The impact of wind generated electricity on fossil fuel consumption.

by

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Abstract

Wind turbines produce electricity which is delivered to the grid. Variations in wind velocity cause yield variations. Conventional power stations are forced to compensate these variations by adjusting their output. This has a negative effect on the efficiency of the latter stations. Using data provided by CBS, the Dutch Institute for Statistics, an estimate is made of the so called "turning point". This is the point where the efficiency reduction of conventional power stations balances out the fuel saving of the wind turbines, and where the CO_2 emission reduction turns negative as well. In the Netherlands the data for the year 2007 show this to be the case at an efficiency reduction of all power stations of about 2 %. The Dutch government uses an incorrect formula for calculating the fuel and emission saving from wind energy. On this subject parliament has been incorrectly advised by government.
In addition, fuel costs required for initial installation of wind turbines are substantial.
Application of wind energy without adequate buffer and storage facilities serves no green purpose.

Introduction

In a previous article[1] we calculated the negative effect on the fossil fuel saving obtained when using wind generated electricity. The effect is caused by the stochastic nature of wind availability, which requires frequent and rapid output adjustments of the fossil fuel powered plants. In our sums we used German data, because wind turbines have been erected there in large quantities. We also used somewhat too high estimates of the efficiency of fossil fuel power stations. We now turn our attention to the Dutch situation, where thanks to our CBS, the National Bureau of Statistics, actual data on the fuel input and electricity output of various kinds of power stations are available.
 Coupling wind farms to the electrical power grid requires additional output adjustments of the other power stations to allow for wind fluctuations. We will call

these other power stations "conventional producers". Without wind farms these producers would provide an amount of electricity E according to demand. This would in turn require an amount F of fossil fuel. The efficiency is then equal to

$$R = E/F \qquad (1)$$

Now if the wind farms produce an amount of electricity E_w and demand remains the same, the conventional power stations will need to produce $E-E_w$.
The Dutch government[2] and public conclude that the fossil fuel saved ΔF can be related to the efficiency and the total fossil fuel use of the system as follows:

$$F - \Delta F = (E - E_w) / R \qquad (2)$$

with $\Delta F = E_w/R$. This leads to an equivalent lower amount of CO_2 production. <u>This is incorrect.</u> Wind energy is not supplied in response to demand, but fluctuates with the weather. This requires the conventional power suppliers to more frequently adjust their output up and down, in order to balance the fluctuating wind generated electricity supply. As a consequence, the other power stations will have to run at below optimum generating capacity more often. This leads to an efficiency decrease from R to $R-\Delta R$.
The amount of fossil fuel used in a situation where wind is providing electricity as well thus becomes:

$$F - \Delta F = (E - E_w) / (R - \Delta R) \qquad (3)$$

and the fuel "saving" ΔF is equal to:

$$\Delta F = F - (E - E_w) / (R - \Delta R) \qquad (4)$$

ΔF can become negative, and then wind power does not save fossil fuel, but causes extra fossil fuel consumption and also extra CO_2 emission. The turning point where no fuel is saved is reached when $\Delta F = 0$
When combining equations (1) and (4) for $\Delta F = 0$ we find:

$$E/R= (E-E_w) / (R- \Delta R)$$

and therefore

$$\Delta R = E_w*R/E \qquad (5)$$

 Thus, at a (conventional power) station efficiency of 50% and 5% of total electricity generated by wind, the turning point (= *no fuel or emission saving during wind farm operation*) is reached at a total conventional power station efficiency loss of 2,5%. Again: the loss is caused by having to cope with extra

demand fluctuations.
Generally the following equation holds for the efficiency loss *at the turning point:*

$$(\Delta F = 0 \text{ if}) \; \mathbf{\Delta R = aR} \tag{6}$$

with

$$a = E_w/E, \tag{6a}$$

a being the fraction wind generated electricity on the total production. Note that the duty factor (= also called: wind turbine efficiency or capacity factor), the fraction of the name plate capacity delivered in a specific time period, is absent in the equation.

Reality

Does an efficiency loss of this magnitude actually occur? We were unable to find data on this effect. In our earlier article we called this " a well-kept secret". We did receive promises from researchers that they would try and send us the relevant information. So far, we have not received data. Electricity producers, apart from EPZ(Zeeland), have not provided us with the information. Again, we have received promises that this will be subject of study.
 F. Udo[3] has made estimates on the basis of performance data of various generating units. These estimates show negligible overall fuel and emission savings during wind farm operations. He also focusses on the technical (in)ability to fit in the wind generators in the overall system.
 B. Chr. Ummels sees no difficulty for this fitting in of wind power, even when the Dutch wind generating capacity would be 12 GW (Ph. D. thesis[4] Delft University). Udo shows however, that according to Ummels' own calculations (in his figure 2.12, ibid.) either the conventional power stations or the wind farms have to be switched off for about half of the time. This of course destroys the security of electricity delivery. Udo estimates the average efficiency of the Dutch conventional power stations to be 50%. The actual figure for the year 2007 is about 43,5% (see below). Comparing these two figures gives an indication of the effect of running below peak efficiency or at variable load. An efficiency loss of about 2% caused by fluctuating wind supply is therefore not unreasonable at all. The effect of such efficiency loss is, however, that no fuel or emission reduction occurs at all.
 J.Soens[5] calculates – in the same way as done by Ummels that for the Belgian situation a maximum wind contribution can only be 700 MW (17 times less than Ummels' goal) to reach the point beyond which adding wind farms becomes counterproductive.
 In the spring of 2009 a Delft group published a report[6] in which the efficiency loss due to wind power addition to the grid was mentioned, but not quantified.
 Kent Hawkins[7] recently published a study of the technical characteristics of gas

powered electricity generators, which are used for back-up of other units. He concluded : *"The general conclusion is clear: industrial wind power does not produce the claimed benefits of reductions in fossil fuel consumption and CO_2 emissions when up-and-down backup generation inefficiencies are taken into account."*

W. Katzenstein and Jay Apt[8] address the emission of CO_2 and other gases as a result of rapid output change of natural gas fired generators. As far as we can make out, their study does not consider the effect of having to replace the slowly reacting, but efficient generator systems (efficiencies up to 58%) by the quickly responding but inefficient (about 30%) gas turbines. Nevertheless, they find that the quick ramping up and down of the gas turbines leads to a reduced (75-80%) emission saving compared to the one expected when this effect is not taken into account. We note that CO_2 emission is roughly proportional to natural gas consumption.

The Dutch **Ministers of Economic Affairs and of the Environment** replied to questions in Parliament on February 10 2010 on this issue. Their answer contains the following passage: *" When wind electricity is supplied, conventional power stations will step down their power, and also use less fuel and emit less CO_2, to allow for the use of wind electricity".* They also state that, on the basis of *"verified"* numbers, a reduction in output by 1/3 leads to 31,6% less CO_2 emission. They have not indicated how these figures were verified. That is impossible anyway, because in the report from the Delft group, that they quote[6], this information is not provided. A simple model calculation for an existing modern, rapidly responding combined cycle power station of known performance characteristics shows that an output reduction of such magnitude causes an efficiency decrease from 55% to 40%. In that case the fuel saving is about zero, as is the CO_2 emission reduction. The Dutch parliament has thus been informed incorrectly. May be members of parliament should directly contact the Delft group.
(New questions by MP De Mos, were answered in March. The ministry sticks to its wrong arithmatic. It does recognize the occurrence of efficiency losses[14].)

  People and organizations go a long way in defending wind farms. NUON, a Dutch electricity provider running an offshore wind farm, renovated a number of old (inefficient) gas-fired power units to cope with the rapid wind variations and its consequences for the electricity supply[8]. Udo (op. cit.) provides an interesting analysis of the resulting effects. Anyway, one keeps stations in operation with low efficiency and thus high fuel use and emissions rather than reducing fossil fuel use and emissions by upgrading to more efficient units.

The Netherlands

The Netherlands uses various power sources for electricity generation. Most use fossil fuel. The share of each power type is presented in table 1.

Table 1

Data CBS Statline 2007[10]			
type	E_i [GWyr]	F_i [GWyr]	R_i
power plants	8,04	18,45	43,6%
other producers	3,97	12,99	30,5%
nuclear	0,48	~ 0	n.v.t.
power plants excl.nuclear	7,56	18,45	41,0%
sustainable	0,87		
grid losses	0,53		
wind	0,39		
nett import-export	2,01		
Tot. central combined heat/elec +decentral ditto	8,04	18,45	43,6%
tot.centr.combined heat/electr.	3,23	7,48	43,2%
tot.centr. not combined	4,81	10,97	43,8%
total supply	14,02		
total production	12,01		
nett import-export	2,01		
total decentralized combined h/e+non combined	3,97	12,99	30,6%
total decentral combined h/e	3,38	12,28	27,5%
totaal decentral non combined h/e	0,59	0,71	83,0% (?)

In the table, the symbols E_i, F_i and R_i refer to, respectively, the produced electricity, fuel used and resulting efficiency for the particular source. We use the most recent year for which almost all values have been verified (and/or 'corrected') by CBS. The numbers for the year 2007 refer to the situation with wind generation "fitted in". E_i, F_i and R_i are not all the same quantities as used in the formulae (1) to (6a). In these formulae E and F are the assumed electricity production and the accompanying fuel use, in case no wind turbines would have been connected to the grid.

Some electricity providers in the Netherlands also supply (waste) heat for space heating and the process industry. We have assumed that this heat supply is driven by the demand for electricity, thus not requiring additional capacity variations in the electrical power generation. This does not apply to decentralized combined heat and power generation. Those systems are in most cases driven by the heat demand. Without further specific data one cannot decide whether this

generating capacity can be varied in response to rapid variations in electricity demand (or supply from other sources). The table also shows data on import and export of electricity. We do not know the degree to which this electricity import into and export from the Netherlands is controlled or controllable by rapid demand fluctuations inside the country, just by price differentials or by any other factor.

The CBS data are generally in line with our own gross estimatess. We are unsure, however, about the fossil fuel use of small scale combined heat and power generators. Are such systems also relying on non-fossil fuel? However, because the contribution of these small generators to the overall system is modest, this has a limited effect on the uncertainty in our results below.

We will calculate the efficiency effect for various assumptions. We want to determine the efficiency loss caused by the wind supply fluctuations at the point where the fuel saved by the wind is equal to the fuel lost by the efficiency reduction of the back up system. In other words, the point where $\Delta F = 0$. At this point the fuel consumption F from formulae (1) to (5) above is obviously equal to the fuel figures given by CBS. However, for the generated electricity E we need to add to E_i the electricity generated by the wind (0,39 Gwyr, from table 1), unless the figure already includes the wind contribution. In the first case we get:

$$E = E_i + 0,39 \text{ [GWyr]}$$

Results are summarised in table 2:

Tabel 2

Efficiency & efficiency decrease at the turning point				
for	E_i [GWyr]	E [GWyr]	F [GWyr]	R	ΔR
total supply	14,02	14,02	31,44	44,60%	1,24%
national production	12,01	12,01	31,44	38,20%	1,24%
ditto excl.sustainable, incl. wind	11,53	11,53	31,44	36,68%	1,24%
ditto, excl.decentral combined heat/electr.	8,15	8,15	19,16	42,54%	2,04%
power stations+wind	8,04	8,43	18,45	45,68%	2,11%
ditto excl.nuclear +wind	7,56	7,95	18,45	43,10%	2,11%

In the first row, the **Total Supply** includes the nett result of import and export. Because the Netherlands was a nett importer this resulted in electricity without fossil fuel expenditure and thus a higher overall fuel efficiency. The import only costs money, but that is not under consideration here.

The second row, **national production** eliminates import, but includes the ("non-wind") sustainable component. This sustainable component is probably not required to adapt to wind fluctuations.

The third row **national Production incl wind, excl sustainable** is probably the most desirable mix to adjust to the wind fluctuations if this could be organized with so many suppliers, each with their own fluctuating demand. A Smart Grid could help accomplish this.

The fourth row eliminates **the decentralized generation,** thus painting the situation where such generation is not involved in compensating for the wind variability.

The next rows show **the large power stations with and without the single Dutch nuclear power station**. The latter has not been required to help out against the wind variations. It remains at full power as long as the electricity demand in the country is larger than the so called 'must-run' level[10]. This power station increases the pseudo fossil fuel efficiency of all large power stations incl. wind with ± 2,6 %. The turning point is hardly affected.

Discussion

These calculations indicate how small the overall efficiency decrease of conventional electricity production needs to be to reach the point where no fuel is saved or CO_2 emission reduced *in the case when these conventional power stations are required to compensate wind electricity variability.* Obviously, wind variability can be larger than that required to reach the turning point and in such a case wind energy leads to increased fossil fuel use and CO_2 emission.
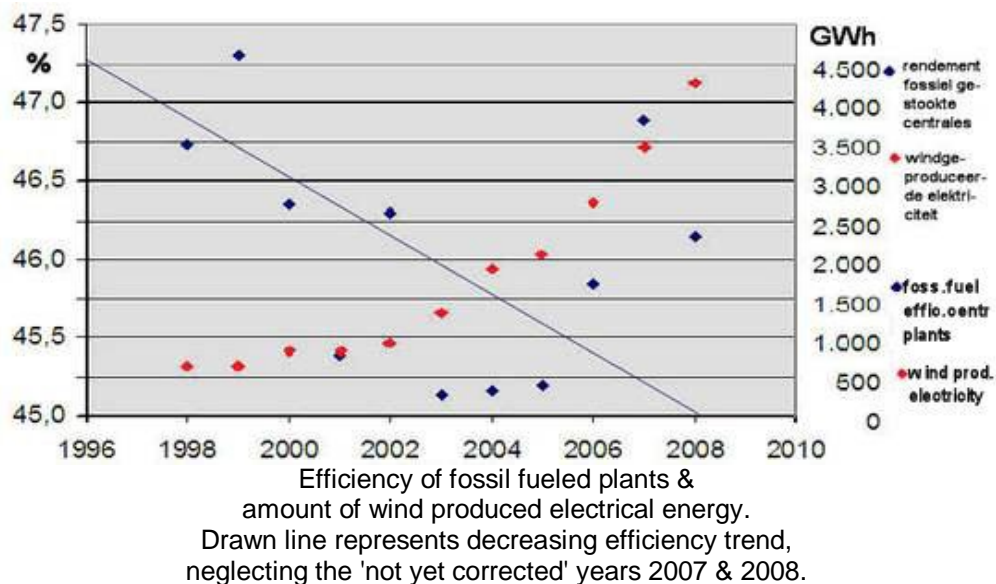
 Let us also bear in mind that the building, erection and maintenance of wind turbines requires fossil fuel as well. The turbine steel and other material and the (concrete) foundation require energy for their manufacture. A wind farm requires a conventional power station with a power equal to the maximum power of the wind farm. A wind farm with a 25% duty factor requires a back up station with four times the power of that belonging to the actual electricity produced by the wind farm. A critical analysis of the pay back time of the wind farm fully accounting for all fossil fuel expenditure in its manufacture, operation, maintenance and back up requires another study.

 Our preliminary estimate, based on data from J. van Oorschot[13] shows the energy pay-back time to be minimally 1,5 years. This period is a very optimistic minimum. In this estimate the energy costs for the manufacture of the back up units, the extra high tension grid, transformers and regulating systems etc. The Dutch Gasunie, managing the natural gas distribution grid, announced in December 2009 to plan extra gas pipelines, amongst others because wind energy requires so much extra natural gas. In our estimate we have used the overly optimistic output formula used by the Ministry of Economic Affairs which we have shown here to be wrong. In addition one has to account for the fossil energy costs of maintenance of the turbines, which especially in the case of offshore placement will be significant.

It is quite conceivable that the efficiency reduction of the conventional power systems is not noticed by the operators. Wind electricity has as yet only a tiny contribution in Holland: only some 3,3% of the national electricity production and therefore less than 0,3% of the national energy use. (Do bear in mind that the amount of conventional back up required is about 4 times as large). The wind contribution has grown rather smoothly, and thus the resulting efficiency decrease is also slowly growing. In the period of wind turbine capacity addition conventional installations have probably been replaced by more efficient ones. This may well have masked the negative effect of the wind turbine addition. As an example, dual cycle gas turbines run at almost 60% efficiency, although it takes about one hour before this level is reached. As long as the steam cycle is not operational (i.e. during this hour) these machines run like open cycle gas turbines at 25 to 30% efficiency.

In figure 1 the development of the efficiency of fossil fuel driven power stations is shown for the period 1998 to 2008. The CBS figures for the years 2007 and 2008 are provisional. (There is also a difference between tables, but within one table there is consistency.) It is clear that the efficiency is not a stable quantity. It can only be calculated 'after the fact' and without detailed additional data from the producers the cause of the variation remains unknown.

Figure 1

Efficiency of fossil fueled plants &
amount of wind produced electrical energy.
Drawn line represents decreasing efficiency trend,
neglecting the 'not yet corrected' years 2007 & 2008.

In an earlier paper[1] we proposed an algorithm to calculate the effect on the overall efficiency of all conventional power stations while only part of the powerstations effectively are required to back up the wind turbines. We start from the equation:

$$E = E_w + E_{bu} + E_n \qquad\qquad (7)$$

in which E_{bu} is the amount of electricity produced by the back up units, and E_n is the amount of electricity produced by the power units that can work without disturbance, i.e. as if no wind variation needs to be compensated. The fuel use when wind electricity is added is now equal to the sum of the undisturbed and the disturbed conventional production, and with formula (3) we can write:

$$(E - E_w) / (R - \Delta R) = E_{bu} / R_{bu} + E_n / R \qquad (8)$$

When the duty factor of the wind turbines is equal to b, one requires conventional capacity to deliver in case there is no wind to the tune of E_w / b. Overall, the back up system only has to deliver $E_w / b - E_w$ Because $E_w = aE$ we get:

$$E_{bu} = aE(1 / b - 1) \qquad (9)$$
$$E_n = E - aE - aE(1 / b - 1) \qquad (10)$$

Inserting (9) and (10) in (8) one gets at the turning point (no overall saving), where ΔR = aR:

$$(\Delta F = 0 \text{ if}) \ \mathbf{R_{bu} = R(1 - b)} \qquad (11)$$

This critical *efficiency value of the back up units at the turning point* is independent of the fraction of the wind generated electricity, but directly related to the 'duty factor' of the wind turbines.

 In the Netherlands in 2007 a = 4,63%, and we assume b to be 25% .(This is more favourable than in Germany, where the nation-wide value for b was on average over several years about 17%, with variations over the years from 14% to 21 %.) The turning point in Holland is therefore always some 75% of the average 'normal' efficiency factor. The result of the calculations is shown in table 3, where we show the overall efficiency reduction ΔR versus the efficiency of the actual units doing the back up.

<div align="center">

Table 3

The efficiency of the units which compensate wind energy fluctuations as a function of the total efficiency reduction of the conventional units (based on CBS-data for the Netherlands, 2007). We thank Kent Hawkins[12] for his contribution to this table.

ΔR (van totaal rendement)	efficiency back-up units (2007) R_{bu}	ditto 2 x as much wind turbines $R_{bu,2x}$
0,00%	45,00%	45,00%
0,50%	41,77%	43,40%
1,00%	38,92%	41,89%

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1,50%	36,38%	40,44%
2,00%	34,10%	39,06%
2,50%	32,05%	37,74%
3,00%	30,19%	36,48%
3,50%	28,50%	35,28%
4,00%	26,95%	34,12%
4,50%	25,52%	33,01%
5,00%	24,21%	31,95%

 Table 3 demonstrates that at a hardly noticeable efficiency decrease for the overall system (Small compared to the yearly fluctuations in this overall efficiency number.) the stations effectively providing the back up are operating at the indicated reduced efficiencies. In case all back up for wind farms in Holland would be provided by open cycle gas turbines, having a 25% to 30% efficiency only (Electricity producer NUON is doing this for its offshore wind farm), in 2007 we would have been beyond the turning point. Under the same conditions as in 2007 (same b, same total of electricity supply, but with twice the amount of wind electricity and consequently less conventional contribution), the R_{bu} threshold would remain ~ 34% and again there would be no saving. More fuel would be burned and more CO_2 emitted than in the case where no wind was being used. Pay-back of the energy spent during construction and being spent to run the extra kit is obviously out of the question.
The conclusion is independent of the wind contribution: If the wind contribution is n times larger, the turning point remains at **R_{bu} = 34%.**
At 9% wind electricity the power stations held hostage by the wind is already about ~41% of the total conventional capacity

 We have also calculated, using formula (4) how much fuel is saved for the 2007 wind energy production of 0,39 GWyr when using different realistic back up configurations. Figure 2 presents the results, being the fuel saving ΔF as a function of the efficiency decrease ΔR. It is shown that in all configurations the fuel saving turns zero when roughly 2% efficiency is lost due to forced output variations to compensate for wind variability.

Figure 2

ΔF [GWyr]
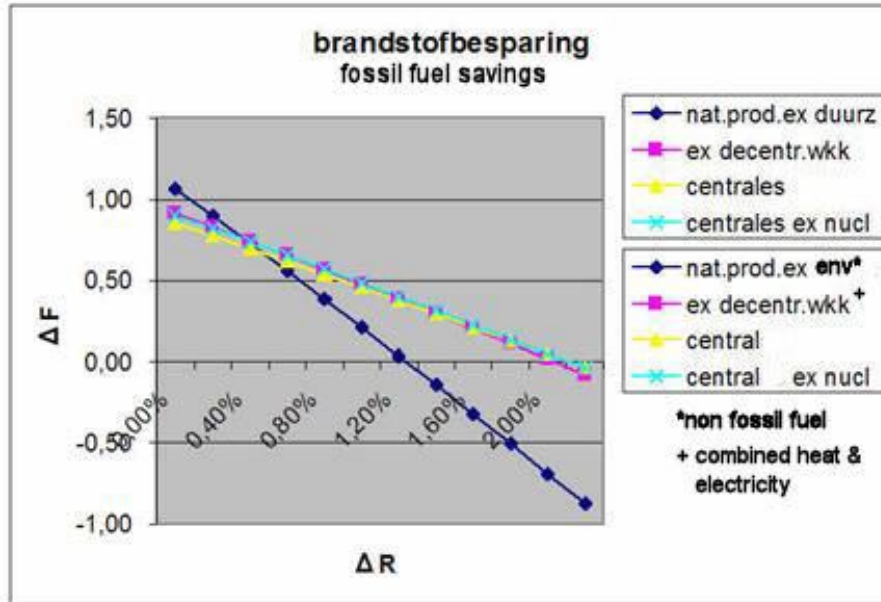
Fossil fuel savings as a function of
decreasing efficiency for different
'back-up' strategies.

Conclusion

The use of wind energy for electricity generation *in combination with the requirement* for fossil fuel powered stations to compensate for wind fluctuations can easily lead to loss of the expected saving in fuel use and CO_2 emission. In addition, the conventional stations will be subject to accelerated wear and tear.
 It is recommended to get an accurate and quantitative insight into these extra effects *before society sets out to apply wind energy on a large scale*. Producers must be required to publish data on the efficiency, the wear effects and the fuel use when wind energy is added on.
 Economical energy storage and buffering methods are an essential prerequisite for large scale application of wind energy for electricity production.
 It is conceivable that the (counter intuitive) use of wind energy in the Netherlands to produce hot water rather than electricity is to be preferred if one wants to achieve the objective of reduction of fossil fuel use and CO_2 emission.

Nieuwegein/Leidschendam
2010 04 18.

References & notes.

[1])   K. de Groot & C. le Pair: De brandstofkosten van windenergie; een goed bewaard geheim (The fuel costs of wind energy: a well-kept secret.); SPIL 263 – 264 (2009) p.15 ff.; also on the WWW .

[2])   Senternovem, the R&D agency of the Ministry of Economic Affairs responsible for a.o. Innovation and energy supply, confirmed as follows: (E-mail S. te Buck to S. Zwerver 2010 01 04) "…In this calculation we start from the primary energy requirement which is avoided and therefore we divide by the efficiency of the electricity generation…". In our symbols: $\Delta F = E_w / R$, as in (2) with $\Delta R = 0$. However, because $\Delta R \neq 0$, the remarkable consequence of this official calculation method is that it would become possible to eliminate fossil fuel use worldwide by causing the wind turbines in the Netherlands to sufficiently lower the efficiency of conventional power stations. ($R \rightarrow 0$, $\Delta F \rightarrow \infty$) ☺ .

[3])   F.Udo: Besparen windmolens CO_2? (Do wind turbines save CO_2?), Dec. 2009: http://www.groenerekenkamer.com/node/946

[4])   B. Chr. Ummels: Power system operation with large-scale wind power in liberalised environments; Diss. TU Delft 26 feb 2009.

[5])   J. Soens: Impact of Wind Energy in a Future Power Grid; Diss. Leuven, 2005 12 05.

[6])   G. Dijkema, Z. Lukszo, A. Verkooijen, L. de Vries & M. Weijnen: De regelbaarheid van elektriciteitscentrales, een 'quickscan' in opdracht van het Ministerie van Economische Zaken; TU Delft, Fac. Techniek Bestuur & Management i.s.m. DNC, Delft 2009.

[7])   K. Hawkins: Wind Integration: Incremental Emissions from Back-Up Generation Cycling (Part I: A Framework and Calculator). http://www.masterresource.org/2009/11/wind-integration-incremental-emissions-from-back-up-generation-cycling-part-i-a-framework-and-calculator/#comments .

[8])   Katzenstein, W & Jay Apt: Air Emissions due to Wind and Solar Power; Environ.Sci.Technol. 43 (2009) 253-258. They notice among else: "...studies have not accounted for the change in emissions from power sources that must be paired with... such as wind..."

[9])   http://www.nuon.com/nl/het-bedrijf/kernactiviteiten/opwekken-energie/centrales/cluster-velsen.jsp .

[10])   The CBS uses different units for electrical and fossil energy. In this paper we use a single unit: GWyr. 1 GWyr = $8,76 \times 10^9$ kWh = $31,536 \cdot 10^{15}$ Joule (Ws). 10^{15} Joule is also called petaJoule, PJ. In de graph, figure 1, we use GWh, with 1GWyr = 8760 GWh.

[11])   J.C.L. van Cappelle, priv. comm.: The efficiency of (the Dutch) nuclear plant at full capacity (= 515 MWe) is 37,7%. At 10% capacity reduction this becomes 37,3%. Below 35% *capacity* the efficiency falls so rapidly, that power generation is no longer realistic. NB. This is the heat efficiency, there being virtually no fossil fuel efficiency.

[12])   Kent Hawkins, Priv.comm. (see note 7) notified us of an error in table 3 of the previous version of this paper. We gratefully acknowledge his contribution to the present version of table 3, in which a third column is now added. We also changed the explanation in the text.

[13])   J. van Oorschot, previously dir. R&D and Bus. Dev. Volker Wessels Stevin, priv. comm.: VWS is involved in the construction and erection of wind farms. His R&D-department made the following sums: a 3 MW wind turbine requires ~ 400 ton steel for its frame and ~ 300 ton for the turbine. Steel costs 8,2 MWh energy per ton. Thus in total 5740 MWh energy. De foundation needs 3000 m^3 concrete (7800 ton). This contains 300 ton cement. Cement manufacture requires 0,5 MWh/ton energy thus total 150 MWh. Together with steel 5890 MWh. In these energiesums no acount is taken of the energy needed for the sand and gravel (dredging), the transportation costs and the installation

costs. VWS estimated total energy requirements to be some 10000 MWh. If the turbine has a 'duty factor' of 25% , it will produce 6570 MWh in one year . Using the simple (wrong) formula this would mean a payback time of 1,5 year. Part of the energy requirements of the manufacture of 'back-up' conventional generators, that of the extra grid (in Germany over 2700 km high tension lines), transformers, here the subsea connectors to England and Norway etc. have to be added. One also has to subtract the energy requirements of the maintenance, which will be substantial in case of off shore operations. We(CIP & KdG) show in this paper that the simple formula for pay back is much too optimistic. We put the nett electricity yield closer to 0 than to 6570 MWh in one year. Assuming it would be 2000 MWh in one year, then we are looking at almost 5 year pay back of the wind turbines themselves.

[14]) The Minister obtained her results by using graphs in the Delft report (6). Non-linearity was not included in the calculations. Neither was the need incorporated to use low efficiency generators because of the rapid change of wind power. Finally, F. Udo, priv. comm., found a calculation error even in the (too) simple, straight forward, departmental computation.