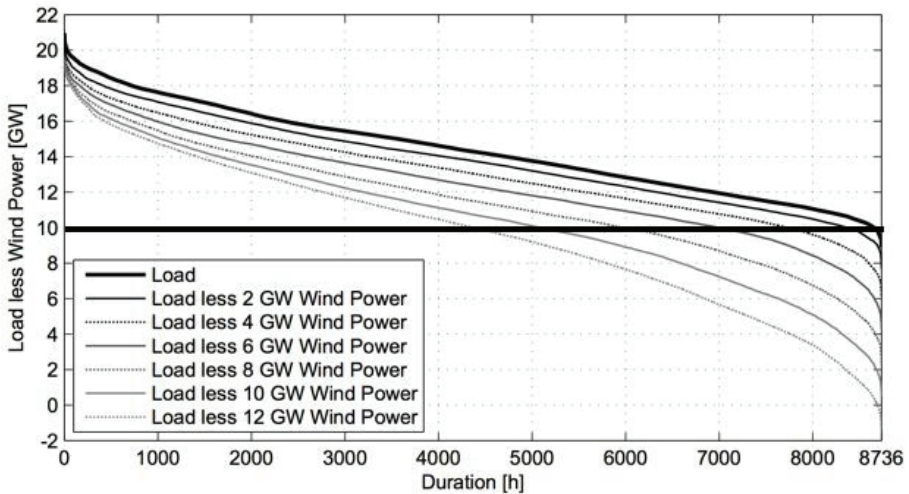


Figure 1. Power duration curves with different wind power capacities

The upper curve is the electric power demand curve, constructed for the Dutch electricity demand in 2005 on an hourly basis. So, for example, it shows that in the country there are one thousand hours each year with electricity demand of 17.8 GW or more. The lower curves are constructed by subtracting for each of these hours the amount of wind electricity fed to the grid when the indicated amount of wind turbine capacity is present (2, 4, 6 etc. GW installed). The wind electricity production has been calculated using the wind force data for the year 2005 for each hour, as provided by the Dutch Meteorological Institute. Please note: points on each curve that lie vertically aligned are not necessarily measured at the same point in time, as the force of the wind is uncorrelated to the demand.

A constant base load or ‘must run’ level is represented by a horizontal line in the figure.

The question to be answered is: What will be the size of the “must run” power of the Dutch (fossil and nuclear) power stations. This is the minimum power below which the electricity demand minus wind electricity supply cannot drop, in order to keep the generators ready to deliver. The answer of the wind industry is: “The must run power will be reduced to a level to keep the losses at a negligible level”

The power duration curves in figure 1 show that a must run level of 10 GW indicates that significant wind electricity oversupply will occur. Integration of the “12 GW wind” *curve* under the horizontal 10 GW *line* shows, that the curtailment (production cut) will be some 40%. Thus 40% of the total yearly wind production cannot be accommodated in the Dutch grid in this case. If we would be able to reduce the “must run” capacity to 5 GW, then the curtailment drops to 10%.

The actual “must-run” power level is difficult to determine, as this depends on the state of the electricity market. It will be between the two limiting cases mentioned above.

Ref. 9 reports on the issue of incorporating wind supply. The conclusion is, that at 9 GW wind capacity 1.5 TWh (5.4 PJ) is lost every year, and at 12 GW wind ditto 5 TWh (18 PJ).

Interpolating linearly, we find the loss at 10.5 GW wind power to be 11.7 PJ per year. According to table 1 10.5 GW wind power yields 104 PJ, so that 11% of the wind power production will be lost per year according to the conclusions of ref. 9.

Figure 2 is taken from a study of the Irish electricity generation¹¹. The graph is based on *actually measured* wind curtailment as a function of the wind electricity production expressed as a fraction of the total generation.

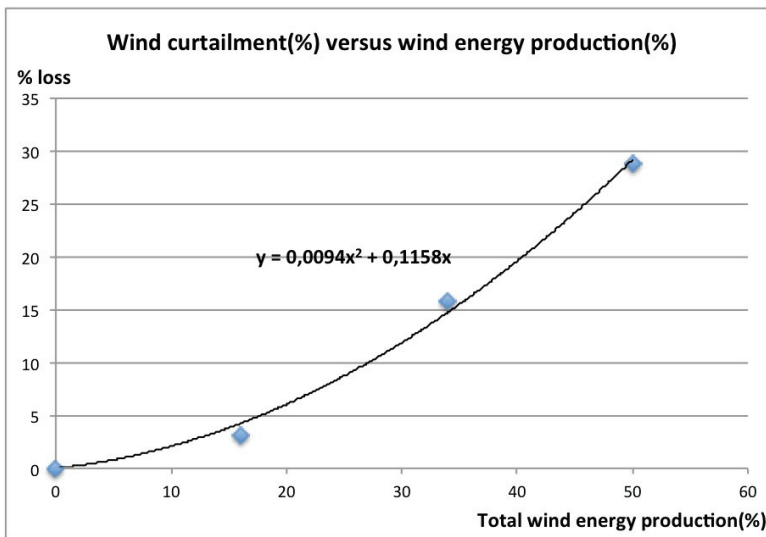


Figure 2. Wind curtailment data for Ireland.

This graph shows 9% loss when wind provides a quarter of the electricity. The situation in Ireland is somewhat more favourable than in the Netherlands, as Ireland has some hydro electricity. Hydro is a good buffer for wind fluctuations. We expect therefore the losses to be a few percent higher in the Netherlands. In this way we arrive at the conclusion, that the estimate of 11% loss made in ref. 9 has been confirmed.

EirGrid data also allowed the calculation of the Irish must-run capacity, which was found to be 1.3 GW. The Irish mix of fossil fuels is comparable to that in Holland, but Ireland has no co-generation (of heat and power). It is used extensively in Holland in greenhouses and in industry.

The Dutch electricity demand is five times the Irish, thus other things being equal the must-run capacity is $5 \times 1.3 = 6.5$ GW. To this must be added the nuclear capacity of 0.7 GW¹² and part of the 7 GW co-generation capacity. We therefore set the must-run capacity in Holland at 8 to 9 GW.

We conclude that the amount of curtailment of wind energy in the Netherlands in 2023, if the plans become reality, will be at least 10%.

5. CONVERSION EFFICIENCY LOSSES CAUSED BY WIND ELECTRICITY

The simplest method to calculate the total CO₂ emissions from power stations is to take the actual fuel consumption of each power station and dependent on the fuel type, convert these numbers into CO₂ emissions. Since the liberalisation of the electricity market, these numbers are no longer available to the public, because this is competition sensitive information. This data would allow an accurate determination of the effects of adding wind and other non-demand driven electricity supply sources to the grid. The best one can do at the moment is to estimate the size of this effect, based on experience presented in ref 15.

The Irish grid operator derives the fuel consumption from the amount of electricity produced by the relevant power stations, taking into account the efficiency achieved by each station as a function of actual capacity fraction utilized in a certain time slice. EirGrid takes the efficiency data measured at a constant rate and does not include the efficiency loss caused by load following and start-stop operations. It also neglects the fuel use of the “spinning reserve”.

The following paragraphs discuss the results based on data from three different countries to estimate the effects of adding wind energy. Please note that accommodation losses are sharply increasing with increasing wind contribution, so the results represent lower limits of the losses, if the contribution of wind was smaller than 25%.

5.1 Spain.

Gutiérrez et al¹³ published a paper on the accommodation of wind electricity in the Spanish grid. They followed the method of EirGrid as described above to calculate the fuel use. In the year 2011 wind supplied 42000 GWh or 14.7% of the electricity generated in Spain. Not all Spanish power stations were ramped up and down to accommodate the varying wind contribution. The ones used for load following generated 62% of the Spanish production.

From the data of Gutiérrez et al we derive the following numbers:

1. The CO₂ emission of the system fossil plus wind is 87.2 Megaton (Mton).
2. Fossil and wind combined generate 151300 GWh.
3. If this amount of 151300 GWh would be fossil generated, it would cause 97.6 Mton CO₂ emission according to generator data from ref. 14.
4. The CO₂ saved by 42000 GWh wind amounts to $97.6 - 87.2 = 10.4$ Mton or in other words:

5. The CO₂ emission saved per kWh wind power is 246 g/kWh

This is less than 50% of the CO₂ saving expected in the case only gas was used to balance wind.

5.2. Ireland.

EirGrid provides detailed figures about the electricity production per 15 minutes time interval: total demand, calculated CO₂ emission, and fossil and wind production. In 2011 wind generated 15% of the total demand. This allows the calculation of the efficiency of replacing fossil by wind. This has been done in two papers, both using the data over 2011.

Udo¹⁴ shows that the efficacy of the wind contribution to replace fossil fuel varies from 40% to 100%, dependent on the availability of hydropower (for back-up and storage) in the system. The average efficacy over 2011 is 70% in his analysis. This means a 30% loss compared to the calculation according to the EU method.

Wheatley¹⁵ made a more extensive analysis of the Irish system over this same year. He also collected data on the actual fuel consumption of the power generators.

“Based on an emissions model and 1/2-hourly generation time-series for each grid connected thermal generator, it is shown that wind power saved 280 gram CO₂/kWh on average, relative to an average carbon intensity in the absence of wind of 530 gram CO₂/kWh.”

The relative efficiency calculated by Wheatley is thus $0.28/0.53 = 53\%$, resulting in a loss of 47%. As this figure is derived from actual fuel consumption data, it is closer to reality than the result quoted in ref. 15.

5.3. Colorado

The Bentek study on the Colorado power system: “How less became more”¹⁶ is based on the official emission data of the US Environmental Protection Agency (EPA) in the period before and after the construction of wind facilities. The study compensates for import and export of electricity across state boundaries. In the case of coal fired power stations providing the back up for wind they find that the total CO₂ emission **with** wind power is higher than **without** the turbines.

We conclude from these three studies that the amount of fuel and thus CO₂ emission saved is at most 50% of the amount the wind proponents state. This is still optimistic for the Dutch situation in 2023: A system with 25% wind electricity without hydro and without export or import possibilities will perform worse than that.

6. SELF-ENERGY OF WIND TURBINES

The economic lifetime of a turbine is set at 15 years due to the Dutch subsidy policy. The time for recuperation of self-energy – the energy required for building and erection the turbines- must be related to this period. The wind turbine industry admits that a turbine must work for 6 months to produce this energy. Calculations by others with less of a stake in the industry find higher numbers.

6.1 J. van Oirschot, M.Sc. , Director R&D of the Dutch construction firm Volker Wessels Stevin, involved in positioning and building foundations for the turbines, calculates that it takes 1.5 years to reclaim the energy involved in building and installation¹⁷.

Udo¹⁸ calculates that a turbine with a 25% capacity factor requires 11.5 months for this. The calculation is based on data from a study done in Sydney¹⁹.

We will take the lowest value from these two, a reclamation time of 1 year, which means a yearly loss of 7% over the 15 year write off period for turbines. This fraction is calculated with respect to the production, without subtracting the losses as discussed in section 5. The fraction of self energy increases to 14% if the losses are taken into account.

7. THE EFFECT OF THE THREE FACTORS COMBINED ON THE REDUCTIONS OF THE FUEL AND EMISSION SAVINGS

In summary the losses in the Dutch grid when accommodating 25% wind electricity are as follows:

Curtailment is sheer loss, so the wind production reduces by 11%. The remainder must be accommodated in the grid at a loss of 50%, so the fuel saving is $0.5 \times 0.9 = 0.45$ of the expected value E_{wind} (Energy replaced by wind).

The 14% self-energy must be subtracted from the fuel saving after accommodation in the grid, so the net saving is
 $0.45E_{wind} - 0.14E_{wind} = 0.31E_{wind}$

The three factors together reduce the effective fuel saving to 31% of the official fuel saving.

8. DISCUSSION

Whenever there was a range of possible outcomes in the foregoing calculations, we have erred on the side most advantageous for the wind industry. In addition, no account was taken of the following factors because of lack of data:

- Building and placing wind turbines are not the only activities and installations taking energy. The extra grid adaptation and high voltage connectors cost energy. These activities are so complex and costly, that the implementation of these adaptations is years behind schedule in Germany. Data on the magnitude of this energy expense are lacking, but we guesstimate that an energy expense comparable to the turbine self-energy is involved.
- When turbines are not producing, they still require energy. This became dramatically clear in Germany, where offshore wind turbines urgently needed current supply from diesel generators in the period before the power connections to shore were ready. It is unknown how significant this energy consumption is.
- In sections 5.1 and 5.2 the fuel consumption of back-up power stations has been derived from the power production and the performance curves of the generators involved. Thus efficiency losses during ramping the generators up or down have

not been accounted for, nor the effect of the fuel consumption when the generators act as spinning reserve.

- The official Dutch capacity factors for the turbines, $C_f = 0.25$ onshore and $C_f = 0.40$ offshore are too optimistic. In 2010 all existing Dutch wind turbines onshore and offshore together had a capacity factor of 0.23. Turbines have planned and unplanned unavailability, and the total unavailability goes up with age. This manifests itself as a diminution of the production with age. Recent work²⁰ has determined the production loss with age as $-1.6\% \pm 0.2\%$ per year. This factor diminishes the total production over the economic lifetime of 15 years by 10%. After 15 years of operation the yearly output is diminished by 22%.
- Maintenance costs energy too. A calculation is reported in the ECN study of O&M costs of wind energy at sea²¹. The result is, that maintenance costs 85 million euro/year for 520 MW installed. With a $C_f = 0.40$ maintenance costs amount to 45 euro/MWh generated. A significant part of this money is spent on energy. It is noted, that the maintenance cost of wind turbines at sea is larger than the market value of the generated electricity.
- The wind electricity generated offshore must be transported over larger distances than is customary for the existing (onshore) power plants. This causes extra power loss in cables and transformers; even when direct current is used, as this technique needs two conversion stations with transformers, valves and filters.

Taking all these factors together the actual fuel saving will be less than 30% of the expected saving. This means that in 2023 the effective wind contribution to the total Dutch energy consumption will be around 1% instead of 3%.

9. CONCLUSION AND POLICY IMPLICATIONS.

A transformation of our electricity supply system is in the long run necessary and unavoidable. However, the direction chosen by the Dutch government in the recent Dutch Energy Agreement is inefficient and expensive, as it focuses on subsidizing the exploitation of old fashioned techniques. It does not facilitate possible future developments like advanced nuclear fission and energy conservation through industrial electro technologies, zero energy housing, district heating and combined heat and power. This article shows, that building wind turbines without means to implement the intermittent production achieves a CO_2 emission reduction that is significantly lower than claimed by the wind industry.

The price Dutch society will pay for saving a small amount of fossil fuel and CO_2 emission through wind turbines will be at least three times higher than the price officially stated.

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